AMC PAMPHLET **AMCP 706-116**

ENGINEERING DESIGN HANDBOOK

ENVIRONMENTAL SERIES

PART TWO

NATURAL ENVIRONMENTAL FACTORS

HEADQUARTERS, U S ARMY MATERIEL COMMAND **APRIL 1975**

DEPARTMENT OF THE ARMY
HEADQUARTERS US ARMY MATERIEL COMMAND
5001 EISENHOWER AVENUE, ALEXANDRIA, VA 22333

AMC PAMPHLET
NO. 706–116

15 April 1975

ENGINEERING DESIGN HANDBOOK
ENVIRONMENTAL SERIES, PART TWO
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PREFACE

This handbook, *Natural Environmental Factors,* is the second in a series on the nature and effects of the environmental phenomena. As the title implies, the handbook addresses a set of natural environmental factors which, for the purpose of this text, comprises:

a. Terrain
b. Temperature
c. Humidity
d. Pressure
e. Solar Radiation
f. Rain
g. Soild Precipitation
h. Fog and Whiteout
i. Wind
j. Salt, Salt Fog, and Salt Water
k. Ozone
l. Macrobiological Organisms
m. Microbiological Organisms

These particular factors were chosen as best representing the needs of the design engineer.

Except for the chapters on macrobiological and microbiological organisms, the information is organized as follows:

a. Description of the factor, its measurement, and its distribution

b. Description of the effects of the factor on materiel and the procedures for design so as to avoid or reduce adverse effects

c. Enumeration of the testing and simulation procedures that assure adequate design.

Thus, the design engineer is provided with a body of practical information that will enable him to design materiel so that its performance during use is not affected seriously by the environment.

It is impractical to acknowledge the assistance of each individual or organization which contributed to the preparation of this handbook. Appreciation, however, is extended to the following organizations and through them to the individuals concerned:

a. Frankford Arsenal

b. US Army Cold Regions Research and Engineering Laboratory

c. US Army Engineer Topographic Laboratories

d. US Army Natick Laboratories

e. US Army Tank-Automotive Command

f. Atmospheric Sciences Laboratory, US Army Electronics Command.

The handbook was prepared by the Research Triangle Institute, Research

Triangle Park, NC—for the Engineering Handbook Office of Duke University, prime contractor to the US Army Materiel Command—under the general direction of Dr. Robert M. Burger. Technical guidance and coordination were provided by a committee under the direction of Mr. Richard C. Navarin, Hq, US Army Materiel Command.

The Engineering Design Handbooks fall into two basic categories, those approved for release and sale, and those classified for security reasons. The US Army Materiel Command policy is to release these Engineering Design Handbooks in accordance with current DOD Directive 7230.7, dated 18 September 1973. All unclassified Handbooks can be obtained from the National Technical Information Service (NTIS). Procedures for acquiring these Handbooks follow:

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CHAPTER 1

INTRODUCTION

This handbook, containing information on 13 natural environmental factors, is Part Two of the Environmental Series of Engineering Design Handbooks. The complete series includes:

Part One, *Basic Environmental Concepts*, AMCP 706-115

Part Two, *Natural Environmental Factors* (this part), AMCP 706-116

Part Three, *Induced Environmental Factors*, AMCP 706-117

Part Four, *Life Cycle Environments*, AMCP 706-118

Part Five, *Environmental Glossary,* AMCP 706-119.

The environmental factors included in this handbook are those of primarily natural origin although certain of them are enhanced, modified, or, in certain circumstances, determined completely by human activities. For example, in urbanized regions the natural effects of terrain are almost completely subdued; within buildings, the temperature, humidity, and pressure to which materiel is exposed are controlled; the occurrence of fog is influenced by human activities; and the ozone generated by equipment can be as important as that produced in nature. So it is with all of the natural environmental factors – they can be deliberately modified by man for his benefit or changed as a result of his activities. Nevertheless, they are predominantly natural.

A design engineer is interested in information that will enable him to make a more satisfactory product. The satisfaction must be expressed by the user and is derived from utility, reliability, maintainability, effectiveness, or cost. These attributes are not, of course, independent of each other. Environmental factors affect each of these; trucks may be useless in deep snow, mud, or sand; electronic devices may be failure-prone in a humid environment; firing mechanisms are difficult to adjust in extreme cold; and aircraft landing systems may be ineffective in a thick fog. These examples illustrate how the environment may limit the satisfaction a user may receive from an item of materiel. The design engineer with knowledge of these limitations can improve his design, thereby producing a better product. This handbook is intended to provide that knowledge in a readily available form.

All existing information on each of the 13 natural environmental factors is not included in this handbook. Rather it is an assemblage of information that was available at the time of preparation. Additional and improved information is available in many cases and, as this is identified, it will be incorporated in subsequent revisions of this handbook. The objective has been to provide as complete a handbook as the time and effort would allow.

The amount and type of information available varies widely among the 13 environmental factors. For example, because of the activities of the US Army Cold Regions Research and Engineering Laboratory, much information is available on the solid precipitants. Also, much information is available on temperature and humidity because of their pervasive importance to materiel. However, since factors such as pressure, fog, and ozone are of lesser importance to design engineers, they are described in shorter chapters. Macrobiological and microbiological organisms are factors encompassing broad topics on which little quantitative information is available. Therefore, these factors are presented in a more descriptive manner than are the other factors for which parametric data are available.

The design engineer is concerned with more than how to improve a given item of materiel so that it better survives a hostile environment. Operational requirements for special materiel capabilities are also within his purview. For example, requirements for fog dissipation and oversnow transport call for special materiel. For this reason, and because future information requirements cannot be forecast, the treatment of environmental factors is broader than would be required for materiel effects alone.

People tend to accept natural environmental factors and their effects on materiel as inevitable. Wood rots, fabric mildews, electronic components fail, shock mounts wear out, food spoils, metals rust, and paints discolor and spall. These common occurrences are often accepted without question. Such deterioration can be avoided, however, by proper selection, protection, and use of materiel. The imposition of procedures wherein such steps are taken involves a decision by the design engineer that the added costs required are justified by total cost of ownership or by operational considerations.

The complex interrelations of the natural environmental factors are prime subjects of investigation in several scientific disciplines. In Table 1-1, a presentation of these interdependencies is given but in a limited sense. The numerical index indicates the degree of knowledge that may be derived on a natural environmental factor, given extensive knowledge of another such factor. In practice, limited information is available on a number of such factors. This combined information provides a much stronger base for deriving additional information than is indicated by the one-to-one relationship given in the table.

Since few of these natural environmental factors are mutually exclusive, the environment at a given place and time is described by a set of factors. All factors in the set interact with materiel, sometimes to produce combined effects and sometimes in synergism to produce effects either in excess of or less than the combined effects. In some cases, these synergisms are discussed. Others are discussed in the *Environmental Series, Part Four, Life Cycle Environments*.

Similar relationships exist with the eight induced environmental factors, which are discussed in Part Three. The importance to materiel of each such induced factor – atmospheric pollutants, sand and dust, vibration, shock, acceleration, acoustics, electromagnetic radiation, and nuclear radiation – is influenced by natural environmental factors.

The set of natural environmental factors in this handbook – terrain; temperature; humidity; pressure; solar radiation; rain; solid precipitation; fog and whiteout; wind; salt, salt fog, and salt water; ozone; macrobiological organisms; and microbiological organisms – is not unique. Different arrangements could have included vegetation, soils and rocks, or moisture in all of its forms, for example, as natural environmental factors. The particular factors that have been included were chosen as best representing the needs of the design engineer.

In the various chapters of this handbook, the International System of Units (SI) is preferred. Often, however, available data and practical considerations have made it necessary to present data in English units so that both systems are employed in almost every chapter. In some cases, data are given in both systems of units in order to relate the less familiar units to those that have been in common usage. An example is the measurement of rainfall for which an immense quantity of data is recorded in inches and the maps showing rainfall distribution are plotted in these units. It would require much effort to convert these data to centimeters; however, presentation of data in both systems of units facilitates the ultimate full conversion.

TABLE 1-1

INTERDEPENDENCE OF NATURAL ENVIRONMENTAL FACTORS

	Terrain	Temperature	Humidity	Pressure	Solar radiation	Rain	Solid precipitants	Fog	Wind	Salt	Ozone	Macrobiological organisms	Microbiological organisms
Terrain		2	2	2	2	2	2	2	1	2	1	3	1
Temperature	2		2	1	3	2	3	2	1	1	1	3	3
Humidity	2	2		1	3	4	2	2	1	1	1	2	3
Pressure	2	1	1		1	2	1	1	2	1	1	1	1
Solar radiation	2	3	2	1		2	4	1	1	1	2	2	1
Rain	2	2	4	2	4		4	2	1	1	1	2	1
Solid precipitants	2	3	3	1	4	4		2	1	1	1	2	1
Fog	2	2	4	1	4	3	3		3	2	1	1	1
Wind	2	1	3	2	1	2	1	3		1	2	1	1
Salt	1	1	2	1	1	2	1	1	1		1	1	1
Ozone	1	1	1	1	1	1	1	1	1	1		1	1
Macrobiological organisms	2	2	2	1	1	1	1	1	1	1	1		4
Microbiological organisms	1	3	3	1	1	1	1	1	1	1	1	2	

Given knowledge of the factor in the left-hand column, the attendant knowledge about the factor at column heading is given by numerical index where 1 = no, 2 = little, 3 = some (or sometimes) and 4 = much.

CHAPTER 2

TERRAIN

2-1 INTRODUCTION

In a broad sense, terrain consists of all the physical features of the landscape (exclusive of the oceans), whether natural or manmade. Thus, terrain includes mountains, rivers, forests, buildings, bridges, etc. In this chapter, however, only natural terrain features and their influence on military operations will be discussed.

Terrain has a profound effect on all military operations. It dictates fields of fire, routes of approach, visibility, cover, and concealment. It has an overriding effect on ground mobility, for terrain is the factor that permits or restricts vehicle and personnel movement. It also affects aircraft operations, determining landing sites, routes during nap-of-the-earth flying, and, to some extent, weather patterns. To the combat soldier, terrain is especially important, requiring study, knowledge, and understanding in order to take proper advantage of it.

This chapter provides information on terrain and its effects on military materiel performance. The chapter begins with a background discussion of engineering geology in which some of the natural forces that largely determine the composition of terrain features are explained. These features occur on a worldwide basis and greatly facilitate the classification of major terrain forms into various subdivisions. Knowledge that a given unknown area has a geological structure and history similar to an already familiar area can provide accurate insights into the properties of the unfamiliar terrain. The classifications of various terrain forms facilitate such associations. Subsequent paragraphs discuss soil properties and standard classification systems for soils. Methods for measuring the physical properties of soils, including structural strength, are summarized in par. 2-4. The resultant effects of these properties are assessed in par. 2-5. Finally, the AMC '71 mobility model is described, and a brief summary of the Army agencies and test sites active in terrain-related studies is presented.

This paragraph does not include consideration of gross geological features such as mountains, hills, or plains, although these are important in terrain considerations. Descriptive geographic information of this sort is available from a variety of sources. For example, one particular type of terrain is discussed in the book *Deserts of the World* (Ref. 1) while the descriptive geography of other specific regions is discussed in many other publications. There is also a series of area handbooks, prepared for the Army. Over fifty of these are available (e.g., see Ref. 2).

2-2 ENGINEERING GEOLOGY

Engineering geology is the study of the composition and structure of the surface and near-surface layers of the earth as they are related to the construction of structures and to vehicle mobility. Observation indicates that these layers are composed of soils, rocks, and water. The actual solid surface is in most places covered with a blanket of soil sometimes extending to a depth of 200 ft, although the soil blanket is usually much shallower.

This paragraph presents the basic fundamentals of engineering geology, independent of the gross geographic features. These fundamentals serve as a general base for understanding and for providing materiel designs suitable for use in any specific geologic environment. A review of similar material is contained in *Earth Science Applied to Military Use of Natural Terrain* (Ref. 3); other general information is contained in books on soil and rock mechanics (Refs. 4-7) and in *Introduction to Terrain-Vehicle Systems* (Ref. 8).

2-2.1 SOIL

It is necessary to distinguish between soil as the farmer thinks of it and soil as the geologist and engineer think of it. Agricultural soil is the fertile land that can be used to grow crops; while engineering soil is any unconsolidated land that is not rock and includes such materials as clay, sand, and gravel. This latter definition of soil is used in this chapter.

Soil lies as a thick blanket on the surface of the earth; in size, however, it is a thin coat of rust on a large iron ball. All soil can be classified as residual or transported. Residual soil is decomposed rock, the result of millions of years of weathering. A cross section of the crust beneath an area of residual soil is similar to that illustrated in Fig. 2-1. On the surface lies topsoil, good for the cultivation of crops, and at the bottom of the sketch is bedrock. Between these fairly homogeneous materials is an area in which the bedrock has only partly decomposed into soil. Since the surface topsoil is a product of the rock, an examination of a soil known to be residual will tell what kind of rock lies beneath it, for different types of rock form correspondingly different types of soil.

Transported soil is residual soil that has been moved from its origin by the wind or water. An important difference between residual soil and transported soil is that residual soil graduates into the underlying rock from which it was derived, while transported soil is usually deposited in layers, not necessarily related to the underlying rock. All soils come from the decomposition of rocks, by a process that has two phases; namely, physical disintegration and chemical decomposition. These are discussed in par. 2-2.2.

Residual soil can be very permeable in its natural state. Consider the geology of Fig. 2-2. Unless something is done to block the flow, water will seep out of the reservoir through the residual soil. To correct this problem, engineers might consider driving sheets of steel piling through the residual soil down into the bedrock. This might be impractical or costly because of the difficulty in driving the piles down to bedrock because of the many boulders and pieces of partially decomposed rock that might exist above the bedrock. Another possible engineering solution might consist of digging a trench through to the bedrock and filling it with concrete. There is, however, a better solution that is cheaper and quicker; it consists merely of filling the trench, not with concrete but with the same soil that came from it. By packing it down, it is possible to reduce greatly the porosity and increase the density of the soil, thus making it very impervious.

Another interesting example is the water pit. Sometimes a water-filled pit having walls and bottom of natural residual soil will lose its water rapidly. However, if the first bit of water poured in is raked around and into the sides of the soil, forming mud, the rest of the water when poured in will be held by the pit. This is called mudding.

It is important to note that residual soil settles and is not nearly as firm as bedrock. Thus, it is best to avoid construction in which one end of the structure rests on rock and the other on soil, for settling of the soil inevitably produces cracks inside the structure.

Soil is not permanently situated, as dust storms make evident. In addition to wind erosion, rivers sweep huge quantities of soil out to sea. The Mississippi River alone dumps 50 tons of soil into the Gulf of Mexico every 6 s; the tremendous quantities of soil washed downstream by the Colorado River will fill the vast lake behind Hoover Dam within 200 yr.

	Organic debris lodged on the soil; usually absent on soils developed by grasses	A_0	Organic debris
	Zone of eluviation	A_1	A dark-colored horizon containing a relatively high content of organic matter but mixed with mineral matter. Thick in chernozem and very thin in podzol.
The solum (This portion includes the true soil developed by soil-building processes.)		A_2	A light-colored horizon, representing the region of maximum leaching for reduction) where podzolized* or solodized.** Absent in chernozem, brown, sierozem, and some other soils.
		A_3	Transitional to B but more like A than B. Sometimes absent.
	Zone of illuviation. (Exclusive of carbonates or sulfates as in chernozem, brown, and sierozem soils. In such soils this horizon is to be considered as essentially transitional between A and C.)	B_1	Transitional to B but more like B than A. Sometimes absent.
		B_2	A deeper-colored (usually) horizon representing the region of maximum illuviation where podzolized or solodized. The orstein of the podzol and the claypan of the solodized solonetz. In chernozem, brown, and sierozem soils, this region has a definite structural character, frequently prismatic, but does not have much if any illuvial materials; it represents a transition between A and C. Frequently absent in the intrazonal soils of the humid regions.
		B_3	Transitional to C
	The parent material	C	Parent material
	Any stratum underneath the parent material, such as hard rock or a layer of clay or sand, that is not parent material but may have significance to the overlying soil	D	Underlying stratum.

*Process of water leaching downward through A and B horizons

**Process of accumulating surface minerals through leaching upward, produced by evaporation in areas of low rainfall causing moisture to be toward the surface.

Figure 2-1. Theoretical Soil Profile With All Horizons Present for Pedological or Engineering Interpretation (Ref. 3)

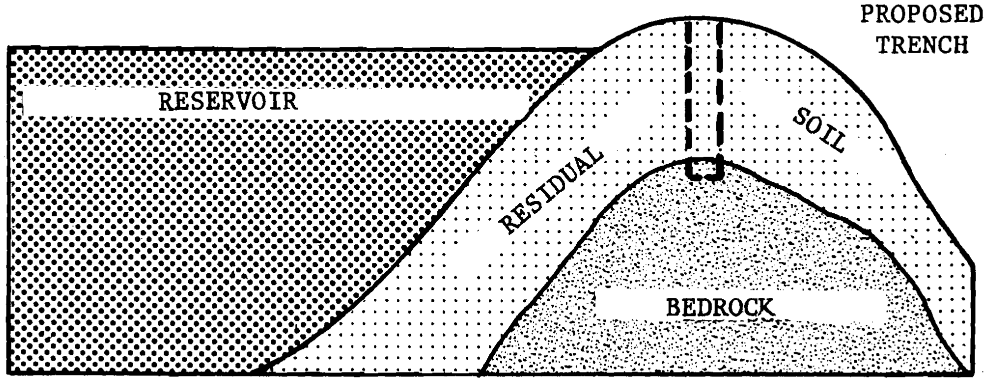


Figure 2-2. Blocking Water Flow Through Residual Soil

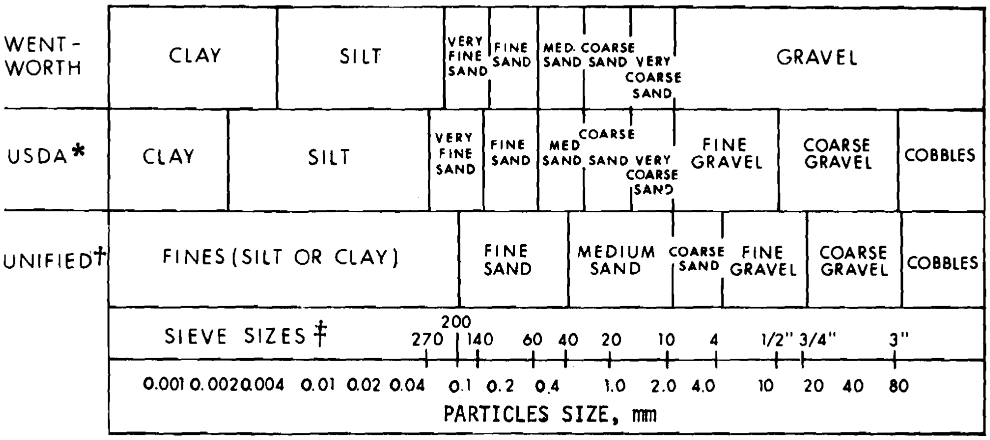
Rainwater also is a chief agent of soil transportation. Ice Age glaciers were effective soil movers because they carried rocks and boulders as well as soil. Since these glaciers retreated some 20,000 yr ago, they are no longer an important consideration in contemporary soil transportation. In local situations, as in arctic and mountainous regions, glacial action continues to transport soil.

A notable effect of this movement of the soil is the sorting of the soil according to coarseness (grain size). The four main classifications of soil with respect to coarseness are:

(1) *Clay*. Very fine particles that, with the addition of organic matter, make up the characteristic features of common mud

(2) *Silt*. Hard, irregular particles, much like sand but much finer

(3) *Sand*. Hard, coarse, irregular particles



*USDA = US Department of Agriculture

†UNIFIED = Unified Soil Classification System (USCS)

‡Sieve sizes are given in the numerical system of the Standard Screen Scale from 270 to 4 and in terms of the sieve opening above 0.25 in.

Figure 2-3. Comparison of Soil Classification Systems (Ref. 3)

(4) *Gravel.* Large, hard particles, including pebbles and small stones.

These classifications are qualitative. Various quantitative classifications exist. Three of these are summarized in Fig. 2-3. Table 2-1 gives additional details of the Wentworth Scale used by geologists.

Sand may be classified by composition as given in Table 2-2 or by origin as in Table 2-3. Mica is a stable material often found in sand. Clay balls – bits of clay that have rolled off a bank, swept downstream, and obtained a protective cover of sand – are also found mixed with sand. Because of the nature of the weathering process, all sand found at a particular location is composed of either rounded or angular particles. Thus, an examination of sand yields information on the nature of the weathering process.

Sands and gravels have a high porosity or void ratio; i.e., the openings and spaces between the grains make ample room for the storage of oil or water. Clay has a still higher porosity than sand – a volume of clay holds more water than an equal volume of sand – but clay will not relinquish water as readily as sand. This indicates that porosity is not the only factor to consider. The water-yielding factor also depends on the permeability, a measure of the ease with which water flows through a material. The spaces between clay particles are too small to permit relatively free flow of water; thus, clay has a low permeability.

The angle of repose (maximum angle from the horizontal of a self-maintaining cone of soil) of dry sand or gravel is about 31 deg. Exceeding this angle during excavation is hazardous, for it invites wall collapse. Sand makes an excellent foundation because it has a high bearing capacity and does not yield by plastic flow as does clay. Quicksand is sand in which there is an upward flow of water. This condition can be eliminated only by draining or pumping.

The clay of most soils is derived chiefly from feldspars. Pure residual clays occur only

TABLE 2-1

WENTWORTH SCALE USED IN GEOLOGIC MEASUREMENT OF SEDIMENTS (Ref. 3)

Descriptor		Size range, mm
Boulder		256
Cobble		64-256
Pebble		4-64
Granule		2-4
Sand		0.06-2
Silt	Dust	0.004-0.06
Clay		< 0.004

TABLE 2-2

SAND CLASSIFICATION BY COMPOSITION

Sand Type	Description
Quartz	A durable weather-resisting sand used in concrete and abrasives
Quartz-feldspar	A product of the weathering of granite, hence, predominately orthoclase
Quartz-feldspar-ferromagnesian	A fast weathering, hence, very scarce sand
Magnetite	(Fe_3O_4) A very hard, durable sand
Garnet	A sand formed from metamorphic mineral rock that is hard, pink, and durable
Coral	A sand formed by the weathering of the coral reef
Gypsum	Very rare sand composed of $CaSO_4 \cdot H_2O$
Placer sands and gravels	Those sands and gravels containing gold, silver, and precious gems from the Spanish placer, meaning a place where gold can be panned
Zircon	Sands bearing rare earths

over pure minerals or sedimentary rocks such as feldspar, kaolin (hydrous aluminum silicate), or slate. Color is a rough measure of purity, since pure clay is quite light in color. Transported clays occur along river banks. Some are washed to sea and deposited as marine clay while others are deposited as lake and glacial clays. Physical properties of clay are described in Table 2-4.

Clay is valuable to the ceramics industry as a material from which to make pottery, tile, etc., but to the engineer it is valuable for grouting because it is highly impervious. Since it is already nearly completely weathered, it may be even better for grouting (as well as cheaper) than portland cement. Engineering applications of clay also employ properties such as:

(1) The more water in a clay, the more plastic it becomes.

(2) Clay is an excellent "puddling" agent.

(3) Clay must be dried before it will slake.

(4) Clay remains suspended in pure water for a long time. However, addition of an electrolyte or almost any salt will cause the clay to settle to the bottom.

(5) Ground water cannot be obtained readily from clay because of its low water-yielding factor, i.e., permeability.

TABLE 2-3

SAND CLASSIFICATION BY ORIGIN

Sand type	Description
River	Variable properties because stream flow produces irregular sorting
Beach	Well rounded and durable because it has been transported far from its origin
Glacial	Produced by glacial action resulting in coarse gravelly texture
Desert	Physically disintegrated fine material washed down mountains by rain and weathered by the wind

(6) Clay cuts easily and trims to sharp surfaces; but it has a low shear strength, so that the walls of a deep trench dug in clay, especially if wet, can collapse without warning.

As a foundation material, clay is extremely treacherous. Because clay is plastic, it may flow from beneath a load. Once the load limit is exceeded, the clay loses much of its original strength due to breakdown in its structure. In construction, this problem of overloading can always be met by simply removing an amount of soil equal to the weight of the structure to be erected. This is quite practical, for most structures are of low density; a skyscraper exerts a pressure equal to that of the average woman's heel. The maximum allowable pressures for various soils or foundations appear in Table 2-5.

2-2.2 ROCKS

Rocks are of two general types: in-place rock and not-in-place rock. In-place rock refers to the bedrock, solid ledge, outcrop, or natural exposure that is part of the rock shell that surrounds the earth and is encountered sooner or later as digging continues downward. Not-in-place rock is rock that is not connected to this bedrock at all but – like large stones and boulders – is loose.

The two main classifications of rocks by origin are igneous rocks and sedimentary rocks. Igneous rocks are rocks that have been formed by the cooling of molten material from deep within the earth. This material was originally magma, a molten mass that exists at great depth beneath the surface of the earth and is periodically forced to the surface as a result of the terrific pressure within the earth. Sedimentary rocks are rocks that have been reformed from disintegrated igneous rocks that are transported and deposited in layers. A third classification is metamorphic rock, a term describing rocks that have been changed and deformed to such an extent (by heat and pressure) that classifying them as either igneous or sedimentary is not practical. Table 2-6 lists the names of various types of each of these major rock classifications.

2-2.2.1 IGNEOUS ROCKS

Igneous rocks are either intrusive (plutonic) or extrusive (volcanic). Intrusive rocks are formed by magma seeping or sweeping through a crack in the crust of the earth but never quite reaching the surface. Instead it

TABLE 2-4

PHYSICAL PROPERTIES OF CLAY

Property	Description
Porosity	High, can hold a large quantity of water
Permeability	Low, can be used to block the flow of water
Color	Wide range. All burnt clays turn red on account of the iron content except glacial clays. Glacial clays turn buff because of their large lime (CaO) content, which combines with the iron to form calcium ferrate ($CaFe_2O_3$).
Plasticity	Depends on the kaolin content. High kaolin content clay can be ground into tiny particles that look like fish scales or small particles of mica. These particles absorb water and give the clay its cohesiveness.
Strength	Varies. Must be measured.
Shrinkage	Large, due to water losses, principally
Fusability	Varies with content. Pure kaolin fuses at about 2,100°C but this temperature is lowered by the presence of basic salts.

forms solidified masses of injected material in the rock that already lies in the crust, tending to take one of the forms illustrated in Fig. 2-4.

Extrusive rock from volcanoes may emanate in a flow or as an explosion. In a flow, lava is the principal constituent, giving off gas and leaving a surface characterized by vesicular zones, flow breccias, and vesicular bubbles; while in an explosion, the main discharge comes in the form of bombs, blocks, ashes, and dust. The vesicular bubbles of lava often become filled with a mineral matter called amygdaloid. Flow breccias are breaks in the lava flow that have been cemented subsequently by fresh flow. The foundation and abutments of Hoover Dam are set in flow breccia.

As various pressures force the magma up toward the surface, heat escapes and the magma cools to a crystalline rock. These crystals are of different sizes, shapes, and compositions and have different thermal and elastic coefficients of expansion; hence, the stresses that act on this crystallized magma as it is forced toward the surface are uneven and tend to produce cracks in the rock. These stresses can be attributed to two sources:

(1) *Thermal contraction*. The hot rock cools as it moves nearer the surface and, as differently shaped crystals with different coefficients of expansion are formed, uneven stresses are set up.

(2) *Elastic expansion*. The tremendous pressure that is on the rock when it is miles

TABLE 2-5

ALLOWABLE PRESSURES FOR THE DESIGN OF SHALLOW FOUNDATIONS (Ref. 3)

Type of base	Maximum allowable pressure*, tons ft^{-2}
Hard, sound rock	40+
Soft rock	8-10
Hardpan overlying rock	10-12
Compact gravel and boulder-gravel deposits; very compact sandy gravel	10
Loose gravel and sandy gravel; compact sand and gravelly sand; very compact inorganic sand-silt soils	5-6
Hard, dry, consolidated clay	5
Loose coarse to medium sand; medium compact fine sand	4
Compact sand-clay soils	3
Loose fine sand; medium compact inorganic sand-silt soils	2
Firm or stiff clay	1.5-2
Loose saturated sand-clay soils; medium soft clay	1

*Values are not applicable if foundation soil is underlain by a weaker soil. Use of the tabular values for the design of shallow foundations of major structures is not recommended unless their use is justified by experience or additional investigation.

below the surface decreases sharply as it approaches the surface. Although rock may not appear very elastic, it expands considerably and, because of the formation of many different crystal types, unevenly, when it is relieved of some of this terrific pressure.

The action of these uneven thermal and elastic stresses produces many cracks and slits in the rock into which water seeps. The rock, must now tend to equilibrium with the water, which usually contains acids (principally carbonic) powerful enough to attack the rock and change its composition over the many years of intimate contact.

Rocks are continuously changing, never reaching a permanent stable state. The rock cycle is illustrated in Fig. 2-5.

Water is not the only agent that breaks down rocks. Rock decomposes in dry desert

TABLE 2-6

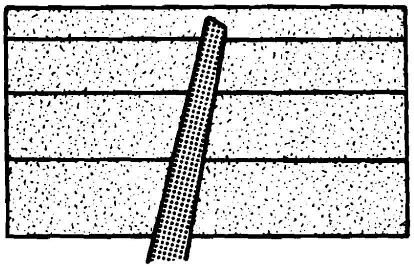
TYPES OF ROCKS (Ref. 3)

Igneous rocks			
	Composition		
Texture	Acidic rocks (more than 50 percent silica)		Basic rocks (less than 50 percent silica)
	Light-colored minerals, chiefly feldspar, predominate		Dark-colored minerals predominate
	Abundant quartz	Little or no quartz	Abundant amphibole pyroxene, and plagioclase feldspar
Coarse-grained (mineral crystals easily visible to naked eye).	Granite	Diorite	Gabbro
Fine-grained (mineral crystals generally invisible to naked eye).	Rhyolite	Andesite	Basalt
Glassy	Obsidian, pitchstone, pumice		

Sedimentary rocks		
Type	Sediment	Rock
Clastic or fragmental	Coarse (gravel) Medium (sand) Fines (silt and clay)	Conglomerate Sandstone Siltstone and shale
Pyroclastic	Coarse (cinder) Fine (ash)	Agglomerate Tuff
Chemical precipitates and evaporites	Calcium carbonate ($CaCO_3$)	Limestone
	Calcium magnesium carbonate ($(Ca(Mg,Fe)\ CO_3)$)	Dolomite
	Silicon dioxide (SiO_2)	Chert
	Calcium sulfate ($CaSO_4$-$2H_2O$) ($CaSO_4$)	Gypsum anhydrite
	Sodium chloride (NaCl)	Rock salt
Organic	Calcium carbonate (animal remains	Coquina, some coral rock, and chalk
	Carbon (plant remains)	Coal

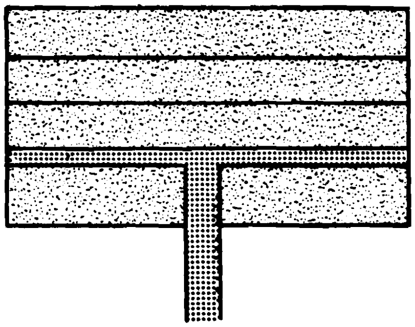
Metamorphic rocks

			Nonfoliated and massive		
Texture	Rock	Characteristics	Mineral Content	Rock	Characteristics
Coarse-grained	Gneiss	Streaked or banded; imperfectly foliated	Chiefly quartz	Quartzite	Hard and brittle
Medium-grained	Schist	Well foliated; splits easily; generally rich in mica	Chiefly calcite (or dolomite)	Marble	
Fine-grained	Slate	Splits readily into smooth sheets	Chiefly hydrous magnesium silicate	Some types of serpentine	Fairly soft; green



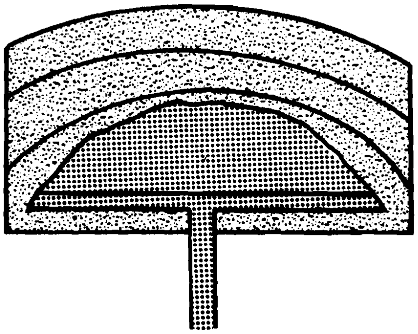
(A) Dike

A dike is perpendicular to the layers of the crust, slipping into a crack in the crust.



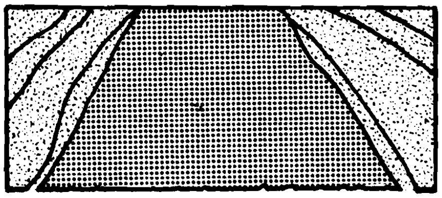
(B) Sheet

A sheet is parallel to the bedding of existing rock. This is because the magma is unable to advance further upward and can only spread laterally.



(C) Laccolith

If a sheet is unable to spread out or advance upward, the magma pressure will lift the entire crust of the earth and form a laccolith.



(D) Batholith

A batholith is a laccolith that has no floor of sedimentary rock (or of any kind of rock).

Figure 2-4. Forms of Intrusive Rock

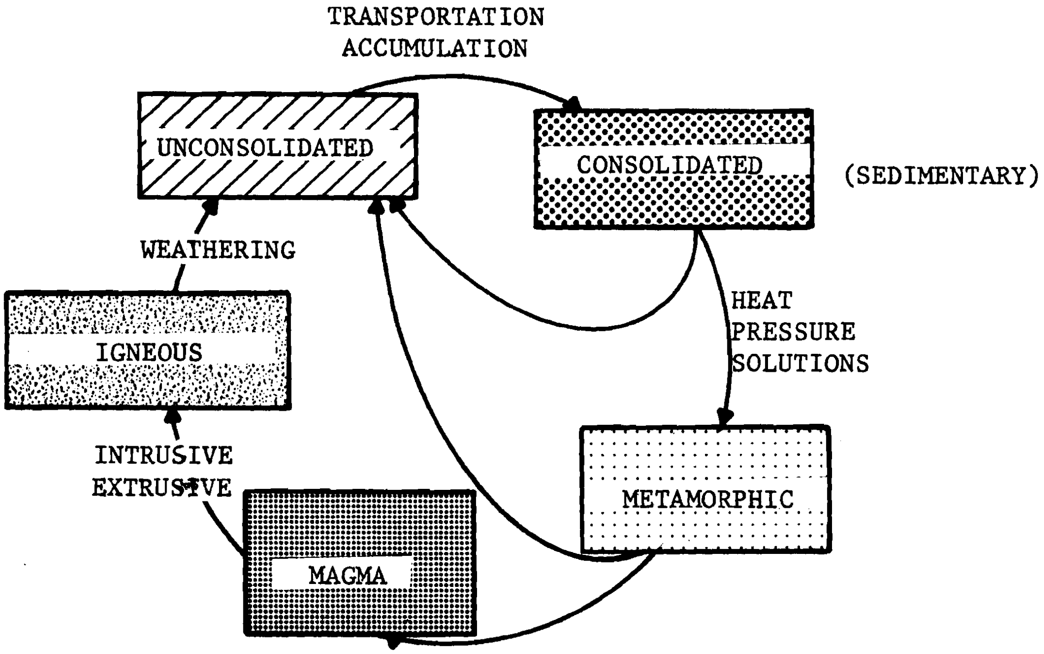


Figure 2-5. Cycling of Rocks

areas as well as in moist areas. Desert sand appears to have been through a fine grinder. It is a product of weathering without chemical action.

As noted in par. 2-2.1 the disintegration of rocks can be classified as either physical disintegration (mechanical breakdown) or chemical decomposition. A number of important mechanisms of physical disintegration are given in Table 2-7. The conditions that favor physical disintegration are those that aid the action of any of the agents. The extreme northern and southern latitudes experience frost action and large temperature changes, and mountainous areas increase the probability of falling and tumbling due to gravity. Consequently, these areas show much physical disintegration of rocks. Physical disintegration produces small sandlike particles with little or no clay.

The chief agents of chemical decomposition of rocks are air and water. The chemical composition of the average igneous rock appears in Table 2-8. Oxygen, originating in the air, attacks only the ferrous oxide, oxidizing it to ferric oxide. To react, however, the oxygen must first be dissolved in water. The most destructive acid is carbonic acid, which forms carbonates with the basic oxides in the rock. Although the acid does not attack quartz (a crystalline form of SiO_2), it does form alkaline salts, which in turn will attack quartz.

Some minerals resist the oxidation/hydration reactions; hence, they persevere longer than others. These include;

(1) *Clay*. Composed of SiO_2 and Al_2O_3 (kaolin or hydrous aluminum silicate)

(2) *Ferric oxide*. Composed of Fe_2O_3 (hematite) and similar iron compounds

(3) *Quartz*. Composed of SiO_2, which weathers extremely slowly

(4) *Mica and feldspar*. Found in increasing depth in the residual soil.

The soluble materials in rock that are missing from the residual soil formed from that rock are chiefly carbonates and silicates. The silicates in the soil come not from quartz

TABLE 2-7

PHYSICAL MECHANISMS FOR ROCK DISINTEGRATION

Mechanism	Description
Temperature change	Produces thermal stresses and strains
Pressure release	Uneven elastic expansion produces internal stresses
Gravity	Rolls rocks down hills and smashes them. There is no more effective pulverizer than an avalanche.
Frost action	Water expands as it freezes; the force of expansion bursts open the cracks and crevices of rocks into which water has flowed and frozen. Frost action may also change the center of gravity of a rock and thereby cause it to topple down a slope and break.
Floral growth	The expansion forces of growing roots of trees crack sidewalks and rocks
Mechanical effect	Rushing streams of water dash boulder against boulder and abrade rock with sand and other rocks.
Chemical processes	Chemical action sometimes causes internal expansion and cracking.

but from other more soluble minerals such as feldspar. Iron can be removed from rock as a carbonate, providing it has not been exposed to oxygen, thus allowing the carbonic acid to attack the iron while it is still ferrous oxide (FeO). An oxygen deficiency can be brought about by water percolating through heavy decaying vegetation, which removes much of the oxygen from the sinking water. The formation of soluble ferrous carbonates is responsible for the formation of iron springs – springs that have red and yellow mineral deposits about them. The action is illustrated in Fig. 2-6.

The soluble products of the weathering of rock are swept away with the water into the streams, rivers, and eventually the sea. Sodium is a typical soluble product that is moved around quite a bit. Neither the rock nor the soil wants it.

A paradox is presented by the washing away of limestone, which is chiefly soluble calcium carbonate. Calcium carbonate is plentiful in the rivers and streams that lead to the ocean but in the ocean itself it is scarce. Where does it go? The answer is found in the fact that for calcium carbonate to dissolve, an extra carbon dioxide molecule must be present in solution. This extra carbon dioxide molecule is very unstable and is easily dislodged from the weak chemical bond it has formed ($CaCO_3 \cdot CO_2$). Carbon dioxide seek-

TABLE 2-8

APPROXIMATE CHEMICAL COMPOSITION OF IGNEOUS ROCK

By elements		By oxides		By minerals	
Element	Percent composition	Oxide	Percent composition	Mineral	Percent composition
O	47.29	SiO_2	59.8 (acid)	Feldspar (silicate)	59.2
Si	28.02	Al_2O_3	17.0 (amphoteric)	Quartz (oxide)	20.4
Al	7.96	Fe_2O_3	2.6 (amphoteric)	Ferro-mag. (silicate)	9.3
Fe	4.56	FeO	3.5 (base)	Mica (silicate)	7.7
Ca	3.47	CaO	4.8 (base)	Misc.	3.3
Mg	2.29	MgO	3.8 (base)		
Na	2.50	Na_2O	3.4 (base)		
K	2.47	K_2O	3.0 (base)		
H	0.16	H_2O	1.9 (neutral)		
Ti	0.46				
C	0.13				
P	0.13				

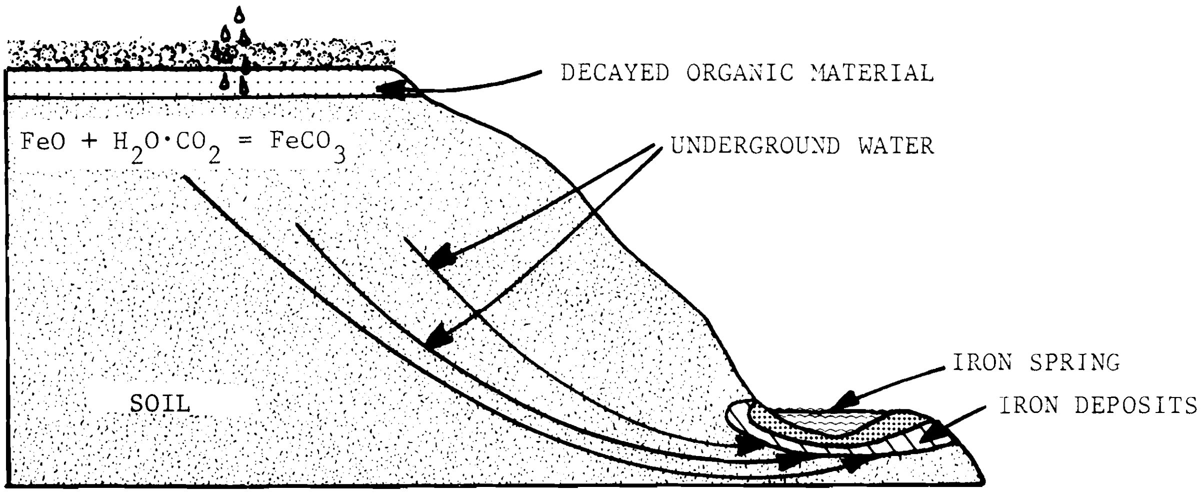


Figure 2-6. Formation of Iron Springs

ing plants are able to break the bond and precipitate the calcium carbonate by absorbing the carbon dioxide molecule. The mere dashing of waves against the shore is often vigorous enough to break the bond and leave white calcium carbonate on the beach. Oysters and other shellfish also absorb large quantities of calcium carbonate in order to live.

2-2.2.2 SEDIMENTARY ROCKS

All products of the weathering of rocks are classified as either regolith or sedimentary rock. Sedimentary rocks are formed by the consolidation of the small constituents of regolith, i.e., the sediments. These sediments include the carbonates and silicates, which are the primary cements in sedimentary rock formation.

The carbonates are carried down rivers and deposited as calcareous ooze, marl, shell layers, or other extraneous matter. These soft deposits are easily solidified for they carry their own cement. They consolidate to form limestone, i.e., solid calcium carbonate; chalk, a soft, inferior rock; and dolomite, which is quite similar in appearance to limestone but consists of calcium magnesium carbonate. Any of these rocks can become more thoroughly cemented and form marble, which is merely ooze that has crystallized and become cemented.

The white cliffs of Dover are a chalky limestone. Indian limestone is a fine limestone for finishing structures since it occurs in uniform color and has large spaces between natural joints, making it possible to obtain many large pieces.

Dolomite and shale are responsible for Niagara (Fig. 2-7). The shale is weathered away much faster than the dolomite and cuts back under the dolomite. This undercut gradually causes pieces of the dolomite to break off but as yet the dolomite has not been exhausted. Thus, the only effect of this weathering has been to push the falls back upstream and produce a rocky gorge containing the remains of the crumbled dolomite.

Pure calcium carbonate will weather away completely. Carbonation is the chief chemical action in this process. Because of this high solubility, limestone country is often full of underground streams. It is the solubility of limestone that makes it a difficult rock to work with. Frequently, cavities and solution channels occur in limestone deposits and often require intensive drilling before they can be located. During the building of the

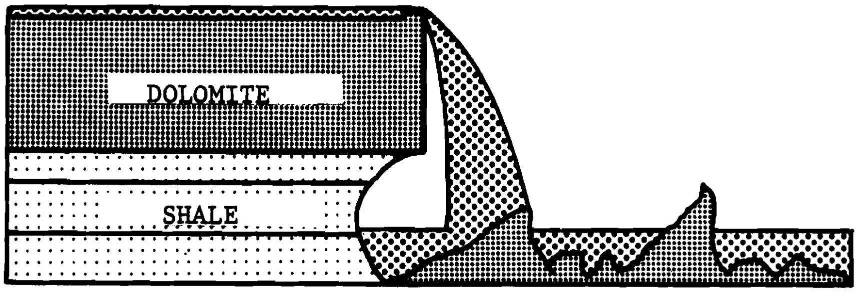


Figure 2-7. Schematic Cross Section of Niagara Falls

Chicamauga Dam, it was necessary to drill over a thousand holes to locate such channels.

Silica salts in solution reach the ocean where they form diatomaceous earth (white deposits of silica). This silica is called flint when it occurs in chalk and chert when it occurs in limestone. The occurrence of chert in limestone determines the difference between good and worthless limestone, since any limestone with the hard bits of chert in it cannot be mined efficiently.

Some sedimentary rocks are formed by organic sediments. The first step is the decomposition into a black muck, which, through progressive consolidation, passes through the following forms in order; peat to lignite to bituminous coal and, finally, to anthracite coal.

Sands and gravel are cemented together by natural processes to form sandstone and conglomerates. The cements are usually silica (silicon dioxide), ferrous oxide, calcium carbonate, or simply clay. Of these, silica probably does the best job of joining. Since they are sedimentary rocks, sandstones and conglomerates usually occur in beds. Ripples that occur naturally on sand beaches sometimes become consolidated in the same pattern in rocks. If a bed has folded, the characteristic that the curvature of the ripple always points upward may be used in identifying the original up side.

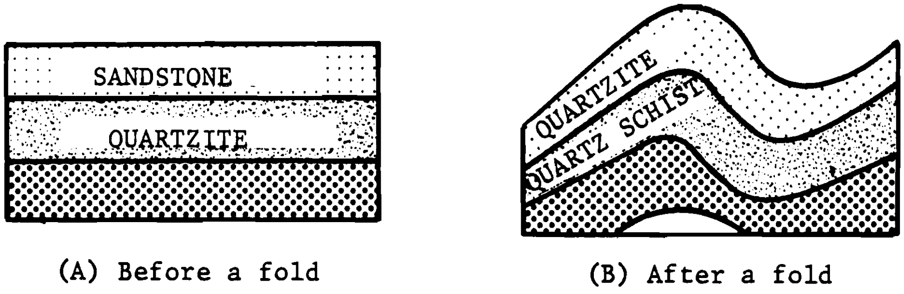
The degree of cementation largely determines the porosity, the resistance to weathering, and the strength of a sedimentary rock. Sandstone formerly was often used for the fronts of buildings and as the final trim to all fancy work, but it has now been largely replaced by Indiana granite, mainly because this granite contains large quantities of calcite, which is strong but is also quite easy to mold.

A sandstone, once cemented, may be either weathered or cemented still further. In the latter process the further cementation changes the sandstone into quartzite. To distinguish between the two, it is necessary to observe the split of a surface – a round split is characteristic of sandstone; a straight split, of quartzite.

Quartzite is a metamorphic form of sedimentary rock, found in layers and beds. Since silica is its principal cementing agent, quartzite is a very hard, strong, weather-resisting rock that, on account of these properties, is quite expensive to drill.

The tremendous earth pressures that accompany a fold are often enough to change quartzite into quartz schist by dynamic metamorphism (Fig. 2-8). This quartz schist may be used as a whetstone.

The rocks of the sand series weather like any igneous rocks. The attack upon them consists of an attack on the cement, which usually weathers relatively rapidly; and an attack on the grains, whose rate of weathering depends largely on the grain composition. The weathering of sandstones produces sand and possibly clay if any feldspar is present.



(A) Before a fold

(B) After a fold

Figure 2-8. Metamorphic Change in a Fold

When clays and muds become metamorphic rocks, they are called shale. Actually the distinction between clay and shale is not so simple as to be explained by physical differences. Often the same material is called clay when it occurs in the regolith and shale when it occurs in the bedrock.

Shale is of two types, compaction and cementation. Compaction shale is formed from clay that has been compressed and squeezed together under a high pressure. Compacted clay will disintegrate if permitted to dry and then soaked in water. The drying and wetting process is called the slake test and is used to spot compaction shales. In cementation shale the clay particles are cemented together and will not slake. However, many gradations exist between pure compaction and pure cementation shale.

Under no circumstances should shale be used as a building stone or as a road material and only a well-cemented shale is used for concrete aggregate. Shale is easy to excavate for it cuts easily and produces no water as clay does. Shale weathers in proportion to the degree to which it has been cemented.

When a shale is subjected to the tremendous pressures that accompany a fold, it becomes slate, a very dense, hard rock without any water. The tremendous pressures squeeze out the water and the carbonates, and mold the remaining elements into thin sheets of higher density. The product is a strong, weather-resistant, watertight slate that makes fine foundation material. Further pressure may convert the slate into a coarse schist.

2-2.3 STRUCTURAL FEATURES

Structural geology is subdivided into two classes of structural features: original and secondary. Original structural features of sedimentary rocks are caused by:

(1) *Stratification.* Sedimentary rockbeds are not infinite but grade into other beds or else lens out (Fig. 2-9).

(2) *Unconformities.* An unconformity is the old land surface now covered by sedimentary rock. The location of an unconformity may tip off the location of sink holes and solution channels that were originally just beneath the old surface.

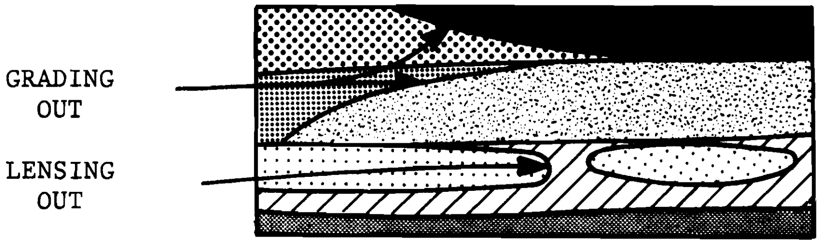


Figure 2-9. Grading and Lensing Out of Sedimentary Rock Beds

(3) *Alluvial fans*. The disintegrated matter washed down the sides of mountains forms long gentle slopes that stretch for miles and miles. These slopes can be very deceptive, leading one to think he is on level ground.

(4) *Delta deposits*. This term describes the sedimentary deposits laid down in a river delta.

(5) *Minor earth movements*. Rock slides and falls in which entire tops of mountains break loose and slide down. The top of a mountain in Alberta slid off and covered 4 or 5 mi^2 below it with 35 ft of rock rubble in a matter of minutes. No important structure should be built around doubtful-looking steep slopes. The collapse of cavern roofs and the consolidation of underlying sediments are other minor earth movements. One should expect many minor earth movements in volcanic country, for the area vacated by the lava when it flows out must be filled, usually resulting in a minor earth movement.

(6) *Major earth movements*. Major earth movements are evidenced by the appearance and disappearance of mountains and other startling changes. Several theories at present attempt to account for these movements:

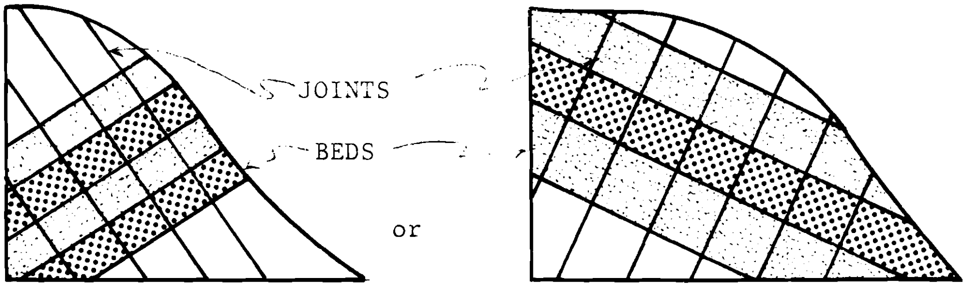
(a) Cooling and shrinking of the earth. The inside of the earth, according to this theory, has cooled and contracted while the crust has not, thus causing the earth to wrinkle. The major premise that the earth is cooling is without proof. Other theories contend just the opposite, that the earth is becoming hotter.

(b) Changes in the rotation rate of the earth. Such changes produce changes in the centrifugal force acting on the earth with the resultant forces causing the folds.

(c) Continental creep. The continents are moving on the surface of the earth. South America and Africa were once part of one landmass, for example.

(d) Isostatic adjustments. Heavy loads cause soil to flow from beneath the load and pile up around the sides till the pressure that the load exerts is equal to that exerted upward by the earth. This action tends to level mountains and valleys. High stresses on rocks produce elastic deformation, fractures, and flows. Rocks need room to crack and burst; if they have no room, they merely flow.

Secondary structural features of sedimentary rocks include joints, faults, and folds. Joints or planes of separation are fractures in rock, produced by earth processes. The spacing of the joints determines how large a piece of rock can be obtained from a quarry. It is the wide joint spacing of Indiana limestone that makes it such good building trim. The attitude of the joints is also an important feature. The attitude illustrated in Fig. 2-10(B) is better in quarrying operations



(A) Poor attitude for quarrying

(B) Good attitude for quarrying

Figure 2-10. Attitude of Joints

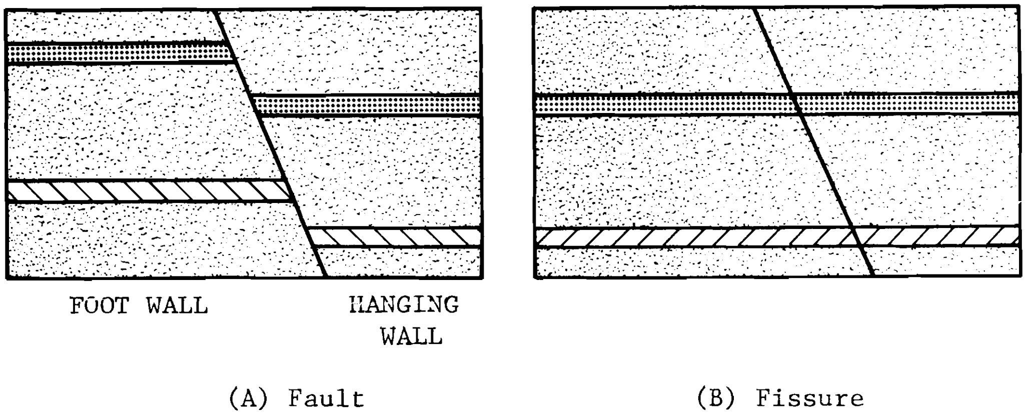


Figure 2-11. Types of Fracture

than that in Fig. 2-10(A), for the rock will fall out naturally as it is cracked and not have to be lifted out as it will in the attitude illustrated in Fig. 2-10(A).

Fractures accompanied by displacements are called faults, while those that involve no displacement are called fissures. Cross sections of each are sketched in Fig. 2-11. The side of the fault that extends above a horizontal plane through a point in the center of the inclined fracture is called the hanging wall side, while the other is called the foot wall side. From this terminology a broad classification of faults is derived in which a normal fault (Fig. 2-12) is one in which the hanging wall has dropped beneath the foot wall, and a reverse fault (Fig. 2-13) is one in which the foot wall has dropped beneath the hanging wall. It is possible to have a totally horizontal fault in which there is no vertical displacement. This was true at the San Francisco earthquake in 1906. Highways and sidewalks had discontinuities in them that ranged up to 20 ft long.

Faults are difficult to find, for nature soon conceals all outward evidence. A fresh fault makes the surface above it look as sketched in Fig. 2-14. This fault scarp is soon eroded away and all that remains is a gouge of shattered and weathered rock, probably overgrown with grass. A stretch of straight stream in a water course that is otherwise ragged and tortuous may mean that in this area the stream flows in a fault gouge.

Since faults are characterized by soft, crumbled rock, they cannot withstand much stress. In tunnelling this fact is important, for unless sufficient support is provided underneath a fault, the walls easily collapse. Building across a fault is dangerous, for any subsequent earth movement will probably cause displacement along the same fault.

When horizontal or nearly horizontal earth pressures pinch a portion of the crust of the earth, the crust often buckles in what is commonly called a fold (Fig. 2-15). A number of special folds are illustrated in Fig. 2-16.

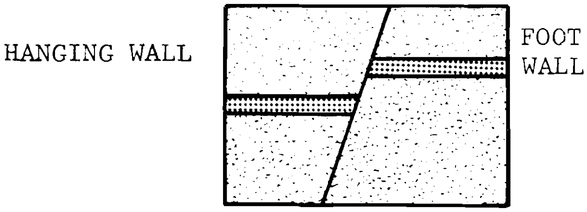


Figure 2-12. Normal Fault

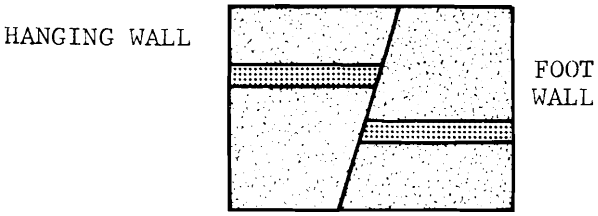


Figure 2-13. Reverse Fault

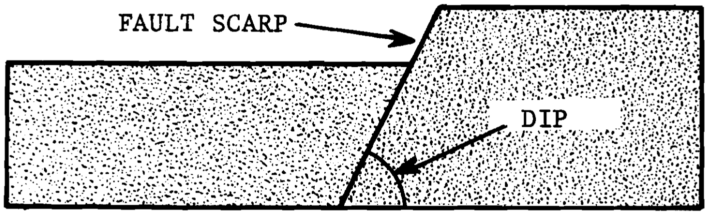


Figure 2-14. Fault Scarp

In mapping, the dip of a bed (the acute angle between the slope of the bed and the horizontal) is indicated by a short arrow perpendicular to the strike (any horizontal line lying wholly in the bed) and pointing toward the younger beds. Mapping illustrations appear in Fig. 2-17.

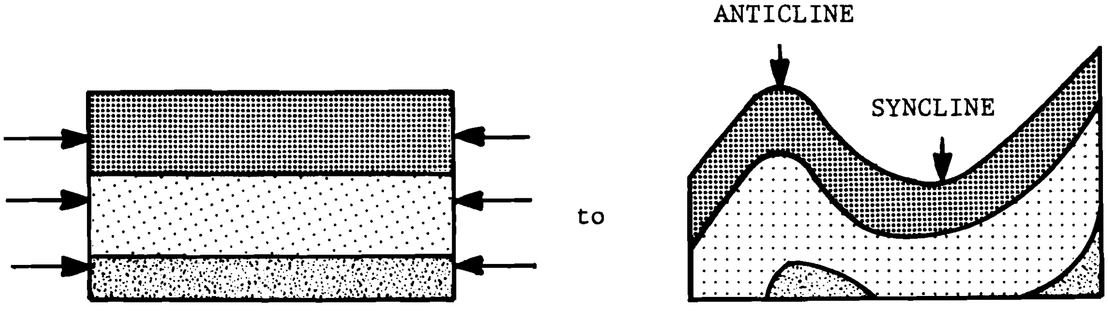
When layers of bedrock are folded, they slip along each other, producing a fractured, slaty cleavage between the beds as in Fig. 2-18. By observing the angle of cleavage, it is possible to determine the direction in which the beds slipped with respect to each other. The "scrub brush" principle states that the bristles of a scrub brush indicate the direction the brush was moved by their slope. Thus, in the illustrations of Fig. 2-19, the brush could have moved only in the direction indicated by the arrows to produce the bristle position shown. The bristles correspond to the angle of slaty cleavage.

2-2.4 GROUND WATER

Ground water is an important source of fresh water. It is found in rocks in original and secondary openings. Original openings include interstices in sediments, partings along bedding planes, vesicules in lavas, and pores in igneous rocks. Secondary openings include solution channels, sink holes, joints, faults, fractures, folds, and domes as seen in Fig. 2-20. Granite is full of water. Farmers used to set off explosives at the bottom of their dug wells to loosen up the granite and get water.

The forces that control the movement of ground water include gravity, capillary action, and gas pressure. The important properties of rock with respect to water are permeability, porosity, water-yielding factor, and chemical weathering.

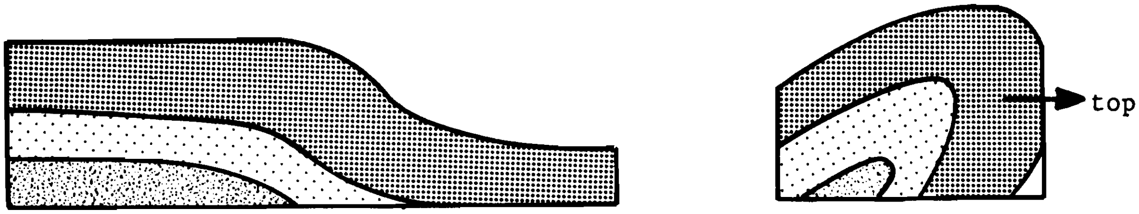
Ground water is principally acidic due to the presence of carbonic acid. Consequently,



(A) Before folding (arrows indicate earth pressure)

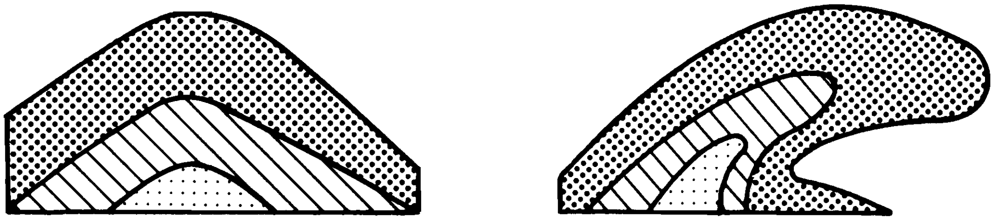
(B) After folding

Figure 2-15. Fold Formation



(A) Monocline (Can be mistaken for a fault)

(B) Overturned



(C) Inclined

(D) Reclined

Figure 2-16. Types of Fold

basic rocks weather faster than acidic ones, producing irregular profiles of weathered rock wherever strips of acidic and basic rock lie side by side. These profiles are important in construction. For example, in Fig. 2-21 the present dam site *A* is poor geologically, for it crosses bands of rock that might easily have a cross-sectional profile like that shown. A much better plan would be to build the dam at site *B* where it would lie wholly within one band that has fairly uniform weathering.

The water table is an imaginary line below which the earth is 100 percent saturated. This line roughly follows the surface but is not constant, varying from wet to dry seasons. The zone of capillarity is the area above the water table into which water is drawn by adhesive forces. Fig. 2-22 illustrates the hydrologic cycle through various media including the terrain.

A perched water table is one that is held at a higher isolated level than the water table of the surrounding area by impervious beds. One can dig a well into a perched water table and find it exhausted and dry the next day or he may drain a lake or swamp dry by drilling a hole through an impervious bed that holds the water up. Water usually runs off ground unless the ground is full of holes, or relatively dry and can absorb it. Topography is a factor. If the water is running rapidly down a steep slope, it will not be as readily absorbed. Plowing across a slope to make the water slow down increases the absorption greatly.

Ground water evaporates directly and through vegetation. The leaves of vegetation transfer moisture from ground to air. In 24 hr a tree transpires many gallons of water into the air. A dust mulch stops evaporation from the ground since it will not permit water to wet it by capillarity. Cultivating crops produces this dust mulch, thus holding the moisture in the ground for the crops.

Artesian springs are those caused by hydrostatic head. Cutting through the water table will produce one under proper condi-

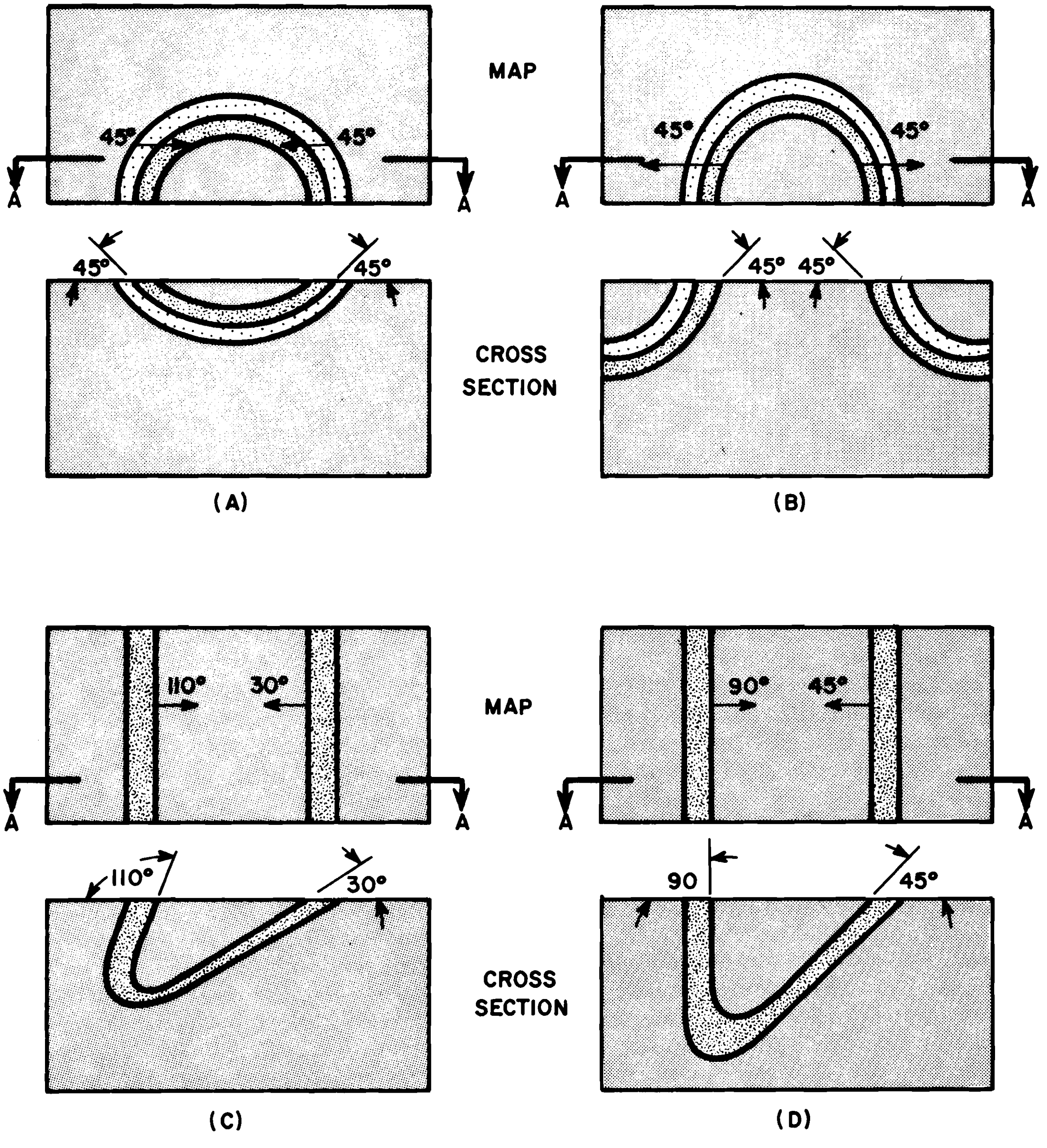


Figure 2-17. Mapping

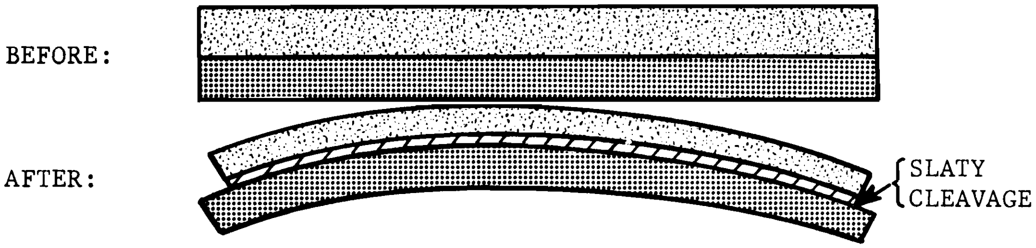


Figure 2-18. Slaty Cleavage

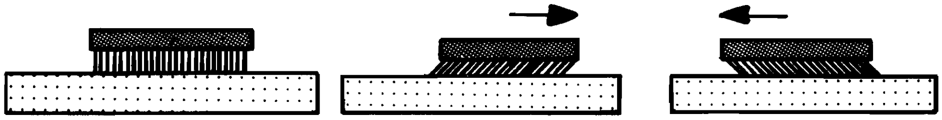


Figure 2-19. Scrub Brush Principle

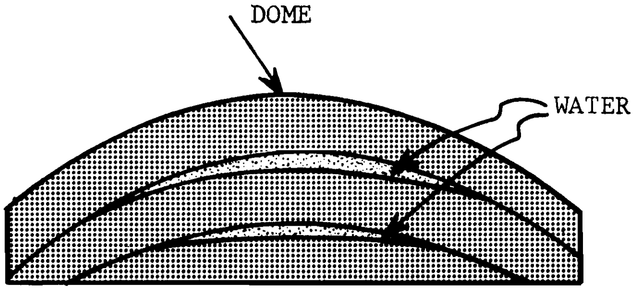
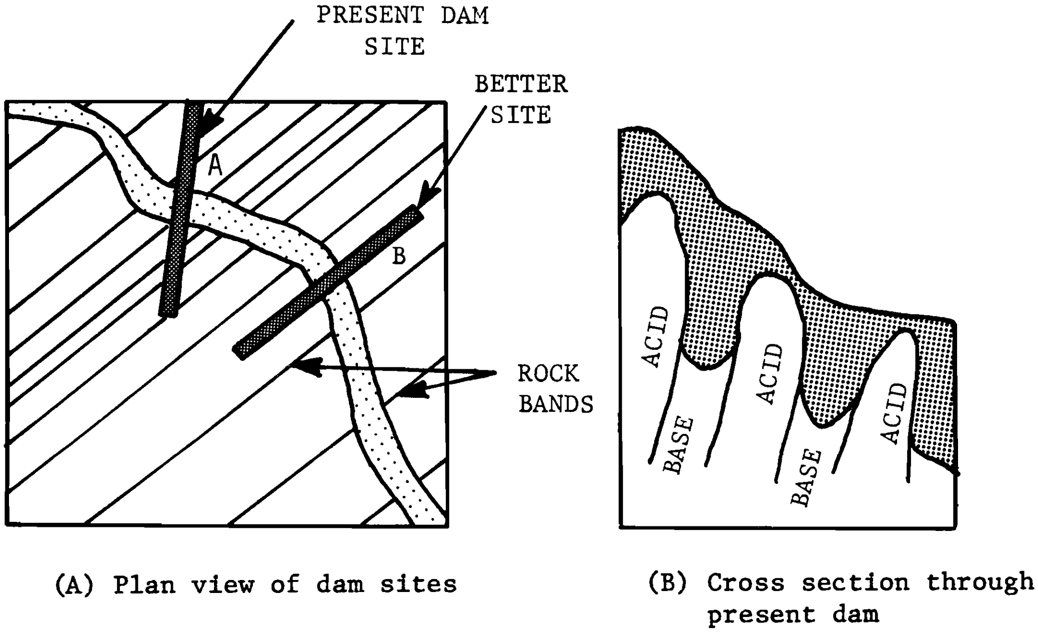


Figure 2-20. Ground Water in a Dome



(A) Plan view of dam sites

(B) Cross section through present dam

Figure 2-21. Chemical Weathering of Acidic and Basic Rocks

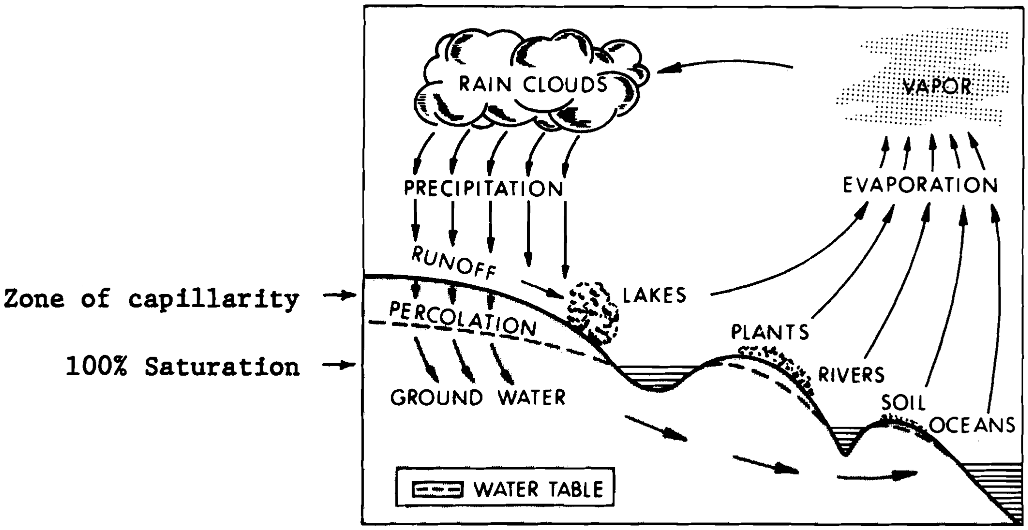


Figure 2-22. Hydrologic Cycle (Ref. 3)

tions. A tunnel spring is one that opens out of a mountain. These are quite common in the limestone country of Tennessee, Kentucky, and Missouri. Sometimes rivers seem to disappear or dive underground so that good water is lost. To prevent the loss, underground dams can be built to block the underground passage of the water.

2-2.5 SURFACE WATER

Surface water includes rivers, streams, ponds, lakes, seas, and oceans. Seas and oceans are excluded here since these larger bodies of water are not part of the terrain as defined in this chapter. Rivers, streams, ponds, and lakes are caused by precipitation in excess of the amount of water absorbed and evaporated. Where the topography is conducive, this excess runs off and forms streams in a large variety of drainage patterns as illustrated in Fig. 2-23. Streams are the principal agency of transportation of regolith. The soil load that a stream can carry depends on the stream velocity, the volume of water, and the size of the soil particles.

The lower parts of a river are areas of deposition. As the river opens into the sea, the velocity is lowered and the load is dropped. This process is responsible for the formation of deltas at the mouths of rivers. In unprotected locations at the mouth of a river, such as on the New England coast, tides carry away the load as fast as it is dropped, and nothing accumulates.

Young streams are found in the mountains and are characterized by clear, fresh water containing rocks and large pebbles that race along with the stream impacting other rocks and fragmenting both. In a mature or old stream the rocks of the once young stream are highly fragmented so that nothing but sand and small gravel remains. An old stream like the Mississippi River meanders widely. It has very gentle flow and carries only the finer particles of sand, silt, and clay.

The nature of a stream is largely determined by the soil it carries. Clay remains in suspension longer than coarser soils. The greater the velocity of a stream, the heavier the material it moves. An increase in the volume and velocity of water flow of the Colorado River does not increase the elevation of the water level much but it does increase the depth since the extra water carries away the bottom load. There is danger here of undercutting the banks as indicated by the dotted black lines of Fig. 2-24. The flood plain is the flat bottom of a river valley

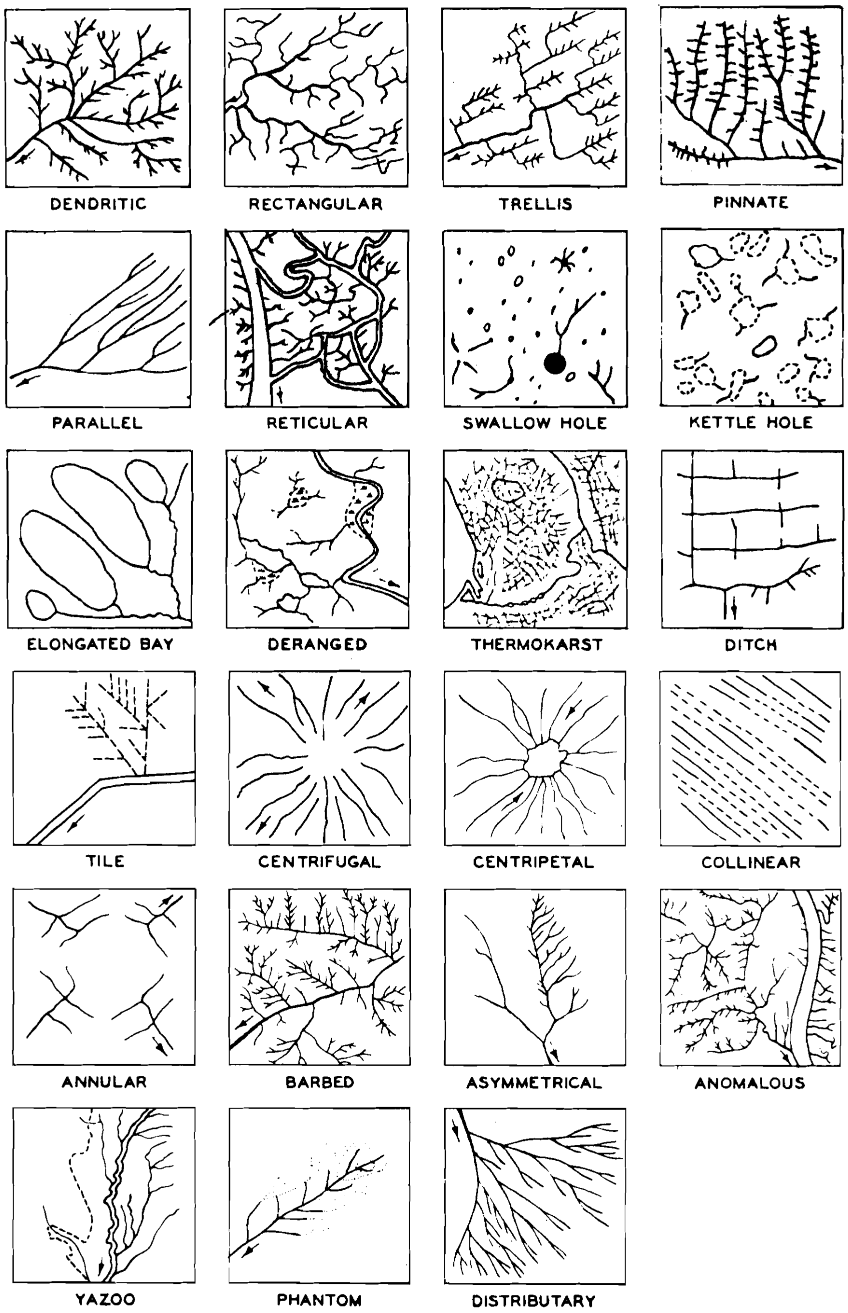


Figure 2-23. Drainage Pattern Types (Ref. 3)

over which the river spreads in times of flood. This produces rich soil but the threat of undercutting and flooding makes farming or building risky.

Meandering old streams are constantly seeking out new paths. Shifting, of course, is quite common and sometimes the phenomenon of Fig. 2-25 is observed. The isolated water remaining on the right as a result of cutting off the meander shown in Fig. 2-25 is called an "ox-bow" lake.

2-2.6 GLACIAL GEOLOGY

Long-term snow accumulation occurs wherever the winter snowfall is greater than that which melts in summer. This unmelted snow

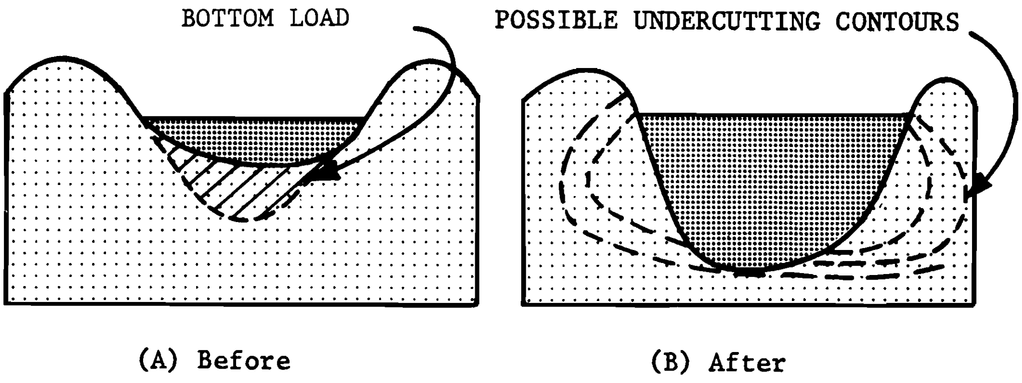


Figure 2-24. The Effect of Increased Flow Upon Bottom Contour

forms a permanent snow cover such as that found on the tops of mountains or in arctic regions. However, as more snow accumulates, the underlying layers recrystallize to a solid, clear blue ice.

If ice continues to form on top, the considerable pressures eventually cause the lower icemasses to move and form a glacier. Ice moves much like a mass of plastic, for it is generally weak and flows readily. It is possible to hear a glacier grinding over the rocks as it moves down a valley. The characteristic shape of a valley formed by a glacier is U-shaped while a valley formed by a stream is V-shaped. A glacier may at times retreat when it melts faster than it advances.

Geologically speaking, a great glacier with ice piled 1 to 2 mi thick has periodically swept down from Canada and across the northern part of the United States. The last retreat of this periodic glacier was 20,000 yr ago. Another may come in 100,000 yr or so.

A glacier leaves marks, usually huge concentrations of sorted gravel and sand. Eskers mark the course of a stream that flowed underneath a glacier with a ridge of sorted material. The last glacier disrupted the drainage systems of New York and New England; consequently, these areas are now teeming with lakes. A terminal moraine is the pile of glacial debris or till that marks the end of the glacier advance. At times a huge chunk of ice originally within the pile of glacial drift melts and leaves a large kettle or crater. An important result of glacial activity is well-sorted gravel and sand deposits.

2-3 TERRAIN DESCRIPTION

Terrain surfaces may be divided into two subcategories: mineral and organic. Mineral

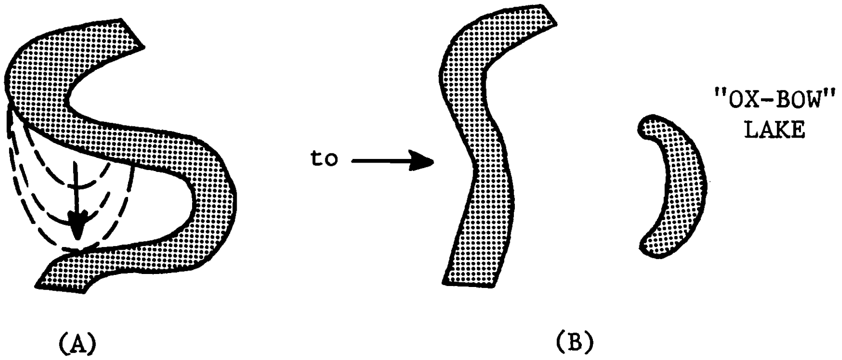


Figure 2-25. Formation of "Ox-bow" Lakes

terrain surfaces are composed of rocks and inorganic soils. Organic terrain surfaces consist of vegetation and organic soils. Many variations of each type of terrain surface exist, and the classifications to be described in these paragraphs, while relatively standard and widely accepted, are nevertheless largely arbitrary.

2-3.1 MINERAL (INORGANIC) SOIL

The soil classification systems that presently appear to be the most widely accepted for general engineering and mobility purposes are the Unified Soil Classification System (USCS) and the United States Department of Agriculture Soil Classification System (USDA). The USCS is based on texture and on organic and plasticity characteristics; the USDA is based primarily on texture, structure, consistency, and color. Usually, it is necessary to obtain bulk samples of a soil for laboratory analysis before a reliable classification can be made. However, fairly consistent classifications of soil can be made in the field by experienced people. The USCS is given in Table 2-9. This classification system is based partly on grain size distribution and partly on determination of liquid limits and plasticity indexes. Soil types from the chart are expressed by use of a letter symbol given in column 3. This letter symbol will be used later to correlate with various terrain properties such as suitability for construction and for off-road vehicle mobility.

The alternative classification system is the USDA system. Classification consists simply of locating the soil in the triangular matrix illustrated in Fig. 2-26. This triangle is a convenient way of representing the three-component mixture of sand, silt, and clay that constitutes soil. The letter classifications of the USDA system depend on the portion of the triangle into which a given soil falls. The names and letters of the 12 groups appear in Fig. 2-26. No provision for organic material or gravel is made by the USDA classification triangle; however, adjectives such as "organic" or "gravelly" may be added to a soil classification.

In both these classification systems, the determination that a soil is clay or sand is one of particle size determination strictly; i.e., whether a given particle is sand or clay depends upon its physical dimensions as defined in Fig. 2-3. However, in the USCS system, silt is not distinguished from clay on the basis of particle size but rather on a plasticity basis.

With certain limitations, laboratory analysis of soil samples has shown that a general correlation exists between the USCS and USDA soil types (Ref. 3). For example, of 1,176 samples classified in one study, many categories of the USDA Agricultural Soil Classification System correlated consistently with one or more soil groups of the United Soil Classification System. The correlations range from 41 to 100 percent, the average being about 60 percent, as shown in Table 2-10. The *LS* type of the USDA corresponds 98 percent of the time to the *SM* class of the USCS; the *SC* type USDA is half *SC* (USCS) and half *CL* (USCS); etc.

2-3.2 ORGANIC TERRAIN

The classifications of the previous paragraphs primarily describe mineral soils. The USCS does include several groups that account for the organic matter in a soil. An equally important contribution of organic matter to the terrain is that of the vegetation above the topographic surface. This paragraph describes the Radforth classification of organic terrain, which again, while quite arbitrary, is probably more widely accepted than other suggested classifications.

The Radforth classification of organic terrain is given in Table 2-11. Most vegetation classes do not occur singly except in rather small patches, but neither do they occur in all possible combinations. For example, the *FI* category implies a short-grasslike terrain with mossy ground cover. An area of *FI* is usually quite flat, but may, if hummocky, present obstructional hazards to small vehicles. The moisture content is usually medium to high

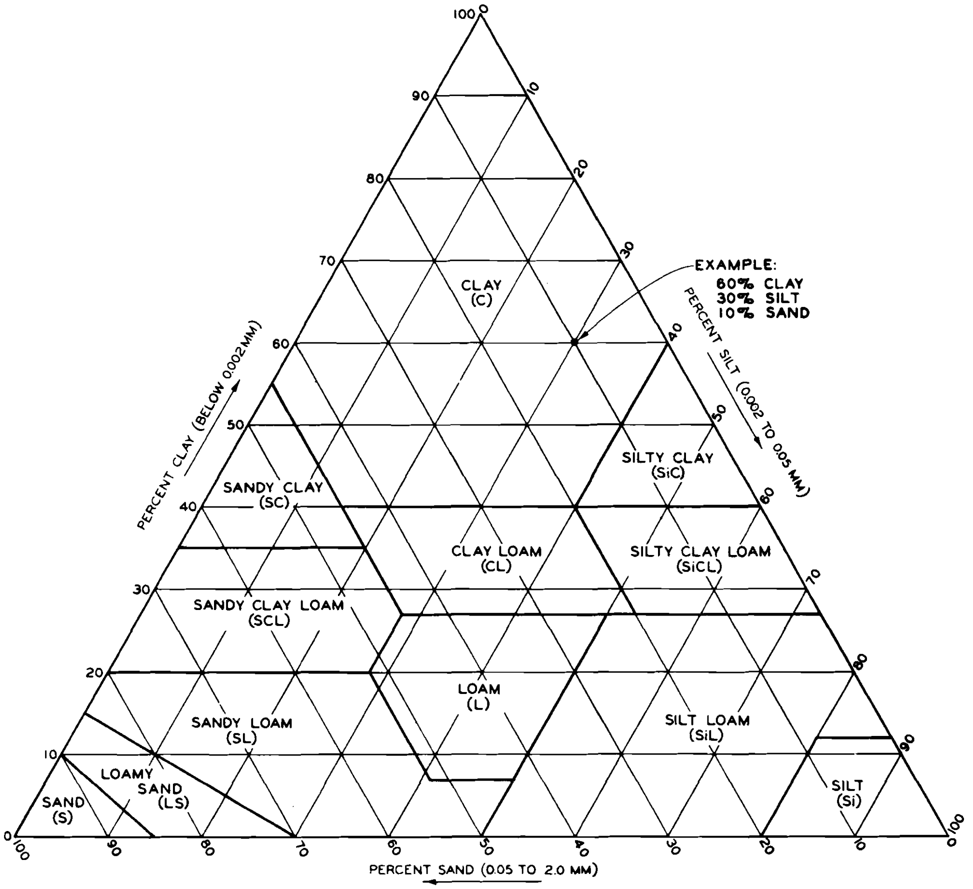


Figure 2-26. USDA Soil Textural Classification (Ref. 3)

and in some areas the vegetation may extend as a floating mat over water or very fluid peat.

The peat below living vegetal cover is usually composed of the remains of plants similar to those on the surface; the peat below *FI*, therefore, is nonwoody, fine fibrous, and largely amorphous-granular in structure. *FI*, therefore, indicates an area low in bearing capacity and subject to rapid deterioration under traffic. The surface vegetation is friable, the peat is of low fibrosity, and the high water content is conducive to the rapid formation of slurry. Most vehicles will have difficulty in this terrain.

EI categorizes organic terrain where the predominant cover comprises low bushes, and mosses provide the ground cover. Where bushes are contiguous, the topography is reasonably flat but, where there is separation, mounding occurs. The mounds have as their core the branch structure of the bushes, but much of the bulk is contributed by compact moss growth. Sometimes ice can persist in the centers of such mounds well into early summer and create unexpected hazards.

AEI-ADI areas are characterized by trees over 15 ft tall forming the predominant class in otherwise *EI* or *DI* areas. Because the peat has the remains of trees incorporated in it and, as the tree growth indicates, conditions are drier, this peat is slightly firmer than that found in *EI* or *DI* areas. Vehicular progress depends on steering facility to avoid trees or on the capability to push the trees aside.

Boundaries between different zones may present a unique terrain problem. A vehicle

TABLE 2-10

FREQUENCY OF USDA TYPES OCCURRING AS USCS SOIL TYPES (Ref. 3)

			USCS Soil Type															
			Coarse-grained soils with fines						Fine-grained soils					Organic soils			Total	
			GM	GC	SP-SM	SM	SM-SC	SC	ML	CL-ML	MH	CL	CH	CL	OH	Pt	%	n
USDA soil type	Sandy soils	S %			47	50	3										100	
		S n			21	22	1											44
		LS %				98		2									100	
		LS n				56		1										57
		SL+ %	*			41	8	14	19	4		9		2	2		100	
		SL+ n	1			85	17	28	40	9		18		5	4			207
		SCL %				11	3	25	7			54					100	
		SCL n				3	1	7	2			15						28
		SC %						50				50					100	
		SC n						1				1						2
	Clayey, silty, and loamy soils	L+ %	*	*					22	11	*	52	3	3	6		100	
		L+ n	1	1					36	19	1	87	5	5	10			165
		SiL %							36	10	3	45	2	2	2		100	
		SiL n							172	47	16	215	12	9	10			481
		Si %							91			9					100	
		Si n							10			1						11
		CL %							5		3	75	15		2		100	
		CL n							2		1	30	6		1			40
		SiCL %							1	1	1	67	27		3		100	
		SiCL n							1	1	1	51	20		2			76
		SiC %							5			24	71				100	
		SiC n							1			5	15					21
		C %							3		10	13	66		8		100	
		C n							1		4	5	25		3			38
	Organic soil	Pt %														100	100	
		Pt n														6		6
Total samples																		1176

n Number of samples.

* Less than 1%.

+ Prefixed with the term gravelly, cobbly, or stony for GM or GC soil types.

	CL
SiL	45 215

Sample Interpretation

45% of all SiL samples were CL. The circle indicates that a greater number of SiL samples occurred as CL than as any other USCS type. 215 samples were classified as SiL and CL.

TABLE 2-11

RADFORTH CLASSIFICATION SYSTEM (Refs. 9, 10, 11)

Class	Description	Example
A	Trees over 15 ft	Spruce, larch
B	Trees under 15 ft	Spruce, larch
C	Grasslike over 3 ft	Reed, sedge
D	Bushes over 2-3 ft	Alder, willow
E	Bushes under 2-3 ft	Leatherleaf, Labrador-tea
F	Grasslike under 3 ft	Sedge, cotton grass
G	Individual herbaceous plants	Lily, pitcher plant
H	Lichens	
I	Mosses	

may not be able to make the transition from a deeply rutted *FI* area to an *EI* area because it is unable to surmount the bushes, root systems, and peat that make up the surface mat edge or it may not be able to surmount the mat edge from a free-floating position in open water. Similar difficulties may exist at *AEI-ADI*, *EI-DI*, or *FI-DI* interfaces.

2-3.3 SOIL MECHANICS*

Soil, the major component of terrain, is an engineering material with many applications. It is used to support structures, as a filter medium, as a thermal insulator, and as a construction material to build buildings, roads, dams, and protective barriers. Its mechanical properties are sufficiently important to provide the theme for academic engineering courses and research laboratories. The literature of civil engineering contains much information on soil mechanics for all of these applications. In this paragraph, the emphasis is on the properties of soil that are important for soil trafficability, since this particular subject is of most concern in military operations.

Immobilization of a vehicle is usually caused by concurrent failure in the tractive and bearing capabilities of the soil over which it is traveling. Traction failure can occur without appreciable sinkage as when a wheeled vehicle spins its wheels on a firm soil that has a soft, slick overlay; bearing failure, however, usually does not occur without also being accompanied by traction failure, since traction requirements increase with sinkage. Tractive and bearing capabilities are both functions of soil shear strength.

A force diagram describing a vehicle moving over soil is shown in Fig. 2-27. The vehicle moves by the reaction R_1 of the soil, which is equal and opposite to the force R exerted upon the soil by the vehicle. Both of these forces have horizontal and vertical components – H and V, and H_1 and V_1.

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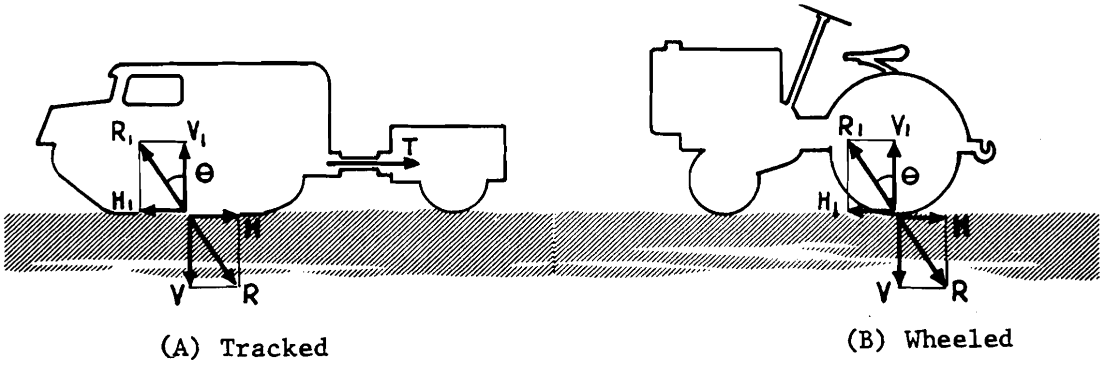
*Much of this paragraph is adapted from AMCP 706-356 (Ref. 12).



(A) Tracked

(B) Wheeled

Figure 2-27. Force Diagram for Moving Vehicles (Ref. 13)

Forces H_1 and V_1 are called the tractive effort and flotation, respectively, in standard terminology.

Tractive effort overcomes the resistance of the vehicle movement. If the vehicle is towing a trailer, then the tractive effort also includes the required drawbar pull T.

Vertical and horizontal reactions are each responsible for ground deformations. The deformation of soil under force is illustrated in Fig. 2-28. Soil does not usually fail by rupture as do brittle materials but generally by plastic flow, which is usually preceded by a small amount of elastic deformation as illustrated in Fig. 2-28. The appearance of plastic flow under the action of external forces marks the onset of soil failure.

The abscissa of Fig. 2-28 is soil deformation. The horizontal component of deformation is called slippage and the vertical component is the sinkage:

$$\text{deformation} = \sqrt{(\text{slippage})^2 + (\text{sinkage})^2} \qquad (2\text{-}1)$$

where each of the parameters is measured as a displacement.

The most useful single soil measurement for ground mobility is shear strength. The shear strength of soil depends upon two basic properties, cohesion and internal friction. Cohesion is a measure of the bonds between soil particles, which are developed from complex chemical and physical interactions. Internal friction is that portion of soil shear strength developed by the interlocking of soil

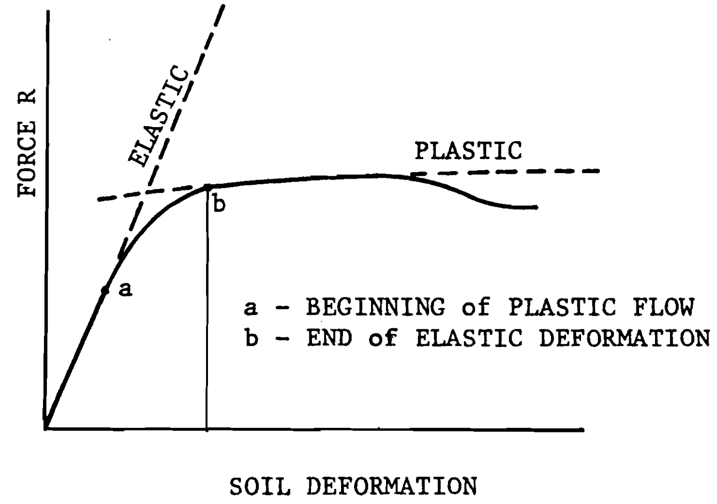


Figure 2-28. Deformation Properties of Soil Under Load (Ref. 13)

grains and the frictional resistance to sliding between the grains. The shearing strength developed by internal friction is proportional to the stress level; i.e., the greater the normal pressure applied to a surface of sliding in the soil, the higher the frictional shearing resistance along that surface.

For problems dealing with the performance of vehicles on soil, the stress-strain characteristics of the soil, including the deformations associated with failure, are important since they relate traction with slip and sinkage with load-carrying capacity and rolling resistance. To express fully soil-vehicle relationships in terms of loads, vehicle geometry, soil strength, and deformation properties, including analysis of both sinkage and slippage, six parameters are required. These are as follows:

ϕ = angle of internal friction, deg

c = cohesion, psi

δ = density, mass ft^{-3} or g cm^{-3}

s = shear strength, psi

p = normal stress, psi

k = deformation modulus, lb in.$^{-m}$ where the exponent m depends on the observed relation of pressure and sinkage

2-3.3.1 PROPERTIES OF SOILS

The important mechanical properties of soil include internal friction ϕ, cohesion c, and density δ. Internal friction and cohesion are by far the more important and are discussed in more detail in the paragraphs that follow.

(1) ***Purely cohesive soils.*** A purely cohesive soil is defined as one that, when unconfined, has considerable tensile strength when air-dried and has significant cohesion when submerged. Its shear strength is derived entirely from cohesion, i.e., its strength does not depend upon the applied loading. Such soil would be classified as an ideal clay, which is a fine-grained soil or the fine-grained portion of soil that can be made to exhibit plasticity (puttylike properties) within a range of water contents and that exhibits considerable strength when air-dried. The term "clay" has been used to designate particles in soil finer than 0.002 mm, but this usage is not preferred because the size alone does not guarantee that the important properties will be exhibited.

The shearing strength of a purely cohesive soil is characterized by its internal cohesion. This value is the force per unit area required to produce shear failure. In English units it is usually expressed in pounds per square inch (psi).

Because of its plasticity, the soil can be deformed beyond the point of recovery without cracking or appreciably changing volume. It will exhibit shrinkage upon drying, and swelling in the presence of water. Because of the small size of the particles, the cohesive soils have low permeability. Hence, consolidation will not occur immediately upon application of load. For this reason, consolidation, which is very important in foundation engineering, will not be an important factor in cohesive soils subjected to vehicular traffic loads.

The shear strength of clay varies considerably depending on the amount of moisture present and, for *in situ* soils, decreases as the moisture content increases. The state of the soil is generally spoken of in terms of its consistency as being soft, medium, stiff, or hard. Shear strength will also change with unaltered moisture content if the soil is subjected to a kneading action due to structural rearrangement. This effect is measured in terms of what is known as the sensitivity of the clay. This is indicated by the term "degree of sensitivity", S_t defined as

$$S_t = \frac{\text{cohesive strength, undisturbed}}{\text{cohesive strength, remolded}} \qquad (2\text{-}2)$$

For most clays, S_t ranges between 2 and 4; for sensitive clays, it is between 4 and 8. Soils for which S_t is greater than 8 are termed extra-sensitive. If a kneaded soil is allowed to stand, it may regain its cohesive strength. This phenomenon is known as thixotropy.

A cohesive soil also tends to adhere to other materials. The shear strength of this bonding is referred to as adhesion. Depending on the moisture content of the soil and the properties of the adjacent surface, the strength of adhesion may be greater or less than the strength of cohesion.

(2) *Purely frictional soils.* A purely frictional or cohesionless soil is defined as one that has little or no tensile strength when air-dried and little or no tensile strength when submerged, i.e., the opposite of a cohesive soil. Its shear strength is a function of the applied loading – the shear strength on any plane is zero when the normal stress on the plane is zero. Soils of this type are coarse-grained with particle sizes usually in excess of 0.002 mm in diameter. Sand, gravel, and silty soils are commonly assumed to be purely frictional soils.

The shearing resistance of a purely frictional soil is characterized by its angle of internal friction ϕ (see Fig. 2-29). The tangent of the angle of internal friction is analogous to the coefficient of friction between solids, but in soil mechanics the practice is to refer to the angle rather than the tangent. Friction is developed due to the interlocking of the soil grains and the frictional resistance to sliding between the grains. As such, the frictional angle is greater with irregular, rough-shaped (or angular) grains rather than with smooth, rounded grains; and it increases with the density since this increases particle interlocking.

Shearing action in soil of this type characteristically produces a change in volume. This change may be either an increase or a decrease, depending on the density of the soil; hence, the degree of soil confinement has a significant effect upon soil behavior. If the grains are very loosely packed, they change to a more compact arrangement as they move due to shear (of course, this volume decrease has a definite limit). When the grains are tightly packed, shearing causes the grains to move around one another with a resultant increase in volume (dilatation).

Purely frictional soils are not particularly sensitive to the presence of water. If the soil is not totally submerged, water will cause an

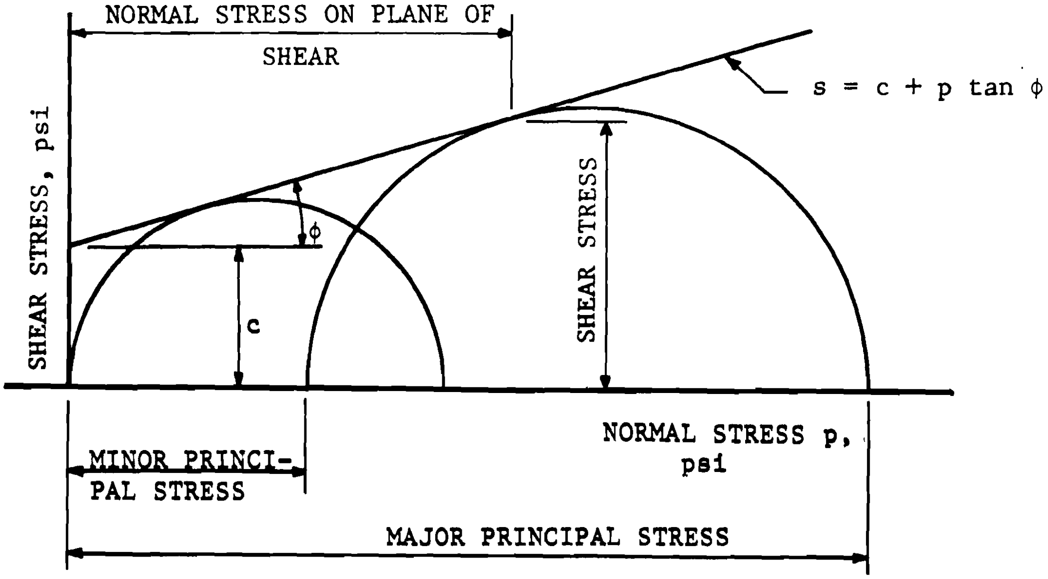


Figure 2-29. Mohr's Failure Circles for Soils (Ref. 12)

apparent cohesion to exist between the soil grains due to capillary attraction; however, if the soil is totally submerged, the cohesive effect is lost and friction is reduced slightly due to lubrication between the particles.

Within the range of loading associated with vehicle design, the soil shear strength on an internal surface may be considered to be proportional to the normal load on the surface and independent of the rate of shearing displacement. Shear strength is thus expressed as

$$s = p \tan \phi, \text{ psi} \tag{2-3}$$

where

s = shear strength, psi

p = effective normal stress on the surface of sliding, psi

ϕ = angle of internal friction, deg

(3) *Real soils.* Most soils are neither purely cohesive nor purely frictional but are a combination of the two. The properties of real soils are therefore partly cohesive and partly frictional, depending upon the proportion of each type present. Relative small quantities of silt or sand in a clay will introduce certain frictional effects, and small amounts of clay with sand or silt will produce some cohesion. It was recognized by Coulomb that soils generally derive strength both from cohesion and frictional resistance. The general expression for the ultimate strength of soil is known as Coulomb's law and is written

$$s = c + p \tan \phi, \text{ psi} \tag{2-4}$$

where

c = cohesion, psi

Actual soils do not generally behave in such a simple manner, but to facilitate design this simplified relationship is frequently adequate. Determination of the proper c, p, and ϕ for a given set of conditions may be extremely difficult, requiring considerable perception to obtain the correct results.

Stability problems in soil mechanics deal with the state of stresses at the moment of incipient failure of the soil through plastic flow. In solving these problems, only strength is involved and no consideration is given to the corresponding state of strain, unless some limitations are imposed on soil deformations due to boundary conditions. However, as a vehicle moves over a soil, sizable sinkage and slip can occur. The resistance to vehicular motion is constantly changing with the degree of sinkage, and the tractive effort varies with the slip. Hence, strength alone is not sufficient for analysis and it becomes necessary to consider the soil stress-strain relationships, which govern sinkage and slippage.

The expression for Coulomb's law (Eq. 2-4) is the equation of a straight line. It may be shown that this line is the envelope of Mohr's failure circles for the soil (Fig. 2-29). Such a diagram may be obtained by performing a series of laboratory tests on specimens representing the *in situ* soil. Among the most commonly used tests are the triaxial and direct shear tests.

The triaxial test is a compression test performed on a cylindrical soil specimen that is subjected to a circumferential confining pressure while being loaded axially (Fig. 2-30). In this case, the axial stress is one of the principal stresses and the other two are both equal to the confining pressure. A series of tests performed at different confining pressures enables a series of Mohr's circles to be drawn. The cohesion c and frictional angle ϕ can be determined graphically from the failure envelope.

In the direct shear test, a specimen is forced to shear on a predetermined plane (Fig. 2-31). Direct measurement is made of shearing strength and normal stress on the plane of shear. A series of tests performed

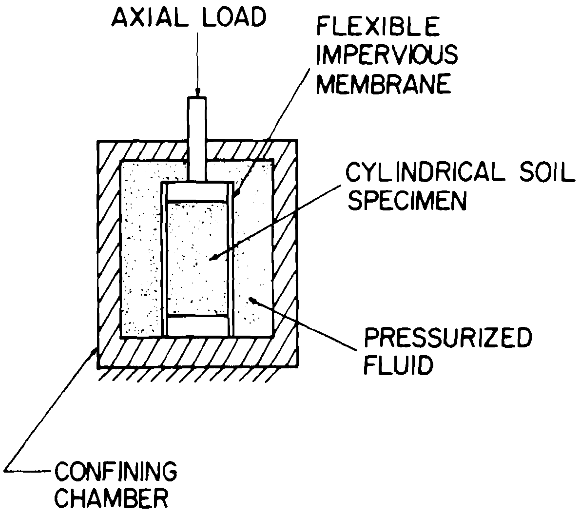


Figure 2-30. Schematic Representation of Triaxial Soil Strength Test (Ref. 12)

with various normal loads determines points along the line of the Coulomb equation and again, c and ϕ may be determined graphically.

Obviously, the most important general consideration in soil strength determination is to represent properly the *in situ* condition for the problem of interest. This includes such factors as degree of disturbance, pore pressures, effective confining stresses, and rate of loading. In practice, this can never be entirely achieved; hence, judgment is needed in the application of the test results.

2-3.3.2 EMPIRICAL PRESSURE-SINKAGE RELATIONSHIPS

An approximate relationship sometimes used in soil mechanics to relate the breadth of a longitudinal footing, its initial depth, loading, and settlement is

$$\frac{p}{z} = C_1 \left(1 + \frac{2d}{b}\right) + \frac{C_2}{b}, \text{ lb in.}^{-3} \tag{2-5}$$

where

p = loading pressure, psi

z = sinkage or settlement, in.

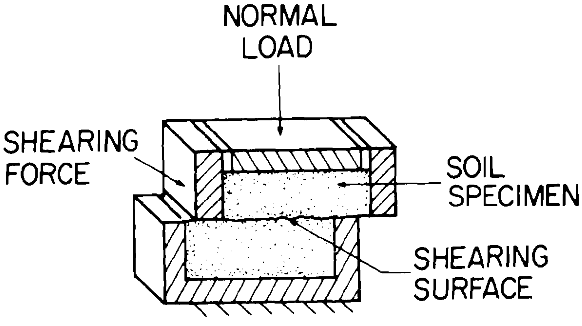


Figure 2-31. Schematic Representation of Direct Shear Soil Strength Test (Ref. 12)

d = initial depth, in.

b = breadth of footing, in.

C_1 = constant due to internal friction, lb in.$^{-3}$

C_2 = constant due to cohesion, psi

The scope of this relationship is limited to small values of z for which a linear relationship exists between load and sinkage. Within this range, however, the relationship is fairly independent of the size the loaded area since size is taken into account by the characteristic dimension b.

For the case of a track at the soil surface, $d = 0$, and the equation reduces to

$$\frac{p}{z} = C_1 + \frac{C_2}{b} \tag{2-6}$$

However, in the case where vehicle sinkage becomes quite large with respect to the breadth dimension b, the load-sinkage curve is nonlinear and the relationships Eq. 2-6 cannot apply.

Bekker has suggested that load-sinkage relationships of a track can be expressed more generally by the equation (Ref. 8):

$$p = \left(\frac{k_c}{b} + k_\phi\right) z^n, \text{ psi} \tag{2-7}$$

where

k_c = soil sinkage (cohesive) modulus of deformation, lb in.$^{-(n+1)}$ (dependent on shape)

k_ϕ = soil sinkage (frictional) modulus of deformation, lb in.$^{-(n+2)}$ (independent of shape)

n = soil sinkage exponent of deformation, dimensionless

z = sinkage, in.

The only difference between Eq. 2-7 and Eq. 2-6 is the exponent n of the sinkage z, to account for the nonlinear relationships between pressure and depth when large sinkages are involved.

Sela and Ehrlich have recently demonstrated that a more general equation would be (Ref. 14):

$$p = p_0 + \frac{H}{R_h} + \left(k_\phi + \frac{k'_c}{R_h}\right) (z + z_i)^n, \text{psi} \tag{2-8}$$

where

p_0 = the initial bearing capacity, independent of footing shape, psi

k_ϕ = the sinkage modulus, independent of footing shape, lb in.$^{-(n+2)}$

k'_c = the sinkage modulus, dependent on footing shape (not the same k_c as in Eq. 2-7), lb in.$^{-(n+1)}$

R_h = the hydraulic radius (area divided by the perimeter) of the footing, in.

H = initial support parameter, lb in.$^{-1}$

z_i = the soil precompaction, in.

n = soil sinkage exponent of deformation, dimensionless

The first two terms on the right side of Eq. 2-8 (p_0 and H/R_h) result from the tensile strength in some soils that gives an initial bearing capacity without any appreciable sinkage. The use of the hydraulic radius R_h in lieu of the width b allowed the relationship to be applied to a wider variety of plate shapes. The term z_i is necessary for describing the performance of soils that have been precompacted prior to load application. Eq. 2-8 has been successfully evaluated against many different sizes of rectangular, square, elliptical, and circular footings.

In each of these cases, the coefficients and exponents are determined by fitting the equations to experimental pressure-sinkage data. The equations become more general, but more complex with the inclusion of additional parameters.

The most commonly used pressure-sinkage relationship for vehicle design has been Eq. 2-7, which utilizes three parameters, k_c, k_ϕ and n, to describe the soil behavior. The effect of size of loaded area is accounted for by the characteristic dimension b (the width of the wheel or track). The soil values k_c and k_ϕ are assumed to be independent of both the size and form of the loaded area, and influence the relative magnitude of sinkage. Studies of pressure-sinkage relationships of various clays and mixtures of clays with silt and sand have shown that in general k_c and k_ϕ decrease in magnitude as water content increases and as the strength decreases. The exponent n influences the shape of the pressure-sinkage curve and generally will have values between 0.5 and 1.5.

None of these equations is a general solution based on a fundamental approach to the problem. The development of such a solution from fundamental principles is a formidable task of long duration. Until such appears, Eq. 2-7 constitutes a reasonable approximation without undue complication. If more accurate results are desired, Eq. 2-8 may be used.

2-3.3.3 DETERMINATION OF SINKAGE EQUATION CONSTANTS

If a plate is pressed into the soil – the force employed, and the resultant sinkage is measured – it would be possible to obtain a plot of sinkage versus imposed force. Dividing each measured force by the plate area yields the pressure on the plate, and, from Eq. 2-7, these data plotted on log-log paper give a straight line with slope n. Data from a second plate of different width produces another line, parallel to the first. The values of pressure where these two lines intersect the value $z = 1$ are called a_1 and a_2, to correspond, respectively, with the two plates whose widths are b_1 and b_2.

The value for h may be read directly from the graph as the tangent of the angle that the two parallel lines make with the z-axis. The values of k_c and k_ϕ may be obtained by solving the following two equations simultaneously:

$$k_\phi = \frac{(a_2 b_2 - a_1 b_1)}{b_2 - b_1} \tag{2-9}$$

$$k_c = \frac{(a_1 - a_2) b_1 b_2}{b_2 - b_1} \tag{2-10}$$

These soil values, of course, vary in natural soils with changes in moisture content, temperature, and other geological factors. Thus the soil strengths of a given area cannot be characterized by one single set of values but must be based on the frequency distribution of values involved. This requires, in turn, a statistical evaluation of soil as a function of location and season as the only practical basis of assessment of mobility in large areas.

2-3.3.4 SLIP EQUATION

The interrelationships of thrust and slip cannot be established on the basis of the sinkage parameters. This is because horizontal ground displacements are of a different character than that represented by Eq. 2-7. The maximum soil shear strength available to provide thrust is given by Coulomb's Eq. 2-4. To determine the actual soil shear strength being mobilized at any instant, if it is less than that maximum value, requires a relationship between shear stress and shear displacement.

Since the stress-displacement curve has an exponential appearance (see Fig. 2-28), it has been suggested that Coulomb's equation be modified as follows to account for the change in shearing resistance s as slip takes place:

$$s = (c + p \tan \phi)(1 - e^{-\frac{j}{K}}), \text{ psi} \tag{2-11}$$

where

j = shear deformation, in.

K = slip modulus, in.

e = base of Napierian (natural) logarithms

This equation describes a family of curves with the general form of soil shear stress-deformation relationships as shown in Fig. 2-32.

The slip parameter K may be obtained from the experimental shear stress-deformation curve for the soil (Fig. 2-32) as the distance between the intercept of the tangent drawn at the origin and the horizontal line $s = c + p \tan \phi$. However, since the shape of the stress-deformation curve is rather erratic near the origin, the value of K may be taken as that value of deformation when the shear stress reaches $1 - 1/e = 0.632$ of its maximum value.

The value of soil shear deformation j may be expressed in terms of slip i_0 and distance x from the beginning of ground-contact area to the point along the wheel or track where shearing strength s is being computed. The relationship is $j = i_0 x$, which indicates that the shearing deformation increases in proportion

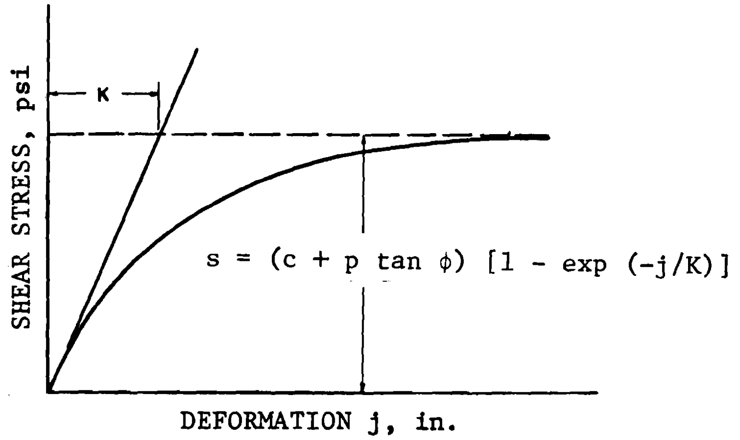


Figure 2-32. Typical Shear Stress-Deformation Curve (Ref. 12)

to the distance along the contact area. The determination of slippage i_0 follows the standard formula: $i_0 = 1 - V_a/V_t$, where V_a is forward vehicle speed and V_t peripheral speed of the traction elements, based on number of revolutions and dimensions of the wheel or track sprocket.

2-3.3.5 CONE INDEX (CI)

Cone index is employed in a technique to determine soil trafficability in the field and to determine whether or not a vehicle or fleet of vehicles can move in a given terrain. The Cone Index of a given soil is determined by a special instrument, called the cone penetrometer, which is pressed into the soil to determine soil strength. Empirically derived equations can be used to relate the cone measurements to vehicle performance.

Since vehicle motion in multipass performance may cause clay soil to remold, tests become necessary to determine the loss of strength due to remolding. The proportion of strength remaining after remolding is called the remolding index *RI*. The rating cone index *RCI*, defined as a product of the cone index measured in the field and the remolding index, describes the soil strength after passage of traffic.

The approximate equation to predict cone index *CI* from k_c, k_ϕ and n of Eq. 2-7 is as follows (Ref. 13):

$$CI = 1.625 \left\{ \frac{k_c}{(n+1)} \left[(z+1.5)^{n+1} - z^{n+1} \right] + 0.517\, k_\phi \left[\frac{(z+1.5)^{n+2}}{(n+1)(n+2)} + \frac{z^{n+2}}{n+2} - \frac{(z+1.5)\, z^{n+1}}{n+1} \right] \right\} \qquad (2\text{-}12)$$

There is no equation, however, that predicts k_c, k_ϕ and n from *CI*.

2-3.3.6 PREDICTION OF VEHICLE PERFORMANCE

By numerous tests, relationships have been established between vehicle performance, various vehicle parameters, and cone index measurements. The vehicle parameters of this relationship are combined into a single term, called the mobility index (MI). The mobility index for self-propelled, tracked vehicles is computed by the following equation:

$$\text{Mobility index} = \left[\frac{\begin{pmatrix}\text{contact}\\ \text{pressure}\\ \text{factor}\end{pmatrix} \times \begin{pmatrix}\text{weight}\\ \text{factor}\end{pmatrix}}{\begin{pmatrix}\text{track}\\ \text{factor}\end{pmatrix} \times \begin{pmatrix}\text{grouser}\\ \text{factor}\end{pmatrix}} + \begin{pmatrix}\text{bogie}\\ \text{factor}\end{pmatrix} - \begin{pmatrix}\text{clear-}\\ \text{ance}\\ \text{factor}\end{pmatrix}\right] \times \begin{pmatrix}\text{engine}\\ \text{factor}\end{pmatrix} \times \begin{pmatrix}\text{transmission}\\ \text{factor}\end{pmatrix} \tag{2-13}$$

where

$$\text{Contact pressure factor} = \frac{\text{gross weight, lb}}{\text{area of tracks in contact with ground, in.}^2}$$

Weight factor: Less than 50,000 lb = 1.0
50,000 to 69,999 lb = 1.2
70,000 to 99,999 lb = 1.4
100,000 lb or greater = 1.8

$$\text{Track factor} = \frac{\text{track width, in.}}{100}$$

Grouser factor: Grousers less than 1.5 in. high = 1.0
Grousers more than 1.5 in. high = 1.1

$$\text{Bogie factor} = \frac{\text{gross weight, lb, divided by 10}}{(\text{total number of bogies on tracks in contact with ground}) \times (\text{area, in.}^2\text{, of 1 track shoe})}$$

$$\text{Clearance factor} = \frac{\text{clearance, in.}}{10}$$

Engine factor: $\geqslant$ 10 hp/ton of vehicle wt = 1.00
$<$ 10 hp/ton of vehicle wt = 1.05

Transmission factor: Automatic = 1.0; manual = 1.05

The mobility index for self-propelled, wheeled vehicles is expressed by this equation:

$$\text{Mobility index} = \left[\frac{\begin{pmatrix}\text{contact}\\ \text{pressure}\\ \text{factor}\end{pmatrix} \times \begin{pmatrix}\text{weight}\\ \text{factor}\end{pmatrix}}{\begin{pmatrix}\text{tire}\\ \text{factor}\end{pmatrix} \quad \begin{pmatrix}\text{grouser}\\ \text{factor}\end{pmatrix}} + \begin{pmatrix}\text{wheel}\\ \text{load}\\ \text{factor}\end{pmatrix} - \begin{pmatrix}\text{clear-}\\ \text{ance}\\ \text{factor}\end{pmatrix}\right] \times \begin{pmatrix}\text{engine}\\ \text{factor}\end{pmatrix} \times \begin{pmatrix}\text{transmission}\\ \text{factor}\end{pmatrix} \tag{2-14}$$

where

$$\text{Contact pressure factor} = \frac{\text{gross weight, lb}}{\begin{pmatrix}\text{nom tire}\\ \text{width,}\\ \text{in.}\end{pmatrix} \times \dfrac{\begin{pmatrix}\text{outside}\\ \text{diam}\\ \text{of tire,}\\ \text{in.}\end{pmatrix}}{2} \times \begin{pmatrix}\text{No.}\\ \text{of}\\ \text{tires}\end{pmatrix}}$$

	Weight range, lb*	Weight factor equations†
Weight factor:	$<$ 2000	$Y = 0.553X$
	2,000 to 13,500	$Y = 0.033X + 1.050$
	13,501 to 20,000	$Y = 0.142X - 0.420$
	$>$ 20,000	$Y = 0.278X - 3.115$

$$\text{Tire factor: } \frac{10 + \text{tire width, in.}}{100}$$

Grouser factor: With chains = 1.05
Without chains = 1.00

$$\text{Wheel load factor: } \frac{\text{gross weight, kips}}{\text{No. of axles} \times 2}$$

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* $\dfrac{\text{Gross weight, lb}}{\text{No. of axles}}$.

† Y = weight factor, $X = \dfrac{\text{gross weight, kips}}{\text{No. of axles}}$.

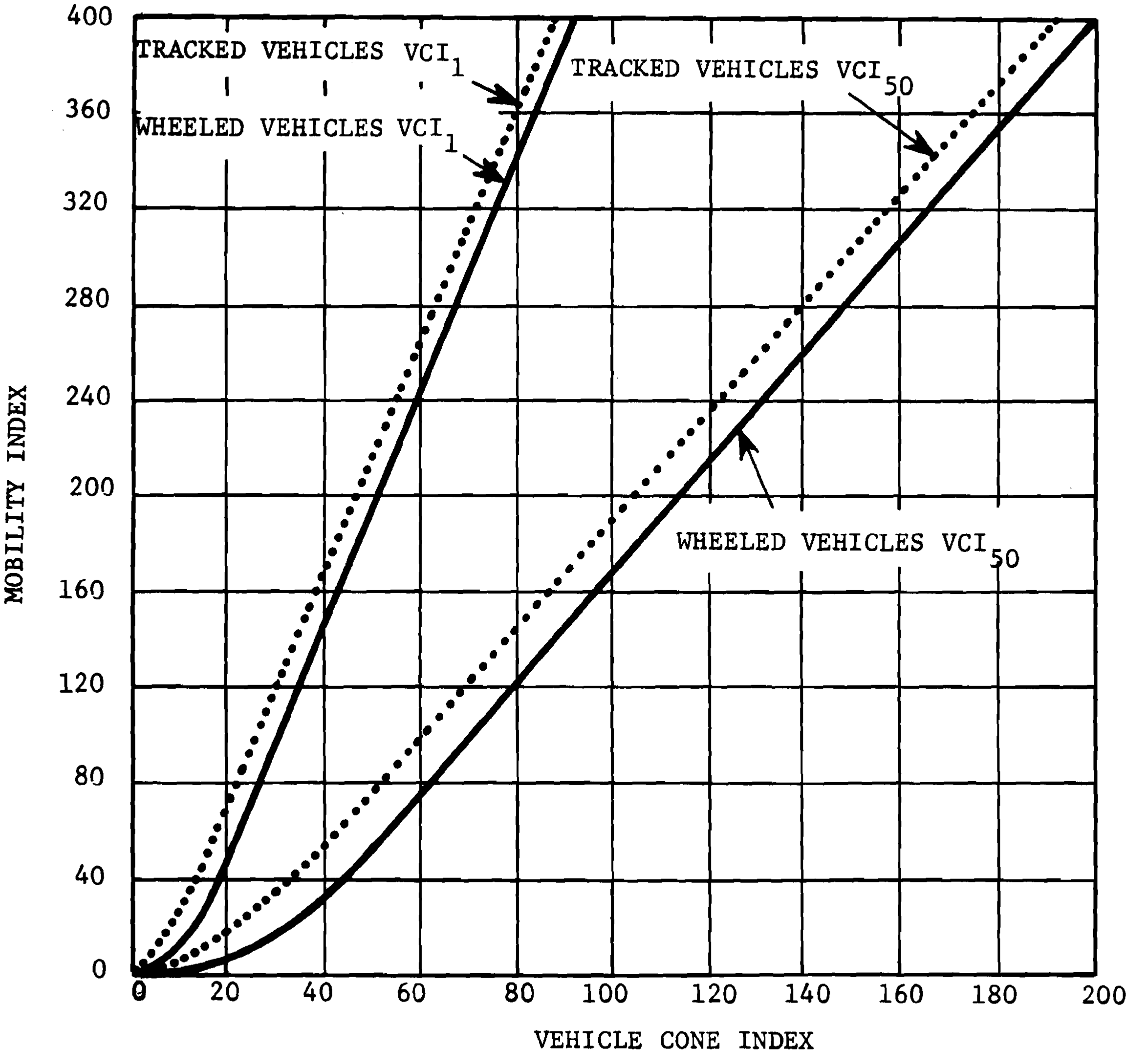

Figure 2-33. Relationship Between Mobility Index and Vehicle Cone Index for Self-propelled Vehicles (Provided by I. R. Ehrlich)

Clearance factor: $\frac{\text{clearance, in.}}{10}$

Engine factor: $\geqslant$ 10 hp/ton = 1.00
$<$ 10 hp/ton = 1.05

Transmission factor: Automatic = 1.00; manual = 1.05

This mobility index can then be corrected to a Vehicle Cone Index (*VCI*) by use of Fig. 2-33. If predictions of a single pass (go, no-go) are desired, curves labeled VCI_1 should be employed; if predictions of fifty passes (essentially infinite), the curves labeled VCI_{50} should be utilized.

If the soil has a measured rating cone index equal to or greater than the vehicle cone index, it probably will negotiate the terrain in question. The curves in Fig. 2-34 predict the drawbar pull coefficient (the maximum obtainable drawbar pull divided by the weight of the vehicle) as a fraction of the difference between the *RCI* and the *VCI*. Obviously, when this difference is zero, the vehicle can just negotiate, hence its extra pulling

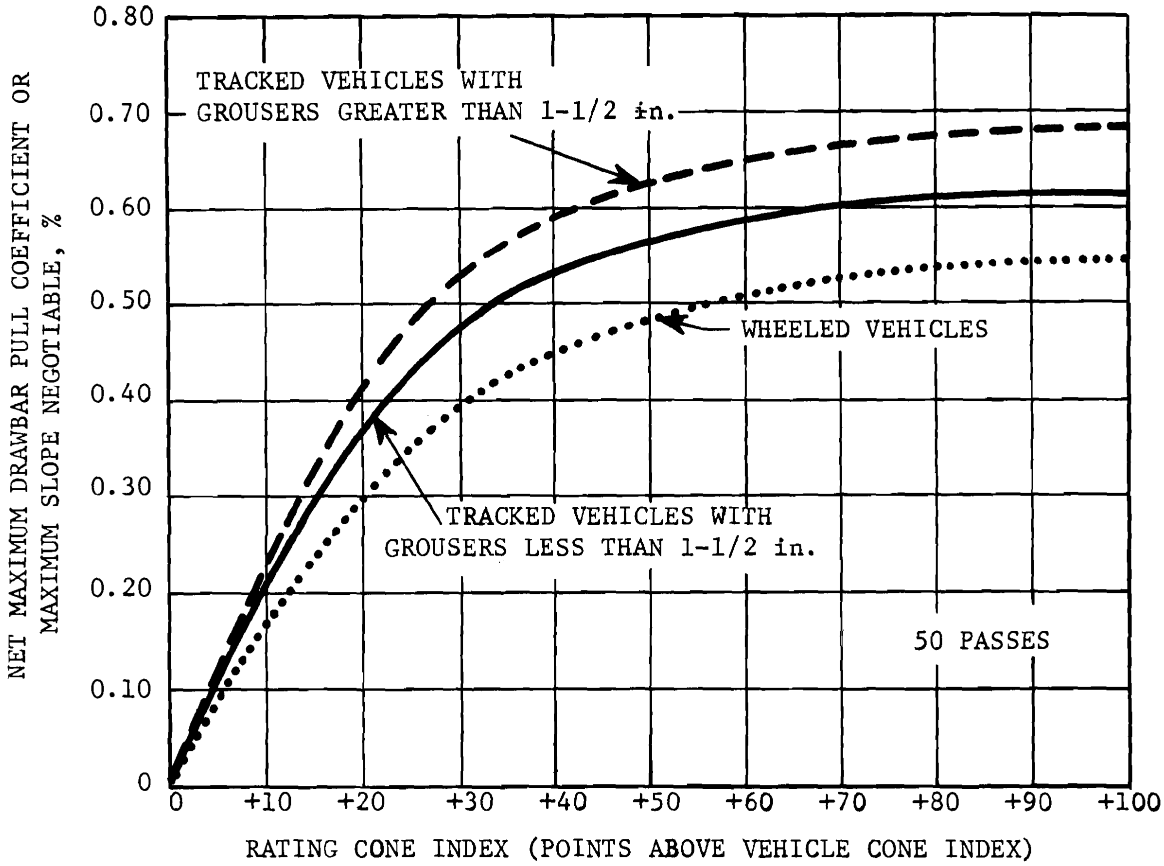

Figure 2-34. Net Maximum Drawbar Pull and Maximum Negotiable Slope (Provided by I.R. Ehrlich)

capability is nil. This pull capability can also be used against gravity; hence the curves also present the maximum slope (expressed in percent) climbable.

2-3.4 DATA DISPLAY

The properties and characteristics of terrain vary from gross, large-scale properties such as mountains, plains, and valleys to small-scale features such as soil composition, texture, and surface detail. Displays showing both these features in adequate detail at the same time do not exist. Different display methods emphasize different properties and, consequently, are of value for different uses. These paragraphs summarize the conventional display methods that span the spectrum from worldwide maps to power spectral density plots of relatively small plots of terrain.

2-3.4.1 WORLD MAPS*

Geological features plus climate are plotted on a worldwide basis in Figs. 2-35 through 2-43. Such maps are of some value for associating areas of similar terrain and terrain properties. They clearly are less useful for solving specific terrain problems such as trafficability through a given area.

2-3.4.2 AREAL AND LINEAR TERRAIN MAPS†

Terrain on the local level generally follows certain repetitive patterns in that the same terrain features seen in one location are readily recognizable in adjacent, contiguous

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*Maps reproduced from Ref. 3.

†Most of this paragraph is reproduced from *The AMC '71 Vehicle Mobility Model* (Ref. 15).

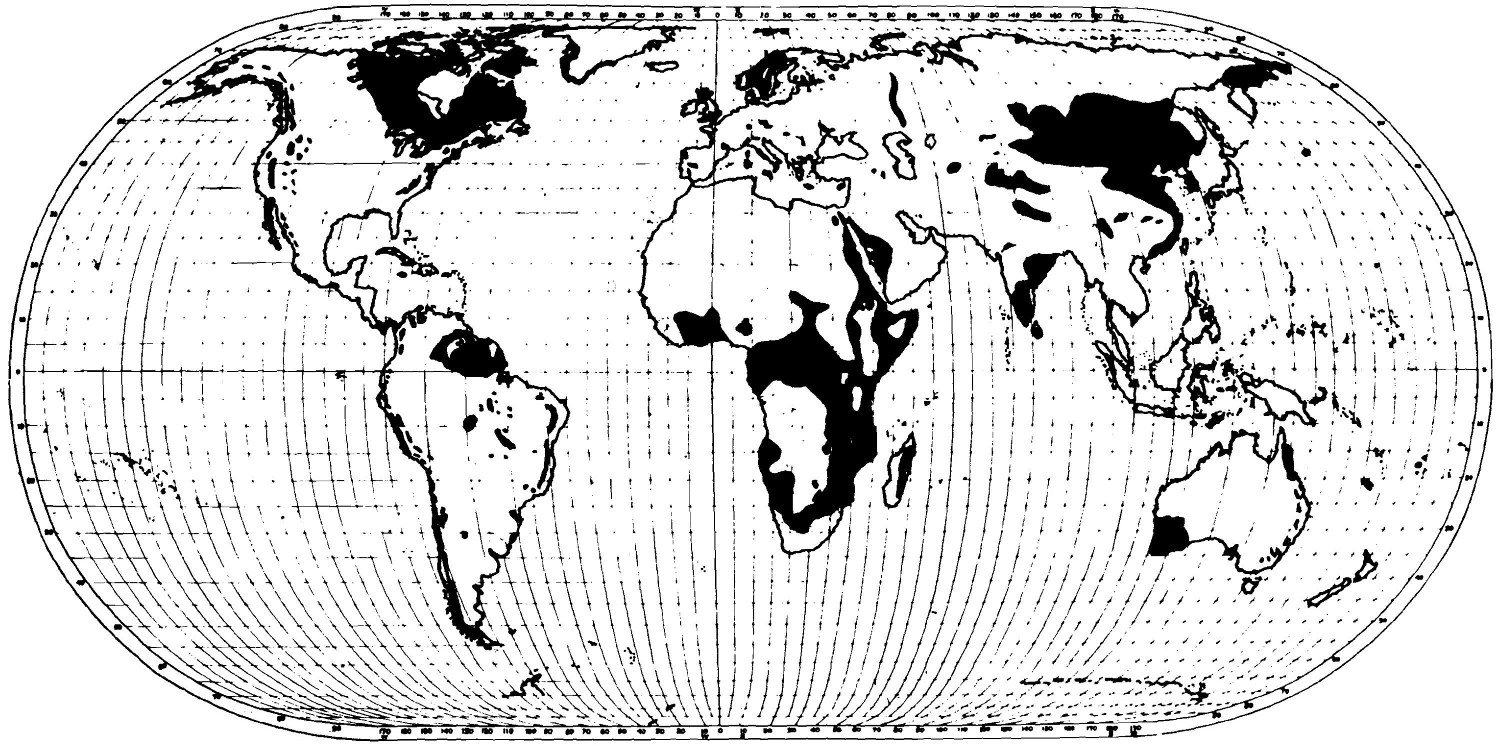

Figure 2-35. Igneous Rocks (Intrusive) (World Distribution) (Ref. 3)

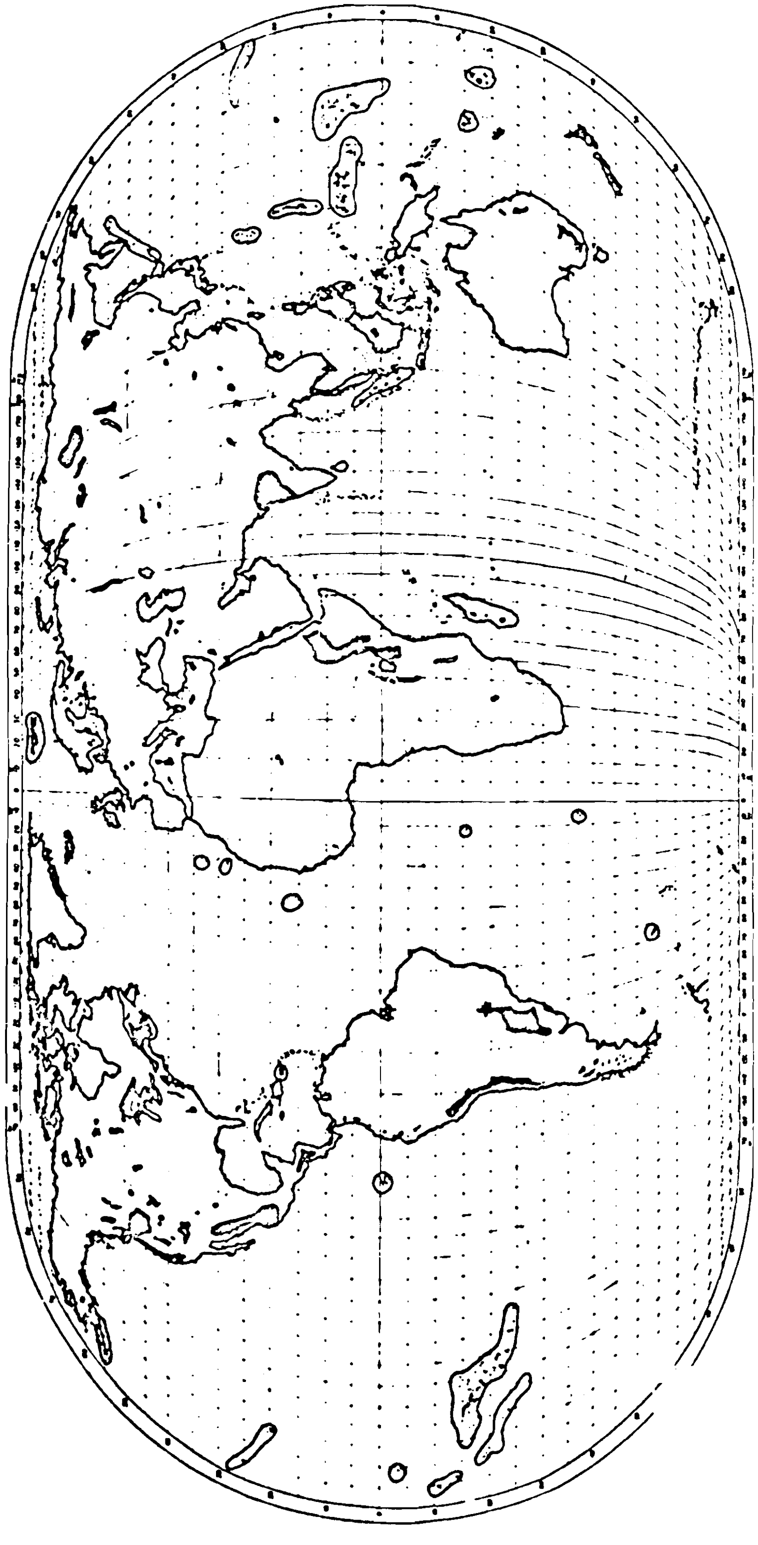

Figure 2-36. Igneous Rocks (Extrusive) (World Distribution) (Ref. 3)

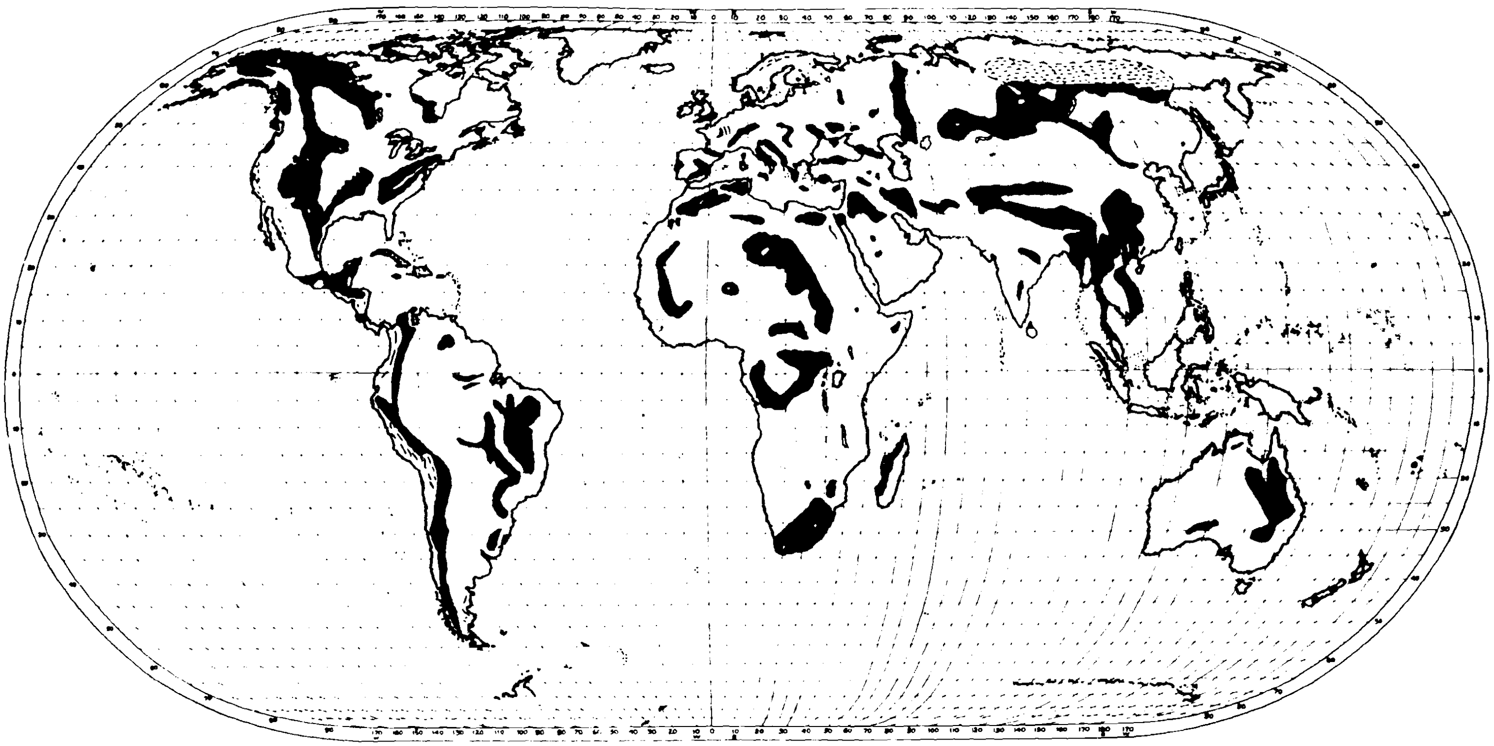

Figure 2-37. Sedimentary Rocks (World Distribution) (Ref. 3)

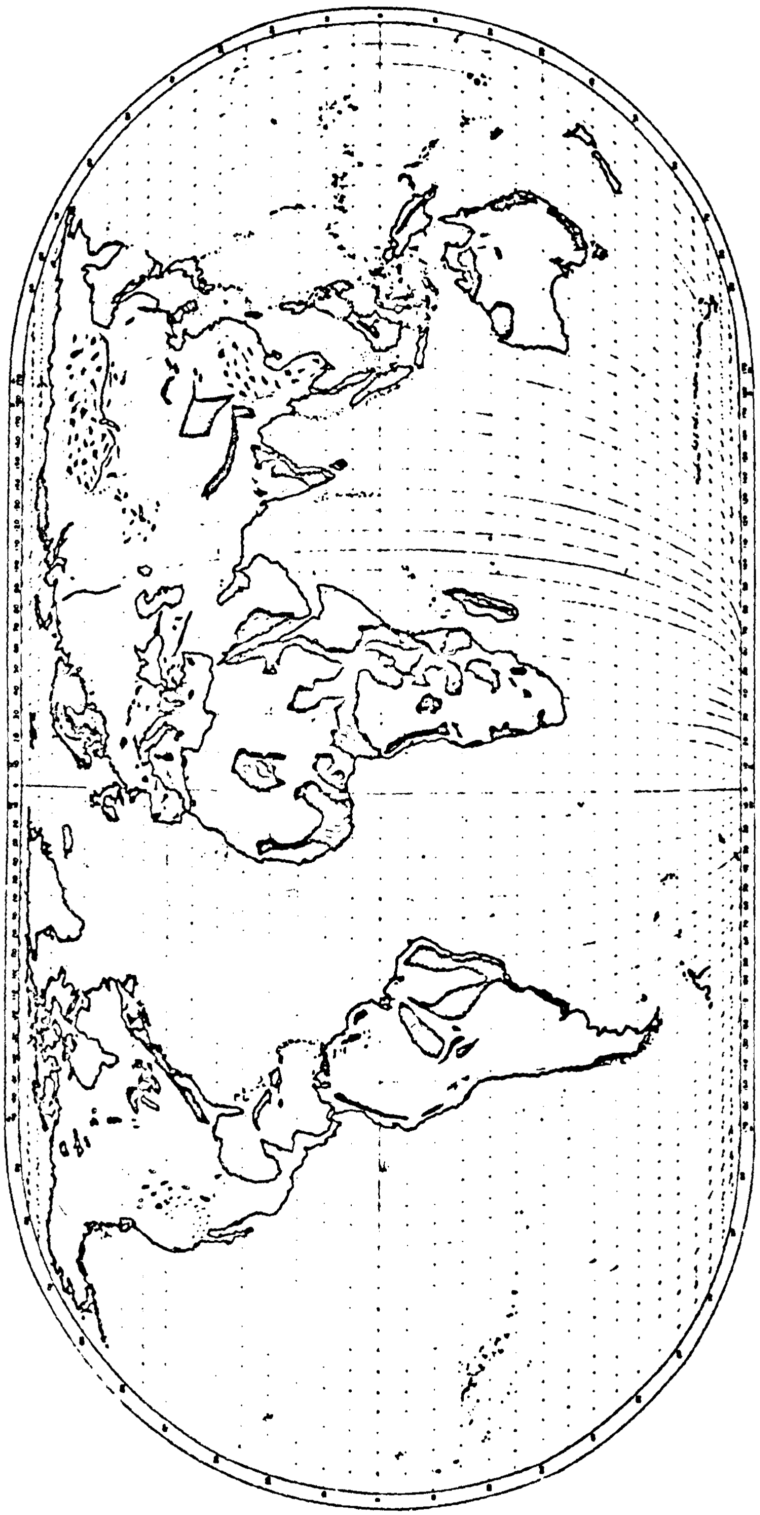

Figure 2-38. Metamorphic Rocks (World Distribution) (Ref. 3)

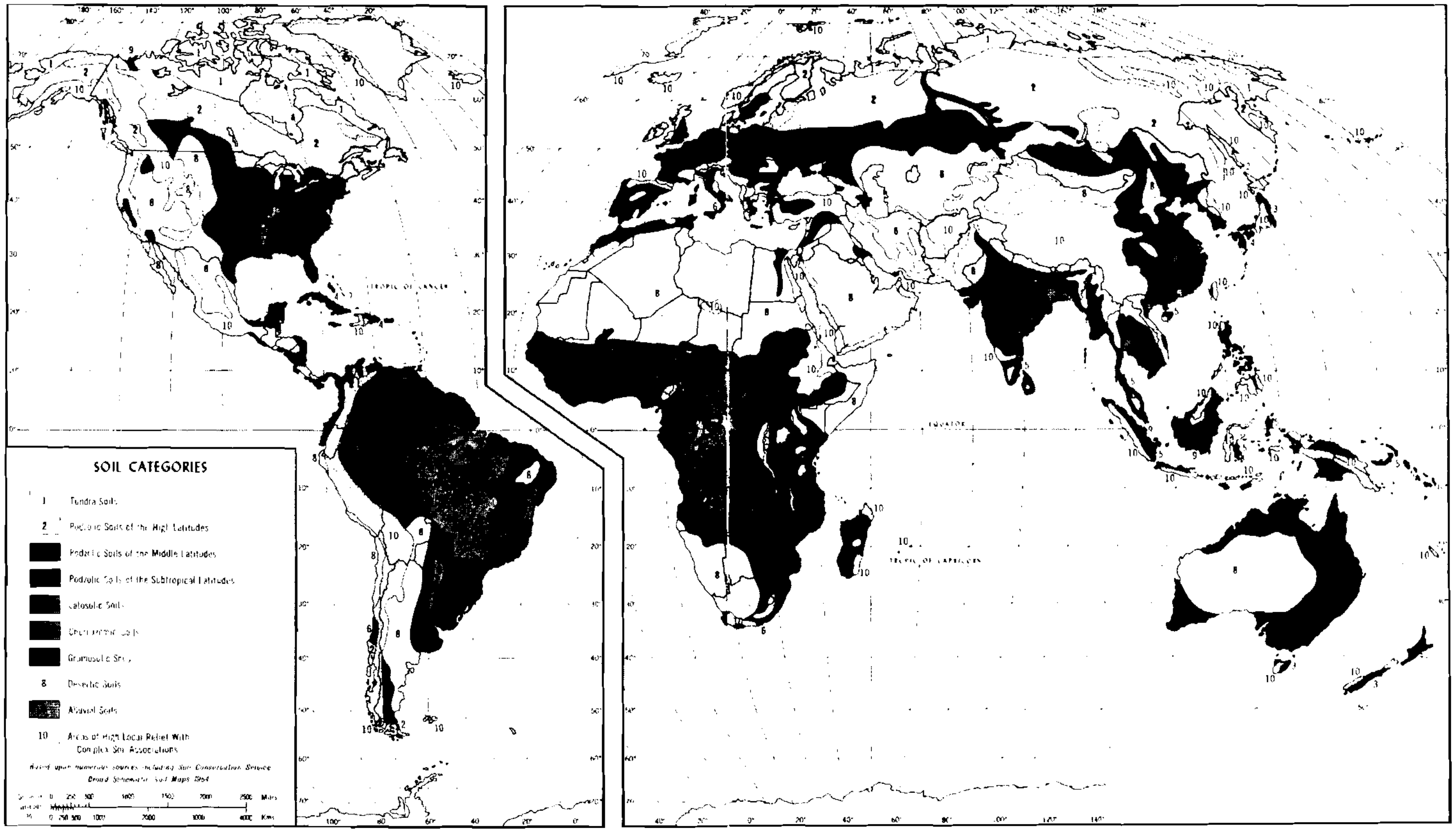

Figure 2-39. Soil (World Distribution) (Ref. 3)

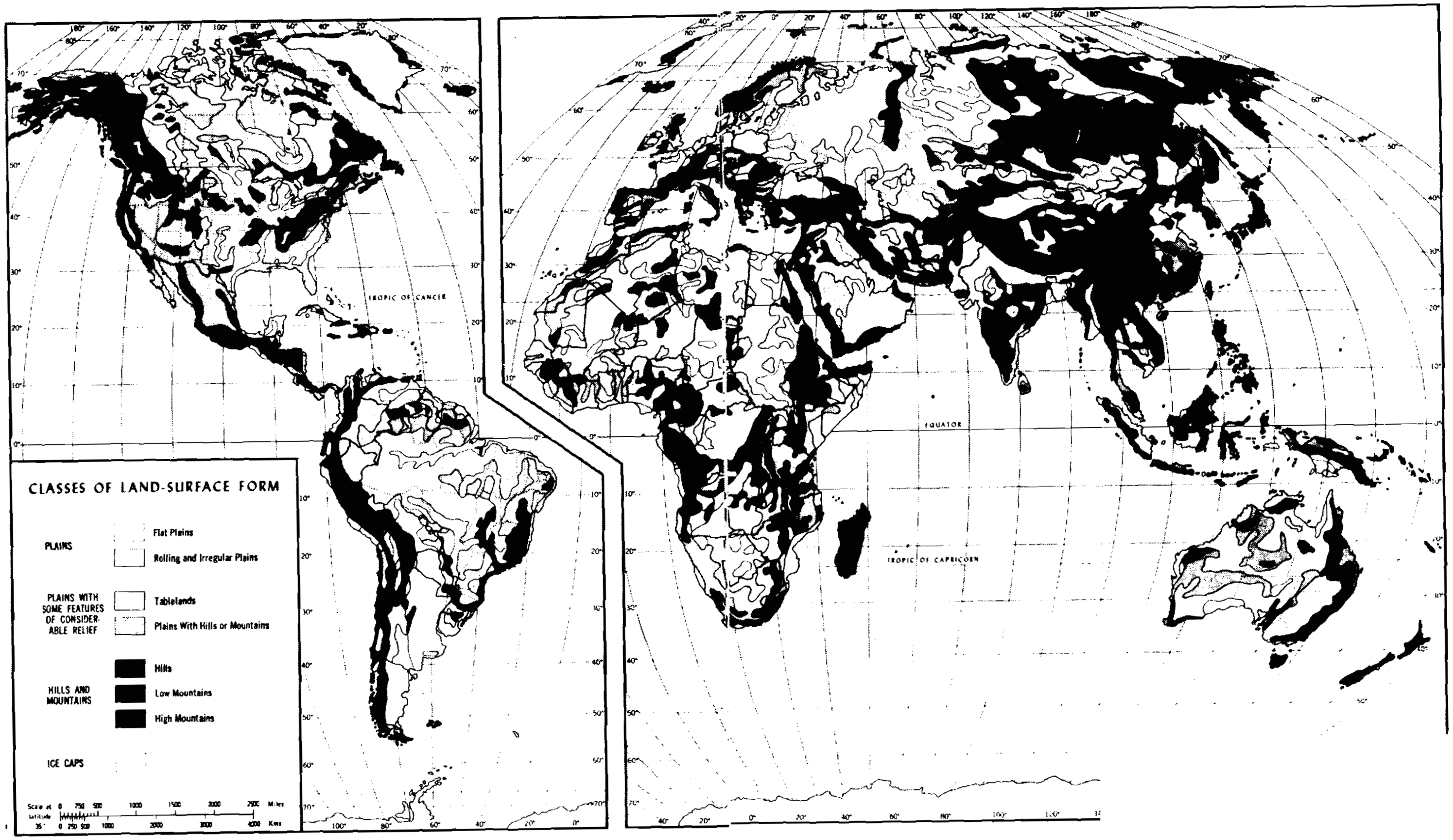

Figure 2-40. Land Surface Forms (World Distribution) (Ref. 3)

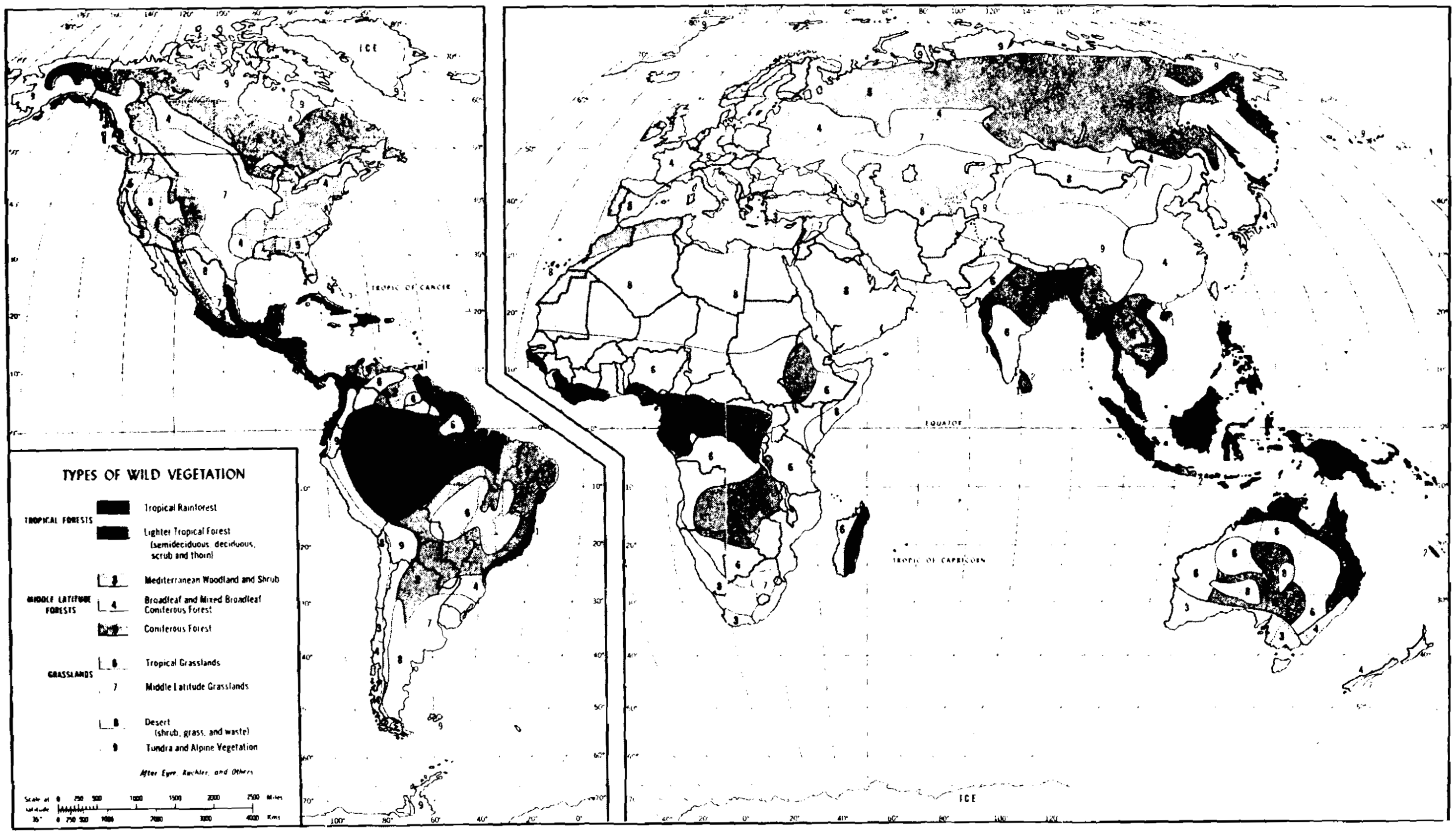

Figure 2-41. Vegetation (World Distribution) (Ref. 3)

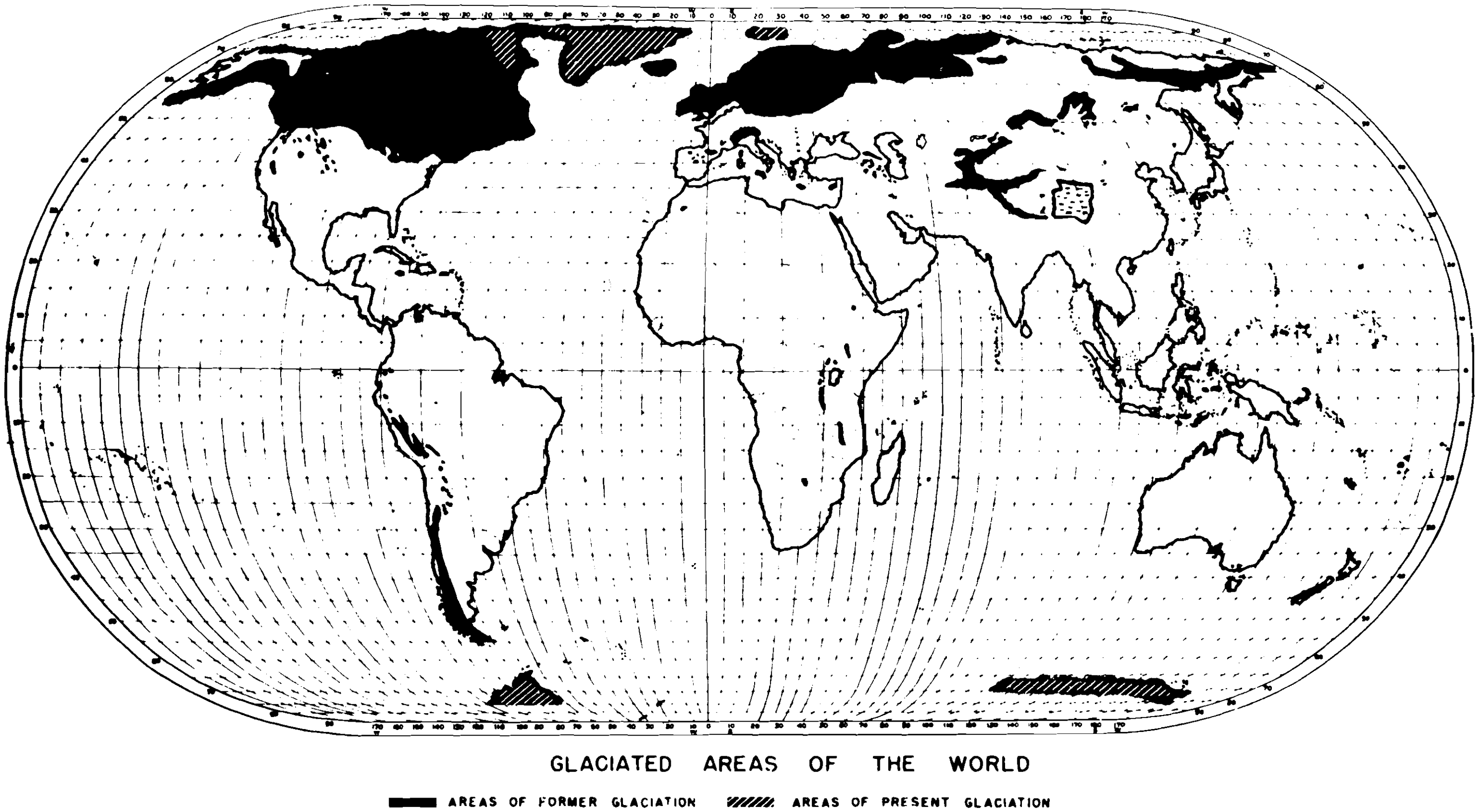

Figure 2-42. Glaciated Areas (World Distribution) (Ref. 3)

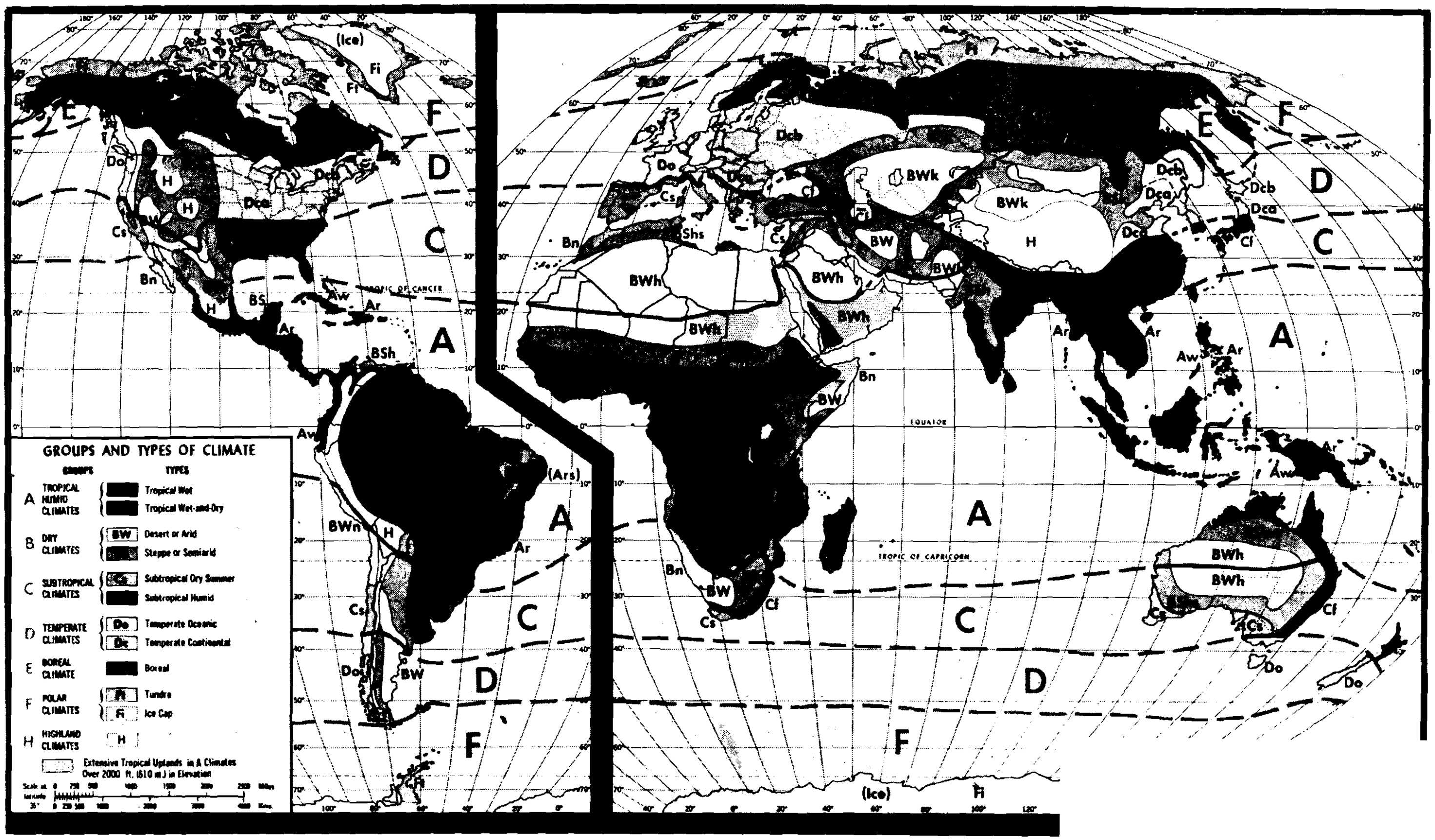

Figure 2-43. Climate (World Distribution) (Ref. 3)

areas and also reappear at other locations within a given area. The repetitiveness of similar terrain features permits the drawing of terrain maps that identify areas having similar terrain features. The areal and linear terrain maps discussed in this paragraph are the work of the U. S. Army Waterways Experiment Station and the Tank-Automotive Command and as such represent but one method of terrain mapping. A particular advantage of this approach, however, is that the data lend themselves quite readily to computer processing. Indeed, it was this desirable property of mapping the terrain that led to development of this method. Having the ability to specify a terrain to a computer enables one to model the interaction of various vehicles, both hypothetical and real, with the terrain (Ref. 15).

2-3.4.2.1 NOMENCLATURE

The definitions of most of the important terms used in describing terrain data follow (Ref. 15):

(1) *General terrain terms:*

(a) Areal terrains. Terrains that can be delineated on a terrain map as a patch with both length and width, e.g., a forest.

(b) Linear terrains. Terrains that appear on a terrain map as lines due to their extensive length and narrow width, e.g., a river or highway embankment.

(c) Terrain factor. Any attribute of the terrain that can adequately be described at any place (or instant of time) by a single measurable value; e.g., slope, spacing of plant stems of a given diameter, obstacle heights, obstacle approach angle, water depth, etc.

(d) Terrain factor family. Two or more terrain factors grouped together. The terrain factor families used to describe terrains are surface composition, surface geometry, vegetation, and hydrologic geometry.

(e) Terrain factor value. A specific value that describes a terrain factor; e.g., 1.5 deg is a factor value that describes the terrain factor. slope.

(f) Terrain factor class range. A specified range of terrain factor values; e.g., a terrain factor class could be a slope from 0 to 1.5 deg. For predictive analysis, however, a single value within that range is selected.

(g) Terrain factor class number. A number assigned to a terrain factor class range. For mobility purposes, the terrain factor class numbers are assigned in order of increasing effect of the terrain on vehicle performance.

(h) Terrain factor complex number. A combination of two or more terrain factor class numbers which describes the terrain characteristics of an area.

(i) Terrain unit. A patch (areal or linear) of terrain described by a specific terrain factor complex number.

(j) Terrain country. An imaginary or geographic area containing two or more terrain units.

(2) *Surface geometry terms* (refer to Fig. 2-44):

(a) Slope. The angular deviation of a surface from the horizontal, measured perpendicular to the topographic contours.

(b) Obstacle approach angles A. The angles (less than 180 deg) formed by the slopes at the base of a vertical obstacle.

(c) Obstacle base width WB. The distance across the bottom of an obstacle.

(d) Obstacle spacing OBS. The horizontal distance between forward edges of vertical obstacles.

A = obstacle approach angle
B = obstacle break angle
H = obstacle vertical height
OBL = obstacle length
OBS = obstacle spacing
WB = obstacle base width

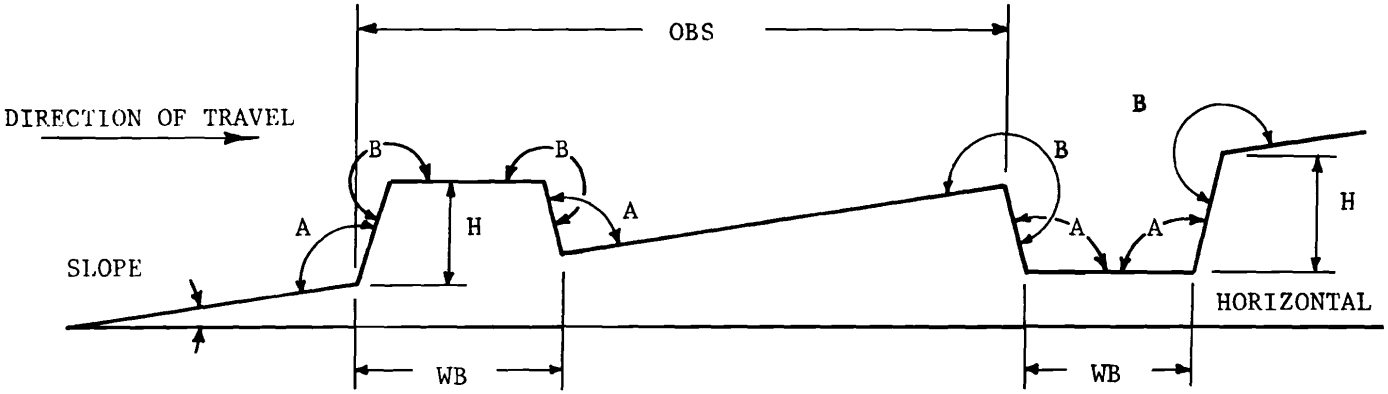

Figure 2-44. Measures of Surface Geometry (Ref. 15)

BD = differential bank height
RW = width of water at surface
WD = water depth
WS = maximum velocity of water in a channel
THI,RBA = gap side slope

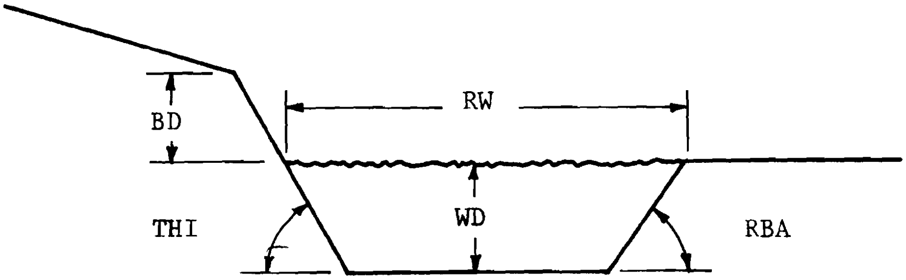

Figure 2-45. River Features (Ref. 15)

(e) Obstacle vertical height *H*. The vertical distance from the base of an obstacle to its crest.

(f) Obstacle length *OBL*. The length of the long axis of the obstacle.

(g) Obstacle break angles (*B*). The angles (> 180 deg) formed by the slopes at the top of an obstacle.

(3) *Vegetation terms:*

(a) Stem diameter. The diameter (cm) of the tree stem at breast height.

(b) Stem spacing. The average distance (meters) between tree stems. This value is computed from the number of stems per unit area, assuming that the stems are arranged in a hexagonal pattern.

(c) Recognition distance. The distance a vehicle driver can see and recognize objects that may be hazardous to his vehicle or himself.

(4) *Hydrologic geometry terms* (refer to Fig. 2-45):

(a) Differential bank height *BD*. The difference in elevation of the two banks of a hydrologic feature.

(b) Gap side slope *THI, RBA*. The slope of the bounding incline at the top of the hydrologic feature, measured with respect to the horizontal.

(c) Water depth *WD*. Maximum depth of water in channel.

(d) Water width *RW*. The width of the water at the surface.

(e) Water velocity *WS*. The maximum velocity of water in a channel.

2-3.4.2.2 VALUES USED IN DESCRIBING TERRAIN UNITS*

The terrain factor values, terrain factor class ranges, and terrain factor class numbers used to describe a terrain unit follow:

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*It should be emphasized that these numerical values were selected for the *AMC '71 Vehicle Mobility Model*. The classes were thought to be fine enough to differentiate between vehicles, yet not "too fine" so as to present an insurmountable computational problem. Validation tests and sensitivity analyses, however, may show the necessity for several changes.

(1) *Surface Composition.* Surface composition is described in terms of type of surface material and the strength of the surface material.

(a) Surface type. The surface types of material are:

Code No.	Material type
1	Fine-grained soil
2	Coarse-grained soil
3	Organic soil

(b) Soil strength. Soil strength is described in terms of cone index (*CI*) or rating cone index (*RCI*) of the 0- to 6-in. layer. *RCI* is used to describe the strength of Type 1 material and *CI* is used to describe the strength of Types 2 and 3 materials. The classes and values used to describe soil strength are:

Class No.	Class range	Value selected for prediction
1	> 280	300
2	221-280	250
3	161-220	190
4	101-160	130
5	61-100	80
6	41-60	50
7	33-40	36
8	26-32	29
9	17-24	20
10	11-16	14
11	0-10	5

The preceding class numbers of soil strength are normally used to describe the soil strength for a terrain unit during the dry, the wet, or the average season. However, a different class number may be required to describe the soil strength during different seasons. For example, for a given terrain unit, fine-grained soils, Class No. 6 may be required to describe the wet season strength and Class No. 2, the dry season strength.

(2) *Surface Geometry*. Surface geometry is subdivided into macrogeometry and microgeometry. Macrogeometry is described by slope angle and is usually considered as a slope that is greater in length than the vehicle under study. Terrain factors used to describe surface features identified as microgeometry are separated into two categories. Category 1 includes those surface features such as boulders, stumps, logs, dikes, potholes, that a vehicle will either override slowly or circumvent. Category 2 includes surface features that are overridden which excite the vehicle in the vertical direction (essentially the ride problem). Obviously, a terrain feature could be macrogeometrical for a small vehicle, but microgeometrical for a large one. Similarly, a feature could be in Category 1 for one vehicle but in Category 2 for another. Terrain features in Category 1 are described in terms of approach and departure angle, vertical magnitude, base width, length, spacing, and spacing type. Surface features in Category 2 are described as a continuous profile (approximately 500 ft long) in sufficient detail that a valid power spectral density can be obtained.

(a) Macrogeometry. The classes and values used to describe *slope* (macrogeometry) are:

Class No.	Class range, %	Value selected for prediction, %
1	0-2	1
2	2.1-5	3.5
3	5.1-10	7.5
4	10.1-20	15.0
5	20.1-40	30.0
6	40.1-60	50.0
7	60.1-70	65.0
8	> 70	72.0

(b) Microgeometry (Category 1). The classes and values used to describe obstacle approach and departure angle, obstacle vertical magnitude, obstacle base width, obstacle length, and obstacle spacing are:

(c) Obstacle approach and departure angle

Class No.	Class range, deg	Value selected for prediction, deg
1	178.6-180	179
2	180.0-181.5	181
3	175.6-178.5	177
4	181.6-184.5	183
5	170.1-175.5	173
6	184.6-190	187
7	158.1-170	164
8	190.1-202	196
9	149.1-158	154
10	202.1-211	206
11	135.1-149	142
12	211.1-225	218
13	90.0-135	112
14	> 225	225

(d) Obstacle vertical magnitude

Class No.	Class range, cm	Value selected for prediction, cm
1	0-15	8
2	16-25	20
3	26-35	30
4	36-45	40
5	46-60	53
6	61-85	72
7	> 85	85

(e) Obstacle base width

Class No.	Class range, cm	Value selected for prediction, cm
1	> 120	120
2	91-120	106
3	61-90	76
4	31-60	46
5	0-30	15

(f) Obstacle length

Class No.	Class range, m	Value selected for prediction, m
1	0-0.3	0.2
2	0.4-1.0	0.7
3	1.1-2.0	1.6
4	2.1-3.0	2.6
5	3.1-6.0	4.6
6	6.1-150	78.0
7	> 150	150.0

(g) Obstacle spacing

Class No.	Class range, m	Value selected for prediction, m
1	Bare	60.0
2	20.1-60	40.0
3	11.1-20	15.6
4	8.1-11	9.6
5	5.6-8	6.8
6	4.1-5.5	4.8
7	2.6-4.0	3.3
8	0-2.5	1.2

(h) Obstacle spacing type

Code No.	Description
2	Linear
1	Random

(i) Microgeometry (Category 2). The terrain required for a Category 2 microgeometry is a terrain profile in sufficient detail for valid power spectral density to be obtained. An example of this terrain description follows:

(j) Surface roughness

Profile Class	Class range, in.$_{rms}$	Value selected for prediction, in.$_{rms}$
1	0-0.5	0.25
2	0.6-1.5	1
3	1.6-2.5	2
4	2.6-3.5	3
5	3.6-4.5	4
6	4.6-5.5	5
7	5.6-6.5	6
8	6.6-7.5	7
9	> 7.5	8

(3) *Vegetation.* Vegetation is described in terms of stem diameter and spacing. For convenience, visibility is also included as a part of the vegetation factor family since it is often closely related. Those stems that can be overridden by a vehicle are identified as longitudinal obstacles and those that must be avoided by a vehicle are identified as lateral obstacles. The classes and values used to describe stem diameter, stem spacing, and visibility follow:

(a) Stem diameter and spacing

Stem diameter

Class No.	Value, cm
1	0
2	> 2.5
3	> 6.0
4	> 10.0
5	> 14.0
6	> 18.0
7	> 22.0
8	> 25.0

Stem spacing

Class No.	Class range, m	Value selected for prediction, m
1	Bare	100.0
2	> 20	20.0
3	11.1-20	15.5
4	8.1-11	9.5
5	5.6-8	6.8
6	4.1-5.5	4.8
7	2.6-4	3.3
8	0-2.5	1.2

(b) Visibility or recognition distance classes at 1.5 ft above ground

Class No.	Class range, m	Value selected for prediction, m
1	> 50	50.0
2	24.1-50	37.0
3	12.1-24	18.0
4	9.1-12	10.6
5	6.1-9.0	7.5
6	4.6-6.0	5.3
7	3.1-4.5	3.8
8	1.6-3.0	2.3
9	0-1.5	0.8

NOTE: The surface code number and obstacle spacing code number are used in the same manner as terrain factor class numbers to form the terrain factor complex number.

Hydrologic geometry factors are used primarily to describe linear features that transport water. One hydrologic geometry factor, water depth, is used also as a part of the description of areal bodies of water such as lakes, marshes, or swamps. Other hydrologic geometry factors are differential bank height, gap side slope, water width, and water velocity. The classes and values used to describe each of these factors follow:

(c) Differential bank height

Class No.	Class range, m	Value selected for prediction, m
1	0	0
2	NW bank (0.1-1) higher than SE	0.5
3	NW bank (1.1-2) higher than SE	1.5
4	NW bank (2.1-4) higher than SE	3.0
5	NW bank (4)	4.0
6	SE bank (0.1-1) higher than NW	0.5
7	SE bank (1.1-2)	1.5
8	(2.1-4)	3.0
9	(> 4)	4.0

(d) Gap side slope

Class No.	Class range, deg	Value selected for prediction, deg
1	180-185	182.5
2	185.1-190	187.5
3	190.1-200	195.0
4	200.1-210	205.0
5	210.1-220	215.0
6	220.1-230	225.0
7	230.1-250	240.0
8	250.1-260	255.0
9	260.1-265	262.5
10	265.1-270	267.5

(e) Water depth

Class No.	Class range, cm	Value selected for prediction, cm
1	0-100	50
2	101-200	150
3	201-500	350
4	> 500	500

(f) Water velocity

Class No.	Class range, mps	Value selected for prediction, mps
1	No water	Not applicable
2	0	0
3	0-1	0.5
4	1.1-2	1.5
5	2.1-3.5	2.8
6	> 3.5	3.5

(g) Water width

Class No.	Class range, m	Value selected for prediction, m
1	No water	0
2	0.1-3	1.5
3	3.1-6	4.5
4	6.1-9	7.5
5	9.1-12	10.5
6	12.1-15	13.5
7	15.1-18	16.5
8	18.1-21	19.5
9	21.1-24	22.5
10	24.1-27	25.5
11	27.1-30	28.5
12	30.1-35	32.5
13	35.1-40	37.5
14	40.1-45	42.5
15	45.1-50	47.5
16	50.1-55	52.5
17	55.1-60	57.5
18	60.1-65	62.5
19	65.1-70	67.5
20	70.1-75	72.5
21	75.1-80	77.5
22	80.1-85	82.5
23	85.1-90	87.5
24	90.1-95	92.5
25	95.1-100	97.5
26	100.1-105	102.5
27	105.1-110	107.5
28	110.1-115	112.5
29	115.1-120	117.5
30	120.1-125	122.5
31	125.1-130	127.5
32	130.1-135	132.5
33	135.1-140	137.5
34	140.1-145	142.5
35	145.1-150	147.5
36	150.1-155	152.5
37	155.1-160	157.5
38	160.1-165	162.5
39	165.1-170	167.5
40	170.1-175	172.5
41	175.1-180	177.5
42	180.1-185	182.5
43	185.1-190	187.5
44	190.1-195	192.5
45	195.1-200	197.5
46	200.1-205	202.5
47	205.1-210	207.5
48	210.1-215	212.5
49	215.1-220	217.5
50	220.1-225	222.5
51	225.1-230	227.5
52	230.1-235	232.5
53	235.1-240	237.5
54	240.1-245	242.5
55	245.1-250	247.5
56	250.1-255	252.5

Class No.	Class range, m	Value selected for prediction, m
57	255.1-260	257.5
58	260.1-265	262.5
59	265.1-270	267.5
60	270.1-275	272.5
61	275.1-280	277.5
62	280.1-285	282.5
63	285.1-290	287.5
64	290.1-295	292.5
65	295.1-300	297.5
66	300.1-305	302.5
67	305.1-310	307.5
68	310.1-315	312.5
69	315.1-320	317.5
70	320.1-325	322.5
71	325.1-330	327.5
72	330.1-335	332.5
73	335.1-340	337.5
74	340.1-345	342.5
75	345.1-350	347.5
76	350.1-355	352.5
77	355.1-360	357.5
78	360.1-365	362.5
79	365.1-370	367.5
80	370.1-375	372.5
81	375.1-380	377.5
82	380.1-385	382.5
83	385.1-390	387.5
84	390.1-395	392.5
85	395.1-400	397.5
86	400.1-405	402.5
87	405.1-410	407.5
88	410.1-415	412.5
89	415.1-420	417.5
90	420.1-425	422.5

2-3.4.2.3 EXAMPLES

Areal terrain units can be represented on a map as an area bordered by an irregular closed line. Linear terrain units appear on the map as lines because their widths are relatively small compared with their lengths.

Each attribute of a terrain that is considered to affect mobility is called a terrain factor. Related factors are grouped in factor families, which are surface composition, surface geometry, vegetation, and hydrologic geometry.

Each terrain factor can be quantitatively characterized in terms of the terrain factor classes given in par. 2-3.4.2.2. A terrain unit is then described by an array of terrain factor class numbers. This array is called the terrain factor complex number. The final product of the system is a terrain map that shows all the factor complex numbers for each terrain unit.

The following procedures are implemented to form an areal terrain map legend. One factor at a time is mapped to form factor maps; factor maps are then overlaid to form factor family maps; and the factor family maps are overlaid to form a terrain factor complex map. Each terrain factor complex number is then replaced by a terrain unit number on the terrain factor complex map, and a legend relating the terrain unit number to the terrain factor complex number is prepared. Examples of an areal terrain map and legend are shown in Fig. 2-46 and in Table 2-12, respectively.

Linear terrain maps are prepared in much the same way as areal terrain maps, except that a single line representing a linear feature is overlaid successively with a factor map until all the factors are overlaid. The factor complex number is then replaced by a terrain unit number, and a legend relating the terrain unit numbers and terrain factor numbers is prepared. Examples of a linear terrain map and legend are shown in Fig. 2-47 and in Table 2-13, respectively.

These figures illustrate drainage features. Other linear features such as road embankments can also be so mapped.

2-3.4.3 POWER SPECTRAL DENSITY (PSD) PLOTS

Power spectral density (PSD) curves are an accepted technique for plotting the roughness of terrain on a local level. Ordinarily these curves display the power in an electrical signal

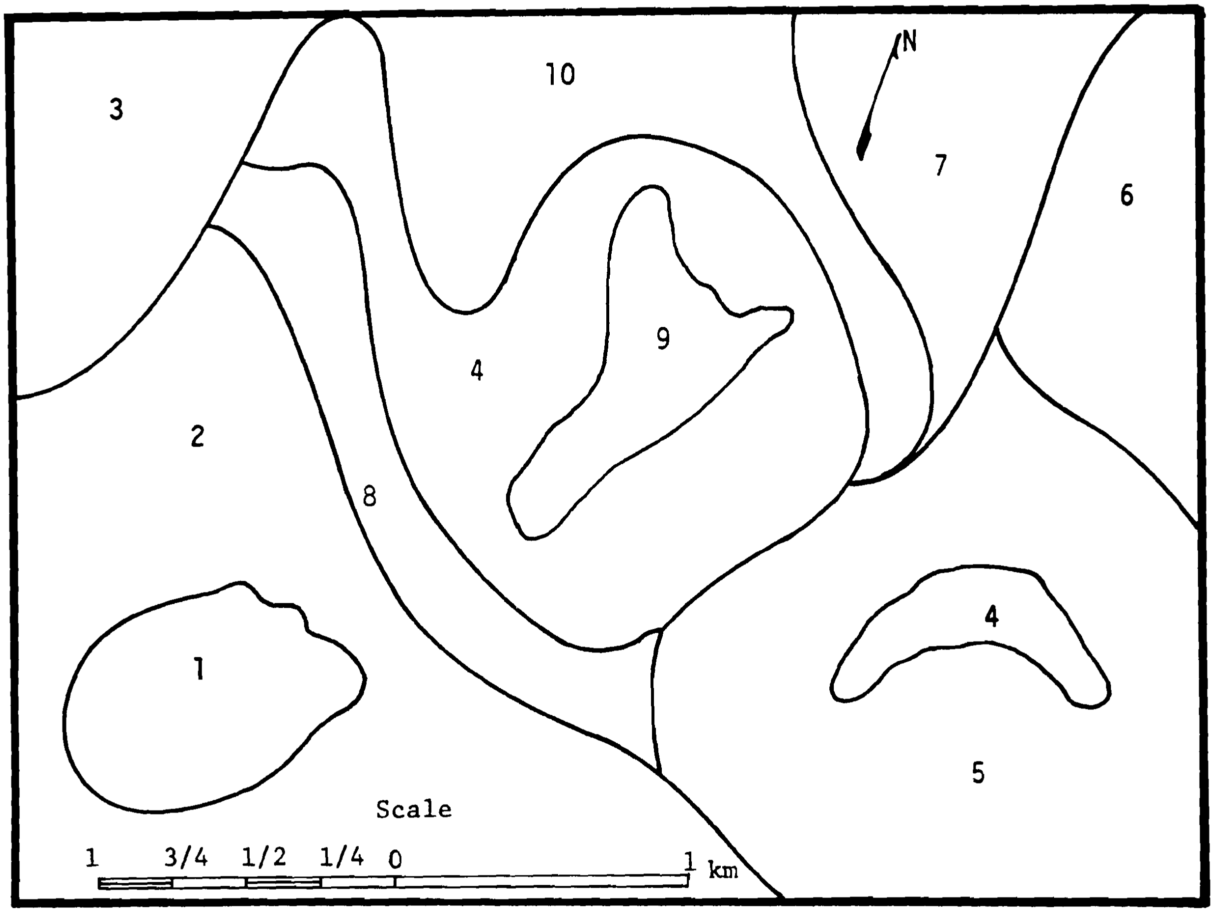

Figure 2-46. Example of an Areal Terrain Factor Complex Map (Ref. 15)

as a function of frequency, since any random time functions can be broken into the sum of the contributions of many periodic functions of different frequencies. The power spectral density curve is a plot of the mean amplitude squared of every contributing frequency present.

The undulations of terrain present a curve of random characteristics. Since this curve is stationary, it cannot be considered to have frequencies as do electrical signals; however, a vehicle traveling across the terrain will encounter these undulations at a rate dependent on vehicle speed; hence, the terrain can be analyzed in a similar manner.

A plowed field contains a contribution to the PSD plot corresponding to the wavelength between furrows; it also contains a component corresponding to the various lump sizes in the overturned soil.

Some representative examples of terrain profiles are given in Fig. 2-48. Fig. 2-49 shows the corresponding spectral densities of the terrain profiles illustrated in Fig. 2-48.

Power spectral density plots of terrain typically have large values at low frequencies and taper off according to the roughness of the particular profile. In Fig. 2-48 the data points were taken 2 ft apart and the altitude was measured to the nearest 0.01 ft. The data points were determined with a tape measure and the elevations were measured with a level and rod.

The general shapes of the PSD curves shown in Fig. 2-49 are similar, although

TABLE 2-12

EXAMPLE OF AN AREAL TERRAIN MAP LEGEND (Ref. 15)

Table of terrain factor complex numbers

Order of terrain factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Terrain unit No.	Surface type	Surface strength (dry season)	Surface strength (average season)	Surface strength (wet season)	Slope	Obstacle angle	Obstacle vertical magnitude	Obstacle base width	Obstacle length	Obstacle spacing	Obstacle spacing type	Surface roughness	Stem spacing of stem diam. $\geq$ Class 1	Stem spacing of stem diam. $\geq$ Class 2	Stem spacing of stem diam. $\geq$ Class 3	Stem spacing of stem diam. $\geq$ Class 4	Stem spacing of stem diam. $\geq$ Class 5	Stem spacing of stem diam. $\geq$ Class 6	Stem spacing of stem diam. $\geq$ Class 7	Stem spacing of stem diam. $\geq$ Class 8	Recognition
1	1	1	2	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	3	4	5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	5	6	7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	1	7	8	9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1	9	10	11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	2	1	2	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	2	7	8	9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	2	9	10	11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	3	1	2	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	3	7	8	9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

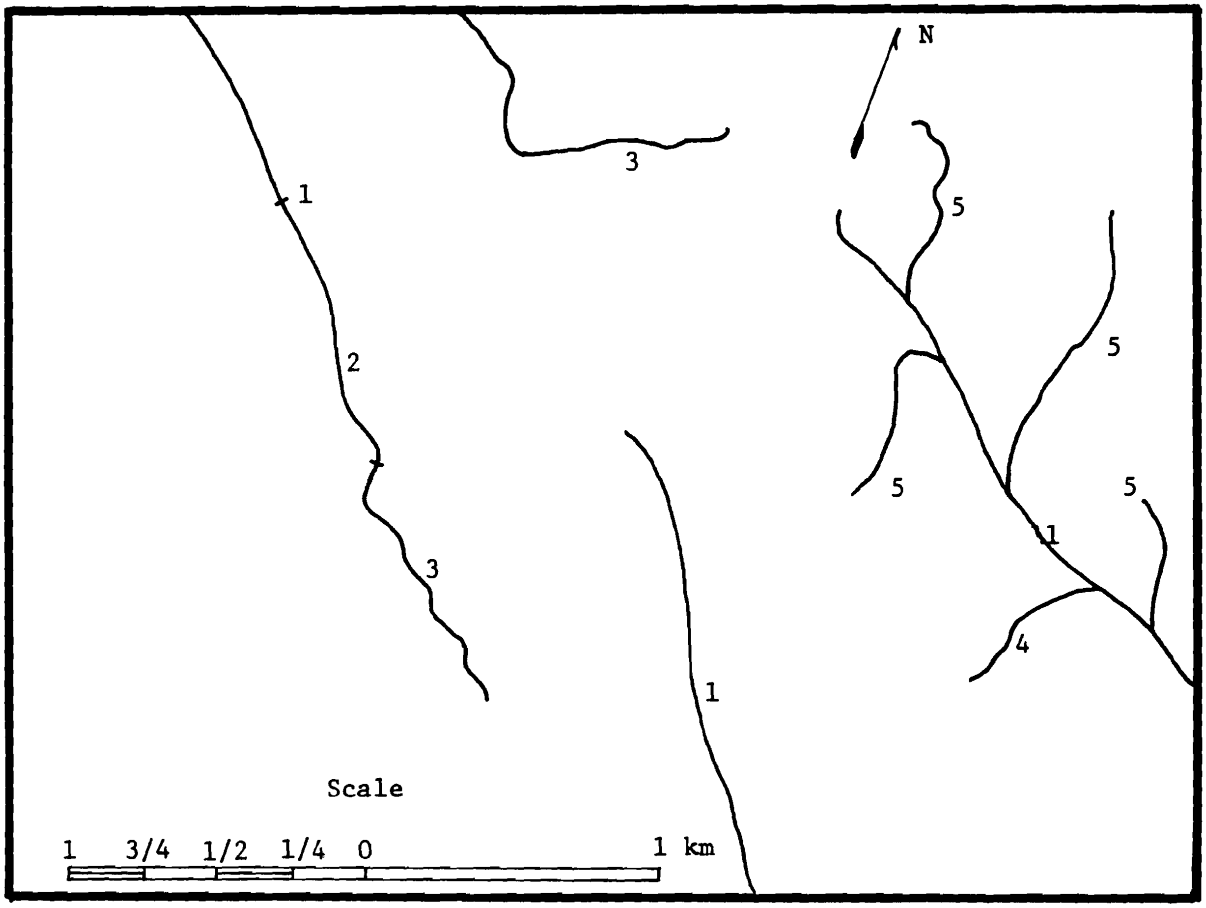

Figure 2-47. Example of a Linear Terrain Map (Ref. 15)

different profiles have different knees or bumps in the PSD curve which correspond to some repetitive feature at a characteristic frequency. For example, the difference between an agricultural field before and after plowing is shown in Fig. 2-50. The bump at the 6 m^{-1} line corresponds to the freshly plowed furrows. The numbers 1 and 2 indicate different fields; field 2, having a greater area under the PSD curve, is rougher both before and after plowing. Since the plots are on semilog coordinates, the influence of the leftmost portion is far greater than that on the right.

PSD curves, besides giving a qualitative scale for comparison, produce a roughness measure that can be classified directly, so that not only random ground waves but also their harmonic content and power level can be accounted for. Fig. 2-51 illustrates the wide spectrum of power spectral density curves that can be encountered. These curves are plotted on a log-log scale rather than the semilog scale of Figs. 2-49 and 2-50. Since all of the curves illustrated in Fig. 2-50 appear to have roughly the same slope, it is plausible that terrain power spectral density curves can all be approximated by a simple exponential function. Such an approximation greatly simplifies the mathematical treatment of power spectral density curves and, in general, does not obscure the important features that may be biased by the methods used to gather the profile sample in the first place. This approximation takes the following form:

$$S_g(\Omega) = K_\nu \Omega^{-n_\nu} \qquad (2\text{-}15)$$

TABLE 2-13

EXAMPLE OF LINEAR TERRAIN MAP LEGEND (Ref. 15)

Table of terrain factor complex numbers

Order of terrain factors	1	2	3	4	5	6
Terrain unit No.	Left gap side slope	Differential bank height	Right gap side slope	Water width	Water depth	Stream velocity
1	1	11	1	2	1	2
2	7	1	7	3	2	2
3	8	1	8	2	1	2
4	10	1	10	10	2	2
5	11	1	8	90	4	1

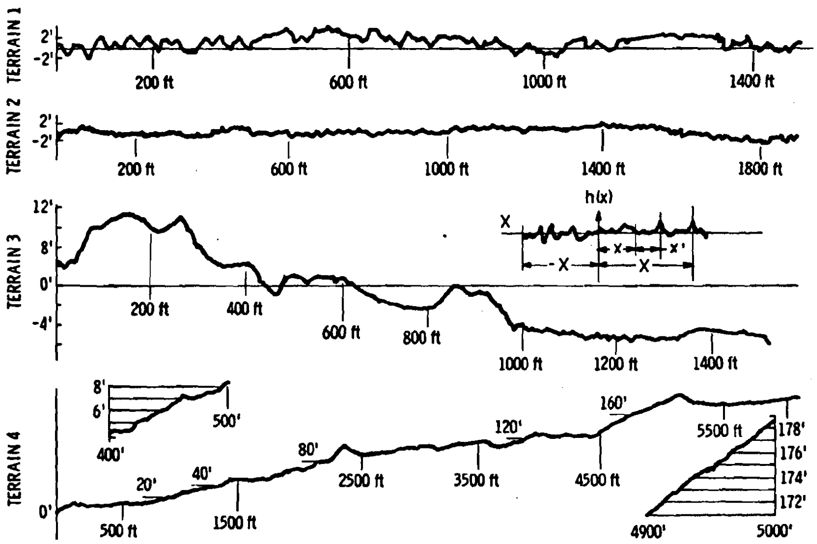

Figure 2-48. Terrain Profiles Measured in Off-road Locomotion Studies (Ref. 8)

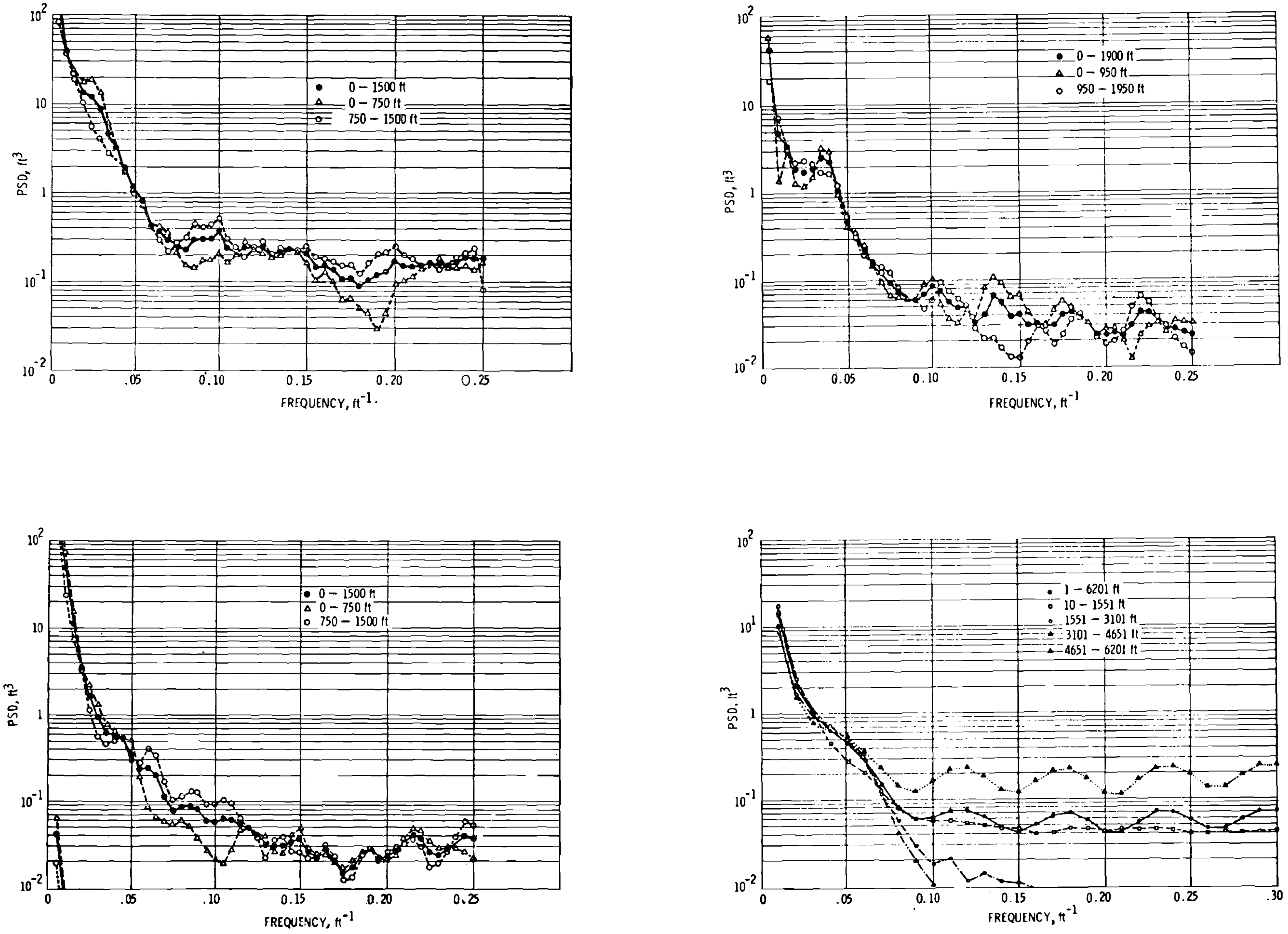

Figure 2-49. Power Spectral Densities for Terrain (Ref. 8)

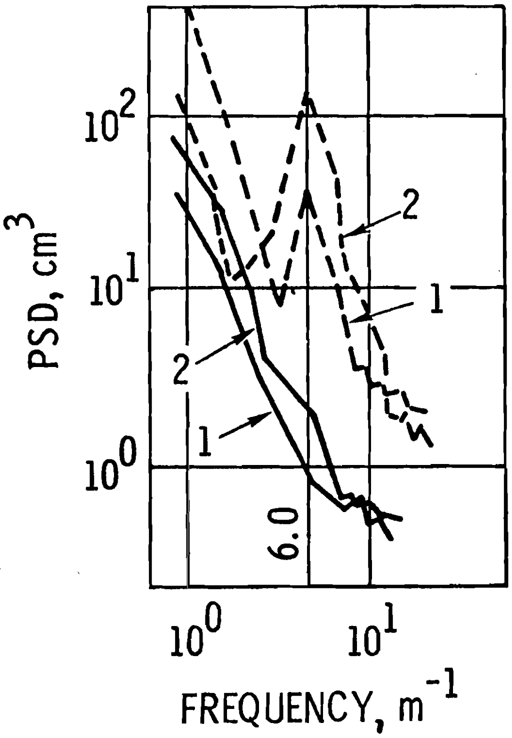

Figure 2-50. Power Spectral Density of Farmland (Ref. 8) (Two fields, 1 and 2, before (solid curves) and after (dashed curves) plowing with furrows at 6 m^{-1})

where

S_g = power spectral density, ft^3 (or m^3)

Ω = spatial frequency, ft^{-1} (or m^{-1})

K_v = empirical constant indicating the magnitude of roughness, ft^{3-n}

n_v = empirical exponent indicating the slope of the *PSD* curve (In most terrains that have been measured $n_v \approx 2.$), dimensionless

2-3.5 AERIAL PHOTOGRAPHY*

The principles and uses of aerial photography using conventional black-and-white film are well known. Such photography with panchromatic film uses the complete visible spectrum, except that haze, or minus-blue, filters are occasionally introduced. It provides a high resolution and generally distortion-free visual map of the terrain essentially as the human eye perceives it. In this type of photography, the objects of interest are recorded in varying shades of gray on the photographic emulsion. The problem of photointerpretation begins here. In many situations the image is of a familiar object or terrain feature, and its geometric properties (size, shape, shadow, or texture) plus its location, contrast, and relationship to surrounding objects enable ready identification. However, when the object is unfamiliar or exhibits a different or unaccustomed tonal value on the image, the interpreter's judgment and experience become critical.

2-3.5.1 RESOLVING POWER

For a given film format, the smallest detectable elevation feature is given by the empirical relation:

$$\frac{\Delta H}{H} = \frac{1}{274\, WR} \qquad (2\text{-}16)$$

where

H = flight elevation, ft

ΔH = elevation of the smallest detectable feature, ft

R = resolving power of the camera system, lines mm^{-1}

W = film format or width, ft

This elevation resolving power is shown for 9-in. film in Fig. 2-52. The range of resolution pictured (up to 80 lines per millimeter) represents that presently used in unclassified state-of-the-art aerial photography.

Photographic interpretation of detail from aerial photography ranges from scales of 1:2,000 to 1:10,000, with ground resolution of object size obtained in terms of inches. In contrast, the common scales for photointerpretation for reconnaissance purposes range

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*Adapted from Ref. 3.

1. Mild roughness
2. Rocky soil
3. Cultivated field
4. Cross country, medium roughness
5. Rock and log, artificial
6. Perryman cross country
7. Grasslands
8. Cross country marker 19
9. Turn off to marker 6
10. Virgin terrain, track 1
11. Virgin terrain, track 2
12. Cross country, severe roughness 1
13. Cross country, severe roughness 2
14. Artificial
15. Artificial
16. Poor runway
17. Good runway
18. Poor roadway
19. Good roadway
20. Poor cobbled pavement
21. Good cobbled pavement
22. Asphalt pavement
23. Concrete road
24. Asphalt road

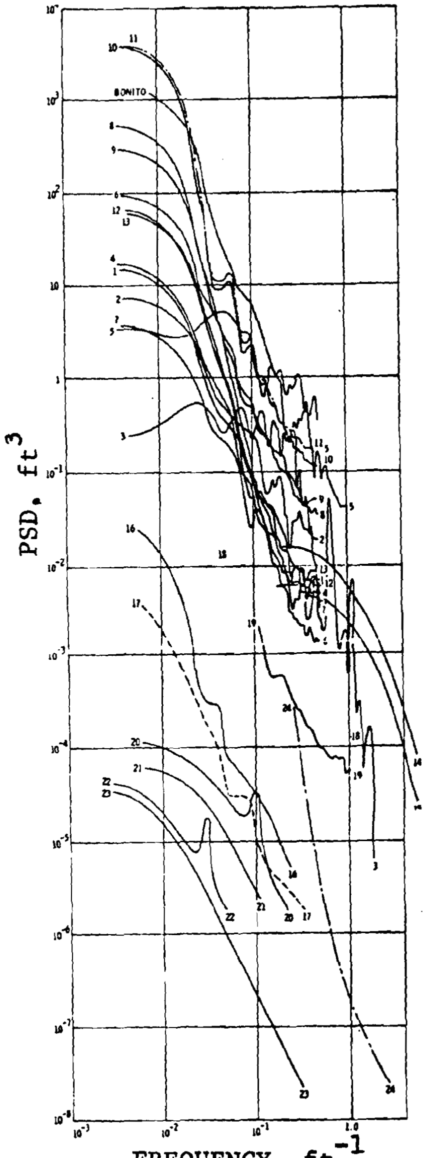


Figure 2-51. PSD Curves for Various Ground Surfaces (Ref. 8)

from 1:10,000 to 1:40,000, with ground resolution attainable in terms of feet. The common photographic mapping scale is 1:60,000, depending on the use of adequate ground control points.

The use of aerial color photography greatly extends the criteria that can be used for terrain property identification. Although the human eye-brain combination can discriminate only about 128 shades of gray, it can discriminate several million different colors.

Many problems complicate the use of aerial color photography, apart from the cost of the film and the necessary processing techniques. The glass covering the camera wells in photographic reconnaissance aircraft is rarely of high optical quality and may act as an image-degrading filter with color tones ap-

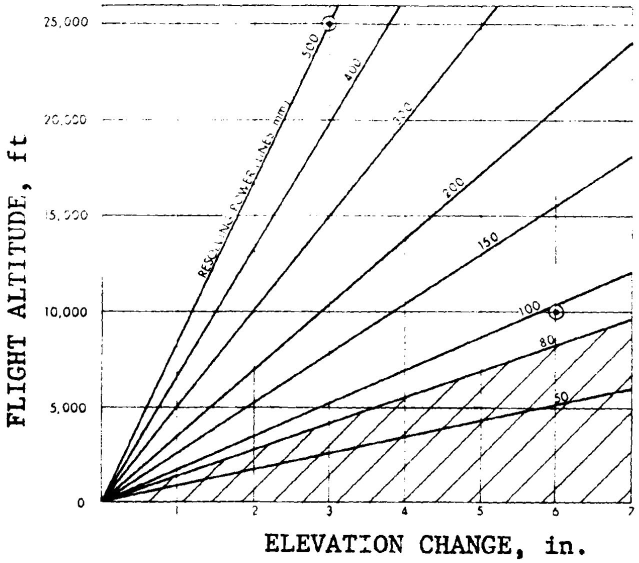


Figure 2-52. Resolving Power of Photography Varying With Flight Altitude (Ref. 3)

pearing on the emulsion being different from the natural object colors. The optical properties and color correction of the camera lenses themselves; the quality, amount, and atmospheric absorption of the reflected solar radiation; and the variability of the dyes making up the film emulsion itself are other factors that can contribute to image color variability. The American Society of Photogrammetry has published a *Manual of Color Aerial Photography* that is highly recommended for pertinent information (Ref. 16). A voluminous report entitled *Photographic Instrumentation–Science and Engineering* prepared for the Naval Systems Command gives a thorough coverage of all photographic equipment and applications (Ref. 17). The Navy Oceanographic Office has recently conducted a test of the water-penetrating ability of color photography, in flights from 2,000 to 30,000 ft altitude (Ref. 18). It was found that 100-ft-sq offshore targets could successfully be detected at depths of 65 ft, even in rough water at sun angles from 20 to 40 deg.

Color photography from satellite altitudes provides coverage of earth areas of unprecedented scope and contrast. An example of this capability is the preparation of tectonic maps of the Middle East at one to one million scale by the North American Aviation Science Center under NASA support (Ref. 19). These maps, prepared entirely from Gemini photographs, show faults, shear zones, and geologic structures, often extending for hundreds of miles, that are unrecognizable in larger scale photography.

Aerial panoramic cameras have been developed and used for over a decade to combine wide-area photographic coverage with very high resolution. They generally have a curved film plane and a high-quality, narrow-angle lens that scans across the flight path of the aircraft so as to "paint" an image of a wide swath of ground onto the film. The maximum scan angle is 60 deg either side of the vertical. With a focal length of 12 in., very high altitude photography can be obtained without sacrificing image detail. Since the center of the lens rotates with the scanning arm, the sharpest possible image is always recorded on the film, even at the edges of the format. An example of the scope and high resolution of panoramic aerial photography is shown in Fig. 2-53.

Modifications to aerial color film to eliminate the blue-sensitive layer have re-

Figure 2-53. Aerial Panoramic View of Terrain (Ref. 3)

cently been proposed to film manufacturers. The standard yellow haze filter would no longer be needed, and a one-stop increase in exposure would be possible.

2-3.5.2 MULTISPECTRAL PHOTOGRAPHY

Multispectral, multiband, and spectro-zonal photography are terms applied to the images simultaneously obtained through various filter combinations in narrowband regions of the visible and near-infrared spectrum. The operating principle of this technique is that different types or conditions of terrain reflect solar radiation differently throughout the photographic spectrum. By interpretation of the relative brightness or tonal contrast appearing on matched, narrowband images, changes in soil or vegetation properties and the composition of or the seasonal effects on the terrain can be detected and analyzed. Such information can be obtained in a more quantitative manner from this type of aerial photography than from conventional black-and-white or even color photography.

A nine-lens camera system has been used extensively by the Air Force Cambridge Research Laboratories (AFCRL) and NASA for airborne terrain research programs (Ref. 20). This "multiband" camera employs three rolls of film, each traversing three matched lenses equipped with appropriate filters to give a narrowband input to the film. The part of the spectrum covered is from 400 to 900 nm, with resolution of approximately 75 lines per millimeter. The resulting nine photographs, taken at one shutter click, are matched within 0.001 in. Six of the images are on two rolls of 70-mm aerial panchromatic film, and the other three are on one roll of 70-mm aerial infrared film. The lenses used are f/2.4, 150 mm with standard gelatin filters that give bandwidths of about 100 nm.

Extension of the capability of the camera to gather signatures of terrain properties is provided by the use of horizontally and vertically polarized filters in two of the bands, and an ultraviolet transmitting lens in another band, applied when desired. The camera has image motion compensation, and can be flown at altitudes of from 600 to over 25,000 ft. A stabilized mount is desirable to provide vertical control of photographic coverage. Wide ranges of shutter speeds and apertures are available for use over various conditions of terrain illumination.

The multispectral camera has been used to record diverse terrain areas—arctic glaciers, lava flows, coastal beaches, desert playas, and

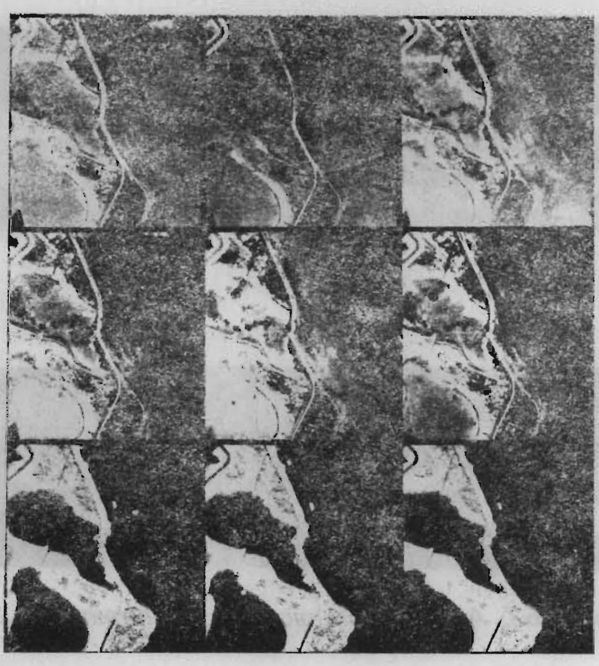


Figure 2-54. Multiband Photography (Ref. 3)

tropical rain forests—all of interest because of their characteristic reflectance properties (Ref. 3). Analysis involves examination of the nine images from each exposure on a light table modified to display the three rolls of film together. Terrain anomalies or patterns of interest can be identified in terms of their reflectance changes for correlation with known patterns and conditions; selected frames can be used for color enhancement or superposition techniques, if desired. In special cases where very subtle tonal differences are worthy of more analysis, a microdensitometer can be used to scan the original negative and yield the detailed reflectance values that were registered as gray tones.

The nine bands were originally chosen to provide wide coverage throughout the spectrum. Since some of these may give no additional or otherwise redundant reflectance information, a lesser number of bands may be practical. Various Government agencies (Rome Air Development Center, Army Cold Regions Research and Engineering Laboratory, AFCRL, and NASA) and many commercial aerial photographic organizations have developed fourband cameras by clustering four separate 70-mm cameras and synchronizing their shutters, a technique that yields worthwhile multispectral photography.

An example of the imagery generated by the nine-lens systems of AFCRL, and the interpretation of the tonal changes evident in contrasting wavelength regions, is shown in Fig. 2-54.

2-3.5.3 COLOR DISTORTION PHOTOGRAPHY

"Camouflage Detection" (CD) or Ektachrome infrared (IR) film is a high-resolution, false-color film that differs from normal color film by having its three sensitized emulsion layers record green, red, and infrared radiation instead of the usual red, green, and blue. It has high color contrast, brilliance, and haze penetration capability. The colors, although appearing visually false, provide a contrast enabling adjacent objects or materials to stand out distinctly. Although the high-resolution values cited by the manufacturer may not generally be realized through exposure and processing, the clarity of CD images provides greater detail than

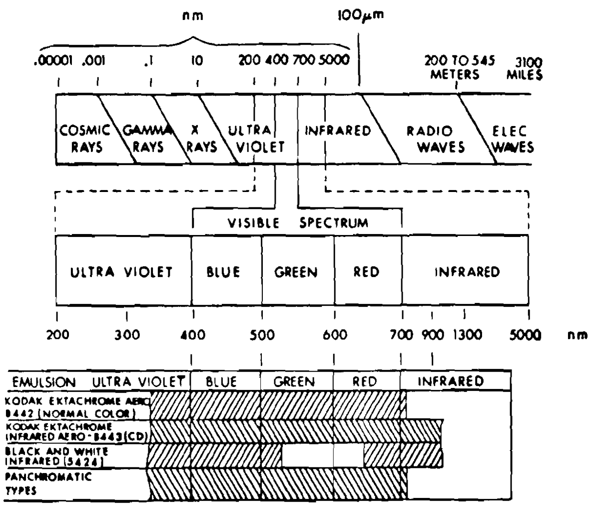


Figure 2-55. Electromagnetic Spectral Sensitivity Ranges of Films (Ref. 3)

comparable color or IR images. Fig. 2-55 illustrates the visible spectral and sensitivity ranges of pertinent films.

The use of color distortion photography also enables distinction between types and health of vegetative cover. Deciduous green foliage reflects green and infrared radiation, and film processing leaves magenta as the indicator for such vegetation; coniferous foliage is recorded as a darker magenta. Due to changes in IR reflectivity of foliage pigments, dead or diseased leaves are recorded in shades of light magenta to orange. The effectiveness of using CD film for determining certain of the properties of vegetative cover has been demonstrated (Ref. 21).

In addition, the use of color emulsions, particularly CD film, enables very good photographic penetration of water. Underwater terrain contours and obstacles can be recognized and mapped by this CD photography, enabling offshore beach or shallow water charting for amphibious operations.

Objects in shadow or shade usually are not detectable on normal black-and-white images, but they stand out readily on CD film. Objects of different colors, which usually show the same shades of gray in black-and-white photography, have definite color contrasts when imaged on CD film. This is especially valuable during conditions of low sun angle or in oblique photography where long shadows are produced.

CD photography is best reproduced and evaluated as transparencies, since the full-color values cannot be duplicated on paper prints.

2-3.5.4 POLARIZED LIGHT PHOTOGRAPHY

In real target-background situations, illumination is by both direct sunlight and diffused skylight. Light reflected from surfaces, in turn, is both coherent and incoherent. Light reflected from most surfaces is considered partially coherent, in that a rough-textured reflecting surface is a fairly good diffuser since the surface as a whole reflects diffusely while the many small facets of which it is composed reflect specularly. The expression σ/λ, where σ is the rms surface roughness and λ is the wavelength of the incident light, can be stated as a measure of the light-diffusing property of the surface. Multireflected light, in the case of a many-faceted rough surface, is randomly polarized. The intensity ratio of multireflected to directly reflected light is dependent on the distribution of facet orientation. This ratio generally increases with increasing total reflectance. Hence, the degree of linear polarization of light reflected from diffusing surfaces is inversely related to the total reflectance.

Many polarized photography experiments on natural terrain and manmade surfaces have been conducted (Ref. 22). These experiments prove that polarization contrasts can be used to detect and discriminate background and target materials, in both direct and diffuse illuminations. A wide variety of natural materials have been photographed in both the visible and near-infrared spectrum. It was found that the largest polarization contrast exists in the 500 to 700 and the 800 to 1,000 nm bands of the spectrum.

Polarization contrast, like chromatic and luminous contrast, can generally be observed for any material; therefore, a discrimination capability is present in the degree of polarization of light reflected from objects in any scene.

2-3.5.5 INFRARED PHOTOGRAPHY

The use of black-and-white infrared film in aerial cameras has both advantages and disadvantages. This film is designed to be sensitive in the red and near-infrared wavelength region, but it is also sensitive in the ultraviolet region below 530 nm. To insure that only the red and infrared portions will be recorded, a Kodak 89B filter is used to eliminate the ultraviolet and almost all the visible portion of the spectrum below 700 nm.

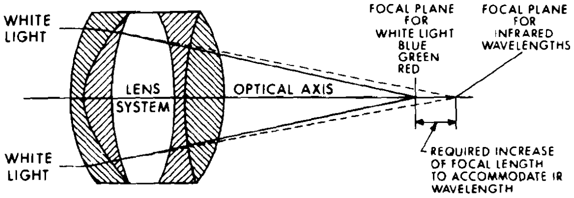
The difference in black-and-white IR photography as compared to panchromatic is most evident in the recording of water and foliage (Ref. 23). Since water does not reflect or transmit infrared radiation, and the blue portion of the rest of the spectrum reflected from water surfaces is filtered out, water appears very dark or black with respect to land, which is a lighter gray tone. Grass, bare earth, and water might all show an equal density or gray tone on panchromatic film. However, IR film will show the grass as light gray and earth as medium gray, enabling ready distinction. Delineation of shoreline contours is an immediately obvious capability.

IR films record healthy, lush vegetation in the lightest tones, while vegetation that does not have enough water reflects less infrared energy and shows as medium tones due to changes in the relative amount of chlorophyl and pigments.

The filtered infrared sensitivity of this film also makes it useful for haze penetration, since the less scattered rays are recorded. This infrared sensitivity also provides increased tonal contrast between manmade and natural objects, such as an asphalt runway against an adjacent grass or soil background.

The resolution of black-and-white IR film is noticeably poorer than panchromatic. Most lenses for aerial cameras are designed for visible light and therefore focus the infrared rays behind the normal focal plane, as shown in Fig. 2-56. Refocusing or lengthening of the focal distance, therefore, is required with IR film. Not all of the IR wavelengths will be brought into the film plane, but a sufficient portion of them will fall into focus to produce an acceptable image. The 89B filter provides a bandpass of 200 nm to minimize the possibility of degraded images generated by the lens-film combination.

A photometer or exposure meter cannot give reliable values to determine proper IR film exposure, since wavelengths beyond the visible spectrum do not register on these devices. The usual technique is to use the manufacturer's exposure index as modified by the appropriate filter factor. Areas highly reflective in the infrared, such as vegetation, require less exposure than industrial areas. A comparison of simultaneous visible and IR photography is shown in Fig. 2-57.



LENS SYSTEM (CHROMATIC CORRECTED) FOCUSSES THE VISIBLE COLORS, BLUE, GREEN, AND RED LIGHT TO A COMMON FOCUS. TO FOCUS INFRARED WAVELENGTHS THE IMAGE FOCAL DISTANCE MUST BE EXTENDED.

Figure 2-56. Focus of Infrared Wavelengths With Focal Distance (Ref. 3)

2-4 MEASUREMENTS*

This paragraph reviews the instruments commonly used to measure the critical parameters of the terrain. What constitutes a critical parameter, of course, varies with the mission. This paragraph attempts to be fairly inclusive, but the emphasis is primarily on terrain trafficability and the measurement of the parameters that are vital for assessing trafficability.

The measurements and quantitative evaluations that can be made of the terrain cover a wide spectrum. Properties amenable to measurement vary from color to radioactivity, from hardness to chemical composition, from obvious physical features to hidden, potentially treacherous, subsurface properties. The list of measurements described here, although extensive, is by no means exhaustive. That this list will increase in the future is virtually assured because the characterization presently available is not completely adequate for the present day military mission.

2-4.1 SOIL PARTICLE CLASSIFICATION

Sands and gravels can be easily identified by visual inspection. Important physical characteristics such as texture, gradation, and particle shape may also be described qualitatively on the basis of a visual examination.

Two simple tests can be used to detect the presence of silt and clay-sized particles since they cannot be distinguished with the unaided eye. If a handful of dry soil is sifted through the fingers and allowed to fall on the ground, the amount of silt and clay-sized particles present can be estimated from the amount of dust created. Secondly, with the soil either wet or dry, a small quantity is placed in a test tube or bottle, water is added, then the bottle is shaken vigorously. Particles larger than about 0.05 mm in size will have settled approximately 3 in. in 30 s. Consequently, if after about 30 s, the top 3 in. of water is not substantially clear, the presence of a significant quantity of the smaller silt and clay-sized particles is indicated.

Inorganic silts, in the wet state, can be rolled into thin threads, but, if the threads are more than a few inches long, they will not support their own weight when held by one end. In addition, at a moisture content corresponding to the plastic limit (the moisture content representing the boundary between the semisolid and plastic states of the soil), these threads will be soft and friable.

When mixed with water to the consistency of a thick paste, the surface of an inorganic silt will appear wet and shiny if a pat is shaken in the palm of the hand. If the pat is squeezed by cupping the hand, the surface will dry up, appear dull, and eventually crack. A clay, similarly treated, will not change its appearance in any way.

Lumps of air-dried silt can easily be crushed between the fingers. If the dry powder of the coarser silts is rubbed between the tips of the fingers, a gritty feeling results.

Clays exhibit plastic properties over a moderate to wide range in water content. They can be molded and rolled into thin threads without breaking or crumbling and threads of considerable length will support their own weight when held by one end if their moisture content is in the plastic range.

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*The discussion of classical soil measurements generally follows that of Ref. 12; the remote sensing portion, Ref. 3.

Figure 2-57. Comparison of Visible and Infrared Photography (Ref. 3)

At moisture contents corresponding to the plastic limit, the more plastic the soil, the harder and tougher it will feel. Consequently, the consistency of a soil at a moisture content corresponding to the plastic limit distinguishes between silts and clays, and also affords a simple method of evaluating the engineering characteristics of the various clays by measuring qualitatively their degree of plasticity.

Lumps of air-dried clay are relatively hard, and the more plastic the clay, the harder they are. These lumps can often be broken but cannot generally be crushed and powdered by hand.

The color of the soil is helpful in distinguishing between soil strata and in identifying soil constituents, but it does not signify that the soil possesses certain specific properties. Color of soil often varies with the degree of moisture present; hence, it is necessary to consider the condition of the soil. Generally, moist soil has more contrast in color and the colors become less distinct as the moisture content is reduced. In fine-grained soils, certain dark or drab shades of gray or brown – including colors that are almost black – are indicative of organic colloidal matter. In contrast, clean and bright-looking colors – including medium and light gray, olive green, brown, red, yellow and white – are generally associated with inorganic soils. Soil color may also indicate the presence of certain chemicals. Red, yellow, and yellowish-brown soil colors may be a result of the presence of iron oxides. White to pinkish colors may indicate presence of considerable silica, calcium carbonate, or aluminum compounds. Grayish-blue, and gray and yellow mottled colors frequently indicate poor drainage.

Organic soils can be identified by their gray to black color, by the presence of undecomposed vegetative matter or shells, and by odor – in many instances they contain gas that is released when the soil is excavated. The odor generally diminishes with exposure to air but becomes pronounced if a wet sample is heated. If a sample is rolled into a thin ball and exposed to the atmosphere for a few days, it will usually show annular rings of discoloration when broken open. The discoloration is the result of the oxidation of thin layers of organic material. Organic soils are highly compressible and are undesirable construction materials.

The general identification of a soil should include prominent characteristics of the undisturbed materials. Sand and gravel are described as being loose, medium, or dense while clays are described as hard, stiff, medium, or soft. The proper designation is determined on the basis of simple tests and observations, previously described, such as the difficulty or ease of pushing a probe into the soil, the ease or difficulty of excavating the soil, or consistency tests.

2-4.2 MOISTURE CONTENT

An understanding of the way in which soils are affected by water is probably more important than any other single factor. The moisture contained in a soil is important to considerations of such soil phenomena as shear resistance, frost action*, volume change with a change in moisture content, and also for an understanding of the properties of compacted soil.

Moisture content (MC) is the term used to define the amount of water present in a given soil. It is expressed as a percentage and is equal to the ratio of the weight of water to that of the dry soil solids.

Techniques that have been applied to the determination of the moisture content of soil include gravimetry, neutron scattering, tensiometry, electrical resistance, thermal conductivity, hygrometry, and microwave absorption (Ref. 24). Of these, the several gravimetric techniques are the older and are employed for calibration purposes. However, gravimetry requires considerable equipment and time. Consequently, considerable attention has been given to alternative faster measurement techniques, and a variety of instruments employing such techniques are available commercially.

The gravimetric technique is the most commonly used technique for measuring moisture in soil. It requires the collection of a soil sample, weighing it, removing the moisture, weighing the dry sample or the removed water, and calculation of the moisture content. It is the most direct way of measuring soil moisture and is employed for calibrating other sensors. In practice, errors are introduced by inhomogeneities in the soil and by moisture lost or gained before or during measurement. It is a destructive technique in that it requires removing a soil sample. Results from gravimetry are also subject to error when water is chemically bound to the soil and when vapors of other materials are present in the soil. Evaporable water is customarily defined as that which is removed under a vacuum of 0.5 torr at 23°C. This corresponds approximately to drying in an oven at 105°C.

While oven drying is the most common method for removing moisture from soil in gravimetric techniques, freeze drying, desiccation, alcohol burning, and other methods are sometimes employed. Alcohol burning, for example, is one of the more rapid gravimetric techniques. It consists of mixing alcohol with the soil sample and igniting the mixture. Most of the water is removed during the process.

Nuclear measurement techniques using neutron scattering depend upon the ability of hydrogen in water to slow down fast neutrons. The form of the hydrogen cannot be distinguished by this method and measurement interferences also exist with sample density, sample composition, surface roughness, and sample homogeneity. A number of nuclear gages are presently employed by

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*Frost action is a general term used in reference to freezing and thawing of moisture in materials and the consequent effects on these materials and the structure of which they are a part, or with which they are in contact.

highway departments to determine soil moisture. Comparative evaluation studies have shown that, while the various interferences lead to errors in moisture measurement, the errors are commonly less than those from other methods. Overall, the nuclear method appears to be a very good method for measurement of moisture in a 3- to 4-in.-surface layer.

Tensiometry is based upon the capillary tension of water, which allows it to permeate a porous cup or membrane. In one version of this instrument, the electrical conductance of salts on one side of the membrane is measured in order to determine the moisture content of the soil; in the other the effective pressure of the water as produced by capillary action in the pores of a ceramic material is measured.

Moisture-measuring techniques that depend on the influence of water on the electrical conductivity of the soil, the thermal conductivity of the soil, or the microwave absorption of the soil have been studied extensively and under certain special circumstances are applicable. For most practicable applications, however, the nuclear measurement technique and the various gravimetric techniques are preferable and most widely employed. Further information on the measurement of moisture content of soils is in par. 2-4.4.

2-4.3 GRAIN SIZE DISTRIBUTION

Few natural soils consist of grains all the same size. The property of a soil that describes the distribution of size groups represented is called gradation. Knowledge of the grain size distribution (gradation) is required in order to classify a soil.

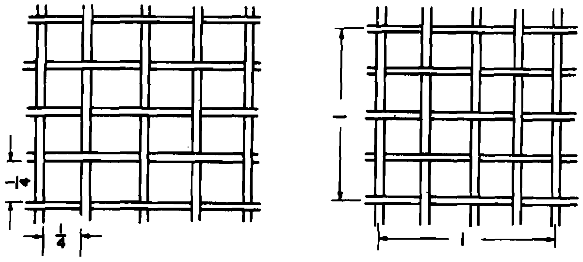
A well-graded soil is composed of particles that vary in amount according to size in such a manner that the void spaces formed by the larger particles can be filled by smaller particles so that a minimum volume of voids is achieved. A soil composed of particles ranging in size between wide limits, but lacking the proper proportions of the respective sizes to qualify as well graded, is said to be poorly graded; if one or more size ranges are completely absent, the soil is said to be gap graded. A uniformly graded soil is one composed essentially of particles of equal size. These four categories of gradation – well graded, poorly graded, gap graded, and uniformly graded – include all possible gradations of soil.

The grain size distribution of the coarse fraction of soils (gravel and sand) may be determined by the sieve analysis procedure. A sample, air-dried and with the aggregates thoroughly broken up, is passed through a set of sieves having openings ranging from 3 in. down to 0.074 mm, and the weight of material retained on each sieve is determined. The number and sizes of sieves used depend on the range of particle sizes in the soil and on the precision desired in the determination of the gradation curve.

Sieve sizes are denoted by two nomenclatures. One refers to the sieve screen size in inches, the other by number. The inch designation refers to the actual linear dimensions of the square openings between the wires of a sieve screen. The number designation of a sieve indicates the number of openings existing in the screen per linear inch. Fig. 2-58 shows the difference more clearly.

The difference in the size of the openings of these two sieves is a result of the thickness of the wires being included along with the four openings per linear inch of the No. 4 sieve. By measurement, the opening in the No. 4 sieve is 4.75 mm while that of the 0.25 in. sieve is 6.35 mm. The sieves with openings larger than 0.25 in. are referenced according to the size of the opening. Sieves 0.25 in. or smaller are identified by the number of openings per linear inch.

The results of the sieve analysis are presented in the form of a grain size distribution curve on a semilogarithmic chart. The grain size distribution curve is obtained



1/4-INCH SIEVE

NO. 4 SIEVE

All dimensions in inches.

Figure 2-58. Sieve Nomenclature (Ref. 12)

by plotting particle diameters (sieve openings) on the abscissa (logarithmic scale) and the percent finer by weight on the ordinate (arithmetic scale).

A hydrometer analysis is required to determine the grain size distribution of particle sizes smaller than 0.074 mm. The use of an immersion hydrometer to measure the specific gravity of a liquid is well known. This same principle is utilized to measure the varying specific gravity of a soil suspension as the grains settle. This information is used to determine the grain size distribution curve by means of the equation

$$N = \left(\frac{G}{G-1}\right)\left(\frac{V}{W_s}\right)\gamma\left(r - r_w\right) \tag{2-17}$$

where

G = specific gravity of soil, dimensionless

V = volume of suspension, cm^3

W_s = total weight of suspended soil, g

γ = unit weight of water, g cm^{-3}

r_w = specific gravity of water, dimensionless

r = specific gravity of suspension, dimensionless

N = fraction of the soil with diameters finer than a diameter given by

$$D = \sqrt{\left(\frac{18\mu}{\gamma_s - \gamma}\right)\left(\frac{z}{t}\right)}\text{, cm} \tag{2-18}$$

where

D = Stokes' diameter of soil grains, cm

μ = viscosity of water, g s cm^{-2}

γ_s = unit weight of soil, g cm^{-3}

z = depth in suspension of measurement, cm

t = time after preparation of suspension, s

Eq. 2-17 is derived in Ref. 12. This determination requires thorough mixing of the soil sample – after its weight and its unit weight are determined – with water, then measurement of its specific gravity at a later time after settling has begun. The specific gravity must be determined for a sample of the suspension from a known depth by withdrawing the sample in a manner similar to the testing of battery acid.

The hydrometer analysis is satisfactory when the grain size curve is desired only for sizes greater than 1 to 2 μm. In fine clays, a large percentage by weight may be finer than these sizes. These particles are colloidal and tend to remain in suspension indefinitely.

An apparatus has been developed for testing fine clays in which the hydrometer jar is suspended at the end of a rotating arm. The centrifugal force caused by rotation introduces acceleration many times greater than gravity causing much faster settlement than occurs under gravity alone. Grain size distribution curves that extend to 0.01 μm may be obtained in a few hours with this apparatus.

The hydrometer analysis is subject to several limitations. Stokes' law defines the phenomenon of a single spherical particle (of constant specific gravity) falling through a fluid that is indefinite in extent. None of these conditions are satisfied. However, the only limitation that cannot be overcome is the requirement of a spherical particle – clay particles are generally plate shaped. Consequently, in connection with the hydrometer analysis, it is necessary to understand the concept of an equivalent diameter. Any particle that has the same velocity of fall as a sphere of the same unit weight and of diameter D will be said to have an equivalent diameter. Therefore, the diameter scale for any mechanical analysis plot based on Stokes' law shows equivalent diameters rather than actual dimensions of particles.

2-4.4 DENSITY

Density is defined in physics as the mass per unit of volume and usually relates to a single homogeneous substance. In soil engineering, however, density refers to weight per unit volume and is generally expressed as either wet density or dry density. Wet density γ_m is computed as

$$\gamma_m = \frac{W_s + W_w}{V_t}, \text{ g cm}^{-3} \tag{2-19}$$

where

γ_m = wet density, g cm^{-3}

W_s = weight of soil solids, g

W_w = weight of water, g

V_t = total volume occupied by the soil particles including voids within and between particles, cm^3

Dry density γ_d is computed as

$$\gamma_d = \frac{W_s}{V_t} = \frac{\gamma_m}{1 + MC}, \text{ g cm}^{-3} \tag{2-20}$$

where MC is the moisture content of the soil, expressed as a decimal fraction by weight.

Several techniques are used to measure soil density. The most common are the direct measurement, the sand cone method, the rubber balloon method, the drive cylinder method, and the nuclear density probe.

(1) *Direct measurement*. In direct measurement, the total weight of a soil sample W is first determined; then its volume V_t is ascertained through immersion in mercury. The sample is then placed in an oven to dry until a constant weight W_s is achieved. If W, W_s, and V_t are known, the wet and dry densities can be computed using Eqs. 2-19 and 2-20.

(2) *Sand cone method*. The sand cone method is intended to determine the in-place density of either fine- or coarse-grained materials. This test is so named because sand is used, following prescribed procedures, to determine the volume of the hole from which a sample has been taken. The test consists of digging out a sample of the material, determining the volume of the hole from which the sample was removed, and determining the wet and dry weights of the sample. The procedure is restricted to soils containing particles not larger than 2 in. in diameter. The standard apparatus is shown in Fig. 2-59.

(3) *Rubber balloon method*. The rubber balloon method is restricted to test hole volumes between 0.025 and 0.050 ft^3 and to bonded soil masses in which the maximum particle size is 0.5 in. It is similar to the sand cone method except that the volume of a test excavation is measured by determining the volume of liquid – contained in a thin flexible membrane – required to fill the cavity. The strength of the membrane is required to be such that a pressure of not more than 5 psi is necessary to cause it to take the shape of the test hole. The sample removed from the test hole is dried and weighed. The standard apparatus is shown in Fig. 2-60.

(4) *Drive cylinder method*. The drive cylinder method of determining in-place

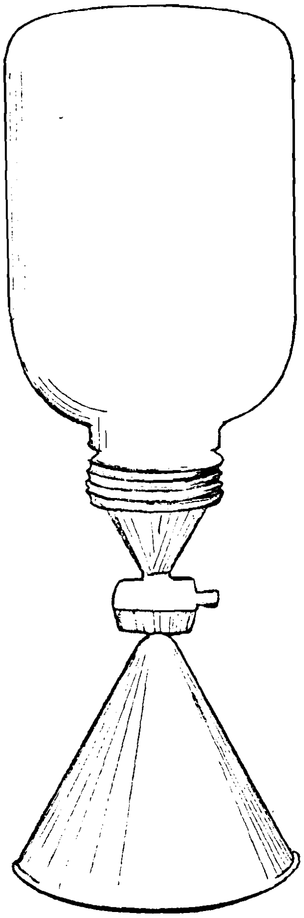


Figure 2-59. Sand Cone Apparatus (Ref. 12)

density can be used satisfactorily in moist, cohesive, fine-grained materials and in sands that exhibit tendencies toward cohesiveness. An undisturbed sample is obtained by driving a small, thin-walled cylinder into the material with a special driving head. The cylinder is driven in until its top is approximately 0.5 in. below the original surface. The driving head is then removed and the cylinder is dug from the ground. If the tare weight of the cylinder is known, the wet weight of the sample, with any excess soil trimmed off, can be obtained immediately. The sample is then removed from the cylinder and the moisture content is determined. The volume of the sample is equal to the volume of the cylinder. Wet and dry densities may then be computed using Eqs. 2-19 and 2-20.

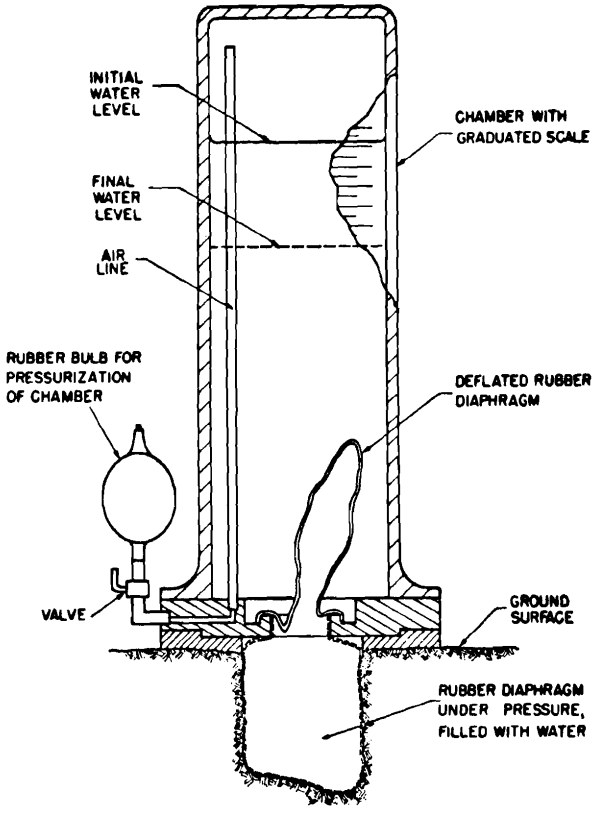


Figure 2-60. Rubber Balloon Apparatus (Ref. 12)

(5) *Nuclear density probe*. As with the nuclear moisture meter, the nuclear density probe is of recent development. The primary components of the density probe are a gamma ray-source, a gamma-ray detector, and a scaler to count detector output.

Two types of density probes are available. The most common is the back-scatter type in which both the source and detector are mounted in a device that rests on the ground surface. Both the source and the detector are shielded from each other in the instrument. The second type is the direct transmission density probe in which either the source or the detector, but not both, is inserted into the soil to various depths – up to 12 in.

The nuclear method of determining density is based on the absorption of gamma rays. A radioactive source is used, which emits gamma rays into the soil (or into some other material, the density of which is to be measured). As the gamma rays pass through the soil, they collide with electrons, lose part of their energy, and continue their travel along deflected paths. Through a series of collisions, the gamma rays are scattered in all directions and their energy may eventually be reduced to a level at which the gamma rays are no longer detectable.

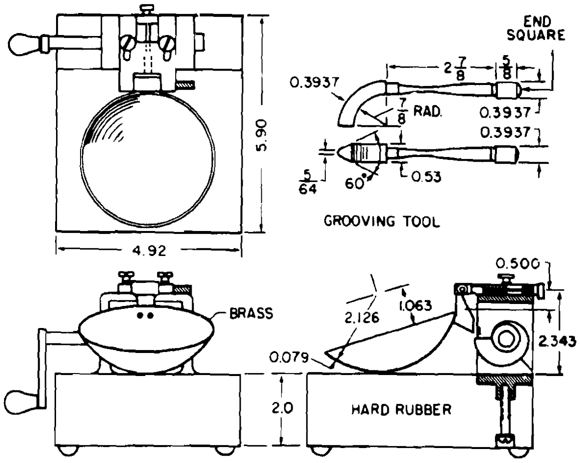
The absorptive capacity of the soil depends on electron density (number of electrons per unit volume), which is a function of the density of the soil. Obviously, the greater the absorptive capacity of the soil, the smaller the number of gamma rays reaching the detector. In other words, an inverse relationship exists between soil density and the gamma-ray intensity indicated by the detector. Because of the complexity of the scattering phenomenon, the functional relationship between absorptive capacity and soil density must be determined experimentally (calibration).

As with the nuclear moisture meter, the measurements made with density probes are very sensitive to surface conditions under the instrument. Air gaps under the instrument of 0.125 in. can cause errors of 10 percent or more.

2-4.5 ATTERBERG LIMITS

The Atterberg limits are parameters characterizing the plasticity and fluidity of soils. These include the liquid limit, plastic limit, plasticity index, and shrinkage limit.

The liquid limit is the water content corresponding to the arbitrarily determined boundary between the liquid and plastic states of consistency of a soil. It is considered to be the moisture content at which two halves of a soil pat, separated by a groove of standard dimensions, will close at the bottom of the groove for a distance of 0.5 in. after 25 impacts in a standard liquid limit apparatus (Fig. 2-61). Trials are performed with samples at several different moisture contents and a plot is made of moisture content (arithmetic scale) versus the number of blows (log scale) required to close the groove over the prescribed length. The liquid limit can then be read from the linear plot obtained and a trial at exactly 25 blows is not required.



All dimensions in inches.

Figure 2-61. Mechanical Liquid Limit Device (Ref. 12)

The plastic limit is the water content corresponding to an arbitrarily defined limit between the plastic and the semisolid states of consistency of soil. It is obtained by rolling soil samples at slowly decreasing water content until a water content is reached at which a soil thread 0.125 in. in diameter just begins to crumble. The soil threads are rolled on a glass plate with the hand; consistent results can be obtained without special apparatus.

The plasticity index (PI) is the range of water content between the liquid and plastic limits, i.e., the range in moisture content over which the soil will behave as a plastic. This index, coupled with the liquid limit, is an excellent indicator of the plastic behavior of soils. Since plasticity is a unique property of clays, the plasticity index is an indicator of the relative clay content of similar soil types. Furthermore, soils with higher plasticity indexes will exhibit greater volume changes with varying moisture contents and will suffer greater loss of stability when wet than the more "lean", low plasticity, soils.

The shrinkage limit w_s is the water content of a clay soil at which the soil ceases to change in volume upon further loss of water due to drying. Two methods are used for determining the shrinkage limit. When the specific gravity is not known, the shrinkage limit can be calculated from the following equation:

$$w_s = \frac{(W_1 - W_s) - \gamma_w (V_1 - V_2)}{W_s} \qquad (2\text{-}21)$$

where

V_1 = initial volume of soil specimen, cm^3

W_1 = initial weight of the soil specimen, g

V_2 = volume of the oven-dried specimen, cm^3

W_s = weight of the oven-dried specimen, g

γ_w = unit weight of water, g cm^{-3}

If the specific gravity of the soil is known, the shrinkage limit may be determined from the values of W_s and V_2 as

$$w_s = \frac{\gamma_w V_2}{W_s} - \frac{1}{G} \qquad (2\text{-}22)$$

where

G = specific gravity of the soil solids, dimensionless.

2-4.6 SOIL STRENGTH

The strength properties of soil are important for a variety of engineering and operational applications. These determine the actual mobility capabilities of open terrain for different vehicles, the suitability of foundations and footings, the wearing capability of unpaved roads, and a variety of materiel requirements for sustaining operations. Most of the measurements of strength parameters are based on a standard technique often associated with use of an especially designed apparatus.

2-4.6.1 COMPRESSION

The compressive properties of soil are described as either unconfined compression or triaxial compression. As the names imply, these measure distinctly different properties of soil.

The unconfined compressive strength of cohesive soils is measured on a cylindrical soil specimen of a length at least twice its diameter. This specimen is loaded axially to failure or to 20 percent strain depending on which occurs first. Two methods of load application may be used; controlled stress or controlled strain. In the first method, load is applied in increments at equal intervals of time and the axial shortening of the specimen is recorded. In the controlled strain method, the specimen is deformed at a constant rate and the load is recorded at intervals as required to obtain the desired degree of precision in the load-deformation curve. In saturated cohesive soils, the shear strength is assumed to be one-half the unconfined compressive strength and is independent of confining pressure.

The triaxial test is presently the most widely used laboratory method for the measurement of soil strength and stress-strain relationships. Its principal advantages are that it permits precise control of confining pressure, drainage, and rate of loading, and provides for the measurement of pore pressures and volume changes. Its versatility in these respects has caused it to be used extensively not only for investigating strength and stress-strain characteristics of soil under conditions representative of those existing in natural soils and embankments, but also as a means of exploring the basic parameters affecting the shearing resistance of soil.

The standard triaxial test specimen is a soil cylinder, normally of a length at least twice its diameter (Fig. 2-30). It is placed between two plates – either pervious or impervious depending upon test conditions – sealed in a watertight membrane and enclosed in a pressure cell. The specimen is subjected to an all-around confining pressure and loaded axially by means of a piston acting on an end plate.

The most common triaxial tests are the following:

(1) *Drained Tests.* Drainage is permitted throughout the test with full pore pressure dissipation, permitting direct measurement of effective stresses.

(2) *Consolidated-Undrained Tests.* Drainage is permitted until the sample is fully consolidated under the confining pressure. No drainage is permitted during the application of the axial load. Pore water pressures may or may not be measured during the test.

(3) *Undrained Tests.* No drainage, and hence no dissipation of pore pressure, is permitted under either the confining pressure or the axial load.

The methods of loading normally used are:

(1) *Controlled Stress.* Load is applied in increments.

(2) *Controlled Strain.* Load is measured at intervals of deformation as the specimen is being deformed axially at a constant rate. The test is performed with a number of different lateral pressures. Test data are analyzed graphically by use of Mohr circles to determine the cohesion and angle of internal friction of the soil. Also, consideration is given to the shape of the stress-strain curve for each test.

2-4.6.2 SHEAR

Shear is measured as direct shear, torsional shear, or vane shear. The results of such measurements are closely correlated among the three techniques since they all depend on the same basic soil properties.

For direct shear measurements, a soil specimen is placed in a split mold and shearing forces are applied to cause one portion of the specimen to slide in relation to the other portion (Fig. 2-31). The test is conducted on several specimens, each with a different load acting normal to the shearing force. If the normal stress is applied and the shear stresses at failure are plotted, the slope of the line through these points is the angle of internal friction; the intercept of this line with the shear stress axis is the cohesion of the soil. The direct shear test may be used for both cohesive and cohesionless soils.

In the torsional shear test a specimen of solid circular or annular cross section, usually confined between rings, is subjected to an axial load and to shear in torsion. The annular cross section is the more difficult with respect to test preparation but is the more preferred because the shearing stresses are more uniform on the cross section and, hence, may be computed more readily.

In-place torsion shear tests are performed by pressing a dentated solid circular or annular plate against the soil and measuring the resistance to its rotation under a given axial load.

The device used for the determination of vane shear consists of a four-bladed vane fastened to the bottom of a vertical rod. The vane is pushed into soil and the torque required to rotate the vane is measured. The soil fails on the cylindrical surface defined by the outer edges of the vane. Average shearing resistance can be computed from the dimensions of the vane and the measured torque.

The vane may then be rotated rapidly through several revolutions to remold the soil. The shearing strength can again be measured to determine the sensitivity of the soil to remolding.

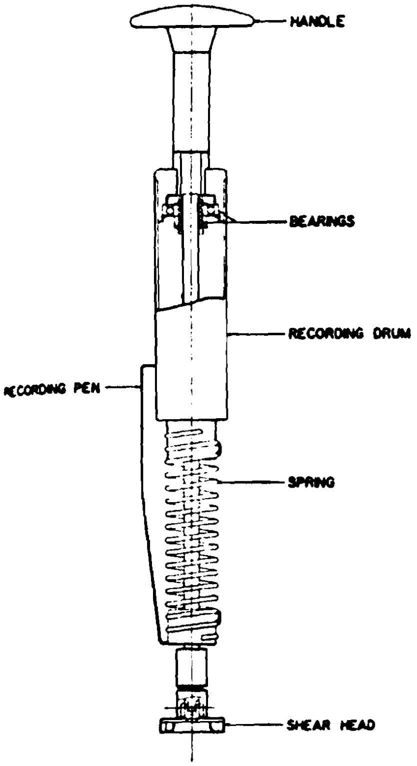


Figure 2-62. The Cohron Sheargraph (Ref. 25)

This device is best suited for use in cohesive soils and is not recommended for use in sandy soils, gravel, or soil deposits containing many large pebbles.

The Cohron sheargraph (Ref. 25) is an instrument for measuring and recording the shear strength of soil, from which the cohesion and angle of internal friction can be deduced. It is rapid in operation and portable – designed for field rather than laboratory use. A cross section of the sheargraph is shown in Fig. 2-62.

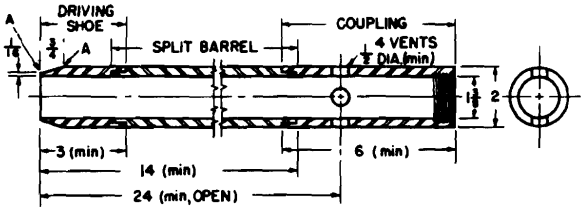
In operation, the shear head is completely inserted into the soil, normal stress is applied to the shear surface through axial deflection of the spring, and shearing stress is applied by twisting the recording drum until the soil fails. After soil shear failure occurs, normal load is gradually reduced. Since the soil will sustain only a given amount of shearing stress for a particular normal load, the recording pen will trace the curve of shear stress versus normal stress as the latter is reduced to zero. The machine is calibrated so that the chart produced on the recording drum is a direct plot of shear stress versus normal stress. The sheargraph can produce large volumes of data rapidly. This is a prime requirement for earthmoving studies since the time available in which to measure soil properties is usually limited. This also allows the determination of the mode failure condition taken from a large number of failure curves superimposed on the same graph, increasing the reliability of the data. Data should be collected throughout the area in which testing is to occur.

2-4.6.3 PENETRATION

When a force is exerted on soil by a structure, vehicle, or foot, the amount of penetration is an important parameter of the strength of that soil. A common empirical approach to this parameter is to determine sinkage by walking on the area in question. However, this method is susceptible to serious error. A variety of penetration measurement techniques are employed to provide a more meaningful data base. These include the simple soil penetrometer, the California Bearing Ratio Test, the cone penetrometer, the bevameter, and aerial penetrometer.

(1) *Soil penetrometer*. A simple penetrometer is a probe that is forced into the ground to obtain a measure of soil strength. If the penetrometer is pushed into the ground slowly, the test is classified as being a static penetration test. If the probe is driven rapidly into the ground, the test is classified as a dynamic penetration test. Static tests are generally performed in soft, cohesive soils and dynamic tests in hard, cohesionless soils.

The most common test performed is the standard penetration test. This is made by driving a split-barrel sampler (Fig. 2-63) into the soil by dropping a 140-lb hammer onto it from a height of 30 in. The penetration resistance is the number of blows required per 12 in. of penetration. Penetration resistance



All dimensions in inches.

Figure 2-63. Standard Split-barrel Sample Assembly (from ASTM Standards) (Ref. 12)

can be related to soil density in accordance with Table 2-14. These data may be considered fairly reliable with sands but only an approximation for clays.

In a sandy soil located below the water table, the blow count may indicate a relative density considerably greater than the actual relative density of the deposit. Under these conditions, for every blow count greater than 15, an additional 0.5 blow count should be added before Table 2-14 is used. This is necessary because the material tends to increase in volume upon shearing, producing an increase in effective stress which results in an apparent increase in penetration resistance. In deposits containing large stones, the results may be unreliable because of the small size of the sampling spoon compared with that of the stones.

The standard penetration test cannot be regarded as a highly refined and completely reliable test; however, the blow count gives a useful preliminary indication of the consistency or relative density of most soil deposits.

(2) *California Bearing Ratio*. In this test, a piston of 3 in.^{2} cross-sectional area is forced into a compacted soil sample of 6-in. diameter in a mold. The rate of piston movement is controlled, and pressure readings are taken for various penetration depths. The standard of comparison for computing the bearing value of a material is based upon the penetration and load, or pressure, on a standard, well-graded crushed stone (1,000 psi to produce 0.1-in. penetration). The bearing value of a sample is determined for a specific penetration by dividing the load for the penetration by the standard load for the same penetration. For example, if a specimen requires a load (or pressure) of 450 psi to obtain 0.1-in. penetration, its bearing value will be (450/1,000) X 100 = 45 percent. This bearing value has become known as the California Bearing Ratio, generally abbreviated to CBR, with the "percent" omitted. The Corps of Engineers and some highway departments use the CBR principle in conducting tests to evaluate the bearing value of materials.

(3) *Cone penetrometer*. The cone penetrometer was developed to obtain an empirical field measure of soil bearing-traction

TABLE 2-14

RELATIONSHIPS OF PENETRATION RESISTANCE AND RELATIVE DENSITY (Ref. 12)

Sand, No. of blows	Relative density	Clay, No. of blows	Consistency
0-4	Very loose	1-2	Very soft
4-10	Loose	2-4	Soft
10-30	Medium	4-8	Medium
30-50	Dense	5-15	Stiff
> 50	Very dense	> 30	Hard

capacity. A 30-deg cone is pushed slowly into the soil and the force required is recorded at desired penetration increments. This device and procedures for its use were developed by the Corps of Engineers to measure the trafficability of soils.

The measure of the trafficability of a soil is referred to as a rating cone index. It is the product of *in situ* cone index and remolding index. Remolding index is obtained as follows: the cone index of an "undisturbed" soil sample, confined in a small cylinder, is measured before and after tamping with 100 blows of a 2.5-lb hammer falling 12 in. The ratio of the average cone index after tamping to that before tamping is called the remolding index.

The cone penetrometer is simple. A vast number of tests have been performed with it, and their results correlate with other soil tests and other soil classification systems. It is one of the most widely used field tests for determining an index of soil strength.

(4) *Bevameter*. The bevameter was developed for predicting the performance of vehicles on soil. It is a device for determining the load versus sinkage curves for two or more different diameter circular plates when pushed into the soil, and also for determining the torsional resistance of a cleated circular plate under a controlled normal load. The data obtained from these tests are used to determine the soil values k_c, k_ϕ, and n (par. 2-3.3.3) required in formulas derived for computing traction, rolling resistance, and sinkage of wheels. A schematic of a bevameter appears in Fig. 2-64.

(5) *Aerial penetrometers*. The most widely used aerial penetrometer is essentially an aluminum cylinder that looks like a small rocket; it is approximately 2.5 ft long, 2 in. in diameter, and weighs less than 2 lb. The original model was dropped from propeller-driven aircraft and had a spring mechanism to measure the impact. If the penetration resistance is greater than the preset level, a flare is released through the hollow barrel and rises to several hundred feet altitude as a visible "go" indicator. If the penetration resistance is less than the preset level, the impact is not great enough to depress the spring and fire the shotgun shell. Hence, no flare is released, indicating "no go". Fig. 2-65 shows an exploded view of this device.

For tactical reconnaissance missions, an improved means of deployment and indication was developed. Penetrometers can be ejected in quantities up to 10 in a preselected sequence from tip-tank launchers on jet aircraft at speeds of approximately 450 kt and at altitudes of 1,000 ft above the terrain. For multiple deployment the firing sequence is 0.5 s apart, causing the penetrometers to land about 300 ft apart. Ejection is by an electrically detonated charge contained within the launching system; the penetrometers are inert. They are nearly buried in their own holes, depending on the soil strength encountered, and are expendable. The launching mechanism shoots the penetrometers downward and backward at a component velocity sufficient to cancel the forward speed of the aircraft, so that the penetrometer hits the ground at 350 ft s^{-1} directly under the spot where ejection takes place. Soil hardness is indicated by the appearance of a self-contained light bulb visible through the vertically impacted cylinder.

The penetrometer is aerodynamically stable with pop-out vanes governing its fall, which takes about 1.5 s from ejection to impact. The strength-indicating mechanism is adjustable to allow determination of soil hardness through a range of values that might be required by various aircraft landing loads.

2-4.7 CONSOLIDATION

The consolidation test is a one-dimensional compression test that involves, simultaneously, the slow escape of water and a gradual compression of the soil structure. The apparatus used for the study is called a consolidometer. The soil sample is placed in a

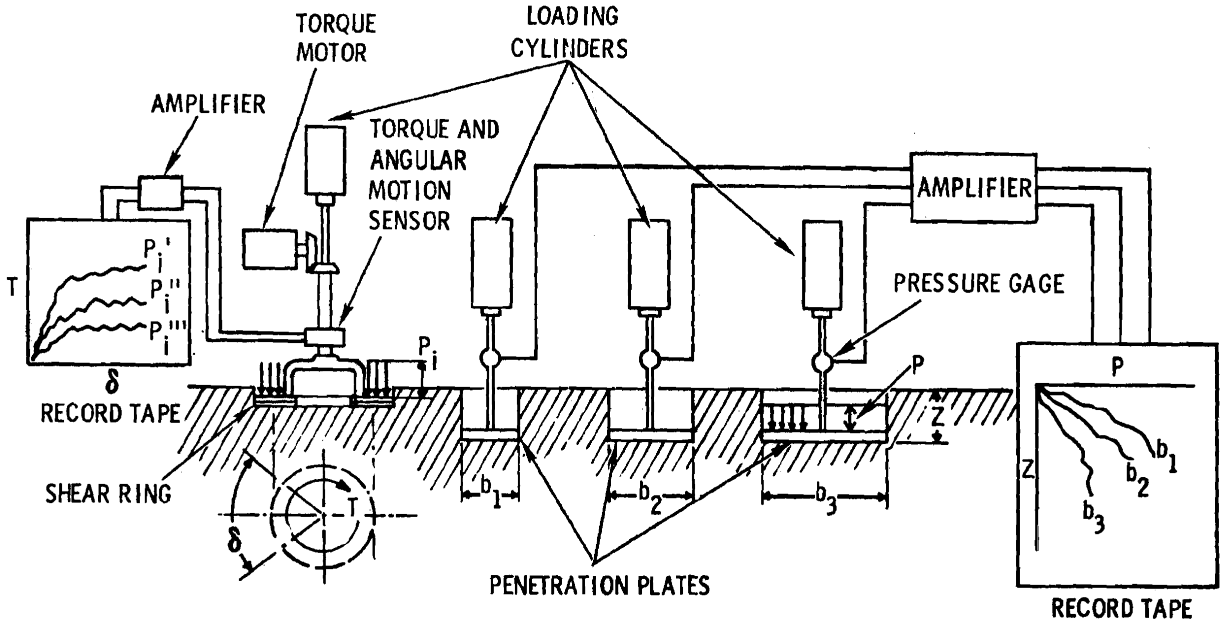


Figure 2-64. Schematic View of a Bevameter-type Instrument (Ref. 8)

standard cylinder with porous disks at the top and/or bottom to provide drainage. The specimen is loaded in steps, each load doubling the previous value of load on the specimen. New loads are not added until compression of the specimen under the previous loading has practically ceased. This may take only a few minutes with sands; but in clays, compression continues for a long period of time and 1-day intervals between loadings are quite common. A curve of compression versus time is plotted for each increment of load. The final data consist of time-compression curves for each load increment and a load-compression curve for the test as a whole. The load-compression data, or final stress-strain relationships, are presented in the form of a curve of log of pressure versus void ratio for the final condition of each load increment.

2-4.8 PERMEABILITY

A material is said to be permeable if it contains continuous voids. Although every soil and every rock satisfies this condition, large differences exist in the degree of permeability of the various earth materials. The quantity of flow through a dense rock may be so small as to pass unnoticed because evaporation prevents the accumulation of water on the exposed face; yet the flow of water through such a material may produce seepage pressures between the mineral grains larger than those exerted in more permeable materials under the same conditions of hydraulic head.

The flow of water through permeable substances is governed by an empirical relationship

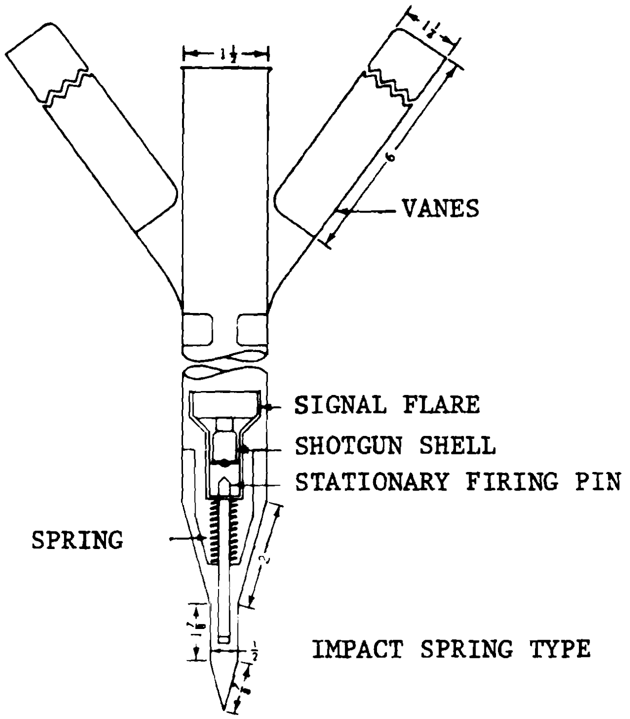
$$v = ki, \text{ cm s}^{-1} \tag{2-23}$$

where

v = discharge velocity (the quantity of water that percolates through a unit area perpendicular to the direction of flow, in unit time), cm s^{-1}

i = hydraulic gradient in the direction of flow (cm of head per cm of flow distance), dimensionless

k = coefficient of permeability, cm s^{-1}



All dimensions in inches.

Figure 2-65. Assembly of Aerial Penetrometer (Ref. 3)

In general, k is a function of the permeable substance and the unit weight and viscosity of the fluid. Because fluid viscosity changes with temperature, the coefficient of permeability, in the general case, also varies with temperature. However, in soil mechanics the only fluid of interest is water and its changes in viscosity over the range of temperature of groundwater are negligible. Hence, the coefficient of permeability is considered a property of the soil or rock.

The coefficient of permeability k generally increases with increasing size of voids, which in turn increases with increasing grain size. However, the shapes of the void spaces also have a marked influence on the permeability. As a consequence, no simple relationships have been found between permeability and grain size except for fairly coarse soils with rounded grains. For example, it has been found that, for filter sands, in the cgs system of units

$$k = 100 D_{10}^2, \text{ cm s}^{-1} \tag{2-24}$$

where D_{10} is the effective diameter (particle diameter corresponding to 10 percent fines on the grain size curve of the soil considered), cm. The conversion factor 100 changes the units of k to cm s^{-1}.

Similarly, it has been found that the coefficient of permeability of coarse-grained soils varies approximately as the square of the void ratio. No such simple relation has been established for soils containing flake-shaped particles.

Permeability tests are performed with both constant-head and falling-head permeameters. In either case, an average coefficient of permeability is determined by measuring the quantity of water that flows through a test specimen in a given time period. The constant-head permeability test is recommended for highly permeable materials such as sand and gravel. The value of the coefficient of permeability k, in ft s^{-1}, computed from experimental results is

$$k = \frac{QL}{hAt}, \text{ ft s}^{-1} \qquad (2\text{-}25)$$

where

Q = quantity of flow in a given time, ft^3

L = sample length, ft

h = head of water, ft

A = sample cross-sectional area, ft^2

t = time, s

The falling-head permeability test is recommended for materials of low permeability. The value of k (units as in Eq. 2-25) is computed from experimental results as

$$k = 2.3 \left(\frac{aL}{At}\right) \log \left(\frac{h_o}{h_1}\right), \text{ ft s}^{-1} \qquad (2\text{-}26)$$

where

a = cross-sectional area of the standpipe, which provides the hydraulic head, ft^2

h_o = original hydraulic head, ft

h_1 = final hydraulic head, ft

The other symbols are defined in Eq. 2-25.

2-4.9 COMPACTION

Compaction densifies soil by mechanical means. The compaction properties that a soil displays may vary widely with the moisture in the soil and the density of the soil. The density to which a soil may be compacted depends on the amount of moisture present and the compactive effort applied, particularly in cohesive soils. For a given controlled method of compaction, the moisture content that permits the greatest density to be obtained is referred to as the optimum moisture content. The optimum moisture content for a given soil is not a constant value but will vary for different methods of compaction and for different compactive efforts. Because of these effects, it is necessary that standard tests be used to define the compaction of a soil. The most common of these tests are the Proctor Compaction Test (modified AASHO* compaction test) and the Harvard Miniature Compaction Test.

The Proctor Compaction Test is a standard test to define degree of compaction. The apparatus consists of a metal cylinder, 4 in. ID and 4.6 in. high, and a metal tamper, weighing 5.5 lb, with a 2-in. diameter face. The soil is placed in the cylinder in three approximately equal layers, and each successive layer is given 25 compaction blows of the tamper falling freely through a distance of 12 in. The weight, moisture content, and dry density of the compacted specimen are determined. The test is repeated a number of times with the soil at various moisture contents and the results are plotted to obtain a moisture versus dry density curve. The peak of this curve indicates the maximum dry density, and the moisture content at which this density is obtained is defined as the optimum moisture content for that particular soil (and compaction effort).

The Proctor Compaction Test was designed to yield maximum dry densities comparable to the highest densities obtainable with field compaction equipment. Since the test was devised in 1934, more efficient compaction equipment has become available.

The Proctor Test has been generally replaced by the Modified AASHO Compaction Test, which is identical to the Proctor Test except that the sample is compacted in five layers (25 blows per layer) with a 10-lb hammer falling 18 in.

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*American Association of State Highway Officials.

The Harvard Miniature Compaction Test is also intended to provide moisture-density relationships of soil. The apparatus used consists of a cylinder, 1-5/16 in. ID and 2.8 in. high, and a tamper, 0.5 in. in diameter, reacting against a spring of desired stiffness. The tamping device applies a kneading action to the soil in compacting it. The selection of the number of layers in which the soil should be placed, the number of tamps per layer, and the tamping force depend upon the soil type used and the use intended for the compacted material.

2-4.10 SEISMICITY

The seismic refraction method can be used to determine the depth to interfaces such as the water table, permafrost, bedrock, or subsurface formations offering a distinct change in the propagation velocity of seismic waves. Delineation of deep-lying deposits is possible and qualitative relationships between seismic velocity and hydrologic parameters such as porosity and density have been established. Mapping of buried aquifers, therefore, is practical.

Compact portable seismographs are now available that utilize a hammer blow against a steel plate on the ground as an energy source. This eliminates the need for drilled holes and explosives, and has greatly enlarged the utility of operation.

Some identification of the type of near-surface material is possible from computation of the wave velocity obtained by a thorough seismic refraction survey. Dry, wind-blown sand or fine gravels have velocities varying from 1,500 to 2,500 ft s^{-1}; heavier gravels with small amounts of clay binder run up to 4,000 ft s^{-1}; while velocities from 4,500 to 6,000 ft s^{-1} represent more compact gravels or those within the water table. Varve clays show a constant velocity of 5,000 ft s^{-1}, while values from 6,000 to 9,000 ft s^{-1} usually represent a hardpan or till material that is heavy gravel and clay, often cemented together by iron rust or oxidation.

2-4.11 GEOMETRY*

Geometric properties of the terrain may be determined by a variety of measurement techniques ranging from aerial photography to the use of conventional surveying. Each of these has its advantages for certain applications, usually determined by the required scale factor of the terrain features. Stereophotography, for example, lends itself to the compilation of data for topographic mapping, while surveying provides detailed data such as that required for construction. Other techniques are applicable to measurement of small-scale terrain roughness, of local slopes and obstacles, or of detailed topographic features of the terrain of a limited area.

The profilometer is one type of contour measuring instrument. It consists of an electromechancial assembly which is towed over a defined path so that data on linear-dimensions and slope are obtained. With some instruments, the frame of a vehicle on which the instrument is attached provides a reference plane and small-scale roughness is measured. In other instruments, a gyroscopic inertial reference system is provided so that slopes are referenced to the horizontal. Each of these measurement systems is optimized for its intended application, which may be the measurement of the roughness of a prepared roadbed or the characterization of the contours of natural terrain.

An example of terrain geometry measuring equipment is shown in Fig. 2-66 (Ref. 12). This is a towed assembly that utilizes the slope-integration method to measure continuously the slope of the ground over which it travels. It consists of two wheels mounted in tandem in a frame, an angle reference device, and an odometer unit.

The pitch angle of the wheel frame is assumed to be identical to the slope of the ground over which the wheels are traveling. Ground slope is determined by a system that

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*A general reference for this paragraph is Ref. 13.

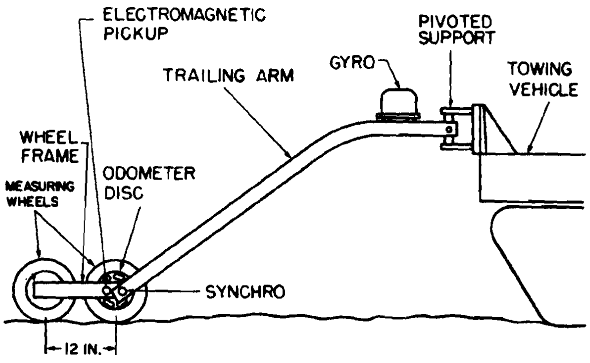

Figure 2-66. Terrain Geometry Measuring Apparatus (Ref. 12)

senses and records the angle between the wheel frame and a gyroscope which establishes a vertical reference.

The odometer system measures the distance traveled. A metal disk containing a number of evenly spaced slots is mounted on the forward wheel. As the wheel rotates, these slots pass an electromagnetic pickup, the reluctance of which varies with its proximity to metal. The reluctance change at the pickup closes a relay contact switch each time a slot passes the pickup. Each closure of the switch indicates an increment of travel along the ground. This distance, multiplied by the cosine of the slope angle, is recorded as the horizontal distance measured.

The signals from both the angular reference and odometric devices are recorded on magnetic tape. The general purpose data processing facility at the U.S. Army Tank-Automotive Command has developed the capability of converting these raw data into a form such that necessary computations can be carried out on a digital computer. The results are presented in the form of a profile of the ground traversed by the apparatus.

The laser profilometer is proving to be a versatile instrument. It may be used on an earth satellite, an aircraft, or a ground vehicle to provide measures of various terrain features. There are two types of laser profilometers, pulsed and continuous wave (CW). The former emits a pulse which is reflected from its target and returned to the profilometer receiver. The time required for the collimated beam of light to return can be converted to distance between the profilometer and the target. The CW profilometer utilizes phase relationships between the transmitted and received beams to calculate the same distance. Profilometers have been used in aircraft to determine terrain profiles, but the technique of its use are not yet perfected. The principal problems are difficulty in keeping the aircraft on a straight and level flightpath and the necessity to determine what the laser beam was reflected from; i.e., whether it was vegetation or the ground surface. The laser principles are used more successfully in surface application; e.g., laser rangefinders and laser transits.

2-4.12 REMOTE SENSORS

Remote sensing of the terrain is usually carried out from aircraft because of their capabilities for long range, high speed, repetitive coverage, and their capacity for carrying much sensing instrumentation. Sensing aircraft have ranged from helicopters and small observation planes through multiengine reconnaissance aircraft to the supersonic X-15 from which much photography has been obtained. A number of Government and private organizations have aircraft devoted to the mission of testing, verifying, and applying remote sensing instrumentation.

High-altitude balloons offer advantages for terrain sensing because they provide a stable, vibration-free, and relatively well-controlled platform with slower passage over the ground than either aircraft or rockets reaching comparable altitudes. Earth photography has been obtained from sounding rockets such as the Viking and Aerobee, and earth satellites are providing a vast library of earth photographs. The ERTS series in particular is providing considerable information on terrain characteristics and mapping.

Airborne sensors have a number of limitations. The more important of these limitations are caused by the atmosphere; e.g., air turbulence; absorption or attenuation of solar radiation by water vapor or ozone, cloud cover, and rain; and lack of natural illumination for night photography. Other restrictions are inherent in the sensors; e.g., photographic resolution, nonlinearity or distortion of camera film, and altitude or slant range limitations. These limitations are different for each type of remote sensing equipment. The more useful remote sensors are described in the following subparagraphs:

(1) *Infrared scanners*. In the last decade, an airborne, electromechanical, imaging, infrared radiometer, generally called an IR scanner, has been widely used for military reconnaissance. IR scanners are valuable for gathering surface data, inasmuch as they generate a two-dimensional thermal map indicative of surface or near surface temperatures and emissivity.

The earth radiates energy in a spectrum approximating that of a blackbody at 300 K, with a maximum near 9.5 μm wavelength. It also reflects solar energy whose spectrum approximates a blackbody at 6,000 K with a maximum near 0.5 μm. The energy emitted by or reflected from the surface of the earth is selectively absorbed by the atmosphere, with only the part that passes through "atmospheric windows" reaching an airborne detector.

In a scanner these detectors, generally sensitive to radiation between 3 and 5 μm or between 8 and 14 μm, convert the radiation into wideband electrical signals that modulate a light source or cathode-ray tube. Recording is generally made on film passing in front of the tube at a rate proportional to the velocity-height ratio of the aircraft. Lateral coverage is provided by rotation of a collecting mirror, and forward coverage by the motion of the aircraft. The resulting gray scale of the image is thus a function of the energy radiated from the surface of the earth, which, in turn, is dependent on the absolute temperature and emissivity of the surface materials. Tape recording of scanner output permits the preservation of a higher dynamic range of imagery for enhanced evaluation.

Typical infrared scanner imagery obtained for terrain evaluation purposes is shown in Fig. 2-67.

(2) *Ultraviolet sensing*. A generally held opinion is that the absorption of solar radiation by the ozone in the atmosphere of the earth causes a nearly complete attenuation of ultraviolet energy. However, experiments have proved that sufficient ultraviolet light may be available for daylight photography using sensitive film and appropriate filters. Also, it has been proved that many terrestrial materials have selective responses to narrowband ultraviolet illumination.

The U S Army Tank-Automotive Command and other Government organizations have performed experimental photography using ultraviolet transmitting filters to distinguish targets and terrain backgrounds, to detect luminescent minerals and rocks, and to discriminate among nonluminescing materials on the basis of selective absorption of energy between 330 and 410 μm wavelengths. Distinct contrasts between materials and vegetation have been found. Sandstone and carbonate materials with a minimal amount of moisture are particularly reflective in the ultraviolet.

(3) *Photometry and spectrometry*. Data on the visible and near-infrared spectral reflectance of various elements of the surface of the earth are valuable in photointerpretation, by permitting discrimination of materials by their tonal brightness appearance on aerial photographs. In addition, spectral reflectance measurements from field or airborne sensors—extending into the far-infrared in some instances—can aid in the determination of the mineralogy, chemistry, particle size, and surface roughness of materials.

Figure 2-67. Typical Infrared Scan Imagery (Ref. 3)

Reflectance measurements are made by a variety of photometers, spectrometers, spectrophotometers, and radiometers, usually filtered for narrowband outputs. Reflectance varies with terrain as shown in Table 2-15.

By matching the measured signatures with predetermined ones in the memory of a computer, rock composition can easily be identified in field operations. Real-time determination at rates up to seven signatures per second, utilizing a filter wheel, are feasible, permitting sensing from aircraft.

(4) *Radar*. High-resolution, side-looking radar in the present state-of-the-art is very useful for airborne determination of local geologic features, particularly geomorphic and gross relief patterns. A beam of radar energy provides unidirectional illumination rather than the multidirectional illumination given by atmospherically diffused sunlight. It therefore produces imagery that is composed of a great number of specular reflections, since the relationship of the surfaces to each other has a strong influence on the intensity of the returned energy recorded on film. Small variations in surface relief thus imaged may express geologic phenomena such as folding, faulting, and drainage channels. Similarly, surface reflective characteristics based on the relationship of surface roughness to the radar wavelength can reveal to the interpreter the probable physical characteristics of the material. Fine materials such as clay, silt, or sand are imaged as a "no return", provided that they are relatively smooth on the surface. A plowed field, for example, may return high energy. Coarser material such as rocks, a talus slope, or a lava flow show strongly textured patterns. An example of a radar image is given in Fig. 2-68.

Although the resolution and definition of side-looking radar images are poorer than aerial photography, radar has many operational advantages. Images can be obtained in any weather condition except heavy rain; the day- and night-scanned images are equally good; returns can be obtained from high altitude and at high speeds; coverage extends many miles to either side of the aircraft; and the scale is built into the system.

Instantaneous airborne determination of the thickness or layering of terrain material, especially floating fresh-water* ice, is approaching feasibility by use of high-resolution, monocycle radar. The analogy is to seismic-reflection prospecting using a single acoustic pulse, in that a single electromagnetic pulse (monocycle) is radiated into the terrain and the thickness determined by analysis of the reflected returns.

Radar scatterometry is an active remote-sensing technique that measures the radar-scattering coefficient of surfaces having different roughness and material. Applications for measuring sea state and ice roughness are fairly well established, but revisions are still being made on techniques. Indications of successful determination of terrain texture and moisture content, both at the surface and somewhat beneath it, are being observed, but, again, refinements in techniques are still being sought. Scatterometry is feasible with wave-

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***The interface of ice and salt water is not clean cut; i.e., not straight or thin. Determination of the thickness of sea-water ice is therefore difficult and uncertain.**

TABLE 2-15

OPTICAL REFLECTANCE OF TERRAIN TYPES (Ref. 3)

Type	Reflectance, %	Peak Wavelength λ, μm
Water surfaces		
Inland waters	3-10	0.4810
Oceans	3-7	0.4810
Bare areas and soils		
Snow	70-86	0.4810
Ice	75	0.5795
Limestone	63	0.5790
Calcareous rocks	30	0.5790
Granite	12	NA
Mountain tops (bare)	24	0.5816
Sand	18-31	0.5616
Clay soil	1.5-15	0.5828
Ground, bare (rich soil)	7.5-20	0.5832
Field (plowed)	20-25	NA
Vegatative formations		
Coniferous forest	3-10	0.5744-0.5758
Deciduous forest	10-15	0.5719-0.5858
Meadow (dry grass)	3-8	0.5758
Grass (lush)	15-25	0.5719
Field crops	7-15	0.5858
Manmade		
Buildings (cities)	9	0.5828
Concrete	15-35	NA

NA = not applicable

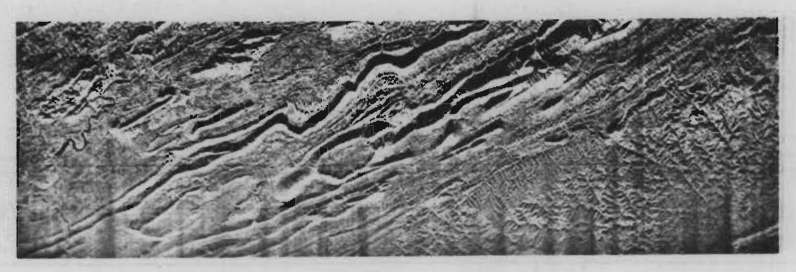

Figure 2-68. Radar Imagery (Ref. 3)

lengths from fractions of a micrometer to tens of meters. The normal range for laser scatterometers is from a few millimeters to a few meters wavelength.

(5) *Passive microwave radiometry.* All objects emit electromagnetic energy due to the random thermal agitation of the electrons within them. The intensity of this radiation depends on the temperature of the object, the frequency at which it is measured, and certain of its physical properties such as dielectric constant, magnetic permeability, electrical conductivity, and surface characteristics. An object may also absorb or reflect any electromagnetic radiation that is incident upon it. The radiometric temperature of an object is thus not only dependent on its emissivity and own temperature but also on its reflectivity and the temperature of the sky environment being reflected.

The radiometric energy emitted from an object or material can be measured at great distances. In the microwave and millimeter wavelength regions the power emitted varies directly with its temperature and inversely with the square of the wavelength. At a given frequency and polarization, the emissivity and reflectivity of a material are functions of its surface roughness and the angle of incidence of the radiometer antenna. The region of a solid object that contributes to its observed radiometric temperature extends from the surface downward to a depth dependent on its dielectric constant and conductivity. Different frequencies, therefore, can be said to have different penetrations. Materials such as water or metals have high reflectivities; conversely, materials such as dry soils or vegetation have low reflectivities.

Passive microwave radiometric sensing of the apparent temperature of natural terrain and objects upon it is a previously neglected technique. With the development of new analytical methods, advanced instrumentation, and data processing techniques, this sensing method can now be employed effectively for ground-based and airborne earth-science studies.

From a boom on an extensively instrumented trailer, a three-frequency microwave radiometer with both vertical and horizontal polarization capability was successfully used to determine the moisture content, layering, and distribution of soils, water, ice, snow, and rocks. An example of the discrimination of soil types on the basis of their radiometric temperatures thus obtained is shown in Fig. 2-69. Soil moisture content can sometimes be identified to a 1-percent accuracy with this technique under carefully controlled conditions.

(6) *Airborne profile recorders.* For many years, combinations of radar and barometric altimeters were used for relative terrain height measurements. These devices, commonly called airborne profile recorders, use the principle of radar reflection over aircraft-to-terrain distances, corrected for aircraft altitude deviation from some barometric datum surface. A reference is established by flying at a preset barometric altitude over a terrain feature of known elevation. Subsequent flights over an area of interest will permit the

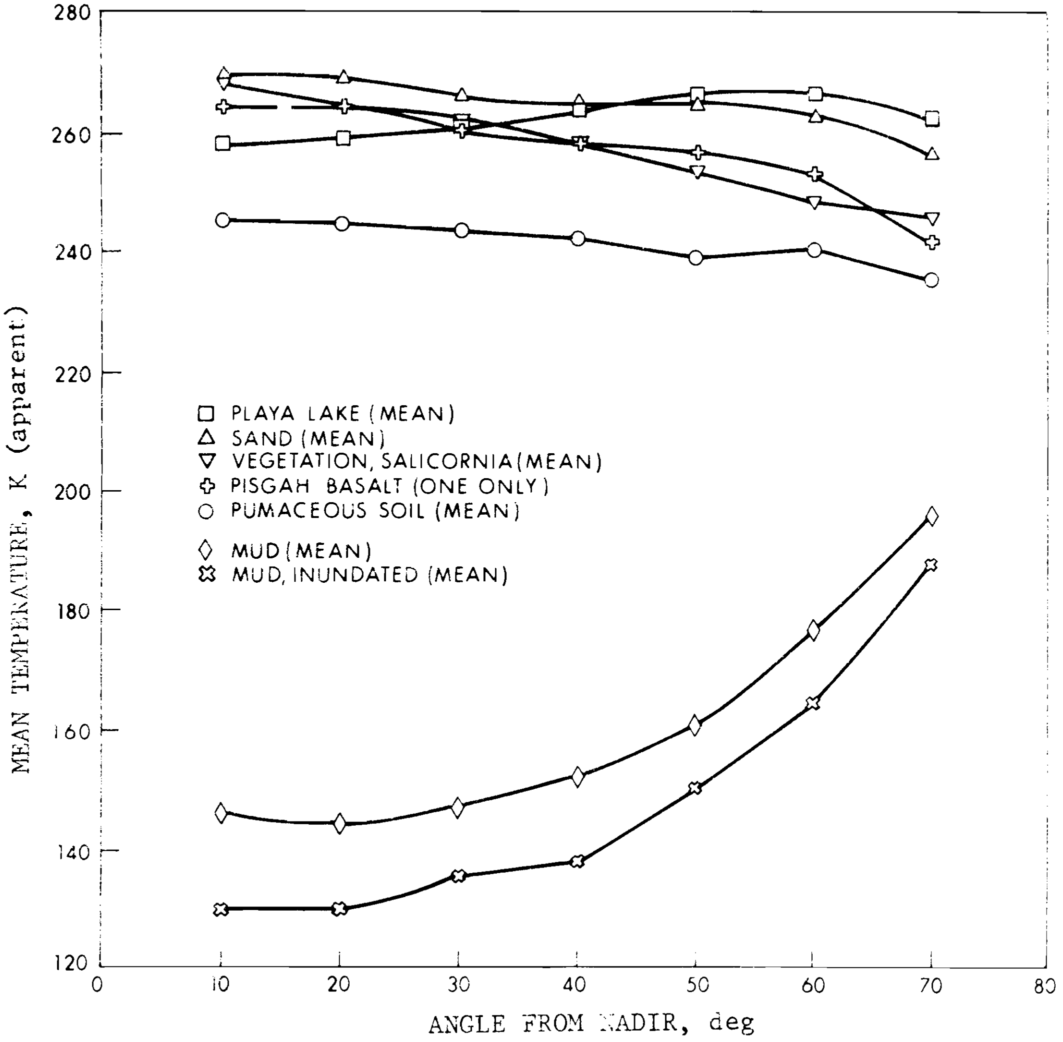

Figure 2-69. Passive Microwave Data on Various Natural Materials (Ref. 3)

application of the aircraft altitude deviation to the radar height record to give the terrain profile. Primary limitations are accuracy (about ±0.5 percent of flight altitude) and beam size (15 deg half angle). Modern narrowbeam airborne profile recorders are estimated to have an accuracy of ±20 ft at altitudes up to 30,000 ft, while illuminating an area 500 ft wide.

(7) *Airborne magnetometers.* The airborne magnetometer has been used since 1946 in petroleum and mineral exploration, with some 20 million mi^2 of survey flown covering a large portion of the surface of the earth. The military services have used airborne magnetometers for reconnaissance of submarines and land-vehicle targets. Gradual improvements in instrumentation have been made, but 1 gamma (10^{-9} tesla) has generally represented the limit of attainable resolution.

Recently the rubidium vapor magnetometer was developed. Although originally designed to measure the magnetic field in space probes, it has had immediate use as an airborne device for oil exploration. The resolution of this device is 0.1 gauss (10^{-5} tesla), enabling a detailed mapping of the total magnetic field, which in turn reflects variations of the sedimentary structure and basement complex of the earth. The system can be located in a towed-bird configuration or mounted in a tail-boom "stinger" on aircraft. Data are presented on a strip chart in analog form, with the linear scale calibrated directly in gammas for easy compilation of area maps.

2-5 EFFECTS

This paragraph considers the effects of various terrain properties on materiel for these application areas: construction, trafficability, and air operations. Of these three topics trafficability has received the most attention in the military literature. Construction implications of the terrain have always been important to civil engineers and architects. The study of the terrain for various airborne missions is a newer, growing field.

2-5.1 CONSTRUCTION

A chief property of soil in construction is its maximum allowable loading value. A list of such values appears in Table 2-5, which gives loading values for various rocks and soils. These values vary from 1 to over 40 tons ft^{-2} but do not apply if the foundation material is underlain by a weaker layer or substrate. Good engineering practice dictates that soil profiles be known before committing a building or a structure to a given location.

Mechanical properties and suitability for various purposes depend greatly on the physical properties of the soil or rock, which in turn can be deduced from the geology of the area they occupy in many cases. Table 2-16 lists the general suitability of various types of rocks for construction purposes. As might be expected, igneous rock constitutes a foundation material unsurpassed in loading capacity although difficult to drill and excavate. Other rock formations provide suitable sources of construction materials as summarized in the table.

Other uses in construction for various soils of the USCS system are given in Table 2-17. This table considers each of the soil types of the USCS, describes its general properties, and assesses its value as a foundation material for roads or airfields. Column 14 of the table lists the California Bearing Ratio span for each type of USCS soil and shows a significant correlation among the different classifications and their bearing strength. Recognizing that a given soil is of a particular type greatly aids in sound field decisions.

Table 2-18 summarizes various landform types and their characteristic soils and lists uses to be expected with each type. Knowledge of the geology of the area occupied by a particular soil permits a reasonable prediction of the properties of the soil and hence its uses.

2-5.2 TRAFFICABILITY*

Trafficability is the ability of a terrain to allow vehicular movement. The term trafficability implies off-road conditions with vehicles traveling over unimproved, natural terrain. The properties of the vehicle, as well as the properties of the soil and other terrain features, are important in determining trafficability. This considers only those properties of the terrain, chiefly the soil and vegetation, that influence trafficability. Vehicle properties, however, cannot be excluded because of their inherent relation to trafficability.

The ability of the soil to support a vehicle, either statically or in motion, and to furnish traction for moving the vehicle is difficult to assess with only one test such as that performed by the cone penetrometer, although this has been the common practice. The ease with which the cone index can be determined accounts for the popularity of this method, but in general it requires empirical correlation of vehicle performance with the cone index to establish useful predictive ratings for a given vehicle. The influence of moisture upon measurements of shear strength such as the cone index is illustrated in Fig. 2-70. This figure shows that

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*Discussion follows that of Ref. 12.

TABLE 2-16

GENERALIZED ROCK PROPERTIES (Ref. 3)

Rock type	Rating of working characteristics																													
	Abrasiveness*					Excavational requirements†					Permeability‡					Stability in steep-walled cuts‡					Roof strength in tunnels‡					Loading capacity‡				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Igneous																														
Intrusive	■									■				■	■	■					■	■	■			■				
Extrusive																														
Solidified		■	■						■	■			■	■	■	■					■	■	■			■				
Cemented			■	■	■		■	■	■		■	■	■	■				■	■	■			■	■	■			■	■	■
Metamorphic	■	■	■					■	■	■			■	■	■	■	■	■			■	■	■			■	■	■		
Sedimentary																														
Sandstone	■	■	■					■	■	■	■	■	■	■		■	■	■	■		■	■	■	■		■	■	■	■	
Limestone			■	■					■	■			■	■	■	■	■	■			■	■	■			■	■	■		
Shale			■	■				■	■					■	■				■	■			■	■				■	■	
Evaporites				■	■		■	■	■			■	■	■	■			■	■	■				■	■			■	■	■

Rock type	Ratings of suitability																													
	Compacted subgrade					Dimension stone					Road metal					Bituminous aggregate					Concrete aggregate					Fill				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Igneous																														
Intrusive	■	■				■						■	■	■				■	■		■	■	■				■	■		
Extrusive																														
Solidified	■	■				■					■	■	■			■	■	■			■	■	■				■	■		
Cemented				■	■			■	■	■				■	■				■	■					■				■	■
Metamorphic		■	■	■	■	■	■	■	■				■	■	■			■	■	■			■	■	■			■	■	■
Sedimentary																														
Sandstone			■	■	■		■	■	■					■	■			■	■	■			■	■	■		■	■	■	■
Limestone		■	■	■		■	■	■			■	■	■	■		■	■	■			■	■	■			■	■	■		
Shale					■					■					■					■					■				■	■
Evaporites					■					■					■					■					■					■

*Abrasiveness as it affects excavation tools and equipment:

1. Extreme
2. Severe
3. Moderate
4. Slight
5. Nominal or none

†Tools and procedures required to excavate rock:

1. Spade and shovel
2. Pick and shovel
3. Pick, crowbar, and wedge
4. Repeated drilling and blasting
5. Almost continous drilling and blasting

‡All other properties:

1. Excellent
2. Good
3. Adequate or fair
4. Poor or usable only in emergencies
5. Inadequate, unsuitable or absent

TABLE 2-17

SOIL CHARACTERISTICS PERTINENT TO ROADS AND AIRFIELDS (Ref. 3)

Major divisions		Letter (1)	Name	Value as foundation when not subject to frost action (2)	Value as base directly under bituminous pavement (3)	Potential frost action (4)	Compressibility and expansion	Drainage characteristics	Compaction equipment (5)	Unit dry weight lb ft^2 (6)	Field CBR	Subgrade Modulus 16 in.^{2}
Coarse grained soils	Gravel and gravelly soils	GW	Well-graded gravels or gravel-sand mixtures, little or no fines	Excellent	Good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment, steel-wheeled roller	125-140	60-80	300 or more
		GP	Poorly graded gravels or gravel-sand mixtures, little or no fines	Good to excellent	Poor to fair	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment, steel-wheeled roller	110-130	25-60	300 or more
		GM d	Silty gravels, gravel-sand-silt mixtures	Good to excellent	Fair to good	Slight to medium	Very slight	Fair to poor	Rubber-tired equipment, sheepsfoot roller; close control of moisture	130-145	40-80	300 or more
		u		Good	Poor	Slight to medium	Slight	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	120-140	20-40	200-300
		CC	Clayey gravels, gravel-sand-clay mixtures	Good	Poor	Slight to medium	Slight	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	120-140	20-40	200-300
	Sand and sandy soils	SW	Well-graded sands or gravelly sands, little or no fines	Good	Poor	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment	110-130	20-40	200-300
		SP	Poorly graded sands or gravelly sands, little or no fines	Fair to good	Poor to not suitable	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment	100-120	10-25	200-300
		SM d	Silty sands, sand-silt mixtures	Good	Poor	Slight to high	Very slight	Fair to poor	Rubber-tired equipment, sheepsfoot roller; close control of moisture	120-135	20-40	200-300
		u		Fair to good	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	105-130	10-20	200-300
		SC	Clayey sands, sand-clay mixture	Fair to good	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	105-130	10-20	200-300
Fine grained soils	Silts and clays LL < 50	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	Fair to good	Not suitable	Medium to very high	Slight to medium	Fair to poor	Rubber-tired equipment, sheepsfoot roller; close control of moisture	100-125	5-15	100-200
		CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Fair to poor	Not suitable	Medium to high	Medium	Practically impervious	Rubber-tired equipment, sheepsfoot roller	100-125	5-15	100-200
		OL	Organic silts and organic silt-clays of low plasticity	Poor	Not suitable	Medium to high	Medium to high	Poor	Rubber-tired equipment, sheepsfoot roller	90-105	4-8	100-200
	Silts and clays LL > 50	MH	Inorganic silts, micaccous or diatomaceous fine sandy or silty soils, elastic silts	Poor	Not suitable	Medium to very high	High	Fair to poor	Sheepsfoot roller	80-100	4-8	100-200
		CH	Inorganic clays of high plasticity, fat clays	Poor to very poor	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller	90-110	3-5	50-100
		OH	Organic clays of medium to high plasticity, organic silts	Poor to very poor	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller	80-105	3-5	50-100
Highly organic soils		Pt	Peat and other highly organic soils	Not suitable	Not suitable	Slight	Very high	Fair to poor	Compaction not practical	-	-	-

Notes:

1. Division of GM and SM groups into subdivisions of d and u are for roads and airfields only; subdivision is on basis of Atterberg limits; suffix d (e.g., GMd) will be used when the liquid limit is 28 or less and the plasticity index is 6 or less; the suffix u will be used when the liquid limit is greater than 28.
2. Values are for subgrades and base courses except for base course directly under bituminous pavement.
3. The term "excellent" has been reserved for base materials consisting of high quality processed crushed stone.
4. These soils are susceptible to frost as indicated under conditions favorable to frost action.
5. The equipment listed will usually produce the required densities with a reasonable number of passes when moisture conditions and thickness of lift are properly controlled. In some instances, several types of equipment are listed, because variable soil characteristics within a given soil group may require different equipment. In some instances a combination of two types may be necessary.
   a. Processed base materials and other angular materials. Steel-wheeled rollers are recommended for hard angular materials with limited fines or screenings. Rubber-tired equipment is recommended for softer materials subject to degradation.
   b. Finishing. Rubber-tired equipment is recommended for rolling during final shaping operations for most soils and processed materials.
   c. Equipment size. The following sizes of equipment are necessary to assure the high densities required for airfield construction:
      Crawler-type tractor--total weight in excess of 30,000 lb
      Rubber-tired equipment--wheel load in excess of 15,000 lb; wheel loads as high as 40,000 lb may be necessary to obtain the required densities for some materials (based on contact pressure of approximately 65 to 150 psi).
      Sheepsfoot roller--unit pressure (on 6- to 12-in.^{2} foot) to be in excess of 250 psi and unit pressures as high as 650 psi may be necessary to obtain the required densities for some materials. The area of the feet should be at least 5 percent of the total peripheral area of the drum, using the diameter measured to the faces of the feet.
6. Unit dry weights are for compacted soil at optimum moisture content for modified AASHO compactive effort.

TABLE 2-18

SUMMARY OF LANDFORM TYPES, SOILS, AND USES (Ref. 3)

Landform	Characteristic materials	Characteristic uses
Waterlaid		
Flood plains	Fine-grained and well-stratified interbedded fine silts, sand, and gravel	Highways, airfield construction; large structures require pilings
Filled valleys	Coarse sands and gravels to fine silts and clays	Highways, airfield construction; drainage structure required
Continental alluvial plains	Thin silt cover underlain by stratified semiconsolidated materials of all textures	Highways, airfield, and building construction; drainage for dam sites required to prevent leakage
Alluvial fans and related forms		
Talus cones	Rock fragments	Highways, airfield, and building construction; drainage structure required; water supply
Alluvial cones	Medium size rock fragments	
Alluvial fans	Silt, clays, sand, gravel	
Delta fan	Silt, clays, sand, gravel (Unconsolidated sands and small gravel with pockets of silt and clay)	
Deltas	Silt, clays, sand, and gravel in stratified, cross-bedded, thick deposits of unconsolidated deposits	Source of construction materials
Dry lakebeds (playas)	Unconsolidated fine sands, clays, silts, and salts	Roads, airfields, and buildings; foundation support for structures required
Beach ridges	Sand and gravel	Roads, railroad lines; source of construction material

TABLE 2-18 (Continued)

SUMMARY OF LANDFORM TYPES, SOILS, AND USES (Ref. 3)

Landform	Characteristic materials	Characteristic uses
Coastal plains	Interbedded clays, silts, and sands in unconsolidated deposits	Roads, railroad lines on undissected areas; landslide conditions; drainage controls required
Tidal flats	Silt, clay, and sand	Roads require stabilization; source of construction materials
Marsh and swamp	Peat, muck, silt	Temporary roads must be stabilized
Glacial		
Eskers	Sand, gravel, and boulders	Roads, railroad lines; source of construction material
Kames	Fine sand, silt, and gravel	Source of construction material
Outwash plains	Stratified sand and gravel	Source of construction material and foundations with stabilization
Terraces	Sand, gravel, clays, silt	Foundations for structures require stabilization; source of construction materials
Lakebeds		
Delta deposits Near-shore deposits Deep-water deposits	Coarse sand and gravel Coarse silt and sand Silts and clays	Foundations for structures require stabilization; drainage controls needed
Till plains	Silt, clay, gravel	Foundation for structures require stabilization; drainage controls needed
Moraines	Silt, clay, sand, boulders	Source of construction material; drainage controls needed; foundation for structures require stabilization

TABLE 2-18 (Continued)

SUMMARY OF LANDFORM TYPES, SOILS, AND USES (Ref. 3)

Landform	Characteristic materials	Characteristic uses
Drumlins	Sand, clay, and gravel	Source of construction material
Windlaid		
Sand dunes	Sand	Source of sand for construction; foundation for structures requires stabilization
Loess	Silt	Foundation for structures requires stabilization

some accounting of the moisture condition is mandatory in order to give the cone index meaning.

The single most important measurement of the soil for trafficability is shear strength. It is the shear strength that develops the thrust required for locomotion and the support of the vehicle without intolerable sinkage. Shear strength depends primarily upon the cohesive and frictional properties of the soil, which in turn depend upon the moisture, vegetation, compaction, and other environmental factors.

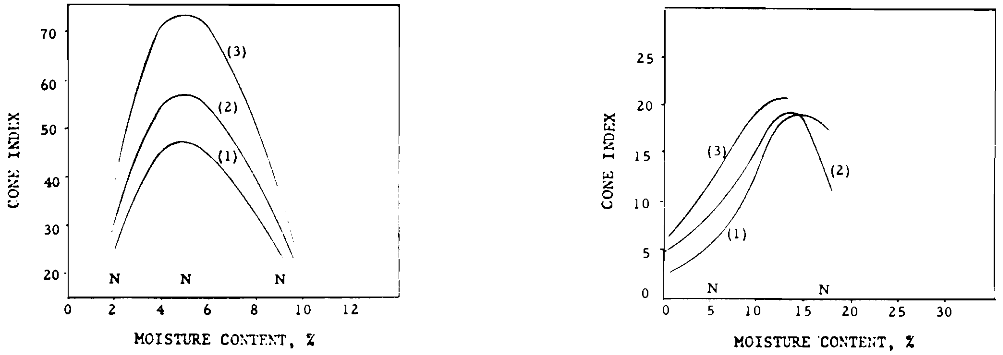
Also important in determining trafficability is the terrain profile, since it is clearly easier to go downhill than uphill. Driver tolerance of vibration also limits speed across rough terrain; hence, terrain roughness limits the speed with which a vehicle can move. Obstacles or ditches can block vehicular passage or cause the center to hang up, as illustrated in Fig. 2-71. River crossings are particularly difficult and are discussed in greater detail in par. 2-5.2.5.

The most readily available data today for assessing the trafficability of a given vehicle across a given soil are empirical data generated with cone penetrometer measurements. The minimum cone index required to assure that a given vehicle can make at least one successful pass or more than 50 passes over a given terrain can be estimated from Figs. 2-33 and 2-34. From many test measurements, the range of cone index strength for a number of soils is shown in Table 2-19.

Fig. 2-72 illustrates a general worldwide map of soil strength. This map, in conjunction with those describing other worldwide geological properties, furnishes an introduction to the trafficability problems of the various regions of the world. It cannot, however, form the basis for any detailed study.

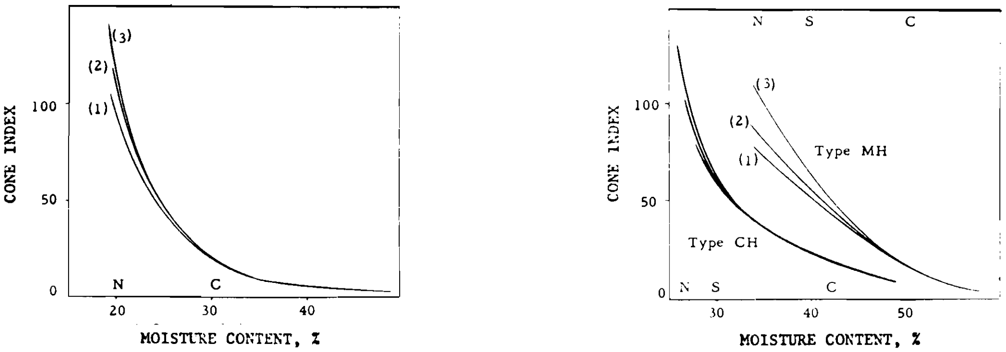
2-5.2.1 FLOTATION

Flotation is a term used to denote the ability of a vehicle to traverse soft soil without undue sinkage. Increased flotation is generally sought by increasing the ground-



(A) Gravelly sand, type GP

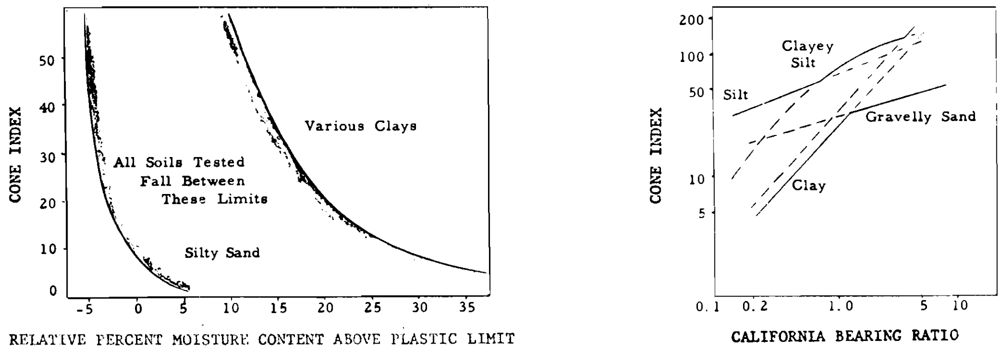
(B) Sand, type SP



(C) Silty, sandy clay, type CL

(D) Clay

(1) - (2) - (3) Increasing compaction of sample tested N-No stickiness S-Some stickiness C-Complete stickiness



(E) Envelope, fine-grained soils only

(F) Correlation envelope

Figure 2-70. Variation of Soil Strengths With Moisture Content and Correlation of Cone Index With California Bearing Ratio (Ref. 3)

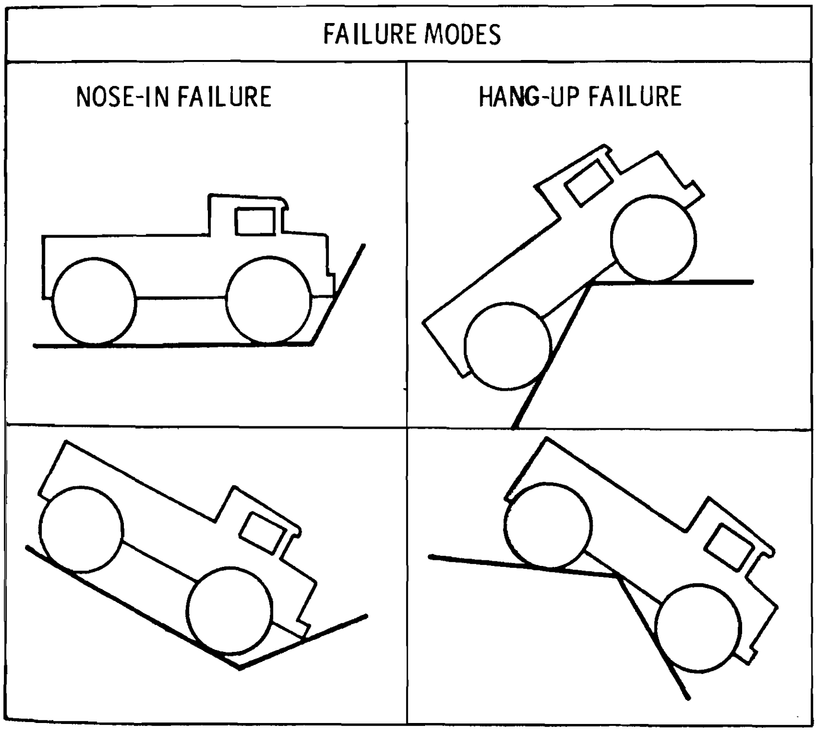


Figure 2-71. Two Types of Vehicle Failure on Four Types of Obstacles, Each Formed by Two Intersecting Planes (Ref. 8)

contact area of the vehicle or by reducing its weight in order to reduce the ground pressure. This approach, although usually successful, is not always valid. Experiments have shown that under some soil conditions vehicles with high ground pressure perform better than those with lower ground pressure.

The task of evaluating flotation effects upon performance becomes more complicated when the variation of soil properties with atmospheric conditions is considered. A soupy mud, when frozen, will have the strength of a concrete pavement. Firm, but wet, soils when disturbed (remolded) often lose their strength. Some soils, though hard when dry, may become very soft when wet. This may be caused even by a light rain since considerable variation in strength may result when water content changes by only 1 or 2 percent.

Flotation is usually thought of in terms of bearing capacity of the soil. However, bearing capacity, as practiced by civil engineers is based upon the soil strength developed with little or no sinkage. For mobility problems, significant sinkage is permitted.

Since flotation is associated with the bearing capacity of the ground, equations relating ground pressure and ground-contact area are similar to the equations for the allowable bearing capacity of footings. For a rectangular footing (length > width), the most commonly used equation for bearing capacity of a surface footing is

$$p_{\text{rect}} = cN_c + 0.5\gamma b N_\gamma, \text{ psi} \qquad (2\text{-}27)$$

where

p_{rect} = allowable ground pressure, psi

c = cohesion, psi

γ = soil density, lb in.$^{-3}$

TABLE 2-19

TRAFFICABILITY CHARACTERISTICS OF USCS SOILS IN WET SEASON (Ref. 3)

Class		USCS soil type*	Probable CI range†	Probable RI range	Probable RCI range	Slipperiness effects	Stickiness effects	Comments
A	Coarse-grained cohesionless sand and gravels	GW, GP SW, SP	80 to 300	1	80 to 300	Slight to none	None	Will support continuous traffic of military vehicles with high traction tires. Moist sands are good; dry sand only fair. Wheeled vehicles with standard tires may be immobilized in dry sands
B	Inorganic clays of high plasticity, fat clays	CH	55 to 165	0.75 to 1.35	65 to 140	Severe to slight	Severe to slight	Usually will support more than 50 passes of military vehicles. Going will be difficult at times
C	Clayey gravels, gravel-sand-clay mixture	GC	85 to 175	0.45 to 0.75	45 to 125	Severe to slight	Moderate to slight	Often will not support 40 to 50 passes of military vehicles, but usually will support unlimited traffic. Going will be difficult in most cases
	Clayey sand, sand-clay mistures	SC						
	Gravelly clays, sandy clays, inorganic clays of low to medium plasticity, lean clays, silty clays	CL						
D	Silty gravels, gravel-sand-silt mixtures	GM	85 to 180	0.25 to 0.85	25 to 120	Moderate to slight	Slight	Usually will not support 40 to 50 passes of military vehicles. Often will not permit even a single pass. Going will be difficult in most cases
	Silty sands, sand-silt mixtures	SM						
	Inorganic silts and very fine sands, rock flour, silty or clayey silts with slight plasticity	ML and CL-ML						
	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	MH						
	Organic silts and organic silty clays of low plasticity	OL						
	Organic clays of medium to high plasticity, organic silts	OH						
E	Peats and mucks	Pt	10 to 100	0.25 to 0.65	10 to 85	slight to none	Moderate to slight	Often will not permit even a single pass. Going will be difficult to impossible

*See Table 2-9

†See par. 2-3.3.5

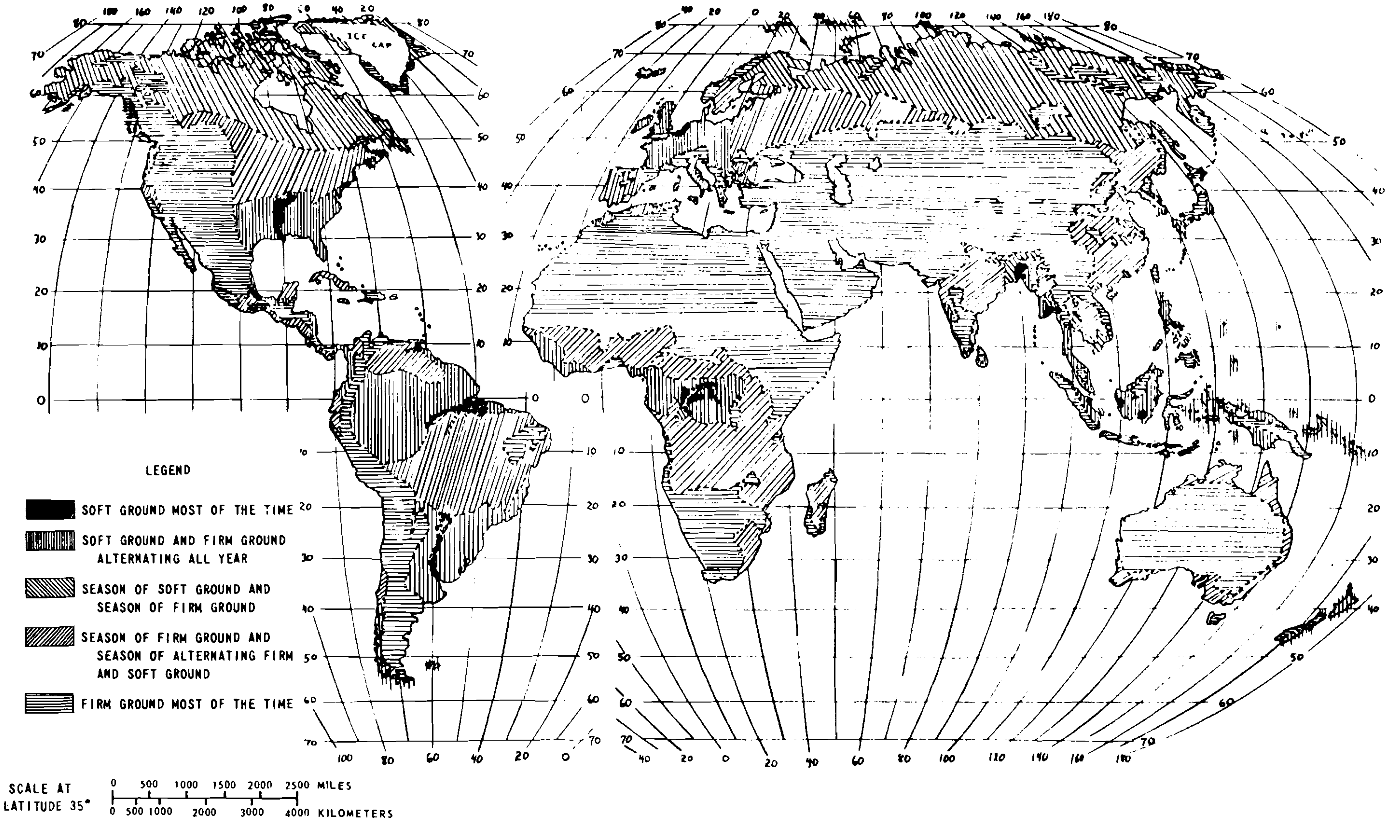


Figure 2-72. Soil Strength Regions (Ref. 3)

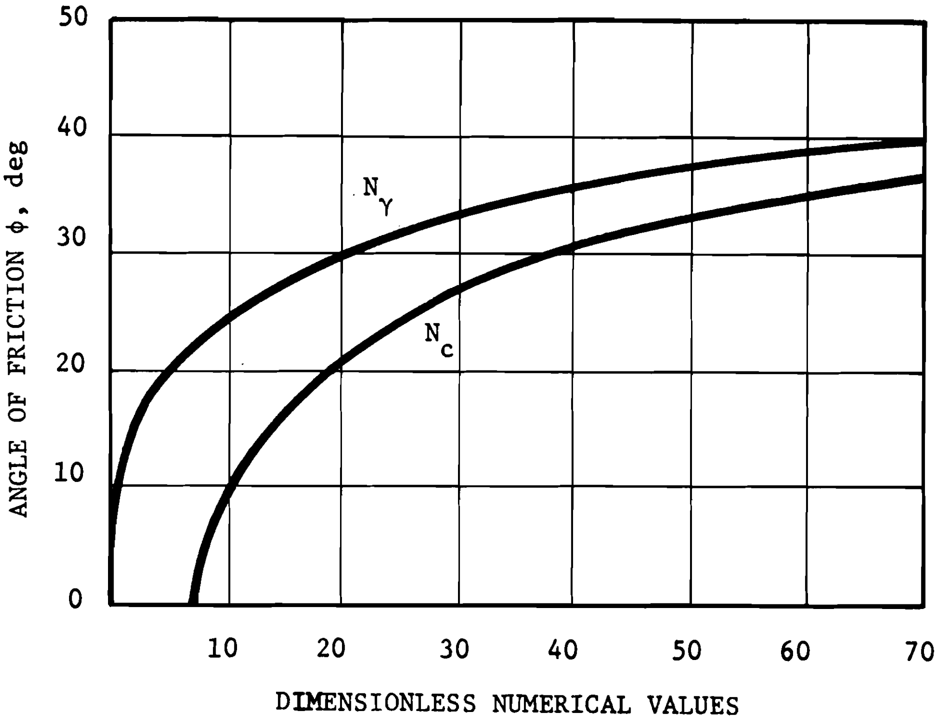


Figure 2-73. Bearing Capacity Factors (Ref. 12)

b = footing width, in.

N_c and N_γ = bearing capacity factors, which are functions of soil internal friction angle ϕ as shown in Fig. 2-73, dimensionless

The equation assumes general shear failure of the soil rather than a local shear failure (Fig. 2-74). General shear failure involves vertical and lateral shearing of the soil over a large area along certain definite surfaces; local shear failure refers to a shearing similar to that generated by a punch which mobilizes strength only near the loaded area.

Eq. 2-27 can be empirically modified as follows to apply to square and round footings:

$$p_{\text{square}} = 1.3cN_c + 0.4\gamma bN_\gamma, \text{ psi} \quad (2\text{-}28)$$

$$p_{\text{round}} = 1.3cN_c + 0.3\gamma bN_\gamma, \text{ psi} \quad (2\text{-}29)$$

where, for the round footing, b is the footing diameter, in.

For a pure cohesive soil where $\phi = 0, N_\gamma = 0$ (Fig. 2-73) and the equations reduce to

$$p_{\text{rect}} = cN_c, \text{ psi} \quad (2\text{-}30)$$

$$p_{\text{square}} = p_{\text{round}} = 1.3cN_c, \text{ psi} \quad (2\text{-}31)$$

Thus a 30 percent greater ground pressure is permissible with square and round footings than with rectangular footings where the length is much greater than the width. However, no discernible difference exists between the round and the square.

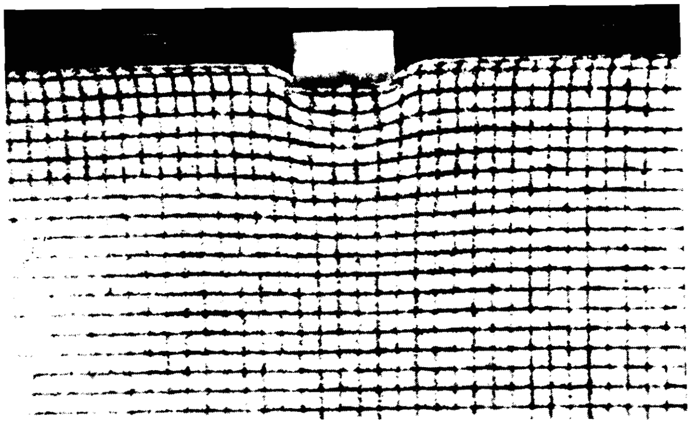
In a pure frictional soil, the cohesion c is zero, and the equations for allowable ground pressure become

$$p_{\text{rect}} = 0.5\gamma bN_\gamma, \text{ psi} \quad (2\text{-}32)$$

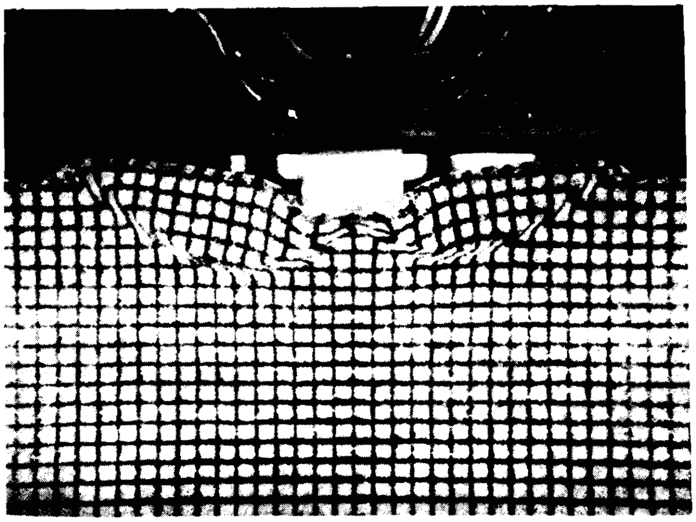
$$p_{\text{square}} = 0.4\gamma bN_\gamma, \text{ psi} \quad (2\text{-}33)$$

$$p_{\text{round}} = 0.3\gamma bN_\gamma, \text{ psi} \quad (2\text{-}34)$$

In this case, in contrast to the pure cohesive soil, the form of the rectangular footing



(A) Local shear



(B) General shear

Figure 2-74. Failure of Soil Beneath a Loaded Area (Ref. 12)

permits the greatest ground pressure, and a difference exists between the square and round footings. It is also seen that the size of footing is a factor in the permissible bearing capacity, the allowable bearing pressure increasing in direct proportion to size. For the case of a rectangular footing, this is especially important since a given plane area can be arrived at by numerous combinations of length and width.

Vehicle mobility cannot be compared on the basis of ground pressure alone; it cannot be assumed that vehicles with the same ground pressure will have the same flotation. Variations in ground pressure along the footprint can influence performance significantly. The form of the ground-contact area also has significant influences. Hence, flotation characteristics cannot be evaluated without a strict definition of the soil and the characteristics of the ground-contact area.

The same is true when flotation is viewed in terms of sinkage. Eq. 2-7 indicates that, for the same ground pressure, the wider ground-contact area will sink deeper. This has also been found to be true in studies in soil mechanics where, for a given ground pressure, large foundations have shown a stronger tendency for settlement than smaller ones. The same results are found with motor vehicles.

Both the sinkage and bearing-capacity equations are based upon the assumption of a flat plate with uniformly distributed pressure. In reality neither tracks nor wheels satisfy these conditions; hence, only approximate predictions can be expected. In general, the sinkage of a wheel, for example, will be greater than that of a flat plate having the same contact area and load.

The horizontal movement of the soil under the wheel or track necessary to develop traction also has considerable influence on the resultant sinkage – the theoretical equations usually assume a pure vertical load.

A soil that is firm in cold months can become impassable with spring thaw, then return to a firm condition as the soil dries. With heavy rain, the firm soil may again become very soft. These changes usually occur only to a depth of a few feet and, hence, the soil is not a semi-infinite homogeneous mass but exhibits a gradual transition with depth from soft to firm. Thus the soil is analogous to a soft plastic layer resting on a rigid base for which the bearing-capacity formulas cannot be used. Based on plasticity theory, it has been suggested that the maximum safe ground pressure for a top layer of soft soil underlain by a hard bottom can be given by

$$p = \frac{sb}{2h}\text{, psi} \tag{2-35}$$

where

p = average ground pressure, psi

s = shear strength, psi

b = width of loaded area, in.

h = thickness of soft layer, in.

This equation applies only when the length of the loaded area is 10 or more times larger than width.

Eq. 2-35 determines an allowable ground pressure that permits a vehicle to float on top of a very soft soil layer. Such layers may be so weak that the shear strength permits only a small ground pressure achievable only with very large tracks or wheels. Eq. 2-35 indicates that the thinner the soft layer, the greater the allowable pressure. As a first approximation it may be assumed that for a given ground pressure p, sinkage would occur until the depth of the soft layer under the loaded area is reduced to $h_1 = sb/2p$. Sinkage z, in inches, would then be $(h - h_1)$ or

$$z = h - \frac{sb}{2p}\text{, in.} \tag{2-36}$$

In Eq. 2-35 the soil strength parameters are combined in the shear strength s. For a constant p, an increase in ground-contact width will result in a decrease in sinkage. This is in contrast to the relationship of Eq. 2-7, which indicates that, for a constant pressure p, an increase in width b results in an increase in sinkage z. The reason is that for the soft layer, the soil is confined by the adhesion at the interfaces, while for firmer soils, the greater width extends the stress levels to greater depths.

Thus, the computation of sinkage depends on soil homogeneity. It is recommended that Eq. 2-7 be used in general. Sinkage will be of greatest concern when it is large with respect to the size of track or wheel load area. As such, if the depth of the soft layer is small, the sinkage will not be a serious problem since the vehicle will be mobile on the firmer substratum. When the soft layer is thick, then the assumption of a homogeneous continuum is more suitable.

2-5.2.2 SOIL TRACTION

A vehicle traveling over the ground surface utilizes the shear strength of the soil to develop its horizontal propelling force. The total force capable of being developed into a propelling force is called traction.

The ultimate soil shear strength is determined by Coulomb's equation (Eq. 2-4). The maximum obtainable traction for a wheel or track can therefore be approximated as the product of the shear strength and the ground-contact area, i.e.,

$$H = sA = Ac + W \tan \phi, \text{ lb} \qquad (2\text{-}37)$$

where

H = maximum thrust, lb

A = area of contact, in.^{2}

W = total vehicle weight, lb

ϕ = internal friction angle, deg

c = soil cohesion, psi

s = shear strength, psi

Eq. 2-37 indicates that the vehicle weight, ground-contact area, soil cohesion, and internal friction are the important parameters in developing traction. The force computed from Eq. 2-37 is the maximum that may be expected to be developed, occurring at the moment of impending shear failure in the soil. The actual traction developed at any time is dependent upon the slippage occurring at the soil-vehicle interface and the soil stress-strain relationships. Coulomb's equation alone does not account for these effects.

From Coulomb's equation some interesting observations may be made. In a cohesive soil, ϕ is approximately equal to zero. Eq. 2-37 then becomes

$$H = Ac, \text{ lb} \qquad (2\text{-}38)$$

Therefore, in a cohesive soil, the greater the contact area of the vehicle, the greater the thrust generated while the vehicle weight contributes nothing to thrust. Hence, in a soft cohesive soil, a track is preferred since a tire of equal area would be unacceptably large. This assumes, of course, that the shearing resistance at the interface is at least equal to the full cohesion.

For a frictional soil, cohesion c is approximately zero and Eq. 2-37 becomes

$$H = W \tan \phi, \text{ lb} \qquad (2\text{-}39)$$

In contrast to the cohesive soil, contact area does not affect the ability to develop thrust. In this soil, thrust is developed in direct proportion to vehicle weight; hence, for maximum traction, the vehicle weight should be as great as possible consistent with the limitation dictated by flotation.

Performance on low friction surfaces – such as icy roads, slippery mud over hard substrate, or vegetation-covered terrain – is another type of problem. It can be basically viewed in terms of the same equation, however. In most cases a track will develop more thrust for a given weight, even for a given contact area, since grousers will bite through the surface layer. The distinction in this case is due to a greater effective cohesion and friction.

2-5.2.3 EXTERNAL RESISTANCE

Resistance to motion occurs as a result of forces acting within the vehicle and upon the vehicle. Internal motion resistance is due to friction between moving parts, and hysteresis in flexing materials such as occurs in the tracks, suspensions, tires, and drive line.

External motion resistance is developed

from the compaction of soil under the vehicle contact area, the bulldozing of the soil in front of the contact area, drag of the particles that adhere to the suspension, and wind resistance (at high speeds).

A perfectly rigid wheel rolling on a perfectly rigid surface requires little power for propulsion because no deformations occur and therefore, no forces of resistance develop between the surface and the wheel. This case is approached by the steel railroad wheel operating on a steel track; in fact, this type of locomotion requires the minimum propulsion power of all land vehicles. However, aside from generalities, little relationship exists between the rigid wheel on a rigid surface and the problems of off-the-road locomotion.

The resistance to forward movement of a wheel rolling over soft ground is due, to a large degree, to the work done in compacting the underlying soil. For a towed, rigid wheel, this resistance decreases with increases in both diameter and width. Because of the curvature of the wheel contact surface and the nature of the distribution of shearing stresses and normal pressures on this surface, however, the sinkage behavior of horizontal flat plates cannot be expected to produce an accurate estimate of the behavior of wheels.

2-5.2.4 DRAWBAR PULL

The shearing strength of the ground utilized by a vehicle to develop horizontal propelling forces is called traction. Part of the total traction available is depleted in overcoming the resistance to motion. The rest – which is available to accelerate the vehicle, climb slopes, or pull loads – is called the net tractive effort or drawbar pull. If the resistance to motion becomes greater than the total traction available, then self-propelled locomotion will cease.

Drawbar pull DP is computed, in pounds, as

$$DP = H - R, \text{ lb} \qquad (2\text{-}40)$$

where

H = total traction available, lb

R = resistance to motion, lb

The influence of vehicle weight on drawbar pull is related to the internal friction angle ϕ. To illustrate, consider a dry sand for which soil cohesion c may be considered zero. For this soil condition, traction H is directly proportional to vehicle weight, but resistance to motion increases approximately as the square of the weight. Initially, as the load on a vehicle is increased, its drawbar pull will increase; there comes a load and sinkage, however, above which the drawbar pull will no longer increase but will decrease with increasing load. This crossover point will vary with soil strength and vehicle design.

Size and form of the ground-contact area are important in a frictionless soil such as a pure clay where the soil strength is entirely due to cohesion. For this type of soil, soil thrust H is a function only of size of contact area, while resistance to motion increases as a function of sinkage. Thus, in a pure clay it is invalid to assume that increasing weight will increase drawbar pull. On the contrary, increasing weight rapidly decreases the drawbar pull.

Eq. 2-40 assumes that full soil shear strength is mobilized and, as such, maximum thrust is realized. This maximum occurs only at the optimal amount of slippage. When the vehicle operates at other than optimal slippage, Eq. 2-40 no longer accurately predicts traction.

2-5.2.5 OTHER FACTORS (TERRAIN GEOMETRY, VEGETATION, RIVERS)*

In addition to the interactions of a vehicle with the soil, trafficability can be limited by terrain geometry or vegetation. The effect of

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*Riverine problem discussion follows that of Ref. 26.

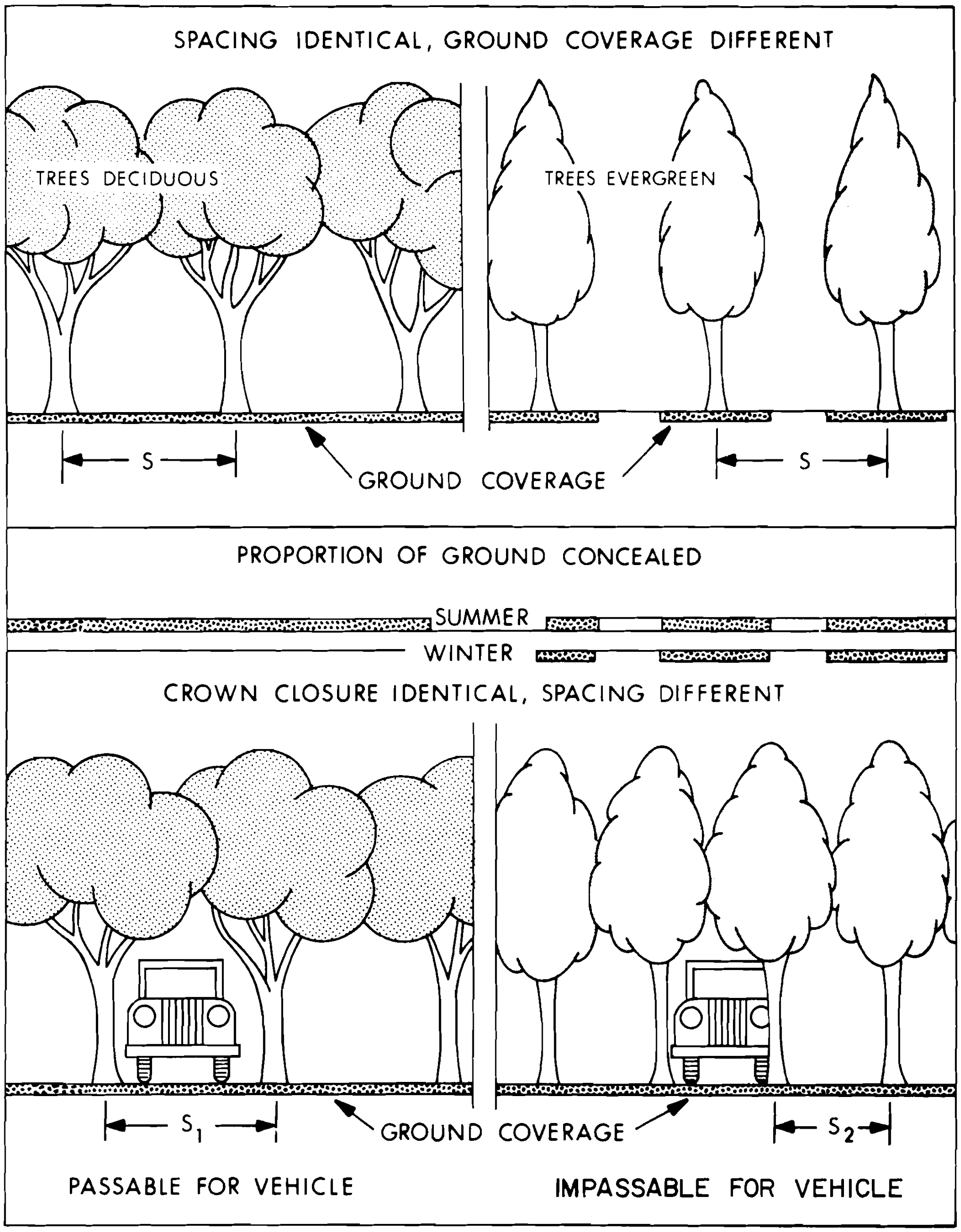

Figure 2-75. Physical Parameters of Vegetation (Ref. 3)

vegetation is easy to understand but hard to predict. When the spacing between trees, for example, becomes so close as to prohibit a vehicle from passing between, then the trafficability of this particular terrain is zero, in spite of the soil condition or any other considerations of vehicle-soil interaction. This role of vegetation is analogous to obstacles created in the terrain that cannot be surmounted or pushed aside. The condition is pictured in Fig. 2-75. Short of this situation, when the vegetation is dense, but not impassable, the vegetation slows down the vehicle by restricting movement and limiting observation. Low brush, even when closely spaced, may not immobilize a vehicle, but its

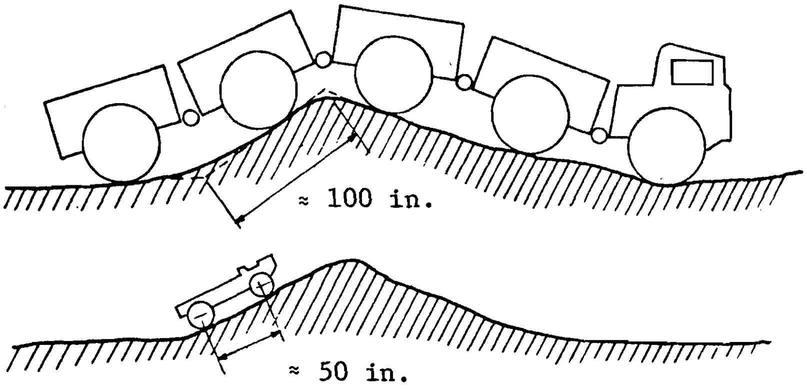

Figure 2-76. Surface Roughness and Vehicle Size (Ref. 8)

presence slows the vehicle down by generating increased motion resistance and hiding terrain features such as rocks and ditches.

The more usual obstacle role of terrain results from slopes, ditches, or mounds that cannot be surmounted. To be a slope, the terrain must have a dimension that is large compared to those of the vehicle. Otherwise, a slope appears as a bump or obstacle. A slope for a small vehicle may be an obstacle for a large one (Fig. 2-76). Some basic obstacle classes are shown in Fig. 2-77.

A particularly important type of obstacle is that presented by rivers. River crossings throughout history have played an important role in military operations. The advance of the German Army into Russia during World War II was greatly slowed by its ineptness at effecting prompt river crossings. Rivers have always been regarded as attractive terrain for

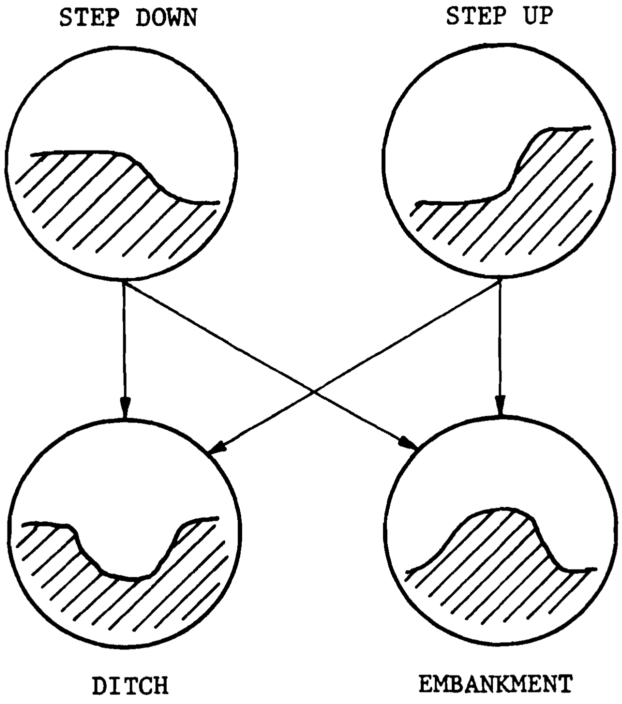

Figure 2-77. Relationship Between Basic Configurations of Surface Obstacles (Ref. 8)

forming lines of defense, simply because of the added difficulty they impose upon the advancing enemy.

The single most difficult part of any river crossing is climbing up the bank on the opposite side. Thus, the single most important parameter with regard to a river crossing is the geometric form of the banks. Tests have demonstrated a maximum bank-climbing ability of the M113 Armored Personnel Carrier of only 17 deg (Ref. 26). Most rivers in the United States have bank slopes greater than 25 deg and in areas such as Thailand most slopes are greater than 30 deg.

Approximate empirical relationship expresses the "geometric severity factor" (*GSF*) of a river bank in terms of an equivalent vertical step height:

$$GSF = H \sin^2 \beta, \text{ m} \tag{2-41}$$

where

H = bank height, m

β = bank slope angle from the horizontal, deg

Exiting performance is estimated by determining the vertical step-climbing ability of the vehicle on both nondeformable (wood or concrete) and deformable (sand or clay) steps. The vehicle is then predicted to have a "go" capability on any bank whose *GSF* is less than the nondeformable step-climbing ability of the vehicle; the vehicle has a "marginal" capability of negotiating a bank with a *GSF* that is less than the deformable step-climbing ability of the vehicle; and it has a "no-go" capability for any bank with *GSF* above the deformable step-climbing ability of the vehicle (Fig. 2-78).

Frequency distributions of geometric severity factors for the Eastern United States and Thailand, developed from survey data, are given in Table 2-20.

High soil strength is of obvious benefit to the exiting vehicle on a bank with a slope free of abrupt discontinuities, such as steps. When the bank contains a step, the situation is reversed. Vehicles exit on step-type banks by bulldozing and excavating (with tracks or wheels) until a ramp is formed. Hence, there is an optimum condition at which the soil strength is low enough to allow a ramp to be formed and high enough to support the normal and shear loading of the vehicle.

Tracked vehicles with blunt, flat front ends and wheeled vehicles with long front overhangs or low bumpers have the most difficulty exiting onto step-type banks. For example, consider a vehicle with a front bumper 8 in. wide and 6 ft long, with a net tractive force of 10,000 lb. A bulldozing resistance on the bumper of only 17.4 psi (a relatively low value) will stop the vehicle. The M113 has a tractive force of 15,000 lb under favorable conditions and a near-vertical frontal area of approximately 1,740 in.^{2}. A bulldozing resistance of less than 9 psi on this frontal area is sufficient to prevent this vehicle from exiting.

Vegetation, even light vegetation such as grass, can produce a condition that will prevent exiting because of added slipperiness or obstacle effects. Vegetation also tends to maintain the bank in a step configuration. Exiting tests in the Canal Zone of Panama showed that a step-like bank configuration had remained relatively unchanged over a period of 60 yr, apparently because of the heavy tropical vegetation.

On banks that approximate a uniform slope (as opposed to those that approximate a step), the ability of the vehicle to exit is governed principally by the net traction that can be developed. Any given soil has a finite soil strength. When the soil is formed into a sloping surface, part of this strength is mobilized just to maintain the slope. This means that the soil strength available to support and supply tractive effort to the

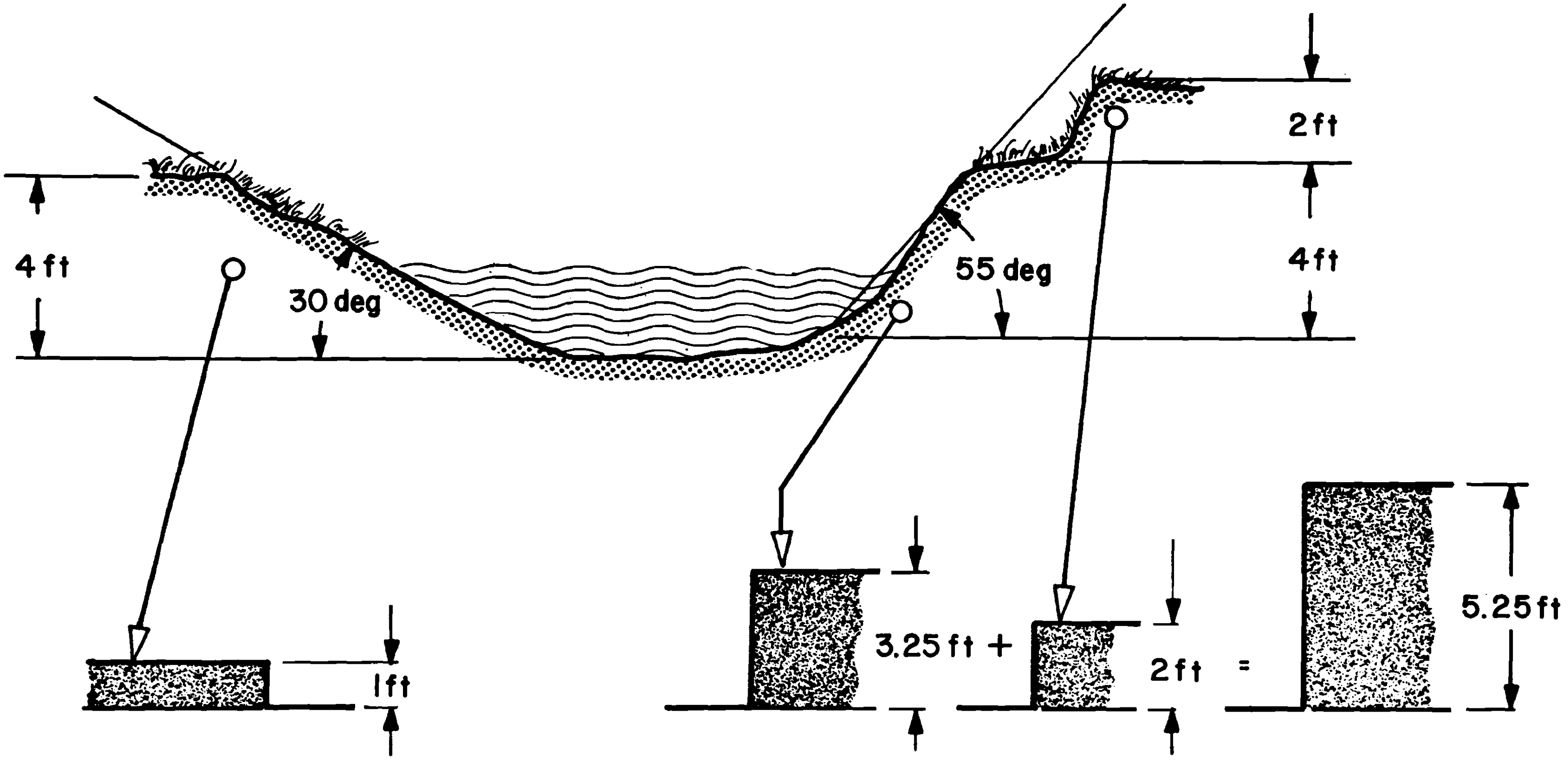

Figure 2-78. Typical River Cross Section With Appropriate Equivalent Vertical Step Heights for Various Banks, as Computed From Eq. 2-41 (Ref. 26)

TABLE 2-20

FREQUENCY DISTRIBUTIONS OF BANK GEOMETRIC SEVERITY FACTORS (Ref. 26)

GSF, ft	Eastern United States			Thailand		
	No. of banks	Percent of total	Cumulative percent	No. of banks	Percent of total	Cumulative percent
1.0	29	12.9	12.9	10	8.1	8.1
1.5	8	3.6	16.5	15	12.1	20.2
2.0	21	9.4	25.9	4	3.2	23.4
2.5	16	7.1	33.0	8	6.5	29.9
3.0	8	3.6	36.6	11	8.9	38.8
3.5	5	2.2	38.8	7	5.6	44.4
4.0	6	2.7	41.5	8	6.5	50.9
4.5	5	2.2	43.8	10	8.0	58.9
5.0	7	3.1	46.9	2	1.6	60.5
5.5	2	0.9	47.8	4	3.2	63.7
6.0	9	4.0	51.8	4	3.2	66.9
6.5	5	2.2	54.0	5	4.0	70.9
7.0	5	2.2	56.3	3	2.4	73.4
7.5	12	5.4	61.6	2	1.6	75.0
8.0	13	5.8	67.4	3	2.4	77.4
8.5	5	2.2	69.6	2	1.6	79.0
9.0	7	3.1	72.7	3	2.4	81.4
9.5	1	0.4	73.2	1	0.8	82.2
10.0	6	2.7	75.9	1	0.8	83.0
Greater than 10	54	24.1	100.0	21	17.0	100.0

exiting vehicle is less than that for the same soil when level.

The following relationship between gross tractive effort and gross vehicle weight as a function of slope angle and soil internal friction angle for dry sand has been suggested:

$$\frac{\textit{Gross Tractive Effort}}{\textit{Gross Vehicle Weight}} = (\tan\phi\cdot\cos\beta) - \sin\beta \quad (2\text{-}42)$$

where

ϕ = soil internal friction angle, deg

β = bank slope angle, deg

Eq. 2-42 is plotted in Fig. 2-79 for various values of ϕ and β. It is emphasized that this relationship was developed for dry sand. Wet sand, or a cohesive soil, can have appreciably

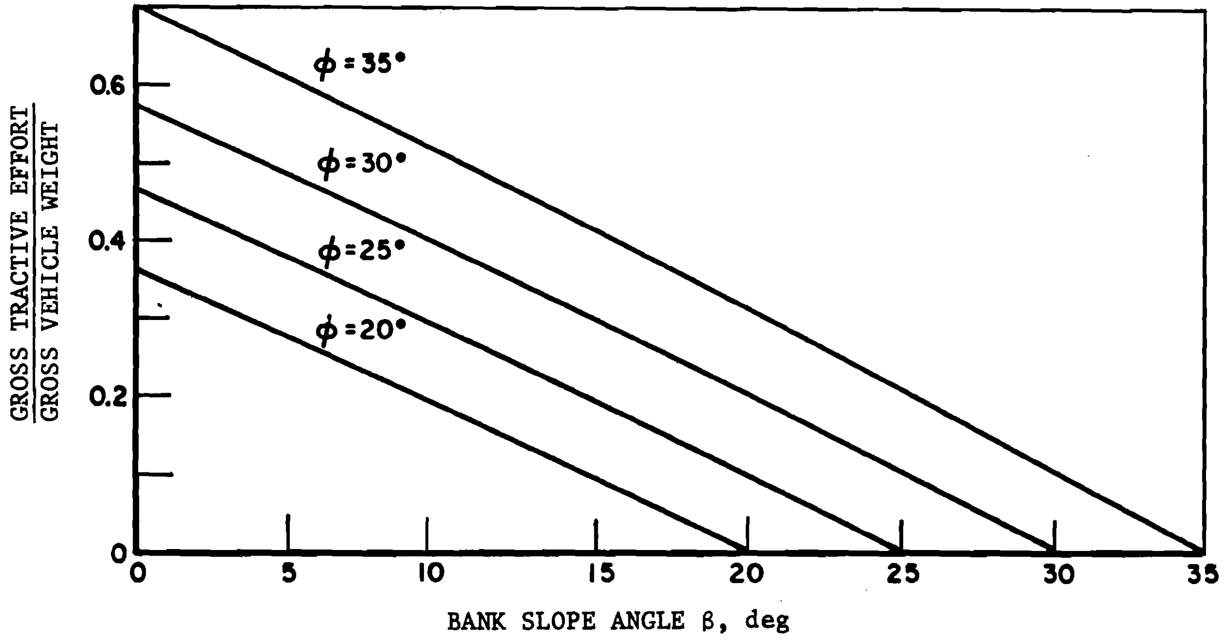

Figure 2-79. Vehicle Tractive Effort-Weight Ratio for Various Stream Exiting Parameters (Ref. 26)

greater strength than would be predicted from Eq. 2-42.

The size of the river to be crossed has an effect on exiting, because river current and depth generally increase with width. Recent tests indicate that nearly all existing standard U. S. Army floating vehicles are uncontrollable in currents that equal one-half the maximum still-water speed of the vehicle*. The effect of current, therefore, is to prevent the vehicle from exiting at the most desirable locations on the opposite bank. River depth near the bank is also a factor, since a vehicle exiting from a floating position has significantly less traction available during the initial phase of egress than when exiting from a fording situation.

Tables 2-21 and 2-22 show river width-and-depth data from field surveys. These data show that most rivers are less than 100 ft wide and less than 3 ft deep. However, it should be noted that even small, shallow rivers frequently pose severe exiting problems.

It has been well established that the steeper cut banks are not good egress points on the upper flood plain of relatively small streams. Along the same stretches of these rivers, shoals are traversed with ease.

In alluvial fan or delta areas, however, it may be desirable to select the cut bank or one along a straight reach as an egress point. Here, the alluvium is composed of fine particles. The water level normally is very close to the top of the banks and frequently overflows them. With a soil moisture content that is constantly near saturation, delta areas are characterized by soft banks (particularly shoals), swamps, and natural levees. The levees consist of coarser, stronger soil particles and actually form the stream banks. Under these conditions, the shoals would probably be untenably soft and the cut banks, by comparison, relatively strong. Because the water level is usually close to the top of the bank, bank heights are not as critical a problem as farther upstream. Furthermore, extensive forest vegetation is not normally associated with these areas (primarily because of cultural influences) and may be considered a less likely deterrent to egress.

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*The only significant exception is the LARC V.

TABLE 2-21

FREQUENCY OF RIVER SURFACE WIDTH (Ref. 26)

	Eastern U.S.		Thailand	
River surface width, ft	Rivers surveyed	Percent	Rivers surveyed	Percent
20- 50	43	38	27	43
50-100	26	23	13	21
100-150	10	9	5	8
150-200	6	5	7	11
200-250	5	4	2	3
250-300	6	5	3	5
300-350	3	3	1	2
350-400	1	1	1	2
400-450	4	4	0	0
450-500	3	3	0	0
> 500	6	5	4	6
	Total 113		Total 60	
Arithmetic mean width, ft		267	171	
Geometric mean width, ft		94	82	
Median width, ft		71	60	

As a consequence, entrance and egress points in the flat, expansive delta regions should be selected on the outside bank of a meander. Special care is required for negotiation, because this location usually has the maximum current velocity and possibly an undertow current as well. There is little choice in the matter of selection; the shoals are soft and their reaches are often long.

Recommended slope requirements have been developed by the U. S. Army Tank-Automotive Command and are summarized in Tables 2-23 and 2-24. The tables show the type of river banks that different vehicle classes should be capable of negotiating. A limited amount of soil data, the soil angle of internal friction, and cohesion are included. The tables were developed from field surveys of rivers. These recommended requirements will undergo continual revision and expansion as additional data become available.

Table 2-23, for tropical areas, was developed from river survey data taken in Thailand. A uniform slope with a relatively high water level is indicated. Table 2-24, for temperature areas, was developed from a survey of rivers in the United States. Lower water levels are indicated, but two types of banks occur; one is a uniform slope, the other is a vertical, or near-vertical step. Two banks are shown because the survey indicated that the step-type bank occurred with about the same frequency as the slope-type bank. Therefore, if the recommended requirement is to represent the environment, both types must be included.

TABLE 2-22

FREQUENCY OF RIVER DEPTH (Ref. 26)

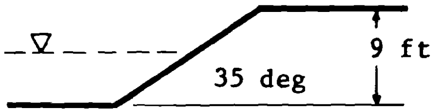
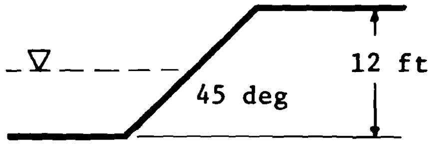
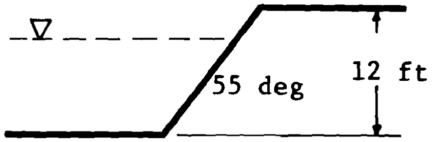
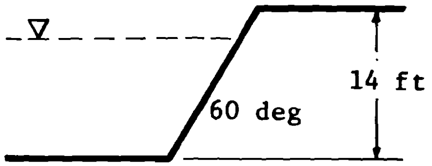
	Eastern U.S.		Thailand	
River depth, ft	Rivers surveyed	Percent	Rivers surveyed	Percent
0- 1	22	19.5	3	5
1- 2	29	25.5	10	17
2- 3	21	19	15	25
3- 4	14	12.5	1	2
4- 5	6	5	7	12
5- 6	2	2	2	3
6- 7	4	3.5	4	7
7- 8	0	0	2	3
8- 9	2	2	4	7
9-10	2	2	4	7
10-11	0	0	2	3
11-12	1	1	1	2
12-13	1	1	0	0
13-14	1	1	0	0
14-15	1	1	2	3
> 15	6	5	3	5
	Total 112		Total 60	
Arithmetic mean depth, ft		4.02	6.14	
Geometric mean depth, ft		2.55	4.53	

It is possible to build a vehicle that, without additional assistance, could negotiate the banks shown for the "wheeled tactical" and "tracked tactical" vehicle classes. The COBRA and MEXA vehicles, which have pitch control, are examples. The banks shown for "current combat" and "future combat" will probably require that the vehicle be equipped with an exiting aid. The amount of force the aid must produce, for the slope-type banks, can be estimated by using the method shown in Fig. 2-80.

Ingress performance may be determined by the ability of the vehicle to enter the water over the banks shown in Tables 2-23 and 2-24. The ingress problems are concerned primarily with hang-up and swamping and the ability of the engine and transmission to operate on the steeper slopes. Existing military engines and transmissions can operate at angles of about 30 deg. At higher angles, the oil pick-ups on both the engines and converter-type transmissions become ineffective. Many gasoline engines also have carbure-

TABLE 2-23

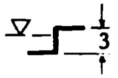
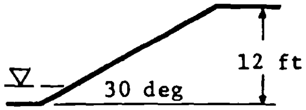
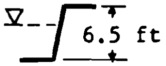
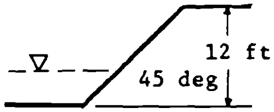
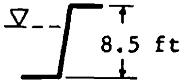
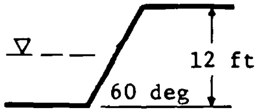
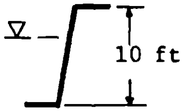
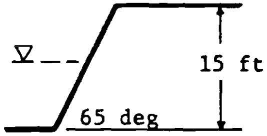
RECOMMENDED RIVER EGRESS AND INGRESS REQUIREMENTS FOR TROPICAL AREAS (Ref. 26)

Vehicle Class	Banks that vehicle will negotiate, %	Bank*		Water depth, ft	Soil cohesion, psi	Soil friction angle, deg	Slope profile
		Height, ft	Slope, deg				
Wheeled tactical	39	9	35	4.75	0.75	10	
Tracked tactical	67	12	45	6	1.0	15	
Current combat	77	12	55	9	1.5	20	
Future combat	83	14	60	11.5	2.0	25	

*Specified with no cover, grain-size distribution 95% of fine gravel or finer

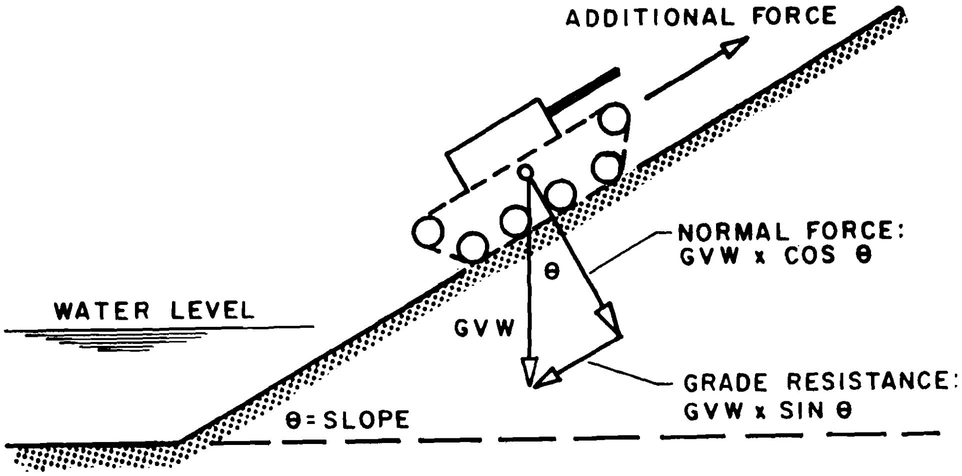
TABLE 2-24

RECOMMENDED RIVER EGRESS AND INGRESS REQUIREMENTS FOR TEMPERATE AREAS (Ref. 26)

Vehicle class	Banks that vehicle will negotiate, %	Bank 1*		Bank 2**		Water depth, ft	Soil cohesion, psi	Soil friction angle, deg	Slope profile	
		Height, ft	Slope, deg	Height, ft	Slope, deg				Bank 1	Bank 2
Wheeled tactical	37	3	90	12	30	2	0.5	26 to 15		
Tracked tactical	52	6.5	80	12	45	4	0.75	31 to 20		
Current combat	67	8.5	80	12	60	6	1.0	35 to 25		
Future combat	76	12	80	15	65	8	1.5	35 to 25		

*Specified with vegetative cover, minimum 12-in. root depth, grain-size distribution 95% of fine gravel or finer

**Specified with no vegetative cover, grain-size distribution 95% of fine gravel or finer



STEPS FOR CALCULATING ADDITIONAL EXITING FORCE

(1) Vehicle data required.
    (a) Gross vehicle weight (GVW), lb: W
    (b) Ground contact area, in.^{2}: A

(2) Bank data required.
    (a) Bank slope, deg: θ
    (b) Soil cohesion, lb in.$^{-2}$
    (c) Soil friction angle, deg: φ

(3) Calculate traction achieved from cohesion, T_c

T_c = ground contact area x soil cohesion

$t_c = A \times c$

(4) Calculate traction achieved from soil internal friction, T_ϕ

T_ϕ = normal force x tan of soil friction angle

$T_\phi = W \times \cos\theta \times \tan\phi$

(5) Calculate total traction, T_T

T_T = traction from cohesion + traction from soil internal friction

$T_T = T_c + T_\phi$

(6) Calculate grade resistance, R

$R = GVW \times \sin\theta$

(7) Calculate additional force necessary to negotiate slope, F

F = grade resistance - total traction

$F = R - T_T$

(8) Calculate percentage of GVW that additional force represents

$$\%\text{ of GVW} = \frac{\text{additional force}}{\text{GVW}} \times 100 = \frac{F}{GVW} \times 100$$

Figure 2-80. Simplified Method for Estimating Additional Force Required to Exit on a Firm, Uniform Slope (Ref. 26) tion difficulties at the higher angles. Thus, to meet the requirements of Tables 2-23 and 2-24, basic power-train design changes are required.

Sandy ocean beaches for major military operations also constitute an area of military research. A polyester resin, sprayed over the sand, has been demonstrated to hold up under beach assault traffic (Ref. 27). The plastic takes an hour or so to set up but once in place it greatly improves beach trafficability.

2-5.3 CONTOUR EFFECTS*

Ground-to-air guided missile systems require that some aircraft fly close to the ground in order to survive. In very flat areas, such as a coastal plain, flight may be made at or near treetop level without crashing into an obstacle. Flights over rough terrain must be made at slower speeds and/or at higher elevations above the ground in order to be as safe as the faster and lower flight over flatter ground. A topographic guide that considers all pertinent factors and produces flight parameters having specified levels of risk for each terrain is required. The first step in the development of such a guide is to determine the roughness of the ground. This paragraph describes an empirical method by which the densities of contours, ridges, and valleys on a topographic map may be made to yield data on the dimensions of the terrain features likely to offer the most difficulty to low-level flight.

Anyone well acquainted with contour flying could probably examine topographic sheets from different areas and form a qualitative opinion as to the relative difficulty of flying each. The methodology requires a rapid means of quantifying the necessary changes in elevation, the horizontal distances allowed for making them, and the frequency of the changes.

The method recommended here applies to any area that is adequately mapped. It is most easily demonstrated with reference to a hypothetical example. The only prerequisite is to determine the average ridge-to-valley spacing and average valley depth.

(1) Select a 15-min, 1:62,500 or 1:50,000 topographic sheet representative of the area to be analyzed. Draw the largest possible circle on the sheet with the center of the sheet as the center of the circle. Draw east-west, north-south, northeast-southwest, and northwest-southeast diameters. Measure the length of the diameters and determine their ground length in feet. Let it be assumed for demonstration purposes that such length is 70,000 ft. The four diameters thus have a total length of 280,000 ft.

(2) Count the contours intersected by the diameters, and multiply contour interval by contour count to determine the amount of elevation change that takes place in traversing the diameters. Let it be assumed that the contour interval is 40 ft and that 900 contours are counted for an elevation change along the diameters of 36,000 (40 X 900 = 36,000)

(3) Count the ridges and valleys encountered in traversing the diameters and divide the total length of the diameters by this count. Do not distinguish the ridges from the valleys, but count the number of times the slope changes from up to down or down to up. The operation may be speeded up and made almost mechanical by counting the number of times the traverse line cuts off a loop of a contour, becomes tangent with one, or, in rather rare cases in crossing a ridge or broad flat-floored valley, passes between two contours having the same value. Let it be assumed in this case that 140 such slope direction changes are counted for a mean ridge-to-valley spacing of 2,000 ft (280,000/140 = 2,000).

(4) Divide the total elevation change by the number of slope direction changes to obtain a mean valley depth; in this case 257 ft (36,000/140 = 257.1).

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*Discussion follows that of Ref. 28.

This procedure yields a quantitative measure of terrain dimensions including mean slope (= mean ridge-to-valley spacing/mean valley depth). Areas of lowest mean slope constitute the areas of easiest contour flying.

The same methods are applicable to other problems associated with terrain contours such as laser target designation, weapon trajectory calculation, and visual range.

2-6 DESIGN

Terrain is very complex and therefore difficult to describe quantitatively. The advantages of being able to do so, however, have led researchers at the U. S. Army Tank-Automotive Command and the U. S. Army Engineer Waterways Experiment Station to make the attempt. The AMC '71 vehicle mobility model is an attempt to describe objectively the terrain, the inventory of Army vehicles, and their interactions (Ref. 29). By means of this model one should be able to predict speeds and performance of any Army vehicle in any kind of terrain, assuming that the independent variables of the model are adequately measured and accounted for. This undertaking is clearly ambitious and optimistic.

The terrain is described in terms similar to those outlined in par. 2-3. The present model is the first generation; new additions and modifications will be made continually.

The performance of a vehicle at any moment is the result of a complex interplay among many different characteristics of the vehicle, numerous features of the particular terrain in which it is operating, its immediate past operating history, and elections and constraints imposed by the driver. AMC '71 postulates that the maximum practical speed of a sound vehicle at any moment, including zero (or no-go) is the proper measure of its mobility at that time and place. Accordingly, each of the many system parameters potentially involved are quantified in engineering terms that permit calculation of probable vehicle speed as limited by one or more of a number of possible specific terrain-vehicle-driver interactions. Table 2-25 outlines system attributes considered in AMC '71 at this time.

The endless variability of real terrain can be represented by a mosaic of pieces, each of which, to some feasible resolution, can be considered uniform (deterministically or probabilistically) in terms of measurable factors affecting vehicle responses. Such a subclass of terrain is called a terrain unit. An areal terrain (see par. 2-3.4.2) unit is currently characterized by 13 measurements (in class intervals) reflecting the type and strength of surface materials, slope, prevailing ground roughness, discrete obstacles, and vegetation (Table 2-26, column *A*); a linear terrain unit by 9 measurements covering type and strength of surface materials, cross section, and water depth and velocity (Table 2-26, column *B*); and a road unit by 5 measurements expressing surface type, strength, slope, curvature, and roughness (Table 2-26, column *C*).

Maximum practical speeds for a vehicle in each areal, linear terrain, and road unit within an area, calculated from validated engineering relations, can be combined by suitable procedures to predict the performance of the vehicle along any given path in the real terrain, and/or to accumulate a statistical representation of vehicle performance in the area as a whole.

The basic structure of AMC '71 is illustrated in Fig. 2-81. Pertinent vehicle characteristics and complete data on all terrain units in an area are stored in computer files and assessed as needed by a central performance module. The performance module accepts descriptors for a single terrain unit and, after examination of a range of possibilities, provides the maximum possible vehicle speed for the terrain unit as well as an identification of the controlling relations. The entire terrain file for an area is iteratively examined, one unit at a time, until performance in each unit has been determined

TABLE 2-25

TERRAIN, VEHICLE, AND DRIVER ATTRIBUTES USED IN OFF- AND ON-ROAD PERFORMANCE PREDICTION MODELS (Ref. 29)

	Terrain or road	Vehicle	Driver
Off road	Surface material Type Strength Surface geometry Slope Discrete obstacles Roughness Vegetation Stem size and spacing Visibility Hydrologic geometry Stream cross section Water velocity and depth	Geometric Mechanical Inertial	Reaction time Recognition distance V-ride limit Vertical acceleration limit Horizontal acceleration limit
On road	Surface material Type Strength Surface geometry Slope Roughness Curvature	Mechanical Inertial	V-ride limit

TABLE 2-26

TERRAIN OR ROAD FACTORS USED IN PERFORMANCE PREDICTION MODELS (Ref. 29)

A. Areal terrain units		B. Linear terrain units		C. Road units	
Terrain factor	Measurement unit	Terrain factor	Measurement unit	Road factor	Measurement unit
Surface		Surface		Surface	
1. Type	NA	1. Type	NA	1. Type	NA
2. Strength	Cone index	2. Strength	Cone index	2. Strength	Cone index or CBR
3. Slope	Percent	Cross section		3. Slope	Degree
4. Surface roughness	Root mean square elevation, in.	3. Left approach angle	Degree	4. Curvature	Degree
Obstacle		4. Differential bank height or differential vertical magnitude	Meter	5. Roughness	Root mean square elevation, in.
5. Approach angle	Degree	5. Right approach angle	Degree		
6. Height	Centimeter	6. Low bank height or least vertical magnitude	Meter		
7. Base width	Centimeter	7. Base width or top width	Meter		
8. Length	Meter	Water			
9. Spacing	Meter	8. Depth	Meter		
10. Type	NA	9. Velocity	Meters/second		
Vegetation					
11 Stem diameter	Centimeter				
12. Stem spacing	Meter				
13. Visibility	Meter				

NA = not applicable

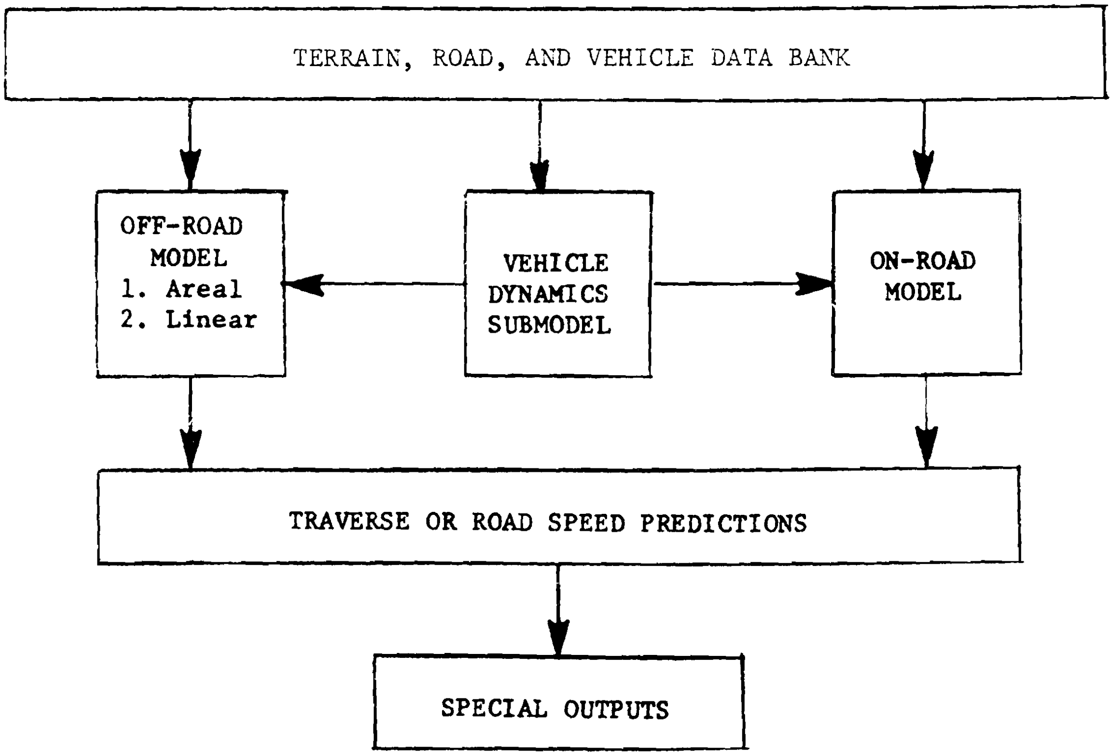

Figure 2-81. General Flow Diagram of AMC '71 Ground Mobility Model (Ref. 29)

and stored. At that point, answers in the temporary file are organized, suitably combined, analyzed, printed, and refiled by an output routine designed to meet the needs of the particular study.

The basic output of AMC '71 is vehicle speed in each of a series of areal terrain, linear terrain, and/or road units. The further processing of these speeds can develop performance predictions along specified paths, determine optimal paths between selected points under various constraints, and/or generate statistics concerning the performance of the vehicle in the terrain as a whole.

The central performance module, the heart of AMC '71, has three parallel forms: one to handle areal terrain, a second to examine linear terrain (rivers, streams, ditches, roads, etc.) offering identifiable linear barriers to vehicle crossing, and a third to predict performance on a network of roads. A given study may involve the use of one, two, or all three performance modules. The areal and linear modules together are identified as the off-road model, and the road module is identified as the on-road model.

A detailed structure of the areal terrain performance module is given in Ref. 29. In it, terrain and data files are assessed by each submodel as needed. In the areal terrain performance module, each terrain unit description is combined with the vehicle characterization to calculate a number of possible operating speeds as limited by power and power train characteristics; available traction; motion resistances engendered by soils, slopes, and overriding of obstacles and vegetation; local maneuvering to avoid vegetation and obstacles; ride and obstacle-crossing dynamics; visibility restrictions; and acceleration and braking performance. The logic of the model examines the least of these several speeds as influenced by obstacles and vegetation. Then it performs a speed analysis to decide how much to override and how much to avoid. From this it determines the maximum feasible vehicle speed within the described terrain unit. The module repeats the procedure three times for each terrain unit (where required), once with the vehicle running straight upslope, once running directly downslope, and once running along the slope contour. The average of these three speeds is assigned to the terrain unit as a whole. When upslope operations is "no-go", the other two are also taken to be "no-go". The areal terrain performance module is constructed with a submodel to assess a time penalty for "no-go" situations rather than to accept a zero speed with its implications of eternal immobility.

The composition of the linear terrain performance module is diagrammed in Fig. 2-82. The module is structured to account for fording (where possible), swimming (where possible) rafting or bridging (where necessary), ingress, and egress. Like the areal terrain performance module, the linear terrain performance module determines speeds (in terms of crossing times) and "no-go's" and assesses time penalties for "no-go's" in recognition of the fact that the Army will arrange the necessary engineer support in advance if it must get through.

The basic workings of the on-road performance model are displayed in Fig. 2-83. In its present form this model is essentially an off-road areal terrain performance module with no vegetation or obstacles, but with an added relation for limiting speed due to road curvature.

The areal, linear, and road speeds for a vehicle in a terrain (or road) unit are predicted for discrete patches of terrain. The principal means of interpreting these for an area is to examine the performance along specific or generalized routes, or traverses, through the area. Traverse predictions are made by adding traverse times across areal and linear terrain units.

2-7 TESTING AND SIMULATION

Because of the complexity and variety of natural terrain, laboratory testing of vehicles or other equipment that is dependent upon the terrain is always subject to the accuracy with which a given terrain is simulated. Reproducing natural terrain to every detail in a laboratory environment is a hopeless task; too many terrain variables cannot be incorporated into any practical experimental setup. Only small portions of the overall problem, such as soil samples, have been simulated. Soils of similar USCS or USDA classification generally exhibit similar shear strength properties. This fact implies that knowledge of the soil type according to one of these classification systems immediately yields valuable information insofar as trafficability is concerned. As always, moisture content is another important variable that must be accounted for in any model used to predict trafficability.

The most ambitious attempt to simulate terrain conditions in a mathematical model is that presently being carried out by the U S Army Tank-Automotive Command and the U S Army Engineer Waterways Experiment Station (Refs. 15,29). As discussed previously, this model has as a goal the complete description of the terrain-vehicle interaction. To carry this out meaningfully requires that both the terrain and the vehicle be adequately described in quantitative terms so that appropriate independent values of any given interaction can be assessed by the model. This model is not yet complete, but progress is encouraging.

In the meantime, tried and true methods of field evaluation continue to be employed in the evaluation of various vehicles in various types of terrain. Test sites have been chosen to span the wide spectrum of general terrain types found in nature:

(1) Puerto Rico – tropical rain forest, mountains, rugged terrain

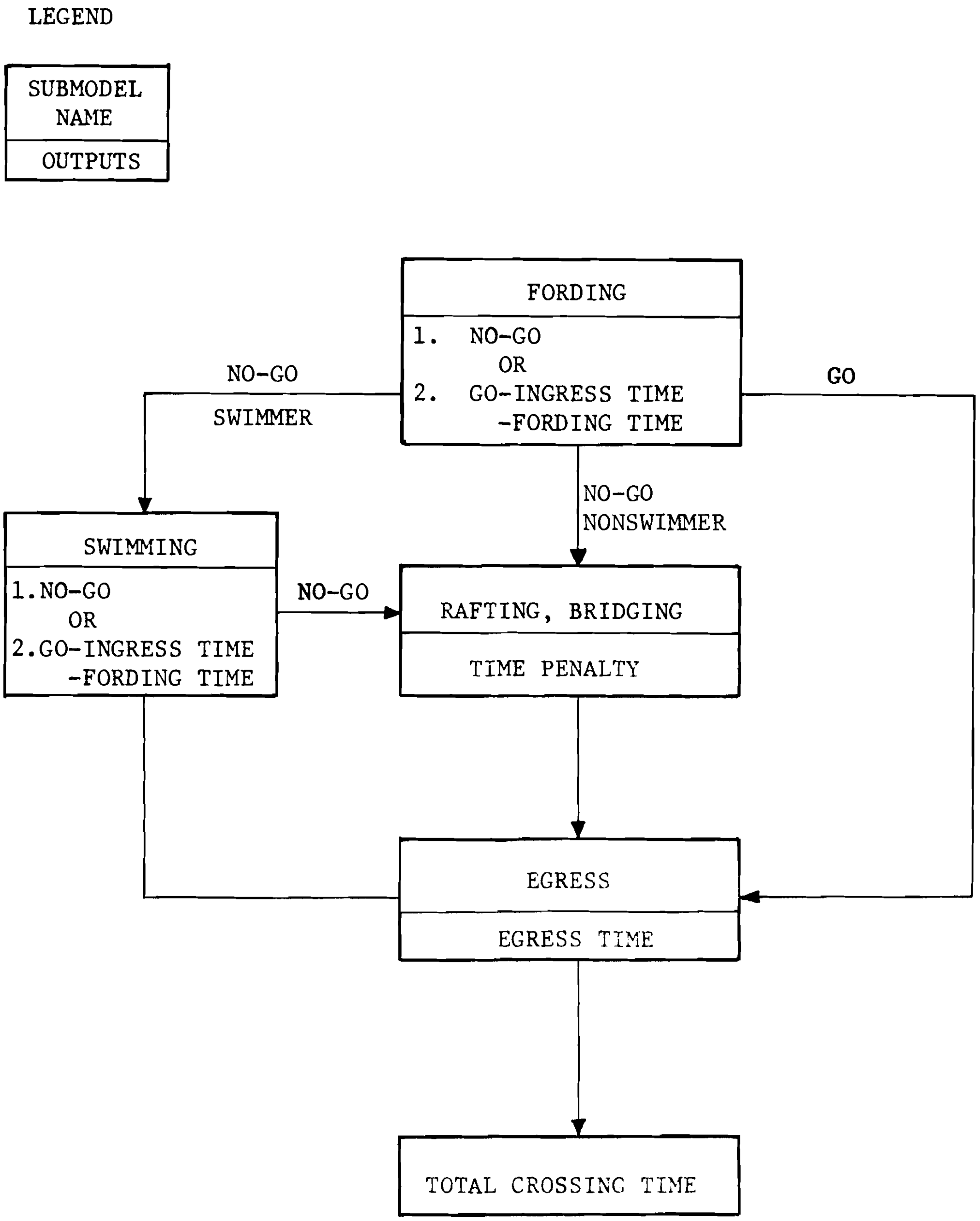

Figure 2-82. Schematic Flow Diagram of Linear Terrain Unit Performance Prediction Module (Ref. 29)

(2) Ft. Sill, Okla. – riverine investigations, containing a large assortment of bank angles and bank heights

(3) Yuma Proving Ground, Ariz. – desert area

(4) Thailand – tropical jungle area subject to large wet and dry seasonal variations

(5) West Germany – forested areas with little undergrowth

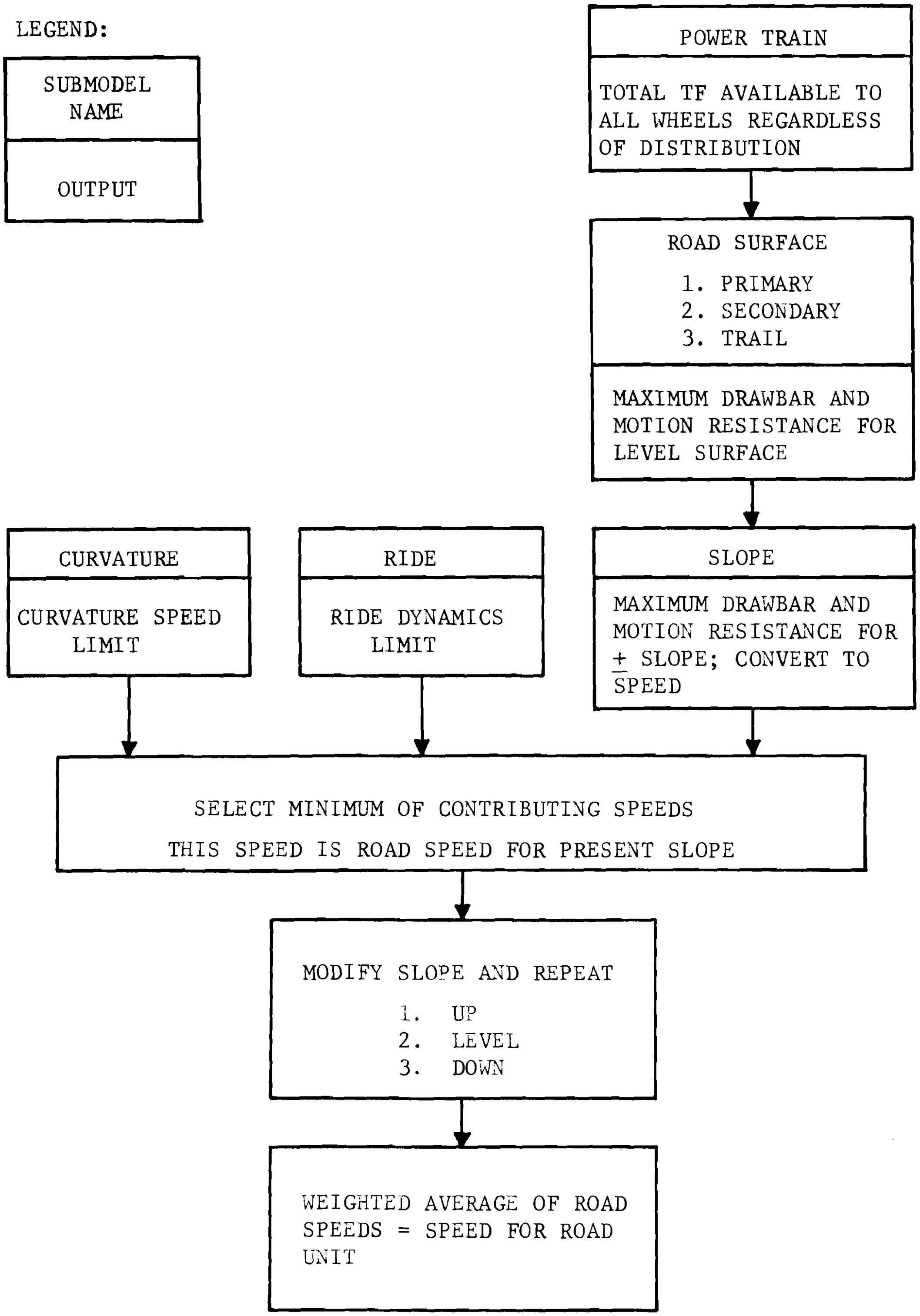

Figure 2-83. Schematic Flow Diagram of On-road Performance Prediction Model (Ref. 29)

(6) South Korea – mountainous testing under severe climatic conditions.

The major U S Army agencies involved in vehicle testing are the Waterways Experiment Station (WES), Vicksburg, Miss.; the Tank-Automotive Command (TACOM), Warren, Mich.; and the Cold Regions Research and Engineering Laboratory (CRREL), Hanover, N.H. This latter organization has field stations near Houghton, Mich., and Ft. Greely, Alaska.

This cross section of testing facilities and agencies covers the complete spectrum from cold weather to tropics, from wet to dry, from a desert inorganic soil to highly organic muskeg. Such testing programs are still the backbone of any vehicle evaluation program and are likely to remain so in the foreseeable future.

Contemporary vehicle research is divided among the major agencies of the Army as follows:

(1) U S Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, N. H. Historically, a major task of CRREL has been to study the trafficability of various vehicles across snow, ice, muskeg, and permafrost. This research has led to the study of pressure distribution of tracked vehicles on snow, shear forces of track grousers, and relationships between snow characteristics and track sinkage and slippage. The contemporary program consists of the development of a snow submodel to be compatible with the overall mobility model (AMC '71). Snow covered terrain is different from other terrains, and it can include a broad range of slopes, vegetation, and geometry. While certain terrains are worsened by snow cover, others are improved. Quantifying these snow-related parameters is imperative for adequate modeling. The appearance of the snow surface is not a satisfactory description of its physical characteristics, and a major task of CRREL is to develop an adequate model.

(2) U S Army Waterways Experiment Station, Vicksburg, Miss. The station has carried out extensive trafficability studies, soil stabilization studies, river research, and the development of artificial landing mats.

(3) U S Army Tank-Automotive Command (TACOM), Warren, Mich. Laboratories within this command have been active in the development of criteria for vehicle design and evaluation of techniques for vehicle performance under a wide variety of soil conditions. A key portion of vehicle terrain interaction is the river-vehicle interaction; methods of improving river-exiting and in-river maneuverability in deep water (swimming) are major programs of TACOM which are conducted by Stevens Institute of Technology under contract.

(4) U S Army Natick Laboratories, Natick, Mass. Methods for protecting military personnel and equipment in all global and regional environments are studied and developed in these laboratories.

In addition to these agencies, considerable mobility research is also conducted at the following organizations.

(1) The U S Department of Agriculture National Tillage Machinery Laboratory (NTML), Auburn, Ala. Most of the activity of NTML is concerned with the performance of tractors and tillage implements as related to farming. Significant studies in soil compaction, performance in soft soils, and soil cutting have been conducted here.

(2) The Davidson Laboratory of Stevens Institute of Technology, Hoboken, N. J. Activities in off-road mobility at Stevens Institute date back to World War II when Stevens was engaged in amphibious studies of the famous DUKW. In 1968 it was selected, by the Department of Defense THEMIS program, as a "center of excellence" in off-road mobility research. Today it is the only U. S. university engaged in significant nonagricultural mobility research.

(3) The Muskeg Research Institute, University of New Brunswick Fredericton, New Brunswick, Canada. The Muskeg Research Institute leads the field of studies of trafficability in the Far North.

2-8 SPECIFICATIONS AND STANDARDS

Specifications exist primarily for highway transportability criteria; very few specifications or standards are concerned primarily with terrain. Army Regulation (AR) 70 lists the criteria and tests for transportation of materiel by land, water, or air. Specifications for highway travel are complete and include highway weight limits of foreign countries among the other specifications.

Various ASTM standards describe in detail methods for evaluating soil properties similar to those discussed in par. 2-4. A list of the titles of relevant ASTM soil standards appears in Table 2-27. Complete copies of these standards are available from the American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pa. 19103.

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TABLE 2-27

ASTM STANDARDS FOR SOIL MEASUREMENTS (Ref. 30)

Category	Number	Title
Soils	D2325-11	Test for capillary-moisture relationships for soils (moisture tensions between 0.1 and 1 atmosphere)
	D425-11	Test for centrifuge moisture equivalent of soils
	D2488-11	Recommended practice for description of soils (visual-manual procedure)
	D2573-11	Field vane shear test in cohesive soil
	D2216-11	Laboratory determination of moisture content of soil
	D423-11	Test for liquid limit of soils
	D1558-11	Test for moisture-penetration resistance relations of fine-grained soils
	D2435-11	Test for one-dimensional consolidation properties of soils
	D2434-11	Test for permeability of granular soils
	D424-11	Test for plastic limit and plasticity index of soils
	D2844-11	Test for resistance R-value and expansion pressure of compacted soil
	D427-11	Test for shrinkage factors of soils
	D653-11	Definitions of terms and symbols relating to soil and rock mechanics
	D2487-11	Classification of soils for engineering purposes
	D2166-11	Tests for unconfined compressive strength of cohesive soil
	D2850-11	Test for unconsolidated, undrained strength of cohesive soils in triaxial compression

TABLE 2-27 (Continued)

ASTM STANDARDS FOR SOIL MEASUREMENTS (Ref. 30)

Category	Number	Title
Soils, bearing strength	D1194-11	Test for bearing capacity of soil for static load on spread footings
	D1883-11	Test for bearing ratio of laboratory-compacted soils
	D1143-11	Test for load-settlement relationship for individual vertical piles under static axial load
	D1196-11	Nonrepetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements
	D1195-11	Repetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements
Soils, compaction	D2168-11	Calibration of mechanical laboratory soil compactors
	D1632-11	Making and curing soil-cement compression and flexure test specimens in the laboratory
	D1557-11	Tests for moisture-density relations of soils, using 10-lb rammer and 18-in. drop
	D558-11	Tests for moisture-density relations of soil-cement mixtures
	D698-11	Tests for moisture-density relations of soils, using 5.5-lb rammer and 12-in. drop
	D2049-11	Test for relative density of cohesionless soils
	D915-11	Testing soil-bituminous mixtures
Soils, density	D2922-11	Determining the density of soil and soil-aggregate in place by nuclear methods (shallow depth)
	D1556-11	Test for density of soil in place by the sand-cone method

TABLE 2-27 (Continued)

ASTM STANDARDS FOR SOIL MEASUREMENTS (Ref. 30)

Category	Number	Title
Soils, density (continued)	D2937-11	Test for density of soil in place by the drive-cylinder method
	D2167-11	Test for density of soil in place by the rubber-balloon method
	D1557-11	Tests for moisture-density relations of soils, using 10-lb rammer and 18-in. drop
	D698-11	Tests for moisture-density relations of soils, using 5.5-lb rammer and 12-in. drop
	D2049-11	Test for relative density of cohesionless soils
Soils, particle size analysis	D1140-11	Test for amount of material in soils finer than the No. 200 sieve
	D421-11	Dry preparation of soil samples for particle-size analysis and determination of soil constants
	D2419-11	Test for sand equivalent value of soils and fine aggregate
	D2217-11	Wet preparation of soil samples for grain-size analysis and determination of soil constants
Soils, sampling	D2113-11	Diamond core drilling for site investigation
	D1586-11	Penetration test and split-barrel sampling of soils
	D1452-11	Soil investigation and sampling by auger borings
	D420-11	Recommended practice for investigating and sampling soils and rocks for engineering purposes
	D1587-11	Thin-walled tube sampling of soils
Soils, sieve analysis	D1140-11	Test for amount of material in soils finer than the No. 200 sieve
	D421-11	Dry preparation of soil samples for particle-size analysis and determination of soil constants

TABLE 2-27 (Continued)

ASTM STANDARDS FOR SOIL MEASUREMENTS (Ref. 30)

Category	Number	Title
	D422-11	Particle-size analysis of soils
	D2217-11	Wet preparation of soil samples for grain-size analysis and determination of soil constants
Soils, specific gravity	D427-11	Test for shrinkage factors of soils
	D854-11	Test for specific gravity of soils
Soils, static load	D1194-11	Test for bearing capacity of soil for static load on spread footings
	D1196-11	Nonrepetitive static plate load tests of soils and flexible pavement components for use in evaluation and design of airport and highway pavements
	D1195-11	Repetitive static plate load tests of soils and flexible pavement components for use in evaluation and design of airport and highway pavements

CHAPTER 3

TEMPERATURE*

3-1 INTRODUCTION AND DESCRIPTION**

Temperature is probably the most important environmental factor because of the nature of the stresses it creates and its pervasive influence on all activities. Throughout recorded history, the success or failure of military operations often has been determined by the ability of an army to remain viable in an extreme temperature environment. Modern military materiel must be capable of surviving wide extremes of temperature – the same materiel may be used in an arctic winter or in desert heat. This chapter provides information on temperature as an environmental factor with emphasis on its general characteristics, its measurement, a description of the temperature environment, the effects of temperature, design techniques useful in guarding against adverse effects, and, finally, testing and simulation techniques.

The definition of temperature can be elusive. Although physiological sensations of hotness and coldness are the most common, they are also the most inaccurate basis for defining temperature. Iron often feels colder or hotter than a piece of wood at the same temperature.

Temperature is more precisely defined as the relative hotness or coldness of a body as measured on the definite scale of any of several types of instruments. It can also be defined as the property of a system that determines whether the system is in thermal equilibrium with other systems.

The rigorous quantitative definition of temperature is based on general thermodynamic considerations. The absolute temperature scale is derived from an analysis of a Carnot (or other thermodynamic) cycle*. Absolute zero results when a Carnot or equivalent engine operating between two heat reservoirs rejects no heat to the reservoir at the lower temperature. The lower temperature is then defined as absolute zero while higher temperatures are defined such that the ratio of any two temperatures on the kelvin scale is the same as the ratio of the heats absorbed and rejected by a Carnot engine operating between reservoirs at these temperatures. As a consequence of this formulation, there is a theoretical lower limit to temperature but not an upper one.

Measurements made with practical instruments such as gas thermometers are proportional to the kelvin or absolute temperature scale. This property gives a physical basis for the use of practical instruments. Temperature is measured, therefore, by providing a reference body whose physical properties change in a known manner with temperature. This body is then called a thermometer and the numerical readings obtained on it against well-defined physical reference points establish the scale.

Since temperature is a relative measure indicating the capacity of a body to transfer

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*This chapter is based on a manuscript originally prepared by Dr. William B. Brierly, now at U S Army Engineer Topographical Laboratories, Ft. Belvoir, Va.

**General references for this paragraph are Refs. 1-3.

*A thermodynamic cycle is a recurring series of processes in which heat is imparted to or extracted from a system and in which energy is stored or given up by the system such that the system returns to its original state. A Carnot cycle is an ideal cycle consisting of two adiabatic and two isothermal processes, all of which are reversible. An engine operating in a Carnot cycle is called a Carnot engine and Carnot's theorem states that no engine can be more efficient than a Carnot engine.

TABLE 3-1

COMPARISON OF TEMPERATURE SCALES AT STANDARD AND FIXED POINTS (Ref. 1)

	Celsius	Fahrenheit	Kelvin	Rankine
Absolute zero	-273.15	-459.67	0.00	0.00
Oxygen point	-182.97	-297.35	90.18	162.32
Ice point	0.00	32.00	273.15	491.67
Triple point of water	0.0100	32.02	273.16	491.69
Steam point	100.00	212.00	373.15	671.67
Sulfur point	444.60	832.28	717.75	1291.95
Antimony point	630.5	1166.9	903.65	1626.57
Silver point	960.8	1761.5	1234.0	2221.2
Gold point	1063.0	1945.4	1336.5	2405.1

heat, some arbitrary scale of temperature must be defined. Practical temperature scales are based on fixed points. The fixed temperatures formerly used to define the scale were the steam point (100°C) and the ice point (0°C) of pure water under a standard atmospheric sea level pressure of 760 mm Hg. The temperature scale is now referenced to one primary standard fixed point, the triple point of water (273.16 K).

The fahrenheit scale referenced to the ice point (32°F) and the steam point (212°F) has long been the common temperature scale of English-speaking countries and much of the data on temperatures are given in this scale.

The most common and convenient temperature scale is the Celsius, more commonly known as centigrade. It divides the temperature interval between the ice and steam points into 100 degrees starting with 0°C at the ice point. The Celsius scale is used extensively in meteorological work, and the World Meteorological Organization (WMO) has officially adopted it for reports for international exchange (Ref. 4).

In the International System of Units, the unit of temperature is the kelvin, a unit that denotes a temperature interval equal to the centigrade degree, but is referenced to absolute zero (0 K) and the triple point of water (273.16 K). The kelvin scale is employed for most scientific, some meteorological, and fewer engineering uses.

On the absolute fahrenheit or rankine scale, the degree interval is the same as that of the fahrenheit scale. However, like the kelvin scale, it starts with a value of 0°R for absolute zero and has values of 491.7°R and 671.67°R for the freezing and boiling points of water, respectively. Both the rankine and kelvin scales are positive-valued scales.

A comparison of standard and fixed temperatures on these four temperature scales is given in Table 3-1 while conversion formulas are given in Table 3-2.

Temperature is one of the four primary quantities – along with length, mass, and time – that form the basis of our physical measuring system. Each of these quantities has its own basic unit, each of which is referenced in an independent, arbitrary standard. Units for all other physical quanti-

TABLE 3-2

TEMPERATURE CONVERSION FORMULAS* (ALL ENTRIES IN SAME ROW ARE EQUAL)

T_C	$\frac{5}{9}(T_F - 32)$	$T_K - 273.15$	$\frac{5}{9}(T_R - 491.67)$
$\frac{9}{5}T_C + 32$	T_F	$\frac{9}{5}(T_K - 273.15) + 32$	$T_R - 459.67$
$T_C + 273.15$	$\frac{5}{9}(T_F - 32) + 273.15$	T_K	$\frac{5}{9}(T_R - 491.67) + 273.15$
$\frac{9}{5}T_C + 491.67$	$T_F + 459.67$	$\frac{9}{5}(T_K - 273.15) + 491.67$	T_R

*T_C = temperature expressed in degrees centigrade (Celsius);
T_F = degrees fahrenheit; T_K = kelvin; T_R = degrees rankine

TABLE 3-3

MATERIAL PARAMETERS THAT GENERALLY INCREASE WITH INCREASING TEMPERATURE

Gas volume at constant pressure $(\propto T)$
Gas pressure at constant volume $(\propto T)$
Velocity of sound in gas
Velocities of particles in gases $(\propto T^{1/2})$
Thermal conductivity of ideal gas
Electrical conductivity of gas
Emission of electromagnetic energy
Volume of liquids and solids
Vapor pressure of liquid
Diffusion of one material in another
Electrical resistivity of metals
Electrical conductivity of semiconductors
Voltage of thermoelectric junction
Thermionic emission of electrons
Ductility of a solid
Rate of chemical reaction

ties are derived from these four basic quantities, and the measurement of all derived quantities is dependent directly or indirectly on the basic quantities. Redefinitions of standards have not affected the measurement of temperature.

Temperature is an intensive quantity in that it is not additive when different masses of equal temperature are joined. Thus, if two bodies having the same temperature are combined, the mass and dimensions of the new body will be different from those of either part, but its temperature will remain that of the original bodies.

Temperature changes reflect the infusion or diffusion of heat or other forms of energy to or from matter. When energy exchanges are large enough, they have distinct effects on the substances themselves. Some of the more significant effects that relate to gases, liquids, and solids – apart from change of phase – are given in Table 3-3.

The molecular motion within a system is larger at higher temperatures than at lower temperatures. As temperature increases this increased molecular activity can result in expansion of the substance, a change in state (e.g., liquid to gas), or a variety of other changes. The molecular motion is one part of the internal energy of the system. Some of the specific temperature points associated with distinct changes in substances are given in Table 3-4.

Heat, often confused with temperature, is the name for energy being transferred between systems by virtue of a difference in temperature. Heat is frequently thought of as any kind of thermal energy, i.e., energy

TABLE 3-4

TEMPERATURE THRESHOLD PNENOMENA

Solidification	Melting point
Vaporization	Boiling point
Loss of magnetization of a solid	Curie temperature
Loss of polarization in a ferroelectric material	Curie temperature
Onset of superconductivity	Superconducting transition temperature
Volume of liquid equals volume of vapor	Critical temperature
Triple point	Temperature (and pressure) at which all phases of a substance coexist

associated with temperature, but in a strict technical sense, heat exists only in energy transmission because of a temperature gradient. Hence, it cannot exist without thermal disequilibrium. When a temperature difference exists, heat transfers in the direction of the lower temperature by means of three processes – conduction, convection, and radiation.

Temperature is associated with all phenomena involving the transfer of energy, whether of natural or induced origin. The extreme values associated with these energy transfers cover an enormous range. In the natural environment, temperature varies from near absolute zero in deep space to the millions of degrees associated with stellar interiors, super-novae, and galactic collisions. Induced (i.e., manmade) temperatures range from the cryogenic temperatures near absolute zero to the extremely high temperatures associated with thermonuclear reactions.

Only a relatively narrow range of these possible temperatures is of practical concern in the design of current military materiel. This practical range may extend from –75° to 200°C (from below the lowest natural temperatures to the upper extreme for materiel exposure in a confined space in which much energy is dissipated). Higher temperatures are found in engines, heaters, weapons, ovens, and in other equipment, but these are usually confined – so that only such materiel as is intended, e.g., piston, breeches, and gun tubes, are exposed to these high temperatures. Problems involving extreme temperatures do impinge upon many areas of current technology, and considerable work has been done in them – from the cryogenic design ranges involved in space launch vehicles and superconducting magnets to the extremely high temperatures encountered in lasers, plasma, and nuclear detonations.

A high temperature materiel environment manifests itself in the degradation of materials and ultimately in the failure of equipment. Failure modes range from loss of structural integrity to catastrophic failures resulting from phase changes. For example, materials such as greases, protective compounds, waxes, and sealing and insulating substances can soften and flow at elevated temperatures. These heat effects can be classified into four main groups – thermodynamic, electromagnetic, radiational, and chemical kinetic; they are discussed in detail in subsequent paragraphs.

While degradation processes in materiel are slower at cold temperatures, several problems are associated with cold temperatures that are of equal importance to those at elevated temperatures. Oils and greases become more viscous, rubbers and plastics are embrittled, the properties of metals change, water freezes, and other changes take place.

Each type of effect brings with it a characteristic set of design problems. Familiarity with them is essential if design difficulties attributable to temperature are to be avoided.

The main emphasis of this chapter is on temperature as a meteorological environmental factor, since all military materiel is subject to exposure to the full range of natural temperatures. The importance of military capabilities for operation in the extreme cold regions as well as in the hot-dry and hot-wet regions of the earth has been recognized and accepted. The impact of induced temperatures on the serviceability, maintainability, and reliability of Army equipment is, however, just as important as that of the natural temperatures. Problems in this area derive mainly from the high temperatures to which materials are exposed in the operation of equipment, plus accompanying heat buildups and the necessity for enduring or reducing the high temperatures.

Temperature is a primary factor of weather. Air temperatures exhibit wide variability because of the irregular distribution of insolation* and the variations in the natural processes of thermal energy exchange. These

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*Insolation is the solar radiation received by the earth (Ref. 5).

variations are sufficient to create a wide range of thermal environments in which military operations are necessary.

Ambient air temperature, as used in this chapter, refers to the temperature observed at weather stations – known as surface air temperature or standard instrument shelter temperature. These are obtained in weather shelters or screens and are known also as shade air temperatures. Air temperature measurement in direct sunlight is difficult because of the effect of direct solar energy absorption in the body of the thermometer. Soil, water, forest, permafrost, and ice temperatures are also briefly considered.

Temperature is closely related to other environmental factors either through synergisms in effects or by correlated variations. Thus Chap. 8, "Solid Precipitation", Chap. 4, "Humidity", and Chap. 2, "Terrain", are all associated with temperature; temperature determines the nature of the sand and dust problem discussed in Chap. 3 of Part Three, *Induced Environmental Factors.* The other natural environmental factors as well as some of the induced environment factors show strong temperature dependencies.

3-2 NATURAL TEMPERATURE ENVIRONMENT

The natural temperature environment of the earth ranges from –88° to 58°C (–127° to 136°F), a span of 146 Celsius degrees (263 fahrenheit degrees). This full range does not occur at any one point – an excursion of greater than 100 deg C (180 deg F) is experienced at some locations. It is impractical to attempt to design materiel for this full range because of the cost penalties involved and basic ambiguities in the requirements. One cannot provide liquid water at subfreezing temperatures, fresh food that will remain unspoiled at temperatures over 100°F, a single lubricant for the full range of temperatures, or clothing equally suitable over the entire temperature span. Instead, an operational capability is obtained by combining materiel selection and design with protective measures while at the same time modifying operational practices to adapt to the temperature environment. In any case, the design engineer must be aware of the factors influencing natural temperatures – the diurnal and seasonal cycles, and the influences of topography, meteorology, and flora. Data on mean and extreme temperatures also must be available in order to ascertain the life cycle temperature experience to be expected for various materiel types.

Detailed consideration of the various thermal processes would require a lengthy treatise. The heat balance of the water surface, bare soil, plant-covered ground, forest, snow cover, and varied topography are separate, complex problems in microclimatology and micrometeorology. Reference must be made to Geiger (Ref. 6) or similar comprehensive texts (Ref. 7) on climate near the ground for this information. Only a few of the more general and more pertinent of these subjects can be covered in the paragraphs that follow.

3-2.1 TERRESTRIAL TEMPERATURE CONTROLS*

In any specific geographic location, the temperature can vary widely. It is dependent on the level of insolation as determined by time of day, season, and meteorological conditions, by the nature of the terrain and its elevation, by vegetation, by proximity to large bodies of water, and by prior temperature history. These factors determine the instantaneous temperature and thus the periodic temperature cycle experienced at that location. The general features of the seasonal temperature cycles are accurately predictable from past history. The specific temperature at any time can be less accurately predicted but, with satellite meteorology and numerical techniques, this short-range predictability is improving rapidly.

The influences of insolation, altitude, meteorology, and surface characteristics on temperature will be considered in order.

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*General references to this discussion are *The Climate Near the Ground* by R. Geiger (Ref. 6) and *An Introduction to Weather and Climate* by G. T. Trewartha (Ref. 7).

3-2.1.1 INSOLATION*

The sun is the primary source of energy of the earth. It has a brightness temperature of approximately 6,000 K and radiates energy at a rate of about 64,500 kW m^{-2} from its surface. Of this energy, about 1.395 kW m^{-2} reaches the upper layers of the atmosphere of the earth. Of the incident energy, 35 percent is reflected back into space by cloud surfaces, 19 percent is absorbed by the atmosphere, and 46 percent reaches the surface of the earth.

If it is assumed that the earth is in dynamic equilibrium with the sun, then the earth radiates at a rate equal to that of the incident energy. From this a maximum surface temperature can be calculated using the radiation law for a blackbody

$$R = \sigma T^4, \text{ W m}^{-2} \tag{3-1}$$

where

R = radiancy, W m^{-2}

σ = universal radiation constant 5.685 × 10^{-8} W m^{-2} K^{-4}

T = temperature, K

This calculation gives

$$T = \left(\frac{0.46 \times 1.395 \text{ kW m}^{-2}}{5.685 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}}\right)^{1/4} = 326 \text{ K} \tag{3-2}$$

This is less than the maximum terrestrial temperature observed, 331 K, because the earth is not a blackbody and heat is supplied by the core of the earth.

Similarly, the mean temperature of the surface of the earth can be found by equating the total energy intercepted by the earth and its atmosphere (0.65 $\pi r^2 S$ where r is the radius of the earth and S is the solar constant, 1.395 kW m^{-2}) to the total radiated energy ($4\pi r^2 \sigma T^4$);

$$T = \left(\frac{0.65\, S}{4\sigma}\right)^{1/4} = 251 \text{ K} \tag{3-3}$$

This calculated mean temperature is less than the 287 K observed because of the hot core and mantle of the earth and because the earth is not a blackbody.

The mean temperature of the earth, averaged over periods of years, shows little systematic change even though the solar constant varies with sunspot activity and with periodic changes in the earth-sun distance.

The insolation level and thus the temperature of the surface of the earth does vary considerably at any particular point. It is dependent on the angle of incidence of the rays of the sun on the surface, which varies with the time of day, season, and latitude as well as with meteorological conditions. At noon the insolation level is a maximum while at night it is zero. At the time of the spring and fall equinoxes, the isolation level at the equator is a maximum while at the poles it is zero. In the Northern Hemisphere, the maximum insolation level is at the summer solstice; minimum at the winter solstice. The variations in temperature induced by these cyclic changes in insolation would be much greater were it not for the considerable transport of thermal energy by atmospheric and oceanic currents. Fig. 3-1 shows the general insolation cycle for the earth as measured at the top of the atmosphere.

It is noted that, in Fig. 3-1, solar radiation is given in units of cal cm^{-2} min^{-1}. This may be converted to the international unit for power density using 6.97 × 10^{-2} W = 1 cal min^{-1}.

The diurnal temperature cycles can be considerably weakened by cloudy skies and are less pronounced in the tropical and polar regions. Typically, the air temperature increases from sunrise to midafternoon since the incoming solar radiation is greater than the energy being reradiated by the earth. In midafternoon this balance changes, terrestrial radiation exceeds solar radiation, and the temperature begins to drop. Several examples

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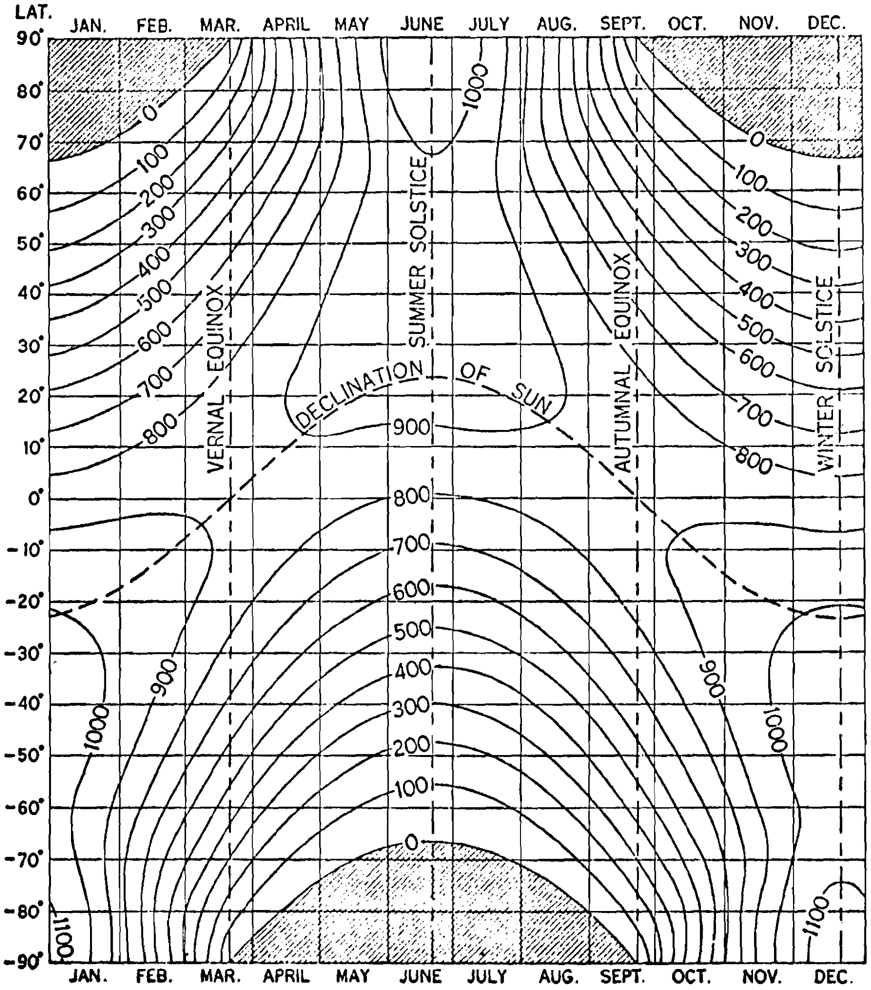
*For a more comprehensive discussion of insolation, see Chap. 6, "Solar Radiation", of this handbook. A general reference for this paragraph is Ref. 1.



$$1 \text{ cal min}^{-1} = 6.97 \times 10^{-2} \text{ W}$$

Figure 3-1. Chart of the Total Daily Solar Radiation at the Top of the Atmosphere (The solid curves represent total daily solar radiation on a horizontal surface at the top of the atmosphere, measured in cal cm^{-2} day^{-1}. Shaded areas represent regions of continuous darkness.) (Ref. 8)

of diurnal temperature cycles are shown in Fig. 3-2. The midafternoon surface temperature maximum lags the maximum level of solar radiation by 2 to 3 hr.

Insolation is absorbed in the upper several inches of soil and the diurnal cycle is barely detectable 1 m below the surface. In the surface layer, however, the effect of solar radiation is to raise the soil temperature to a level above that of the air. Typical diurnal cycles for surface soil are compared with those for the adjacent air in Fig. 3-3 with the drier soil showing a larger amplitude for the cycle. Seasonal changes in temperature are detectable as much as 15 m below the soil surface. An example of the annual soil temperature cycle is shown in Fig. 3-4.

Since water is relatively transparent to the rays of the sun, the deposited insolation is distributed through a much larger volume. About one-tenth of the insolation reaches a depth of 30 ft. Daily temperature changes are

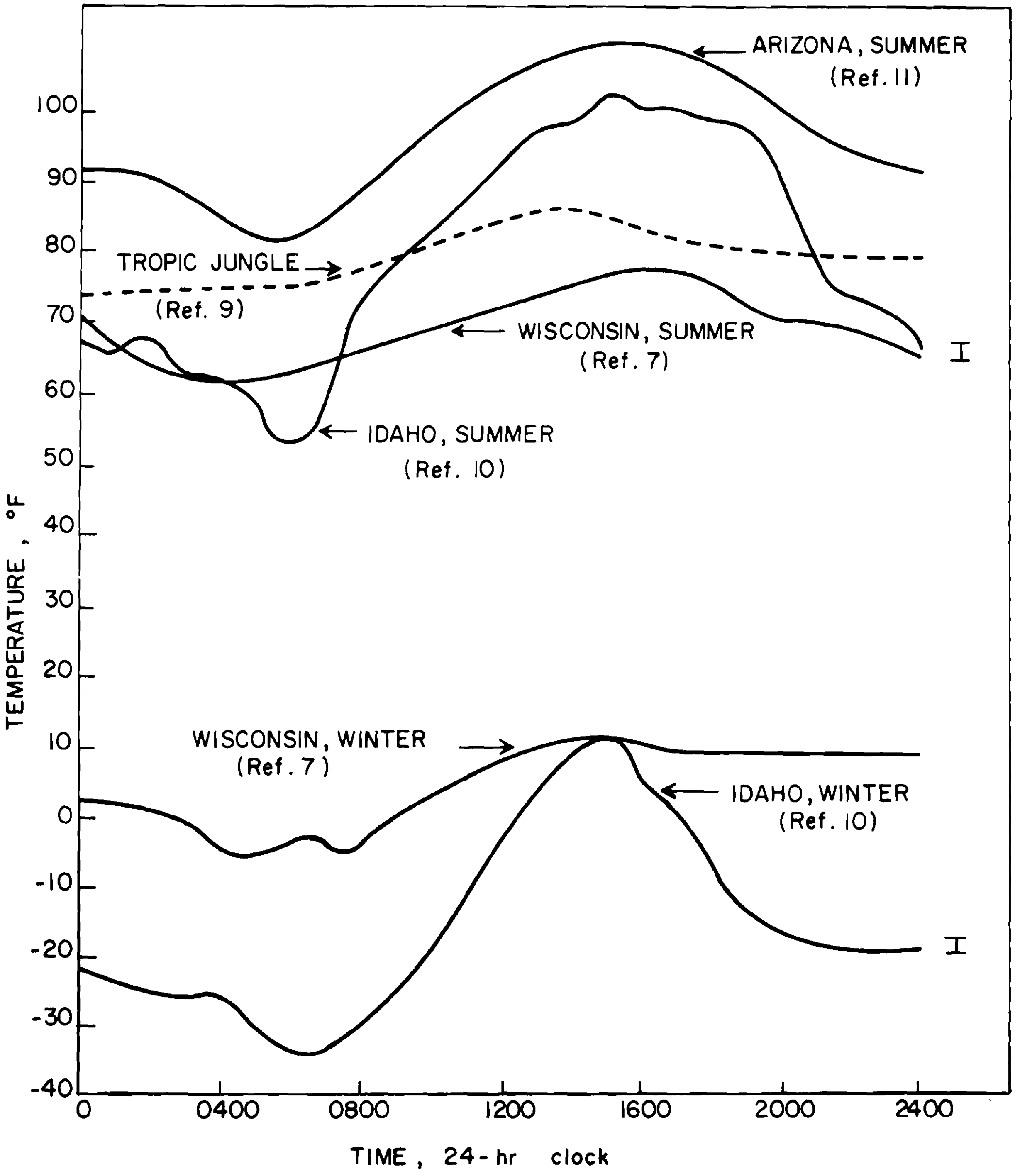


Figure 3-2. Diurnal Temperature Cycles

observable at least 20 ft below the surface. Because of circulation and convection in water, the annual temperature effects extend to depths of from 600 to 2,000 ft, dependent on the nature of the water body and its geographic location. When water is either heated or cooled, a much larger mass is thereby affected and the temperature changes are much slower.

The atmospheric temperature cycles that result from the variations in insolation depend

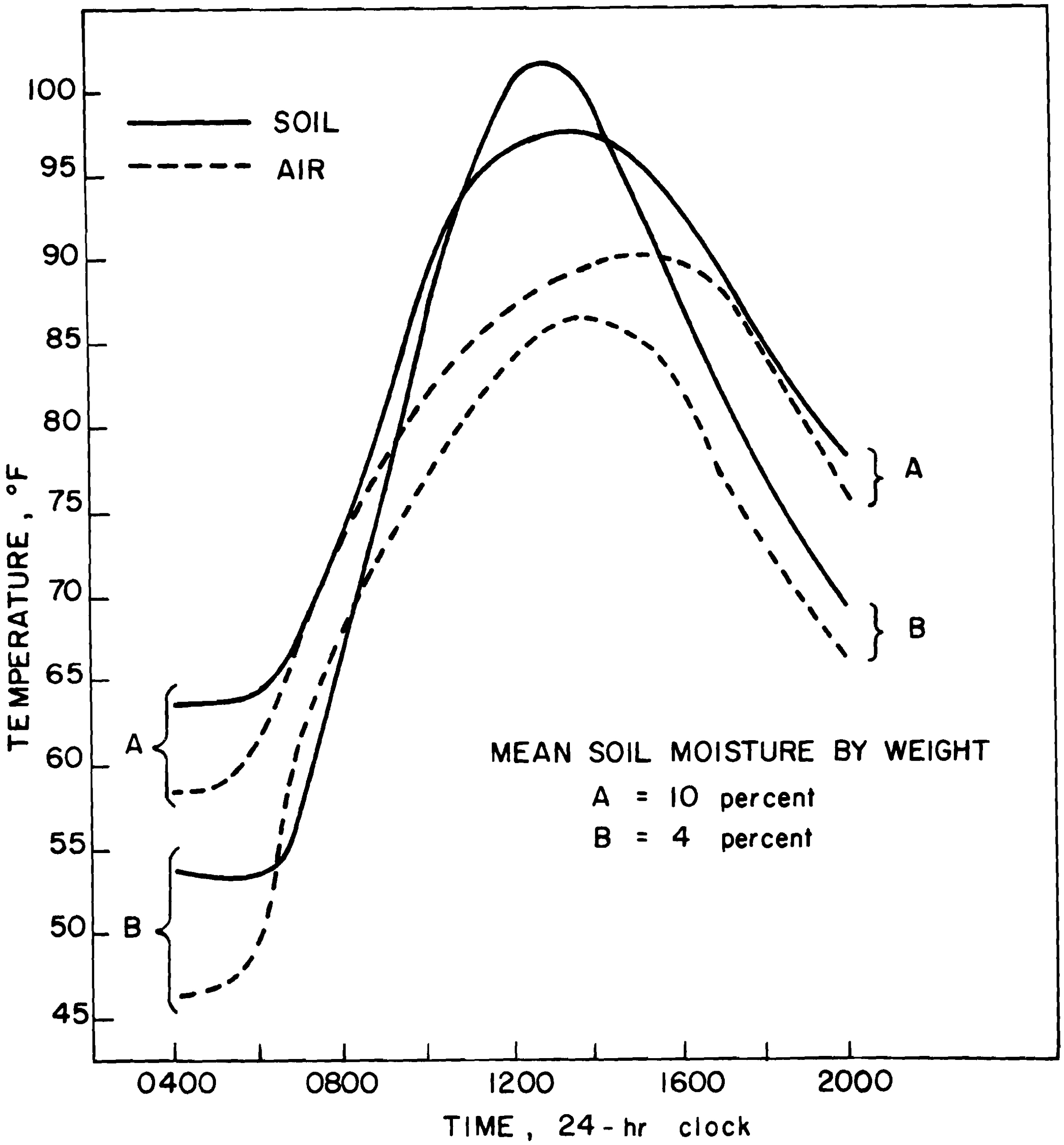


Figure 3-3. Diurnal Variation of Air and Soil Temperatures (Ref. 12)

on the processes by which the surface soil and water are heated and on the disposition of the thermal energy. Where the heat capacity, thermal conductivity, and convection are small, the energy is reradiated into the atmosphere but at a wavelength (6.8 to 100 μm) that is much longer than that of the incoming solar radiation (0.3 to 2.2 μm). At these longer wavelengths, 75 to 80 percent of the energy is absorbed by the atmosphere and the temperature is raised. As noted earlier, this process has an associated time lag because of the heat capacity of the earth and air. Maximum temperatures are thus attained first in the surface soil or water, then in the adjacent air, and subsequently at higher altitudes.

The annual temperature cycle depends on insolation in much the same way as the

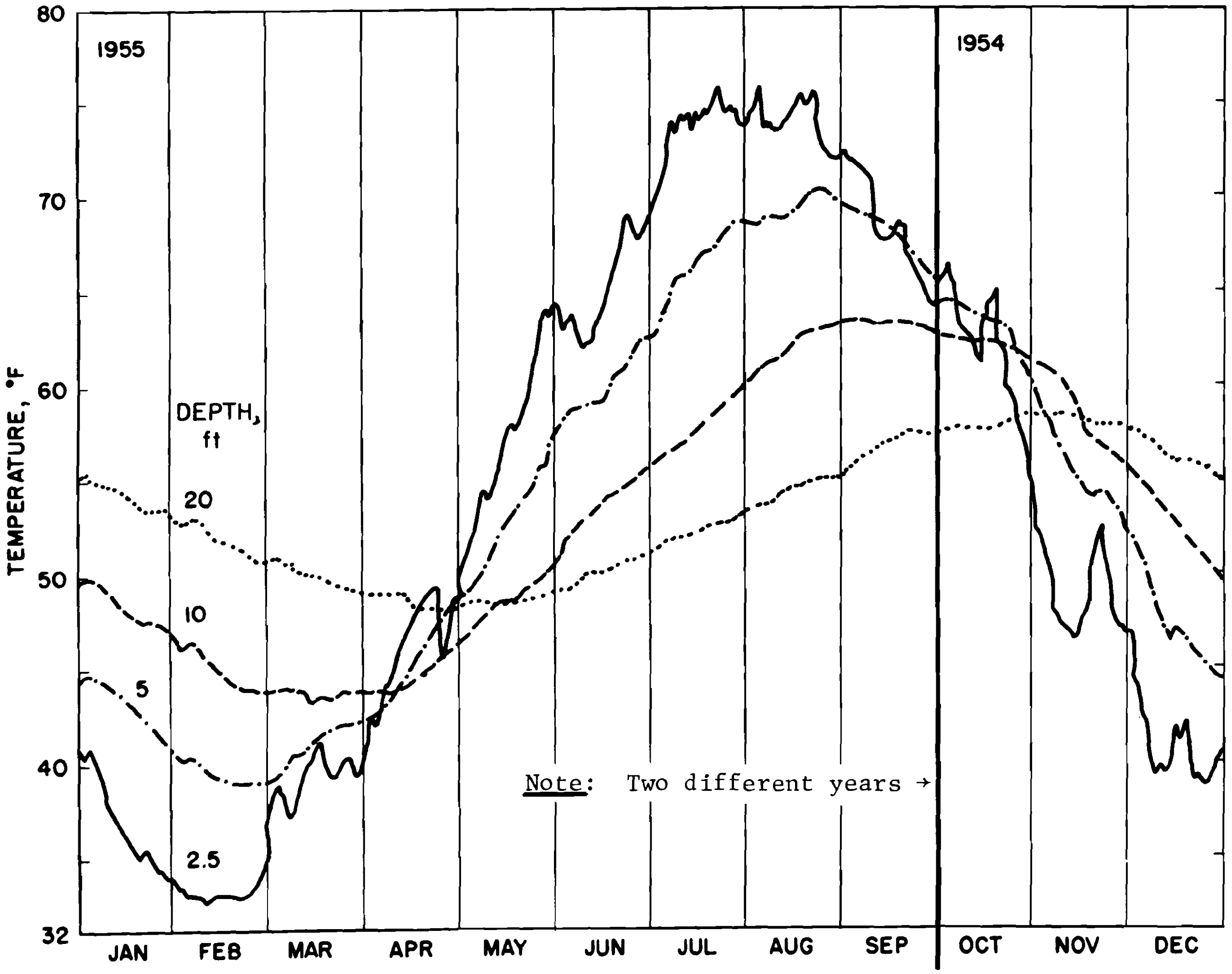


Figure 3-4. Annual Cycle of Soil Temperatures (Ref. 12)

diurnal cycle. It is, however, described in terms of mean monthly temperatures, with the temperature minimum and maximum occurring in January and July, respectively. The temperature lag, in this case the time between the maximum (or minimum) insolation occurring at the solstice and the maximum (or minimum) air temperature, is about 24 days for continental regions. This lag results from the heat capacity of the land and airmass, which is either being heated by a net excess of insolation over the terrestrial radiation or being cooled by a deficit. In oceanic regions, the temperature lag is longer, typically 55 days. In the eastern Pacific and eastern Atlantic between the Equator and Tropic of Capricorn, the temperature lag can be over 100 days. In coastal regions, the lag is intermediate, being generally greater on the western margins of continents. The smallest lag reported is 10 days in South Africa while a number of other continental areas have reported extreme mean temperatures occurring within fewer than 25 days following the solstice.

Some typical annual temperature cycles are illustrated in Fig. 3-5. The lag is readily evident as is the small span of the tropical climate. This small span results from the relatively small variability in seasonal insolation as well as the larger heat reservoir associated with surface and atmospheric moisture in the tropical region.

3-2.1.2 SURFACE TEMPERATURE CONTROLS

The nature of the surface of the earth is an important factor in determining the percentage of the incident solar radiation that is absorbed and thus the surface air temperature. Thus, while both insolation and the differences between land and water determine the general temperature level and the diurnal and annual cycles, the particular temperature observed at any point is influenced greatly by local surface types. Snow and ice surfaces such as are found in the Antarctic, Greenland, and the Arctic Ocean generally reflect more than 75 percent of the incident radiation—sometimes more than 90 percent. Dark, plowed fields absorb close to 100 percent of the incident radiation but, on the average, land areas absorb 85 to 90 percent. Some of the incident energy is used in evaporating water from the surface, whether it is land or a water body.

Over water, approximately 60 percent of the incident radiation is absorbed and subsequently used for evaporation of water or reradiated into the atmosphere. Since the specific heat of water is from two to five times that of soil and circulation results in a large mass being heated, much more thermal energy is required to raise the temperature of a water body. Thus, a water surface and the air over it will not be warmed as rapidly as a land surface. Marine climates, therefore, have smaller ranges of temperature than continental climates.

Moist air in the humid tropics absorbs long wavelength radiation during the day so that the surface of the earth is required to give up less at night; the same moist air prevents the heat of the surface from being transmitted into space and being lost. The daily ranges of temperature, therefore, are small compared to those of the temperate zones with drier air. In arid climates, the dry air transmits more solar radiation; the surface of the earth is heated more during the day; and at night the longwave terrestrial radiation is again readily transmitted by the dry air. The daily ranges of temperature are, therefore, large. In summary, the average annual ranges of temperature are smallest in low latitudes and over oceans, and largest over continents in the middle and higher latitudes.

A snow cover results in more pronounced cooling of the atmosphere. Not only is the daily insolation in a region with a snow cover smaller than in other regions of the earth but also much more of it is reflected. At night, the snow, being a poor thermal conductor, allows little ground heat to come to the surface to replenish that lost by radiation. As a result, the snow surface and the air above can become very cold.

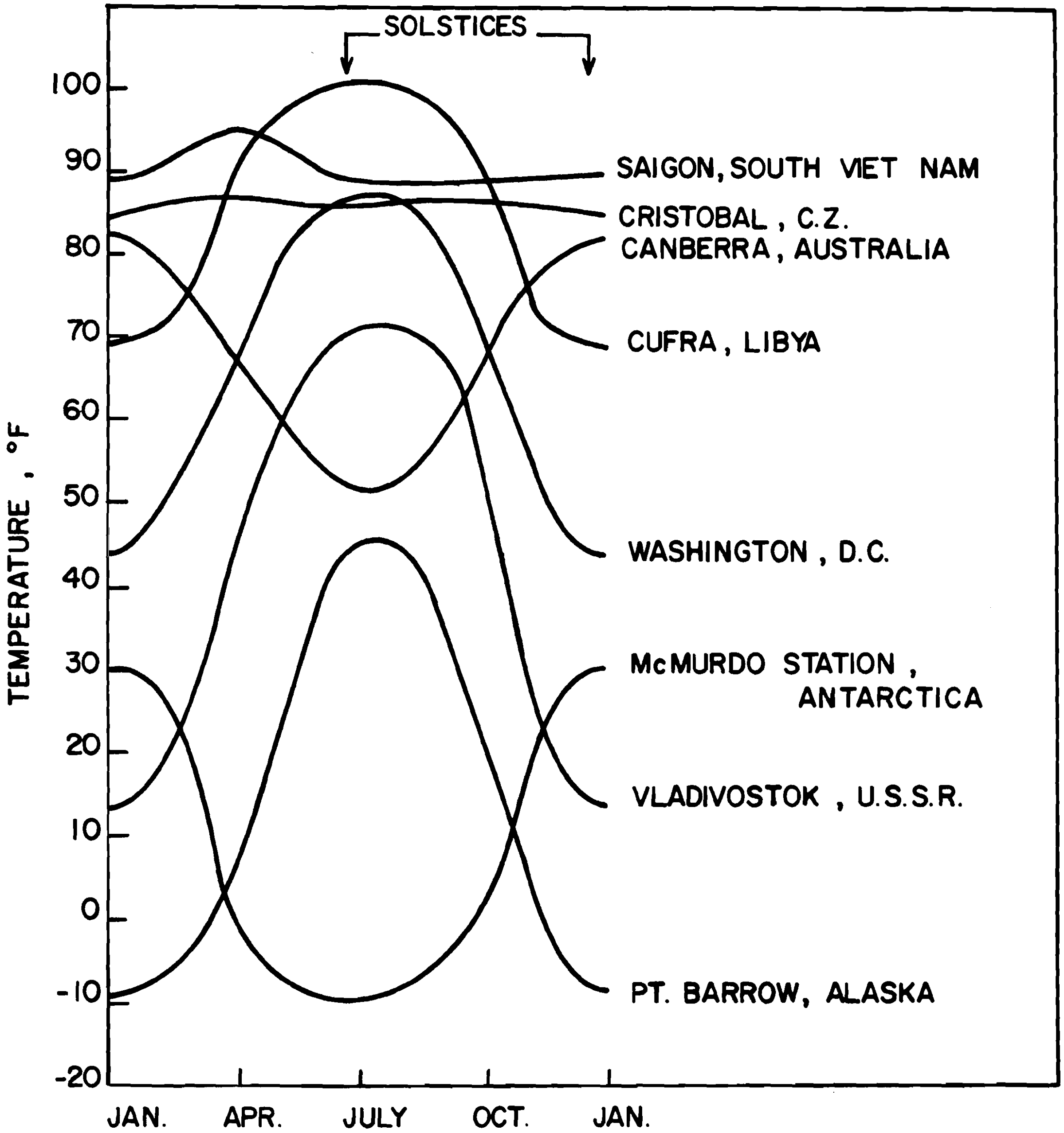


Figure 3-5. Average Daily Maximum Temperatures (Ref. 13)

3-2.1.2.1 FOREST TEMPERATURES*

Vegetation has a large effect on temperature, particularly in a forest where the trees prevent much of the insolation from reaching the surface and heating the soil. This effect is sufficient to define a somewhat different temperature regime in a forested area and, therefore, to warrant special attention. In the free air above the forest canopy, temperatures are much the same as over open ground, with the tree tops taking the place of the ground surface. The temperatures of leaves are often 5.5 deg C (10 deg F) warmer than the surrounding air; dry leaves can be even warmer. The canopy and the air above it undergo a diurnal variation with a maximum in the afternoon and a minimum before sunrise. Lapse conditions develop in the sun-

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*General references for this paragraph are Refs. 14 and 15.

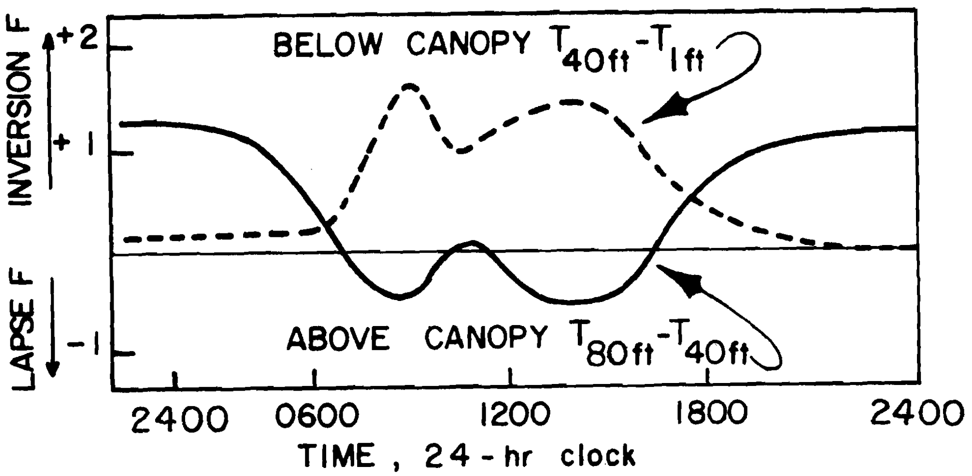

Figure 3-6. Temperature Differences in Jungle Between Air Above and in Canopy, and Between Air in Canopy and Near Ground (Ref. 14)

shine above the canopy and inversion conditions develop on clear nights as they do over open ground.

If the forest canopy is dense and if there is little or no direct exposure to sun or sky, the surface temperature of the ground and lower vegetation undergoes a smaller diurnal range than that experienced on the surface of the canopy. A temperature difference of 2.8 deg C (5 deg F) has been found between open spaces in the jungle of a tropical island and the forested areas. In the Withlacoochee drainage area woods southwest of Ocala, Fla., during May and June, the average daily range in ground surface temperature on clear days was only 8.9 deg C (16 deg F) while the temperature range in a nearly grass-covered open area was 22.2 deg C (40 deg F). A difference of only 1.1 deg C (2 deg F) was observed between the ground temperature in a well-shaded forest area and the adjacent air.

The air is usually cooler than the ground surface at night and warmer in the middle of the day. Under a heavy forest canopy, lapses develop at night and inversions develop during the day. In open areas the opposite occurs, with inversions usually developing at night and lapses in the day. Fig. 3-6 shows temperature differences in a jungle on a small tropical island. $T_{80ft} - T_{40ft}$ is the temperature of the free air well above the tree crown minus that of the air in the crown. $T_{40ft} - T_{1ft}$ is the temperature of the air in the crown minus that of the air near the gound. Position differences indicate inversions. Single measurements of temperature profiles in forested areas should be accepted with caution when used for equipment design or operational purposes because there are rapid changes in temperature due to vertical and horizontal motions of air brought about by differential heating and cooling. Changes from inversion to lapse can occur within a few minutes at the canopy interface.

Leaves at the top of the canopy, depending on their position with relation to the rays of the sun, are heated to temperatures higher than that of the surrounding air. The leaves in turn warm the adjoining air. Inside and under the canopy, fewer leaves are exposed to the rays of the sun so that, depending on the density of the understory, hot spots develop that decrease in number from the canopy to the ground surface and result in convective turbulence. Consequently, even though inversions occur under a heavy canopy in the daytime, the air is not necessarily stable. Similarly, on clear nights leaves at the top of the canopy radiate freely to the sky, become cooler, and cool the surrounding air. At lower stories fewer leaves are exposed; thus, the air is warmer than that in the canopy and the temperature distribution is that of a lapse. This generalization of forest temperatures will vary with the type, density, and climatic regime of the area. For less dense forests, lapses by day and inversions by night may be expected as in open areas. If the sun is able to penetrate to the forest floor only during midday, the temperature will show a lapse near the ground at midday but an inversion in the morning and afternoon. These aspects of forest instability show that care must be exercised in using forest temperature data for design purposes.

Temperature profiles inside a heavy, low-canopy jungle showed the same relationship as in high-canopy jungle except that effects are concentrated over a much smaller height interval. These seem to be intensified by extremely heavy cover, producing, in effect, a second ground surface at the top of the jungle in tropical areas. Where a 1 deg C (1.8 deg F) lapse or inversion may occur over a 10-m deep layer over a high canopy, the same temperature difference is possible in only 1 m over a low canopy because of compactness.

3-2.1.2.2 SOIL TEMPERATURES*

The soil surface, with its plant cover, plays a vital role in the heat and water budgets of the atmosphere by absorbing, reflecting, and otherwise converting the solar energy incident on it. This absorbed energy is used to heat the air above and the soil below and to evaporate water. The amount of insolation reflected back towards space and the partition of energy between the air and soil depend to a considerable degree on the thermal characteristics of the soil and its cover—reflectivity, conductivity, specific heat, and moisture content. The atmosphere is heated by the sun primarily by way of the surface of the earth. Therefore, any investigation of the heat economy of the atmosphere must consider the thermal properties of the underlying medium as well as those of the air.

During the day the surface of the soil is heated by solar radiation to a temperature much higher than that of the air above or the soil below. Consequently, the heat energy not used to change the phase of water in the soil is conducted away from the surface into both the air and deeper soil layers. The amount of heat energy absorbed at the surface of the earth depends on the intensity and duration of solar insolation and the reflectivity of the surface. Since air is a poor conductor of heat, appreciable conduction occurs only in the very lowest layer of the air from 0.1 to 1 cm deep. Radiation and molecular conduction are the primary mechanisms of heat transfer in this layer; convective transfer mechanisms then carry the heat to higher levels. The amount of energy penetrating the soil will depend upon the thermal properties such as its conductivity, diffusivity, and specific heat, as well as plant cover, exposure, and slope. Part of the radiant energy impinging on the soil surface is used to evaporate water from the soil and to transpire water from plants. The amount of energy used depends upon the availability of soil water and energy, the ability of the air to remove the vapor, and other factors. The penetration depths of the diurnal and annual temperature cycles are indicated in Table 3-5.

Physical, chemical, and biological processes in the soil are all strongly affected by temperature. The water retention capacity of mineral soils decreases with increasing temperature. The rate of flow of air through the soil decreases, and that of water increases, with increasing soil temperature. Increasing soil temperatures also promote the solvent action of water, the weathering of parent material, and similar chemical radiations. Soil temperature also controls the rate of growth, multiplication, and activity of soil micro-organisms. Most micro-organisms grow best at temperatures from –7.8° to 40°C (18° to 104°F) with optimal growth somewhere around 34.9°C (95°F).

The soil surface acts as a heat reservoir, absorbing part of the excess midday and

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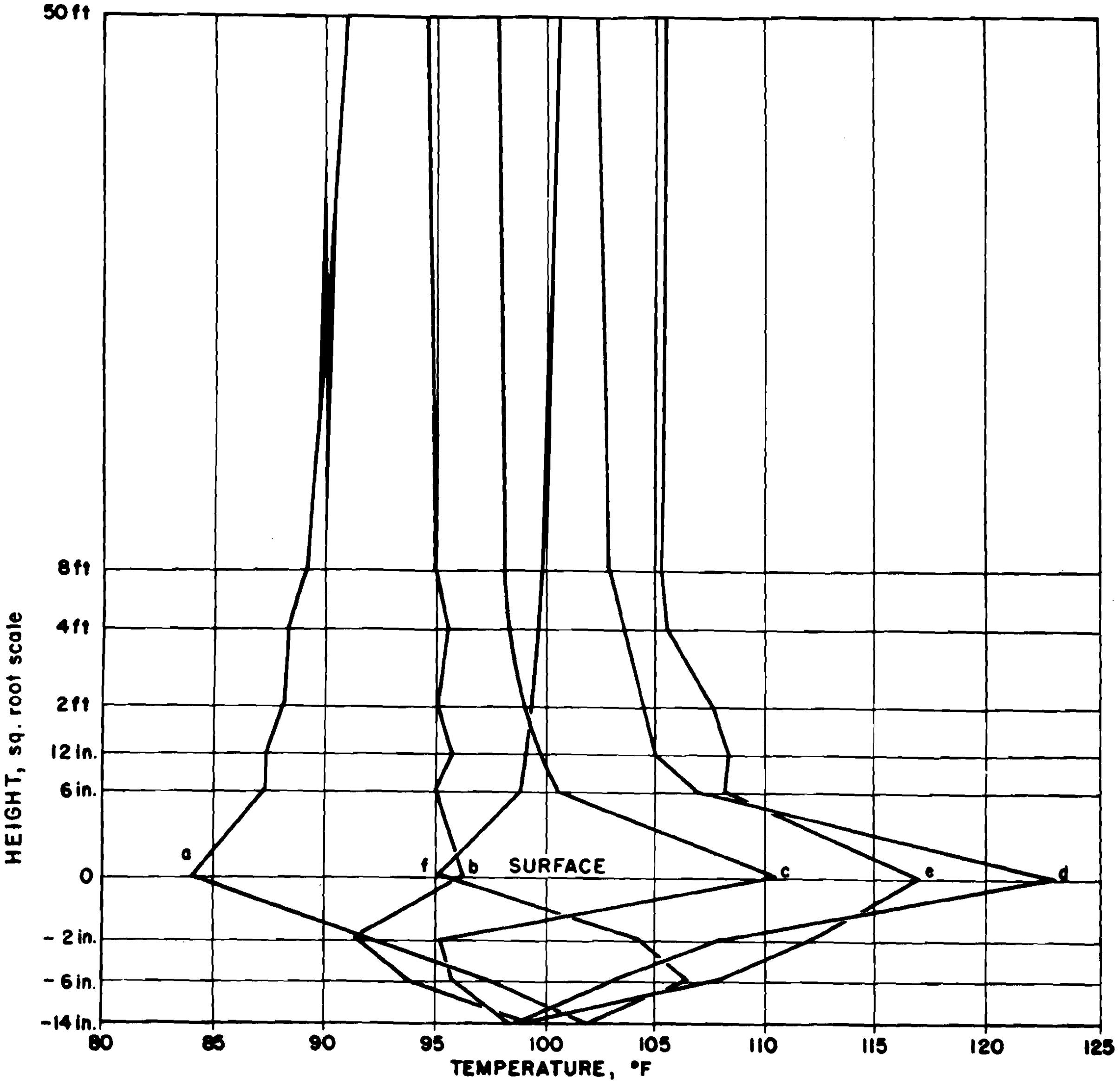
*General references for this paragraph are Refs. 16, 17, and 18.

TABLE 3-5

TEMPERATURE VARIATION IN DIFFERENT NATURAL MATERIALS (Ref. 12)

	Depth at which temperature variation is 0.5 that of surface, ft	
	Annual cycle	Diurnal cycle
Quartz sand, dry	3.2	0.17
Quartz sand, 8 percent moisture by weight	5.1	0.27
Quartz sand 22 percent moisture by weight	4.9	0.26
Sandy clay, 15 percent moisture by weight	4.4	0.23
Swamp land, 90 percent moisture by weight	3.4	0.18
Basalt rocks	5.9	0.31
Sandstone	7.2	0.38
Granite	8.1	0.42
Concrete	7.4	0.39
Loose snow	2.2	0.12
Packed snow	4.6	0.24
Ice	4.5	0.14
Still water	2.7	0.24
Turbulent water	200-2000	10-100



CURVE LABEL	a	b	c	d	e	f
HOUR OF OBSERVATION (PACIFIC STANDARD TIME)	0425 TO 0540	0755 TO 0813	0930 TO 1000	1155 TO 1305	1327 TO 1550	1430 TO 2047
INSOLATION, LANGLEY min^{-1}	0.006	0.76	1.18	1.38	1.02	0.00
BLACKBODY SKY TEMP, °F	66	54	52	62	61	–
WINDSPEED AT 12 ft, mph	5.0	3.6	3.0	4.1	4.0	14.2
NUMBER OF OBSERVATIONS	5	11	8	9	8	5

Figure 3-7. Average Vertical Temperature Gradient Above and Below the Surface in Death Valley, Calif. (Ref. 12)

summer heat, and returning it during the night and winter to the atmosphere. This storage of energy lessens the temperature extremes of the atmosphere and acts as a climatic stabilizer. The heat-storage capacity of the soil acts to reduce climatic stresses imposed by airmasses invading a region. During the day, when the soil surface is usually much warmer than the adjacent air, a steep lapse rate is formed in the air. This unstable

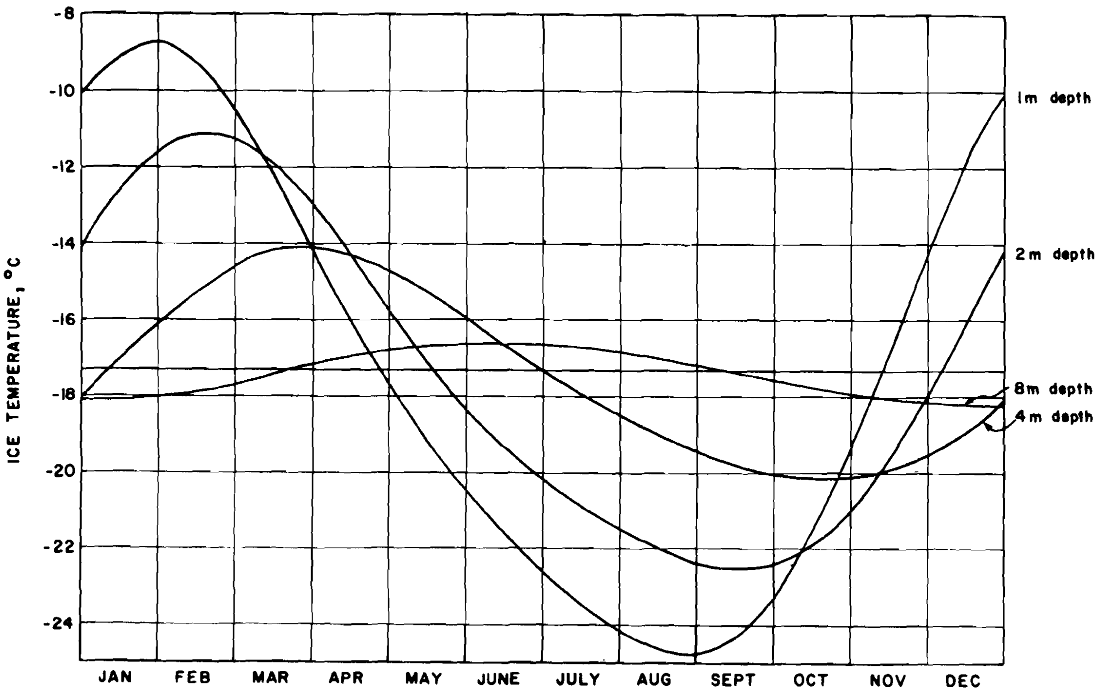


Figure 3-8. Annual Temperature Waves (Smoothed) at Various Depths in the Upper Layers of an Antarctic Ice Shelf (Ref. 18)

condition leads to air convection, turbulence, and wind gustiness, and through these motions, to the removal of atmospheric pollutants and water vapor from the air-soil interface. During the night, the cool soil surface creates a stable lapse rate, reducing the diffusing power of the atmosphere and perhaps creating a pollution problem. On the other hand, if the air is sufficiently cooler than the soil, enough heat may flow upward to inhibit the formation of a nocturnal inversion and thereby reduce the concentration of pollutants near the ground. Soil temperature gradients are shown in Fig. 3-7, and diurnal and annual soil temperature cycles in Fig. 3-3 and Fig. 3-4. In Fig. 3-8 annual temperature cycles for Antarctic ice are shown.

3-2.1.2.3 URBAN HEAT ISLANDS*

An urban complex acts as a heat reservoir producing a positive perturbation in the temperature distribution which has been called an "urban heat island" (Ref. 21). The horizontal temperature pattern associated with the heat island is a function of the urban terrain but can be 5.5 deg C or more above the temperature of the surrounding country.

More typically, an average temperature difference of 1.2 deg C exists between the downtown area of cities and the typical environs (Ref. 19). Within the city, the temperature differences between the areas containing manmade structures and parks are significant due to the differences in thermal properties of manmade structures and foliated regions. The highest temperatures are found in structure-containing regions of the city – the minimum in the surrounding suburban or agricultural areas. Bodies of water have marked effects on the temperature patterns.

The urban heat island exhibits a marked diurnal oscillation with the maximum effect being seen at night.

In addition to the thermal properties of the structures and the direct heating by combustion sources, air pollutants can contribute

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*General references for this paragraph are Refs. 19 and 20.

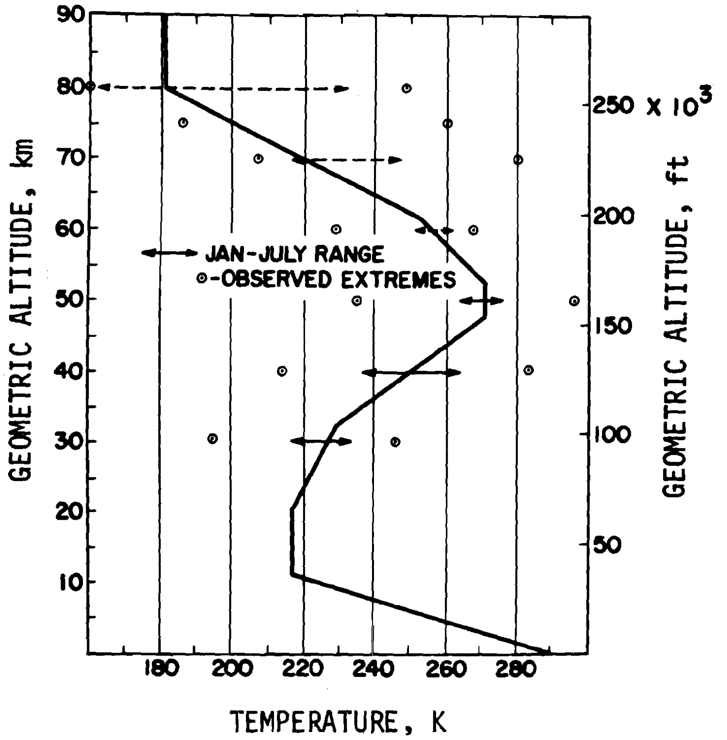

Figure 3-9. Northern Hemisphere Seasonal Variability of Temperature About the U.S. Standard Atmosphere, 1962 (Horizontal arrows show range of mean January and mean July temperature. Points are observed extremes.)

significantly to the heating of the city by preventing the radiated heat from escaping to the higher atmosphere.

3-2.1.3 ALTITUDE*

The decrease in air temperature with increasing altitude up to about 15 km is known as the vertical temperature gradient or lapse rate. This decrease in temperature results from (1) increasing distance from the surface of the earth, which provides the heat to the atmosphere; (2) decreasing water vapor content of the atmosphere with elevation, which results in less heat being held in the air; and (3) temperature decreases that result from expansion of the air rising from the surface of the earth.

The rate at which temperature decreases with altitude varies widely from place to place. The rate for a given place is determined by measurement. Readings are averaged to obtain an average or normal lapse rate of approximately 0.65 deg C/100 m. Lapse rates refer to the temperature gradient existing in a stationary column of air at a given place and time.

An inversion occurs when the temperature of the air increases instead of decreasing with altitude. This condition results when:

(1) Air near the ground cools off faster than the overlying air

(2) A warm layer of air passes over a lower colder one

(3) Warming occurs due to air subsidence

(4) Little or no air is moved by turbulence.

The temperature profile of the U S Standard Atmosphere is shown in Fig. 3-9

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*The relations between altitude and temperature are considered in all meteorology texts, cf. Refs. 6, 7, 22, 23, and 24.

TABLE 3-6

DIURNAL TEMPERATURE AMPLITUDE AND LAG (Ref. 12)

Height, ft	Amplitude, °F	Time lag, min
5	10.5	0
10	10.1	+15
25	8.9	+30
50	8.8	+30
100	8.6	+30
200	8.3	+40
300	7.5	+50
500	6.7	+70

with observed variability around the standard temperature indicated.

In Fig. 3-7, temperature changes in the immediate vicinity of a desert surface are shown for both daytime and night conditions. With increasing altitude, the temperature (maximum or minimum) lags that observed at ground level. As seen in Table 3-6, at a height of 100 ft above ground level, the lag is approximately 30 min. The amplitudes (difference between daily maximum and minimum) all decrease with increasing altitude.

3-2.1.4 CIRCULATION*

Thermal energy, as noted in previous paragraphs, is almost totally derived from insolation. Insolation is distributed very unevenly in both time and space on the surface of the earth. As has also been noted, the heat capacities of the soil and water as well as the latent heat of the water do much to even out the temporal fluctuations. However, observed temperatures would vary much more drastically than is the case if this were the only mechanism for redistributing thermal energy. Circulation currents in both the atmosphere and the oceans are the primary mechanism for this redistribution. In the atmosphere, a large amount of the thermal energy is transported as the latent heat of water vapor – extracting heat from the environment when water vaporizes and providing heat to the environment on condensation. The global mean available solar energy is 230 W m^{-2}, of which 70 W m^{-2} is expended in evaporation of water to be later released as the latent heat of condensation.

Most weather changes are produced by temperature differences in the atmosphere. Weather phenomena consist essentially of atmospheric motion with the accompanying evaporation, condensation, and precipitation of moisture. Air movement depends upon temperature differences in the atmosphere, while condensation and evaporation of moisture depend, respectively, upon atmospheric cooling and heating. Heating and cooling take place by radiational processes, by molecular and turbulent conduction, and by the transfer of latent heat in the form of water vapor (about 586 calories of heat are released when 1 g of water is condensed at 20°C (68°F)). Heating and cooling of air by adiabatic processes of compression and expansion also contribute to meteorological processes.

Horizontal difference of temperature can arise both from large-scale weather disturbances and local influences. Cold and warm fronts, thunderstorms, and tropical storms produce widely varying values of an unsystematic nature, varying with time and place. Frontal systems, cyclonic disturbances, squall lines, or thunderstorms cause changes in the vertical mixing in the lower troposphere, cloudiness, and large-scale vertical air motions. Temperature variations accompanying changes in air movement are usually attributable to the differing temperatures of the climatic regions from which the air comes. Arrival of low-moisture-content air from the arctic airmass, or high-moisture-content air from the subtropical airmass, in the midlatitudes, in addition to bringing about a change in air temperature, affects net solar radiation so as to change the temperature even further.

Sea surface temperatures in the vicinity of the Equator are near 80° F. At latitude 40

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*General references for this paragraph are Refs. 6, 24, and 25.

deg N. they are between 50° and 60°F in the winter and between 60° and 70°F in the summer (Ref. 26). In the Gulf Stream, for example, it is estimated that 70×10^6 m^3 s^{-1} of water are transported from the tropics to the North Atlantic (Ref. 27). A very large amount of thermal energy is transported by similar currents found in every oceanic region.

3-2.2 THERMAL BUDGET

If one considers the thermal energy budget at the surface boundary of the earth, an equation can be constructed to identify the flow of energy across the boundary. Geiger (Ref. 6) gives this equation as

$$S + B \text{ (or } U) + L + V + Q + N = 0 \qquad (3\text{-}4)$$

where

S = net solar radiation

B = thermal energy flow to or from the surface in the ground

U = exchange of thermal energy between water and its surface

L = exchange of thermal energy between air and the surface

V = thermal energy entailed in vaporization or condensation

Q = thermal energy from the air provided by advection

N = thermal energy carried with precipitation

Each of these factors may be either positive or negative, corresponding to downward or upward flow of energy across the surface.

The relative magnitudes of these factors as reported by Geiger are as given in Table 3-7. Units employed are cal cm^{-2} min^{-1}, which can be converted to international units using

$$1 \text{ cal } m^{-2} \text{ min}^{-1} = 6.97 \times 10^2 \text{ W } m^{-2}.$$

3.2.3 TEMPERATURE DATA LIMITATIONS*

Many kinds of temperature data are measured and recorded by climatologists. Probably the most common temperature value is the daily mean, from which monthly and annual values may be obtained. The daily mean temperature is usually computed by adding the 24-hr maximum to the 24-hr minimum and dividing by 2. Relatively few weather stations in the world take hourly temperature readings despite the fact that they provide the best basis for the mean. The difference between the highest and lowest temperatures of the day is known as the diurnal or daily temperature range.

The mean monthly temperature is computed by adding the daily means and dividing by the number of days in the month. Mean monthly values for the year, when considered in sequence, indicate the annual march of temperature through the seasons. The term "annual range" is used to denote the difference between the mean temperatures of the warmest and coldest months. For most stations in the Northern Hemisphere, the warmest month is July, and the coldest is January, but some variation exists, depending on location.

When temperature values for a number of years are averaged to provide a climatic description of an area, they tend to mask the variability and local peculiarities that may be important to the military. The parameters of air temperature of interest to design and test engineers differ from those usually reported in standard temperature summarizations. The engineer is interested in extremes, ranges, durations, heating degree-days, air-conditioning data, probabilities of occurrence, and distributional patterns in different parts of the world. With these types of data, he is better able to establish design criteria for satisfactory equipment performance in a given area.

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*A general reference for this paragraph is Ref. 25.

TABLE 3-7

REPRESENTATIVE DAILY HEAT BUDGET IN TEMPERATE CLIMATE (Ref. 6)

Period	Flow of thermal energy across surface boundary, cal cm^{-2} min^{-1}				
	Radiation	Flow in ground	Exchange with atmosphere	Vaporization	Total flow
Summer day	+0.407	-0.165	-0.094	-0.148	0.407
Winter day	+0.091	-0.082	-0.003	-0.006	0.091
Summer night	-0.080	+0.070	+0.021	-0.011	0.091
Winter night	-0.065	+0.021	+0.060	-0.016	0.081
Annual balance	+19,819	-181	+387	-20,025	20,206

In view of the ranges of temperature – or any climatic parameter for that matter – arithmetic averages are usually unsatisfactory in specifying the state of the temperature although the description of temperature throughout the world has usually been so limited. Fully as significant – but less convenient to summarize – are the durations, frequency distributions, and extreme values of temperature, or the frequency distributions of joint occurrences of two or more elements. The latter treatment is particularly important to designers who may be unaware of the possible synergistic interactions of elements of the environment whenever they consider only individual factors extracted from the total environment.

Temperature often differs significantly in a surprisingly short distance through the air or along the ground, and a careful description or definition of the kind of site to which an observed temperature refers is required. The collection of climatic statistics is, therefore, a sampling process, and existing statistics should be taken as indicative rather than definitive.

Since climate is known to be changing or fluctuating irregularly, the numerical description of temperature depends, to some extent, upon the time period over which the temperature statistics are compiled. A standard climatological period has been defined by the World Meteorological Organization as consisting of the 30-yr period ending with the most recent decade year. Averages over this period are defined as "normals"; averages of other periods should properly denote the exact period that was used.

The lengths of temperature series vary from station to station; the series, moreover, are usually not homogeneous and no statistical methods exist for making them so. A homogeneous series is one that refers to the same site or its equivalent throughout the period of record. Long temperature series, widely published without qualifications, must be used with discrimination. Detailed histories of site locations, which are available for many countries, must be examined to assure homogeneity of the series. Because of data variability from such sources, the representativeness, hence, the utility, of all temperature (or climatological) data is constrained to some extent by a variety of sampling and data processing uncertainties.

In the United States, an average temperature station represents 500 mi^2 of land surface; a given temperature, therefore, represents a sample of the temperature of other points in the surrounding region. Typically, this region is nonuniform in geographical character, and the sample is complexly biased. Stations are usually found concentrated in the lower-lying, flatter valley locations. Furthermore, the towns that have usually been built up around the instrument site alter the temperature environment. The sampling density is insufficient to interpolate the climate of every town; it is, however, more than sufficient to indicate relative variations of temperature from 1 yr (or decade) to another because simultaneous departures of these from their normals are closely parallel over large areas. For these reasons, homogeneous series for one station may reflect satisfactorily the historical variations of temperature over 10,000 or even 100,000 mi^2, but not the climate itself.

Many factors operate to compromise the homogeneity of typical climatic series. Expanding cities have introduced warming trends in temperature and complex changes in precipitation that are not representative of their rural surroundings. The need to move stations to new locations, with their slightly different temperatures, has left their combined record with discontinuities. In the United States, only 2 to 3 percent of city first-order National Weather Service (formerly the U S Weather Bureau) stations have remained in one location for their full history. Changes in daily observational time and in exposure of instruments have caused further discontinuities over the years. Other sources of nonhomogeneity are neglect or interpolation of occasional missing daily records, the calculation of monthly averages, and human

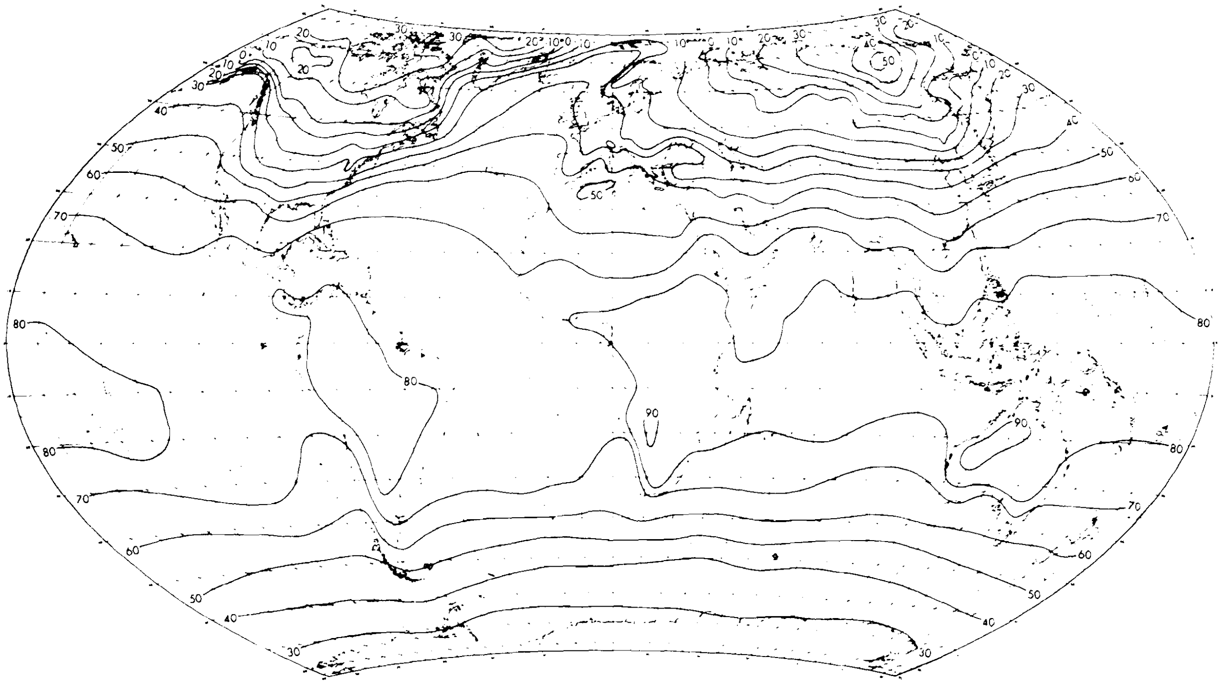


Figure 3-10. Worldwide Average Temperatures—January, °F

error in instrument reading, recording, editing, computing, and printing.

3-2.4 MEAN TEMPERATURE DATA

A large amount of data on temperature is recorded and presented in a variety of forms, depending on the sources and planned use for the data. Mean, maximum, minimum, and range are recorded for temperature on a daily, monthly, and annual basis. Data are available on the number of days during which temperature either exceeded or was less than a specified value, on the last day of frost in the spring, on the length of the above-freezing growing season, on the normal maxima and minima temperatures, and on other similar temperature-based descriptors. In Table 3-8 some of the sources of such data are listed along with the types of data that they contain. Further sources are listed in the *Selective Guide to Climatic Data Sources* (Ref. 28).

Temperature patterns over large areas are indicated by isotherms, lines connecting points of equal temperature. Examples are given in Fig. 3-10 and 3-11 in which maps of the world are shown with isotherms for average temperatures in January and July. Obviously, such maps can depict only the gross features of the temperature distribution, which can be seen more clearly by comparing Fig. 3-10 with Fig. 3-12. The latter shows, with equal validity, the isotherms for the ocean regions of the world to compare with those of Fig. 3-10. Differences are evident although the general pattern is the same. In Fig. 3-13, the normal daily average temperature in January for the United States is shown. Comparison with Fig. 3-10 shows the change in detail brought about by a change in scale of the map.

Isotherms may be employed equally well for indicating temperature extremes. In Figs. 3-14 and 3-15, the minimum temperature in January and the maximum temperature in July are shown for the United States. In all of these maps it is evident that isotherms have a

TABLE 3-8

SOURCES OF TEMPERATURE DATA

Source book	Ref.	Type of data
Climates of the world	13	Maximum and minimum average daily temperature for Jan, Apr, July, and Oct and annual extremes for approximately 800 weather stations throughout world.* Maps of average Jan and July temperatures for world
Atlas of Mean Daily Minimum Temperatures	29	Mean daily minimum temperatures on 24 maps, four (Jan, Apr, July, Oct), each for 6 world regions
Estimated Frequency of Cold Temperatures Over the Northern Hemisphere	30	Percentage of time during the coldest month that temperatures as cold as or colder than -40°, -50°, -60°, and -70°F are presented in 4 maps of the Northern Hemisphere.
Atlas of Surface Temperature Frequencies for North America and Greenland	31	Approx. 85 maps showing percentage frequency of temperatures below a specified level with 6-8 maps given for each month for North America and Greenland
Atlas of Surface Temperature Frequencies for Eurasia	32	Same as above except for Eurasia
Climatic Atlas of the United States	33	Normal daily maximum, minimum, average, and range of temperatures for each month with both isopleth and station maps for each month. Mean number of days with maximum temperature of 90°F or above, monthly and annual. Mean number of days minimum temperature 32°F and below, monthly and annual. Mean date of last 32°F temperature in spring. Mean date of first 32°F temperature in autumn. Mean length of freeze-free period Mean total heating degree-days, monthly and annual
Statistical Abstract of the United States, 1971	34	Tabular data on occurrence of freeze, monthly average temperatures, normal monthly maximum and minimum, and highest and lowest temperature of record for select U.S. cities.
World Weather Records	35	Tabulated data on mean temperature (°C) by year and month with monthly and annual means for a large number of worldwide weather stations from before 1920 to 1960 in a number of volumes
Marine Climatic Atlas of the World, Vol. VIII, The World	26	Mean, maximum, and minimum air temperatures and mean sea surface temperatures for ocean areas of the world by month
Study of Worldwide Occurrence of Fog, Thunderstorms Supercooled Low Clouds, and Freezing Temperature	36	Monthly maps of percentage frequency of surface air temperatures freezing or below.
Ground Temperature	37	Soil temperature maps for the world for various depths by month
Local Climatological Data with Monthly Supplements	38	Current tabular weather data including degree-days, average, minimum, and maximum daily temperatures for 287 weather stations
Climatological Data	39	Current publications on U.S. and possessions giving temperature data
Monthly Climatic Data for the World	40	Summaries of worldwide climatic data
Engineering Weather Data	41	Detailed temperature data for large number of locations on every continent, primarily frequency of occurrence of temperatures in 5-deg increments.

*These data are included in Appendix B of this handbook.

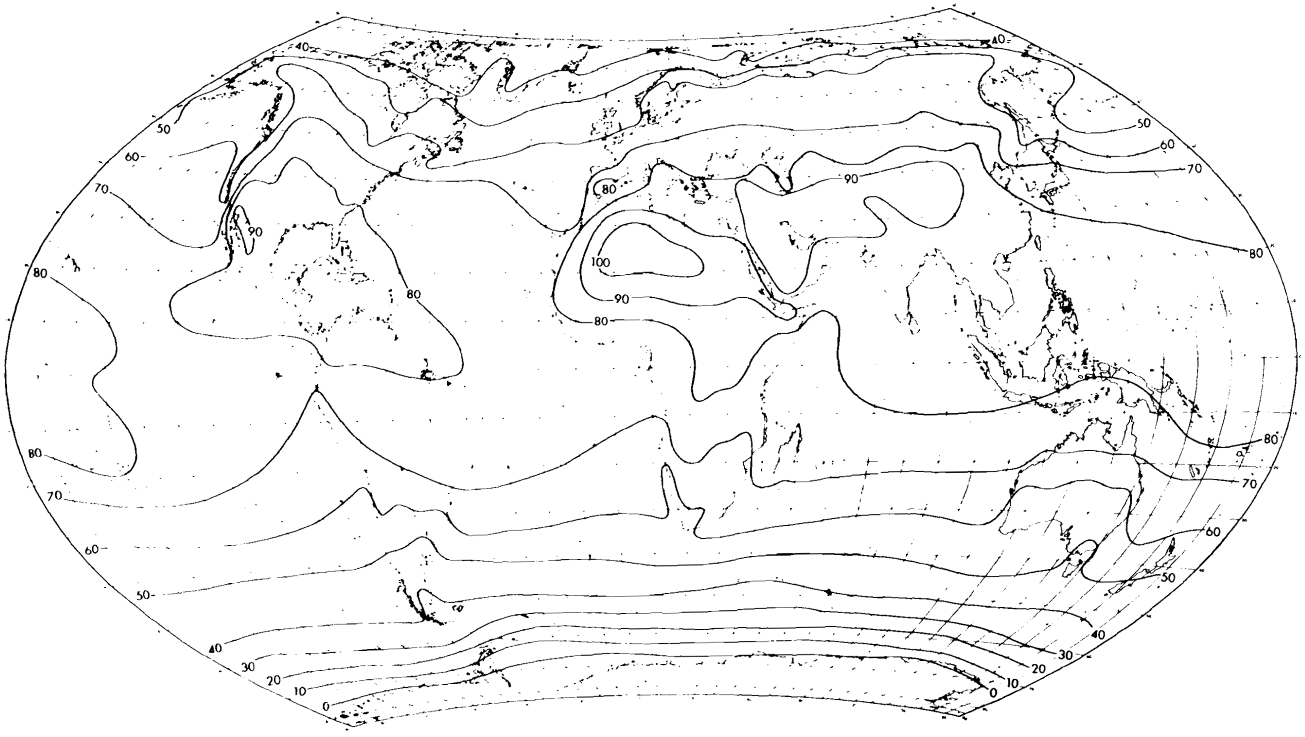


Figure 3-11. Worldwide Average Temperatures—July, °F

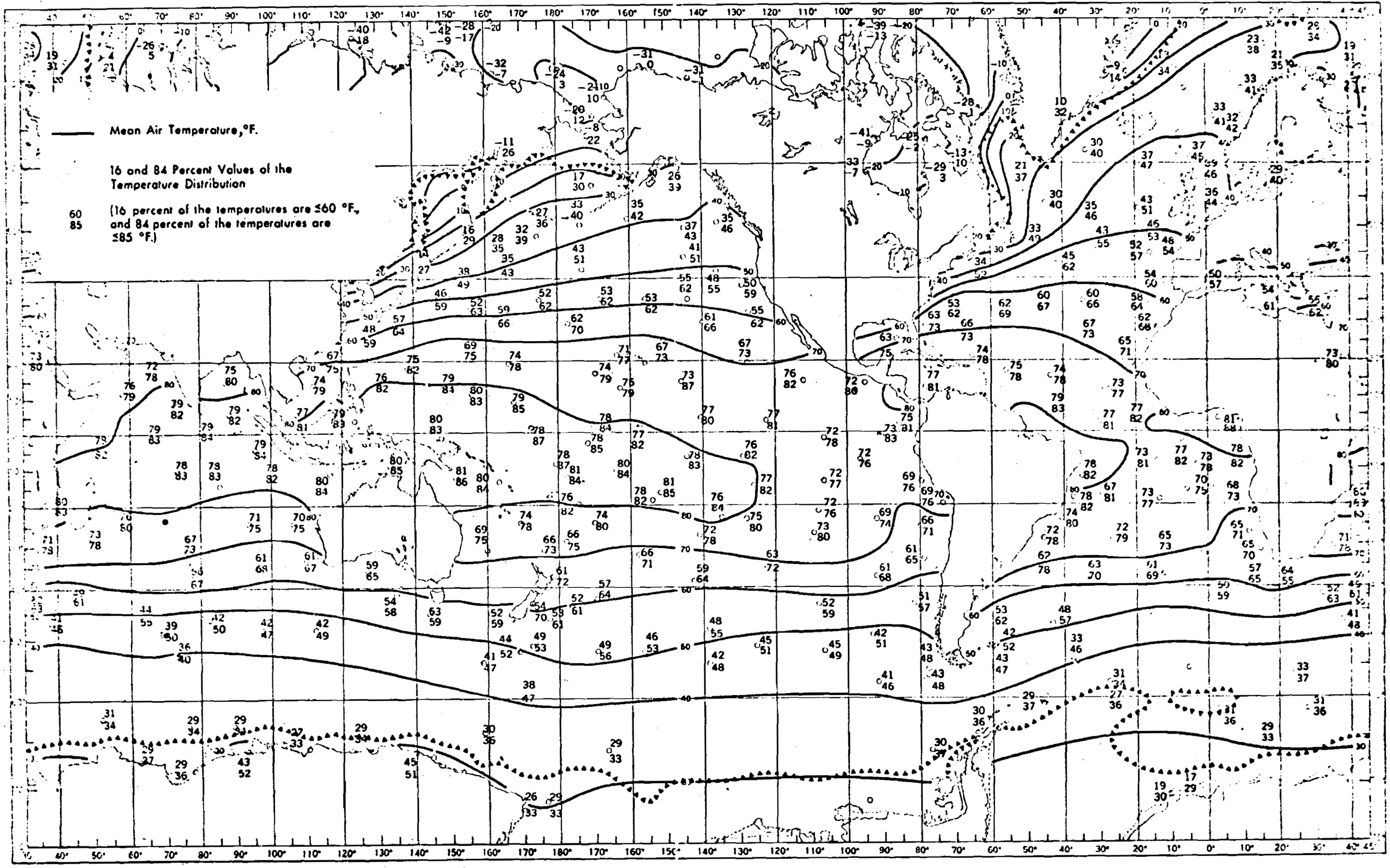
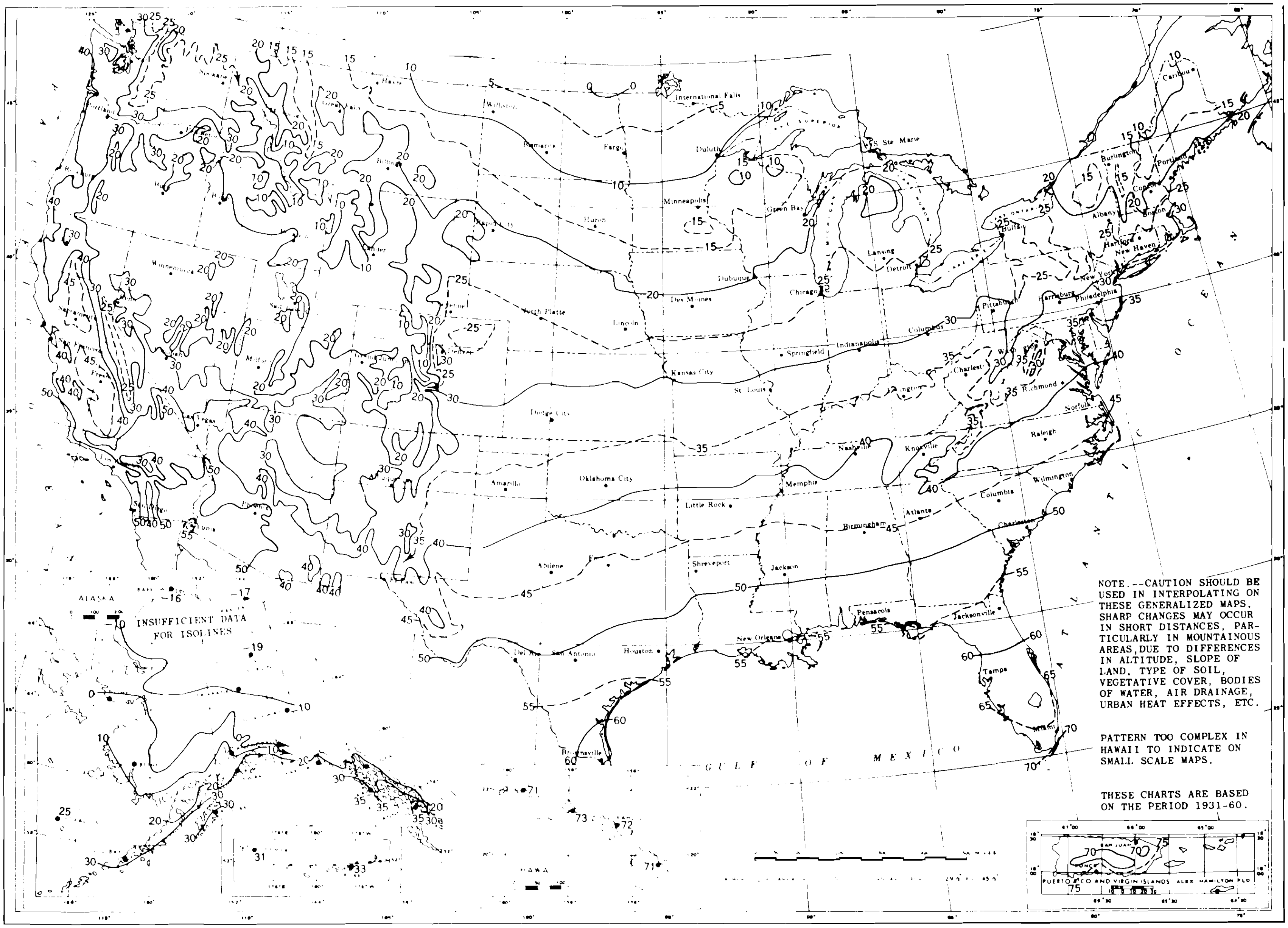


Figure 3-12. Mean Air Temperatures Over Oceans—January, °F (Ref. 26)

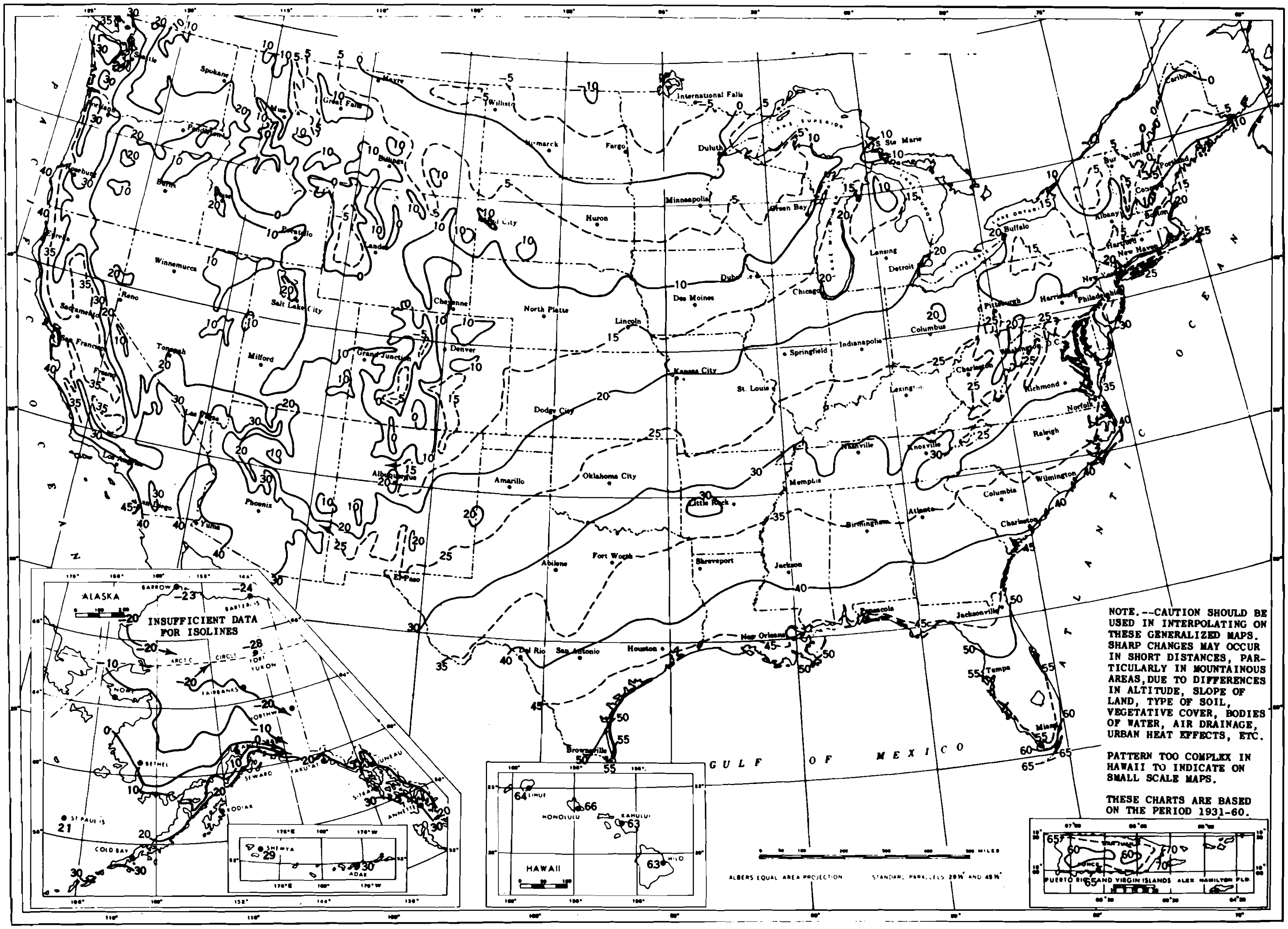


NOTE.--CAUTION SHOULD BE USED IN INTERPOLATING ON THESE GENERALIZED MAPS. SHARP CHANGES MAY OCCUR IN SHORT DISTANCES, PARTICULARLY IN MOUNTAINOUS AREAS, DUE TO DIFFERENCES IN ALTITUDE, SLOPE OF LAND, TYPE OF SOIL, VEGETATIVE COVER, BODIES OF WATER, AIR DRAINAGE, URBAN HEAT EFFECTS, ETC.

PATTERN TOO COMPLEX IN HAWAII TO INDICATE ON SMALL SCALE MAPS.

THESE CHARTS ARE BASED ON THE PERIOD 1931-60.

Figure 3-13. Normal Daily Average Temperature in the United States—January, °F (Ref. 33)

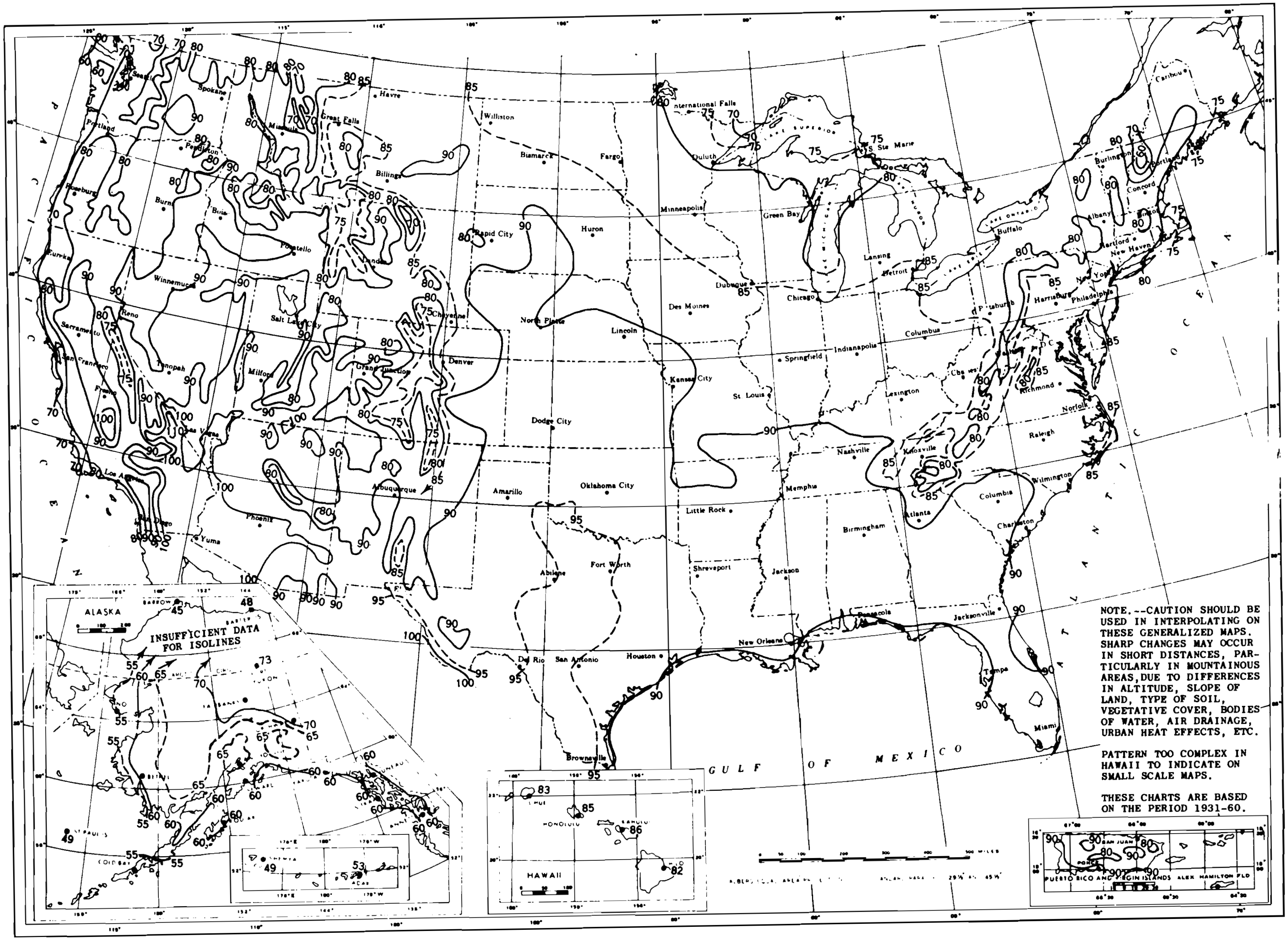


NOTE.--CAUTION SHOULD BE USED IN INTERPOLATING ON THESE GENERALIZED MAPS. SHARP CHANGES MAY OCCUR IN SHORT DISTANCES, PARTICULARLY IN MOUNTAINOUS AREAS, DUE TO DIFFERENCES IN ALTITUDE, SLOPE OF LAND, TYPE OF SOIL, VEGETATIVE COVER, BODIES OF WATER, AIR DRAINAGE, URBAN HEAT EFFECTS, ETC.

PATTERN TOO COMPLEX IN HAWAII TO INDICATE ON SMALL SCALE MAPS.

THESE CHARTS ARE BASED ON THE PERIOD 1931-60.

Figure 3-14. Normal Daily Minimum Temperature in the United States—January, °F (Ref. 33)



NOTE.--CAUTION SHOULD BE USED IN INTERPOLATING ON THESE GENERALIZED MAPS. SHARP CHANGES MAY OCCUR IN SHORT DISTANCES, PARTICULARLY IN MOUNTAINOUS AREAS, DUE TO DIFFERENCES IN ALTITUDE, SLOPE OF LAND, TYPE OF SOIL, VEGETATIVE COVER, BODIES OF WATER, AIR DRAINAGE, URBAN HEAT EFFECTS, ETC.

PATTERN TOO COMPLEX IN HAWAII TO INDICATE ON SMALL SCALE MAPS.

THESE CHARTS ARE BASED ON THE PERIOD 1931-60.

Figure 3-15. Normal Daily Maximum Temperature in the United States—July, °F (Ref. 33)

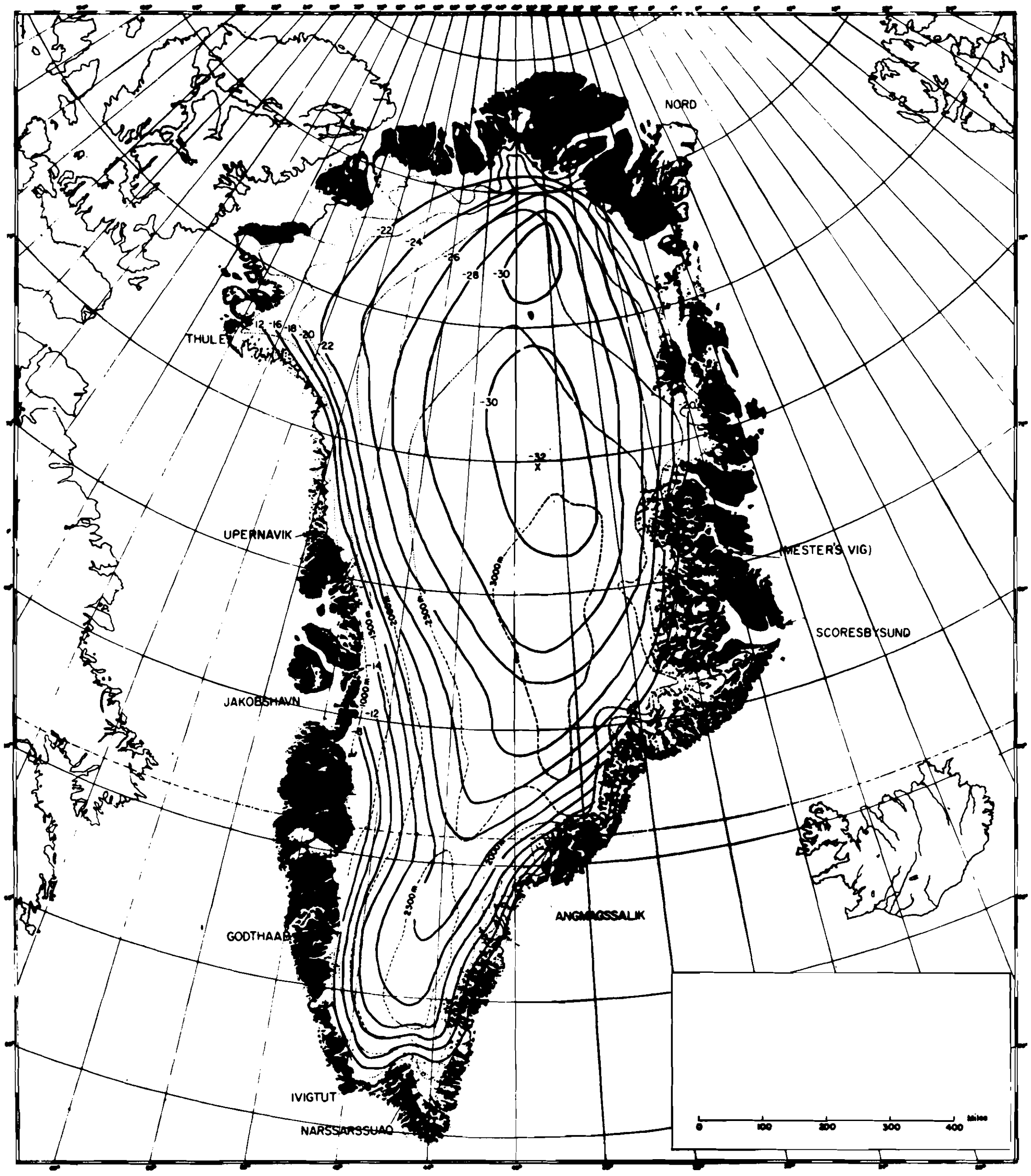


Figure 3-16. Mean Annual Temperature on the Greenland Ice Cap, °C (Ref. 42)

generally east-west orientation brought about by the rotation of the earth on its axis. The isotherms are distorted as they cross land-ocean boundaries and the effect of warm ocean currents is evident. The greatest distortion results over land because of the influence of various geographic features.

Definite centers of high and low temperatures occur over continental landmasses. High temperature regions are found in Africa and Australia in January; over the Southwestern United States, North Africa, and southwestern Asia in July. In January, a cold region develops over northeastern Siberia attaining temperatures below −50°F. Permanent centers of low temperature are found over the Greenland Ice Cap and in Antarctica. In Fig. 3-16 the mean annual temperature isotherms for Greenland illustrate the annual temperature profile of a permanent cold region.

The spacing between isotherms over the ocean regions in the world maps (Figs. 3-10, 3-11, and 3-12) indicate the relative constancy of sea temperatures. The 0°F isotherm in January is pushed far northward by the oceans but extends southward in continental regions.

Another way of presenting temperature data is illustrated in Figs. 3-17 through 3-20. In these, the percent frequency of time that temperatures are below the indicated value are given. Maps were selected for 0°F in January and 70°F in July in order to show data on the Northern Hempisphere for the two extreme months. In Fig. 3-21 another map of the United States is shown on which the normal daily range of temperature is plotted, using isopleths, for the month of July.

Much more data are available on surface temperatures in the sources listed in Table 3-8, from which the maps in this paragraph have been extracted. In addition, temperature data from approximately 800 worldwide stations are given in Appendix B.

Air temperatures above the surface are of increasing importance in design. These are currently available in limited quantities for temperatures in the troposphere, and that portion of the stratosphere below 30 km at a number of stations in the Northern Hemisphere. Data on the properties of the atmosphere above 30 km are too scarce at present to permit the development of reliable design criteria.

Meteorological parameters of the upper air vary considerably, both spatially and temporally. Tabulations of averages obtained from model atmospheres are generally of little value in accurately quantifying the environment, since actual values may vary widely within the ranges established. The use of extreme values can be needlessly expensive in design practice, since extremes may be encountered infrequently or not at all. Therefore, a calculated risk quantity derived from a station probability level is often preferable. Since the degree of risk will undoubtedly vary, depending on the problem, different probability levels are required.

Tables 3-9 through 3-11 present, for various geographic zones of the Northern Hemisphere, estimated values of atmospheric temperature that may be exceeded 1, 5, and 10 percent of the time in the atmosphere at 1-km intervals between the surface of the earth and an altitude of 30 km (approximately 100,000 ft). Annual data from a number of stations located in the Northern Hemisphere, principally in North America, were used to produce these values. The data for altitudes below 20 km (65,000 ft) are considered more reliable because they reflect a larger sample size. Since the number of stations from which summarized data on temperature can be obtained is rather limited, more data are required before these probabilities can be considered final.

A note of caution on the use of the data is justified. The temperature values have been determined statistically for 1-km intervals, without regard to the relationship between levels. Consequently, they do not represent hydrodynamically consistent atmospheres.

In each geographic zone, the minimum and maximum temperature values for a given probability were obtained from the station having either the minimum or the maximum value for each level between the surface and 30 km. At some stations, the 1-, 5-, and 10-percent empirical probability levels were available. At other stations listed, the 84.1-, 97.72-, and 99.85-percent empirical probability levels were interpolated, assuming an approximately normal distribution (Gaussian) and computing the estimated value by a ratio taken by the 1-, 5-, and 10-percent cumulative values in the assumed normal distribution. Some stations that had available only mean values and standard deviations were used largely as checking stations.

Temperature data have been employed by the Army in identifying the eight climatic

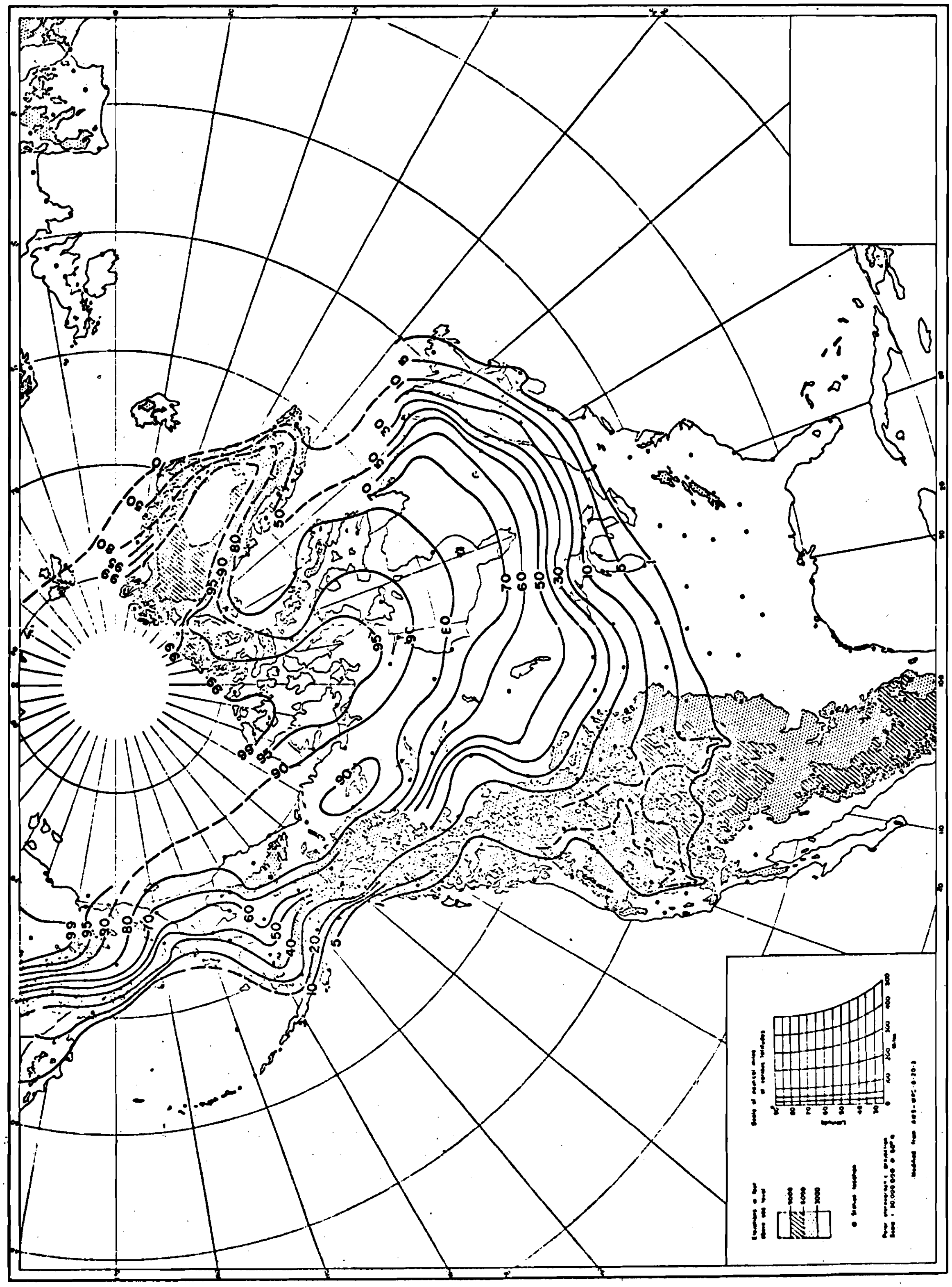


Figure 3-17. Percent Frequency of Temperatures Below 0°F—North America in January (Ref. 31)

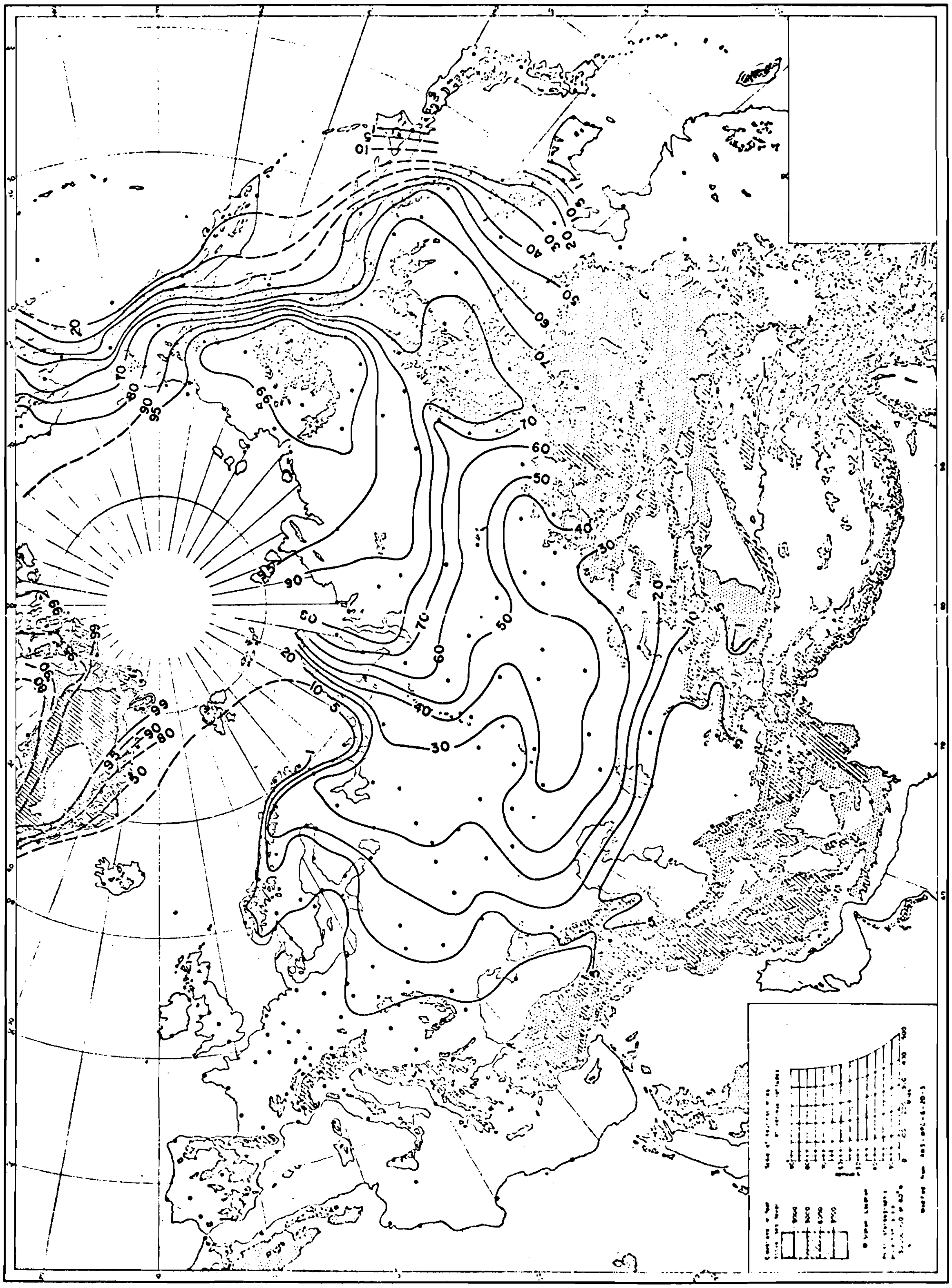


Figure 3-18. Percent Frequency of Temperatures Below 0°F—Eurasia in January (Ref. 32)

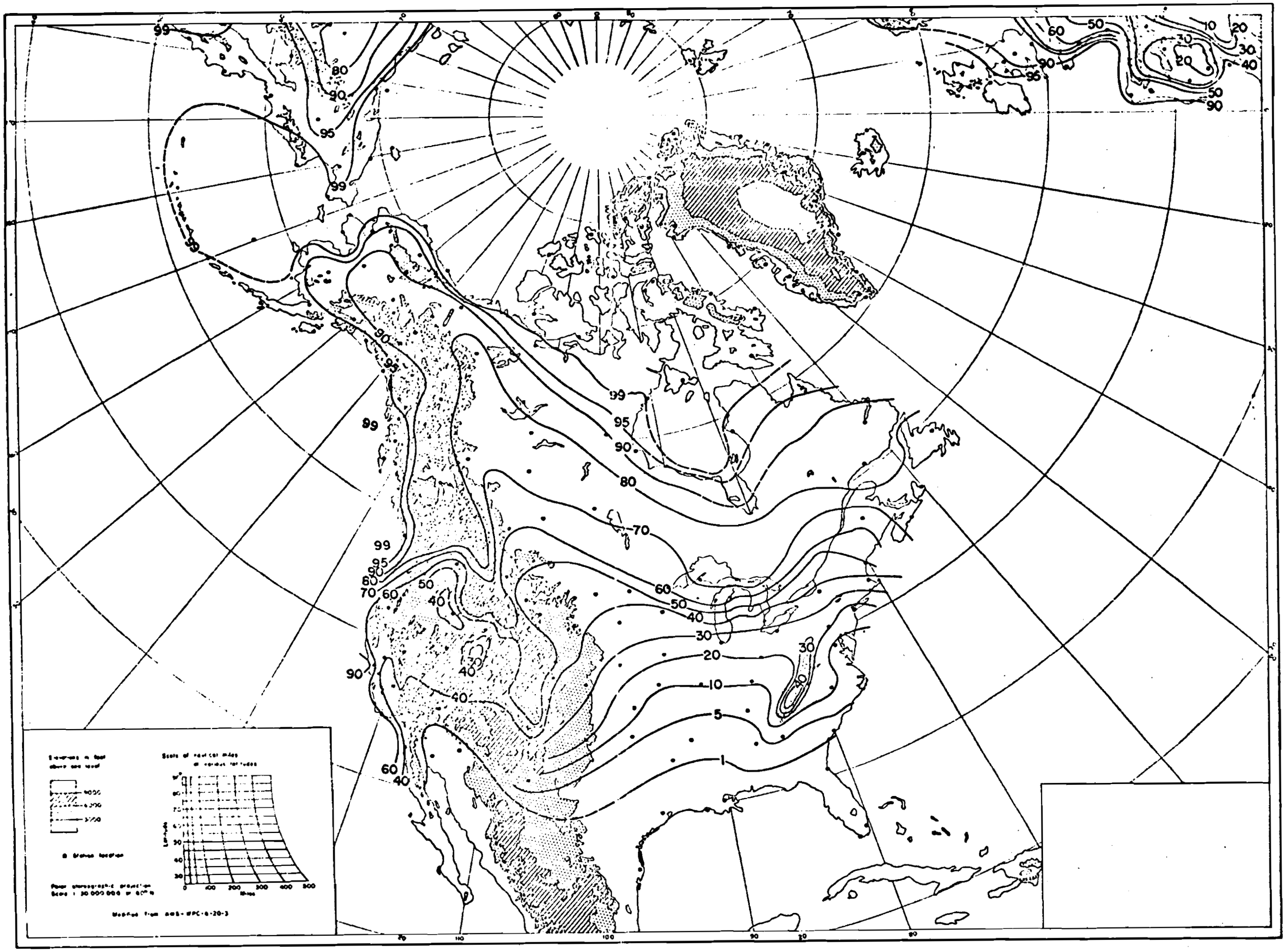


Figure 3-19. Percent Frequency of Temperatures Below 70°F—North America in July (Ref. 31)

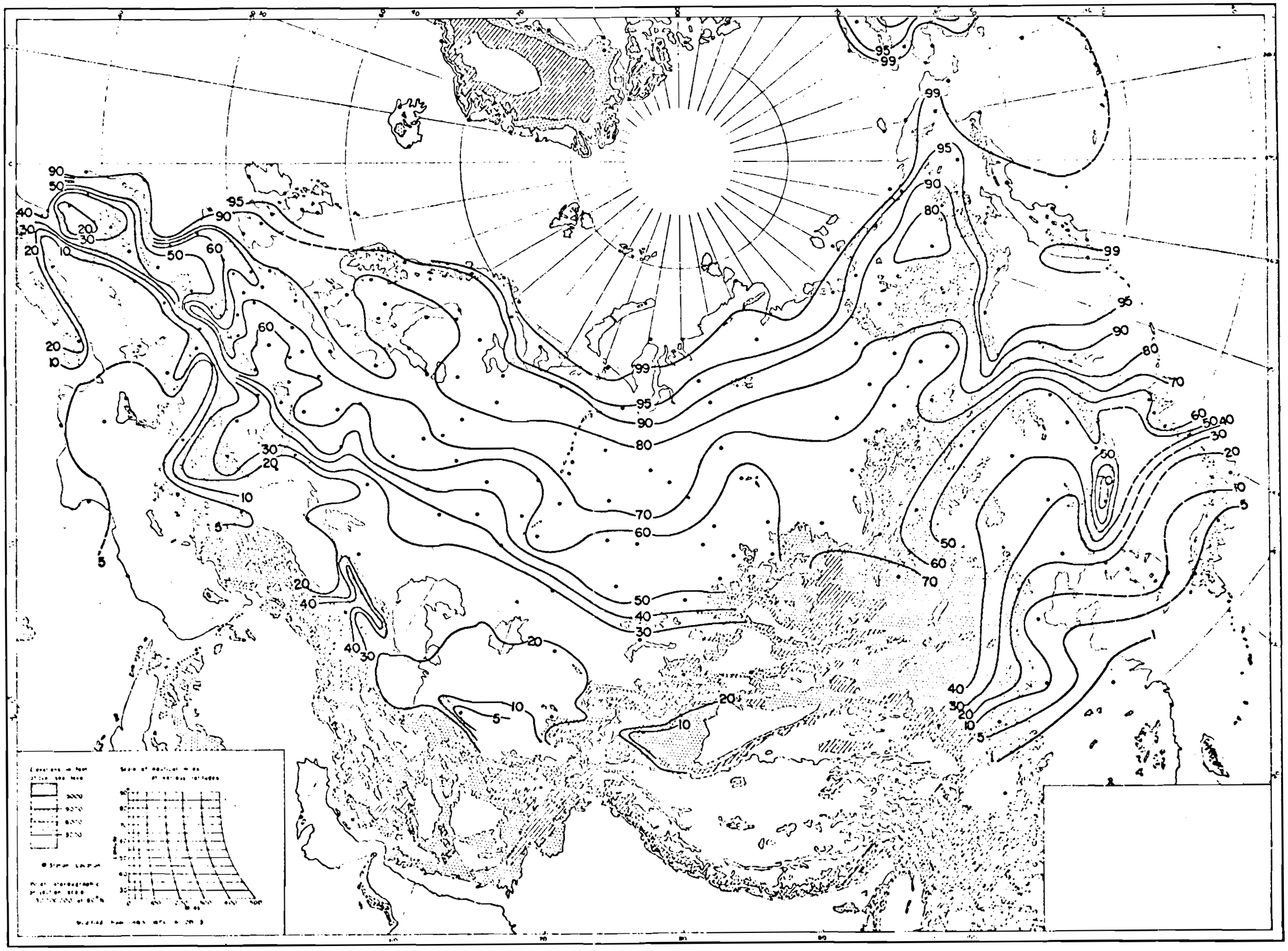


Figure 3-20. Percent Frequency of Temperatures Below 70°F—Eurasia in July (Ref. 32)

NOTE.--CAUTION SHOULD BE USED IN INTERPOLATING ON THESE GENERALIZED MAPS. SHARP CHANGES MAY OCCUR IN SHORT DISTANCES, PARTICULARLY IN MOUNTAINOUS AREAS, DUE TO DIFFERENCES IN ALTITUDE, SLOPE OF LAND, TYPE OF SOIL, VEGETATIVE COVER, BODIES OF WATER, AIR DRAINAGE, URBAN HEAT EFFECTS, ETC.

PATTERN TOO COMPLEX IN HAWAII TO INDICATE ON SMALL SCALE MAPS.

THESE CHARTS ARE BASED ON THE PERIOD 1931-60.

Figure 3-21. Normal Daily Range of Temperature, °F—United States in July (Ref. 33)

TABLE 3-9

NORTHERN HEMISPHERE TEMPERATURE OCCURRENCE WITH ALTITUDE—1-PERCENT PROBABILITY LEVEL, °C (Ref. 43)

Altitude, km	Low latitude Min	Low latitude Max	Midlatitude Min	Midlatitude Max	High latitude Min	High latitude Max	Hemisphere Min	Hemisphere Max
0	15.0	35.1	-21.1	33.1	-41.3	26.8	-41.3	35.1
1	11.3	25.2	-31.8	34.1	-36.5	17.9	-36.5	34.1
2	4.5	19.2	-31.0	28.0	-37.7	10.5	-37.7	28.0
3	0.9	14.6	-31.4	19.0	-41.3	4.1	-41.3	19.0
4	- 4.7	9.4	-36.0	10.8	-43.0	- 1.6	-43.0	10.8
5	-11.0	4.0	-40.7	2.5	-50.6	- 7.1	-50.6	2.5
6	-18.1	- 2.0	-45.5	- 4.3	-55.5	-13.6	-55.5	- 2.0
7	-26.1	- 8.0	-50.2	-10.3	-58.5	-20.8	-58.5	- 8.0
8	-33.7	-14.1	-55.0	-17.0	-63.0	-27.7	-63.0	-14.1
9	-41.1	-20.7	-59.5	-24.1	-65.9	-34.7	-65.8	-20.7
10	-49.0	-28.0	-64.5	-30.2	-68.8	-36.0	-68.9	-28.0
11	-55.8	-35.9	-69.3	-33.2	-68.8	-35.5	-69.3	-33.2
12	-61.4	-43.9	-73.0	-36.1	-70.7	-35.3	-73.0	-35.0
13	-67.0	-51.6	-72.3	-39.3	-70.4	-37.3	-72.3	-37.3
14	-72.0	-57.4	-72.2	-42.0	-70.6	-38.0	-72.2	-38.0
15	-77.8	-61.1	-74.4	-43.4	-71.7	-38.4	-77.8	-38.4
16	-83.7	-62.8	-76.1	-44.8	-72.6	-38.5	-83.7	-38.5
17	-87.0	-63.5	-77.1	-48.5	-73.1	-39.2	-87.0	-39.2
18	-86.1	-62.9	-77.5	-48.5	-72.7	-39.0	-86.1	-39.0
19	-81.4	-58.9	-76.2	-48.6	-66.9	-39.0	-81.4	-39.0
20	-75.4	-57.1	-72.9	-48.0	-63.4	-36.4	-75.4	-36.4
21	-71.0	-52.6	-69.6	-47.4	-68.2	-32.0	-71.0	-32.0
22	-67.2	-50.9	-68.0	-46.5	-66.6	-33.0	-68.0	-33.0
23	-65.0	-48.5	-67.3	-45.2	-67.7	-27.6	-67.7	-27.6
24	-62.7	-45.5	-67.0	-43.9	-67.4	-27.1	-67.4	-27.1
25	-61.0	-43.5	-66.4	-42.1	-68.5	-26.6	-68.5	-26.6
26	-59.7	-41.4	-66.4	-39.4	-68.3	-25.3	-68.3	-25.3
27	-59.3	-38.3	-66.5	-37.8	-66.5	-24.3	-66.5	-24.3
28	-59.7	-39.1	-66.4	-35.6	-65.8	-29.9	-66.4	-29.9
29	-61.9	-31.9	-66.8	-32.4	-66.8	-32.0	-66.8	-32.0
30	-57.2	-29.3	-66.8	-30.8	-66.0	-32.5	-66.8	-29.3

categories identified on the map of Fig. 3-22. These climatic categories are identified as follows:

(1) *Category 1, wet-warm, and Category 2, wet-hot*. The areas designated as wet-warm and wet-hot are the humid tropical regions of the world. Wet-warm conditions occur under the forest canopy and wet-hot conditions occur in the same area, but in the open. Both wet-warm and wet-hot areas are differentiated on the basis of seasonality of occurrence of the conditions. In the areas identified on the map as "nonseasonal", the conditions can be expected to occur only during the rainy season. In the "seasonal" areas, temperatures

TABLE 3-10

NORTHERN HEMISPHERE TEMPERATURE OCCURRENCE WITH ALTITUDE—5-PERCENT PROBABILITY LEVEL, °C (Ref. 43)

Altitude, km	Low latitude		Midlatitude		High latitude		Hemisphere	
	Min	Max	Min	Max	Min	Max	Min	Max
0	18.3	33.2	-15.3	29.2	-33.0	21.3	-33.0	33.2
1	12.9	23.7	-26.7	31.0	-32.2	13.9	-32.2	31.0
2	4.5	17.8	-26.1	25.0	-32.4	8.0	-32.4	25.0
3	3.3	13.1	-27.1	16.5	-35.8	2.1	-35.8	16.5
4	- 2.1	7.8	-31.9	9.0	-39.5	- 3.6	-39.5	9.0
5	- 8.4	2.3	-36.8	1.0	-46.3	-10.2	-46.3	2.3
6	-15.3	- 3.5	-41.6	- 5.7	-51.4	-15.5	-51.4	- 3.5
7	-22.7	- 9.6	-46.7	-11.8	-55.9	-22.8	-55.9	- 9.6
8	-30.3	-15.8	-52.0	-18.5	-59.8	-29.9	-59.8	-15.8
9	-38.2	-22.7	-57.0	-25.7	-62.3	-36.9	-62.3	-22.7
10	-45.6	-30.2	-61.5	-33.1	-63.4	-38.8	-63.4	-30.2
11	-52.5	-38.2	-66.5	-37.0	-64.0	-39.3	-66.5	-38.2
12	-58.9	-46.4	-69.0	-40.8	-64.5	-39.9	-69.0	-39.9
13	-64.8	-54.4	-69.2	-43.0	-64.0	-40.1	-69.2	-40.1
14	-69.6	-60.1	-69.9	-45.0	-64.6	-40.4	-69.9	-40.4
15	-75.9	-63.9	-72.6	-46.0	-65.6	-40.2	-75.9	-40.2
16	-81.6	-65.8	-74.4	-47.1	-66.5	-40.0	-81.6	-40.0
17	-84.7	-66.5	-75.3	-50.3	-65.2	-41.2	-84.7	-41.2
18	-83.4	-65.2	-75.2	-50.2	-64.6	-41.0	-83.4	-41.0
19	-78.1	-62.7	-73.5	-50.0	-61.5	-40.7	-78.1	-40.7
20	-71.8	-60.0	-69.9	-49.4	-57.7	-40.4	-71.8	-40.4
21	-67.4	-57.0	-66.3	-48.8	-62.1	-40.2	-67.4	-40.2
22	-64.1	-54.3	-64.1	-48.1	-61.5	-40.0	-64.1	-40.0
23	-61.8	-51.6	-63.8	-47.1	-63.1	-39.8	-63.8	-39.8
24	-59.8	-49.2	-63.2	-46.0	-63.1	-39.4	-63.2	-39.4
25	-57.6	-47.3	-62.4	-44.8	-63.7	-39.0	-63.7	-39.0
26	-55.8	-45.1	-62.0	-43.3	-63.0	-38.3	-63.0	-38.3
27	-54.7	-43.0	-61.7	-41.6	-60.3	-37.2	-61.7	-37.2
28	-53.8	-40.8	-61.4	-39.7	-60.6	-35.8	-61.4	-35.8
29	-52.9	-38.8	-61.2	-37.5	-61.0	-34.7	-61.2	-34.7
30	-51.7	-37.5	-60.9	-35.5	-59.0	-34.0	-60.9	-34.0

higher than the 95°F wet-hot limit may occur during the dry season. For example, in most of Southeast Asia, wet-hot conditions prevail during the wet monsoon season but, during the dry monsoon season, the higher temperatures associated with intermediate hot-dry conditions apply.

(2) *Category 3, humid-hot coastal desert.* The desert areas on the immediate coast of the Persian Gulf and Red Sea designated as humid-hot are characterized at times by relatively high temperatures (100°F) combined with extremely large amounts of water vapor in the air near the ground (dewpoint 86° F).

TABLE 3-11

NORTHERN HEMISPHERE TEMPERATURE OCCURRENCE WITH ALTITUDE—10-PERCENT PROBABILITY LEVEL, °C (Ref. 43)

Altitude,	Low latitude		Midlatitude		High latitude		Hemisphere	
km	Min	Max	Min	Max	Min	Max	Min	Max
0	19.7	32.3	-12.9	28.2	-26.7	17.6	-26.7	32.3
1	13.5	23.1	-23.8	29.1	-29.8	11.4	-29.8	29.1
2	7.9	17.3	-23.3	23.4	-29.7	6.4	-29.7	23.4
3	4.2	12.6	-24.5	15.2	-33.4	0.9	-33.4	15.2
4	- 1.2	7.2	-29.4	- 7.5	-37.2	- 6.5	-37.2	7.5
5	- 7.4	1.7	-34.5	0.0	-44.3	-13.8	-44.3	1.7
6	-14.2	- 4.1	-40.0	- 6.5	-49.7	-17.0	-49.7	- 4.1
7	-21.5	-10.1	-45.0	-12.7	-54.4	-24.8	-54.4	-10.1
8	-29.0	-16.4	-50.4	-19.4	-58.4	-32.1	-58.4	-16.4
9	-36.7	-23.3	-55.5	-26.7	-60.5	-39.5	-60.5	-23.3
10	-44.2	-30.8	-59.7	-34.4	-61.3	-41.0	-61.3	-30.8
11	-51.2	-38.8	-63.6	-39.2	-62.0	-41.2	-63.6	-38.8
12	-57.8	-47.1	-66.8	-43.2	-62.2	-41.3	-66.8	-41.3
13	-63.8	-55.2	-67.5	-45.6	-61.4	-41.3	-67.5	-41.3
14	-69.0	-61.2	-68.4	-46.9	-61.4	-41.2	-69.0	-41.2
15	-75.2	-65.0	-71.6	-47.6	-62.2	-41.1	-75.2	-41.1
16	-80.8	-67.0	-73.5	-48.4	-62.8	-41.0	-80.8	-41.0
17	-83.7	-67.5	-74.3	-51.2	-60.6	-41.9	-83.7	-41.9
18	-82.2	-66.0	-73.8	-51.1	-61.0	-41.7	-82.2	-41.7
19	-76.8	-63.4	-71.8	-50.9	-58.8	-41.4	-76.8	-41.4
20	-70.6	-60.7	-68.1	-50.3	-55.8	-40.9	-70.6	-40.9
21	-66.4	-57.8	-64.6	-49.7	-59.5	-40.8	-66.4	-40.8
22	-63.1	-55.2	-61.8	-49.0	-59.0	-40.5	-63.1	-40.5
23	-60.8	-52.7	-61.2	-48.1	-60.3	-40.3	-61.2	-40.3
24	-58.6	-50.2	-60.6	-47.1	-60.1	-40.0	-60.6	-40.0
25	-56.4	-48.2	-59.5	-46.0	-60.3	-39.5	-60.3	-39.5
26	-54.5	-46.2	-58.9	-44.6	-59.3	-38.9	-59.3	-38.9
27	-53.3	-44.0	-58.1	-43.0	-57.1	-37.8	-58.1	-37.8
28	-52.4	-42.0	-57.3	-41.4	-57.1	-36.6	-57.3	-36.6
29	-51.2	-40.3	-56.8	-39.4	-57.7	-35.7	-57.7	-35.7
30	-49.7	-38.6	-56.0	-37.5	-56.3	-34.8	-56.3	-34.8

Occasionally, higher temperatures occur in these areas, but not in combination with such a high humidity value.

(3) *Category 4, hot-dry*. The areas designated as hot-dry were delimited on the basis of the occurrence of high temperatures. During the hottest month in a normal year, the temperature may be expected to be above the intermediate hot-dry extreme of 110°F, and is expected to be hotter than 125°F no more than 1 percent of the time in the most extreme part of the area.

(4) *Category 7, cold, and Category 8, extreme cold*. The areas designated as cold

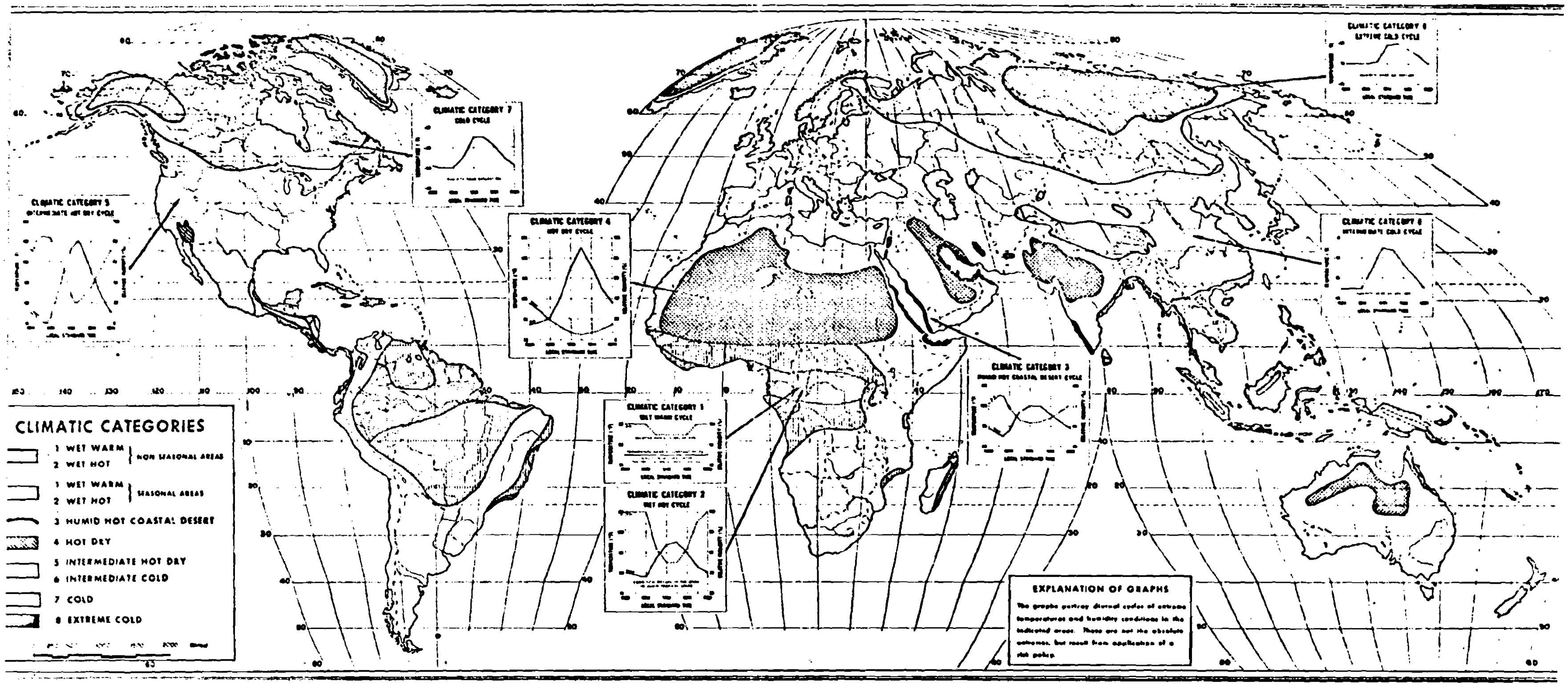


Figure 3-22. Areas of Occurrence of Climatic Categories (Ref. 44)

and extreme cold were delimited on the basis of the occurrence of low temperatures. In the cold areas, the temperature during the coldest month in a normal year may be expected to be colder than the intermediate cold extreme of −25°F, but colder than the cold extreme of −50°F for no more than 1 percent of the time in the most extreme part of the area. In the extreme cold areas, the temperature during the coldest month in a normal year may be expected to be colder than the cold extreme of −50°F but colder than −70°F no more than 1 percent of the time in the most extreme part of the area.

(5) *Category 5, intermediate hot-dry, and Category 6, intermediate cold*. Intermediate hot-dry and intermediate cold conditions apply in the remaining area after the other climatic categories are delimited. Intermediate hot-dry conditions occur primarily near the boundary of the hot-dry category, and intermediate cold conditions occur near the boundary of the cold climatic category. Temperatures warmer than 110°F and colder than −25°F are rare in the intermediate areas in accordance with the 1-percent risk policy. Parts of the area with intermediate conditions are not subject to high or low temperatures.

3-2.5 WORLD TEMPERATURE EXTREMES

Materiel designers are most interested in the extremes of temperature at which stresses are most severe. Thus, the inland, high-latitude regions of North America, Greenland, Eurasia, and Antarctica, which experience extremely low temperatures during their long winter nights, comprise the cold extremes of most interest. Hot extremes are found in the dry, low-latitude deserts – the Sahara, the Arabian, the Thar in India, the Sonoran in North America, and the Australian Desert. An additional extreme is associated with the humid regions where hot or temperate air combined with the moisture presents a combined environment that is particularly difficult to cope with (Ref. 45). In tropical regions, a marked change in climate is found as elevation increases – a mountainside can compress the equivalent of hundreds of miles of latitudinal climate change into the relatively short distance from its hot humid base to its cold peak.

Some of the notable temperature extremes, both in the natural air and in enclosures for comparison, are given in Table 3-12.

3-2.4.1 COLD REGIONS

Three of the four extremely cold winter regions are outlined in Fig. 3-23. The other is Antarctica. In three regions, the mean temperature of the coldest month of the year is −25°F or lower while the coldest parts have temperatures below −40°F at least 10 percent of the time in the coldest month. The four regions are described separately on the basis of climatological records.

(1) *North America*. As seen in Fig. 3-24 the center of the cold zone in northwestern North America lies in central and eastern Alaska and in the adjoining area of northwestern Canada. A less extensive cold zone is located in north-central Canada between longitude 80 and 100 deg W. and latitude 60 and 70 deg N. In these regions, the annual march of temperature follows the pattern shown in Fig. 3-25 where data for Pt. Barrow, Alaska; Alert, Northwest Territories, Canada; a North Pole station; and the floating T-3 station are given. In these regions, diurnal cycles are very weak as shown in Fig. 3-26. Of particular interest to the design engineer is the duration of cold temperatures as given in Table 3-13. At Alert in Canada, −40°F temperatures have persisted up to 6 days.

In Alaska, temperatures of −61.1°C (−78°F) have been reported at Ft. Yukon, −60°C (−76°F) at Tanana, and −57.2°C (−71°F) at Tok. During the severe winter of 1964-1965 – the coldest winter in 50 yr for the area – the temperature at Tok between 11 December and 10 January was −56.7°C (−70°F) or below on 3 days, −53.9°C (−65°F) or below on 12 days, and −51.1°C (−60°F) or lower on 23 days (Ref. 61).

TABLE 3-12

TEMPERATURE EXTREMES IN THE WORLD

Type	Place	°C	°F	Ref.
Air	El Azizia, Libya	57.7	135	46
Air	Oimyakon, Siberia	-71	-95.8	47
Air	Vostok, Antarctica	-88.2	-127	48
Air	Musandam Peninsula, Persian Gulf	59.9	140	49
Air	Omiakon, Siberia	-77.8	-108	50
Air	Mt. McKinley, Alaska	-73.3	-100	50
Sea air	Persian Gulf	40.6	105	51
Sea air	Bering Sea	-40	-40	52
Surface water	Oceans	(-1.8 to 30)	29 to 86	53
Surface	Moon	-178.9 to 121.1	-293 to 250	54
Soil	Loango, French Equatorial Africa	65.6	180	37
Soil	Sahara desert	72.2	172	51
Soil	Alaska permafrost	-10.6	12.9	52
Sea surface	Red Sea	42.2	108	55
Air	Inside tank, Yuma, Ariz.	60	140	56
Air	Inside box car, Yuma, Ariz.	66.7	152	57
Air	Airplane cockpit, Yuma, Ariz.	84.4	184	58
Air	Airplane cockpit, Edwards AFB, Calif.	102.8	217	58
Surface	Metal boxcar, Yuma, Ariz.	77.2	171	57

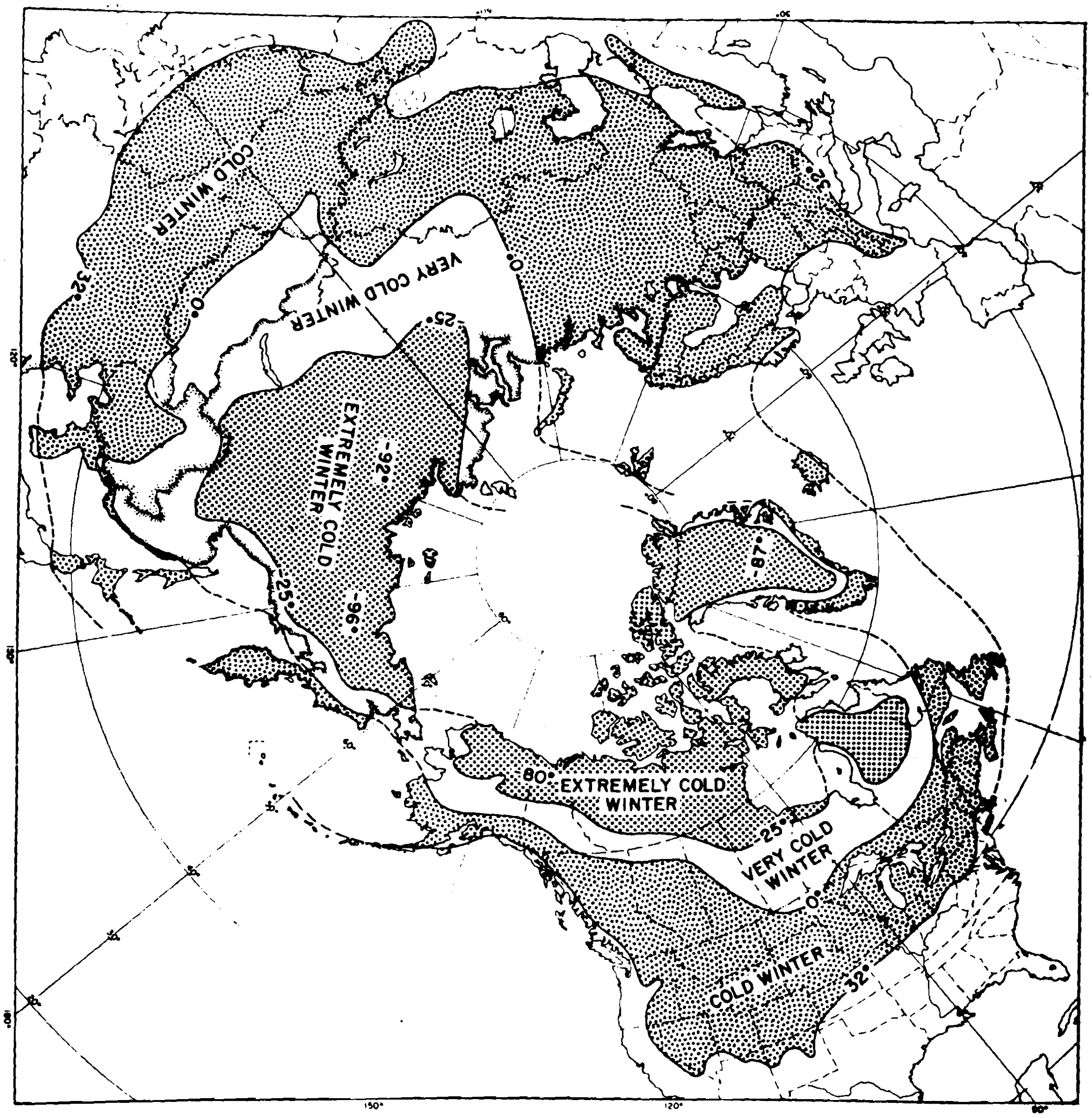


Figure 3-23. Climatic Zones of the Cold Regions of the Northern Hemisphere (Ref. 59)

In Northwestern Canada, an extreme temperature of −62.8°C (−81°F) occurred during an extended cold period at Snag in the Yukon Territory in 1947; over a period of 13 days, temperatures were below −56.7°C (−70°F) for a total of 71 hr on 10 days, below −53.9°C (−65°F) for a total of 119 hr on 11 days, and below −51.1°C (−60°F) for 163 hr on 11 days (Ref. 46).

In North-central Canada, temperatures as low as −53.9°C (−65°F) have been recorded at Isachsen on one occasion, and −51.1°C (−60°F) on eight occasions in a 10-yr period. Five times during the same period at Eureka, −51.1°C (−60°F) has been recorded and on one occasion at Resolute. Other populated places that have a reported temperature of −51.1°C (−60°F) or lower over a 10-yr period include Norman Wells, with three occurrences, Watson Lake with four occurrences, and Coral Harbor and Embarras with one occurrence each (Ref. 62).

(2) *Greenland.* The frequency of occurrence of −40°F temperature in Greenland is

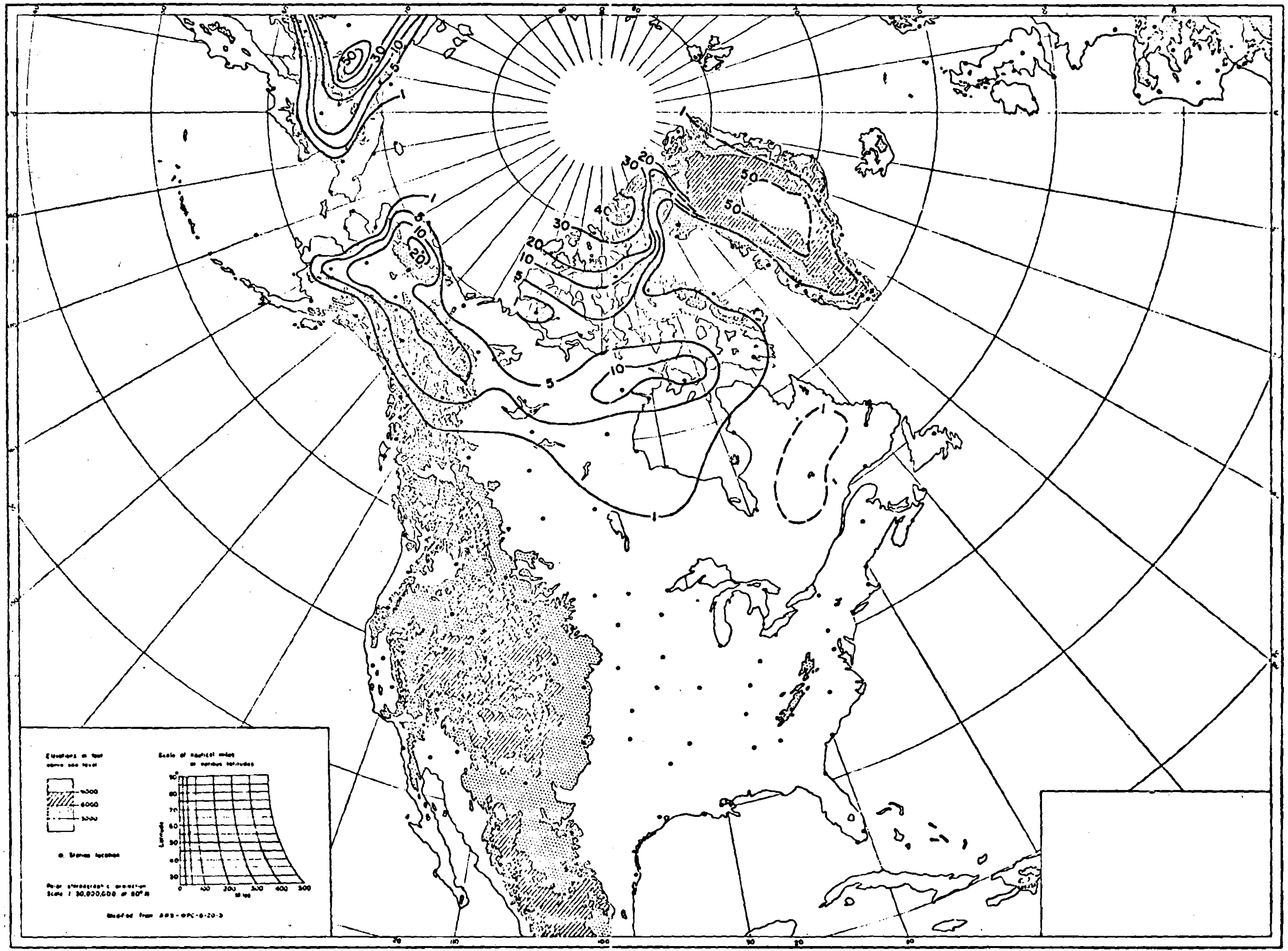
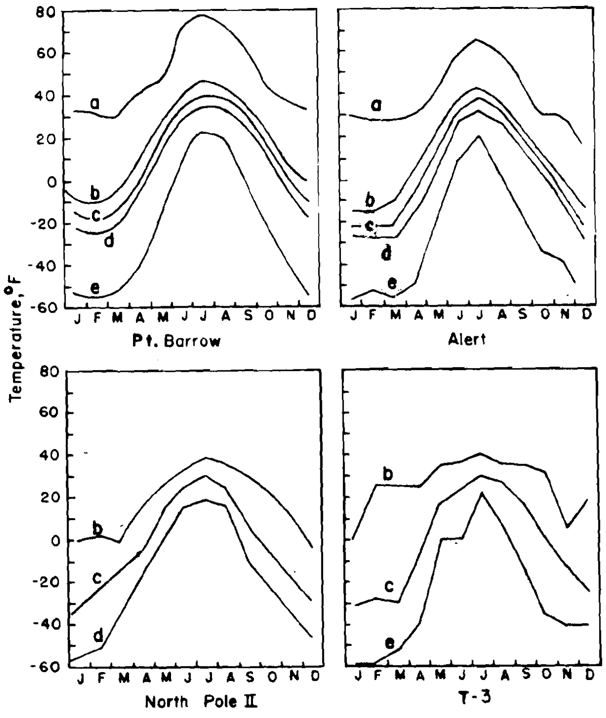


Figure 3-24. Percent Frequency of Temperatures Below –40° F–North America in January (Ref. 31)



a = absolute maximum
b = mean maximum
c = mean
d = mean minimum
e = absolute minimum

Figure 3-25. Annual March of Temperature in Extremely Cold Regions (Ref. 60)

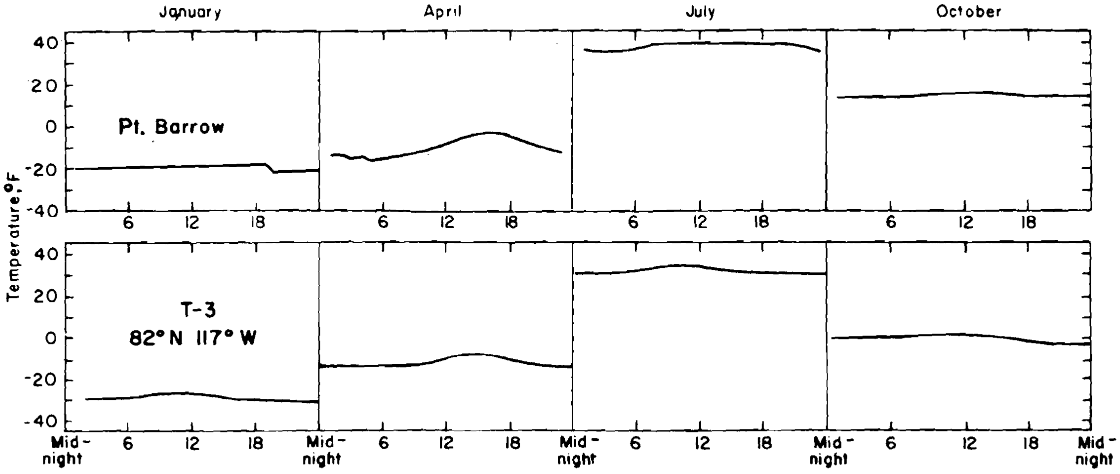


Figure 3-26. Diurnal Temperature Fluctuations, °F (Pt. Barrow data represent a 10-yr mean; T-3 data represent a 2 yr-mean.) (Ref. 60)

TABLE 3-13

DURATION OF COLD TEMPERATURES, DAYS (Ref. 60)
(AVERAGES ARE FOR THE 10-yr PERIOD OF RECORD, 1950-60)

Location	-30°F			-40°F		
	Average	Longest	Shortest	Average	Longest	Shortest
Alert	6.4	15	1	1.6	6	0
Barrow	5.2	12	1	1.1	2	0
Resolute	7.6	12	4	1.7	4	0
Mould Bay	7.6	12	2	2.2	5	0

also shown in Fig. 3-24. The lowest temperature reported in Greenland is −70°C (−94°F) at Northice (latitude 78 deg N. at about 2,500 m in elevation). A low temperature of −65°C (−85°F) has been recorded at Eismitte, located 500 mi south of Northice. At Eismitte, the temperature was below −60°C (−76°F), for a total of 113 hr in the period 15 January through 26 March 1931 (Ref. 46).

During winter, extreme minimum temperatures in the marginal zones of the ice sheet are likely to be between −31.7° and −45.6°C (−25° and −50°F), and in the interior between −51° and −65°C (−60° and −85°F). During the summer, the lowest temperatures in the marginal zone usually range from −1.1° to −17.8° C (30° to 0°F); inland they drop to between −17.8° and −34.4°C (0° and −30°F). The daily minimum temperatures on the ice sheet fluctuate considerably. On 10 occasions in a single winter at Eismitte, the temperature fell more than 16.7 deg C (35 deg F) in 24 hr, and in one instance, the temperature dropped from −14.4° to −64.4°C (6° to −84°F) within 3 days. At another site, on 2 May 1956, the temperature increased from −37.2°C (−35°F) at 0600 hr to −2.2°C (28°F) at 1800 hr (Ref. 63).

(3) *Northeast Siberia*. As seen in Fig. 3-27, the cold zone in Siberia extends from longitude 90 to 160 deg E. and from latitude 70 deg N., and is centered in the Verkhoyansk Basin and the Oimyakon Plateau. Oimyakon with −71°C (−95.8°F) and Verkhoyansk with −68°C (−90.4°F) are the coldest spots. Nearly 100 weather stations near the Arctic Circle record minimum temperatures of −60°C (−76°F) or lower each year. These stations are located in an area that is dominated by a stable, high-pressure system in winter, and is characterized by long polar nights with frequent temperature inversions due to excessive radiation (Ref. 47).

(4) *Antarctica temperature extremes**. The station with the highest maximum temperatures on the Antarctic Plateau is Byrd. During an early winter blizzard in May 1957, the temperature rose to −6.9°C (19.6°F) at Byrd, reflecting the advection of relatively warm air from the Ross Sea to Byrd. In January 1961, Byrd experienced a temperature of −0.8°C (−30.6°F) which was 1.9 deg C (3.4 deg F) warmer than the previous station maximum recorded in 1958. No other inland station has recorded a temperature within 8 deg C (14.4 deg F) of 0°C (32°F).

Minimum temperatures observed in Antarctica have been far lower than any minimum experienced in the Northern Hemisphere. All the interior stations in Antarctica experience minimum temperatures below −73.4°C (−100°F) except Vostok I with a

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*A general reference for this paragraph is Ref. 48.

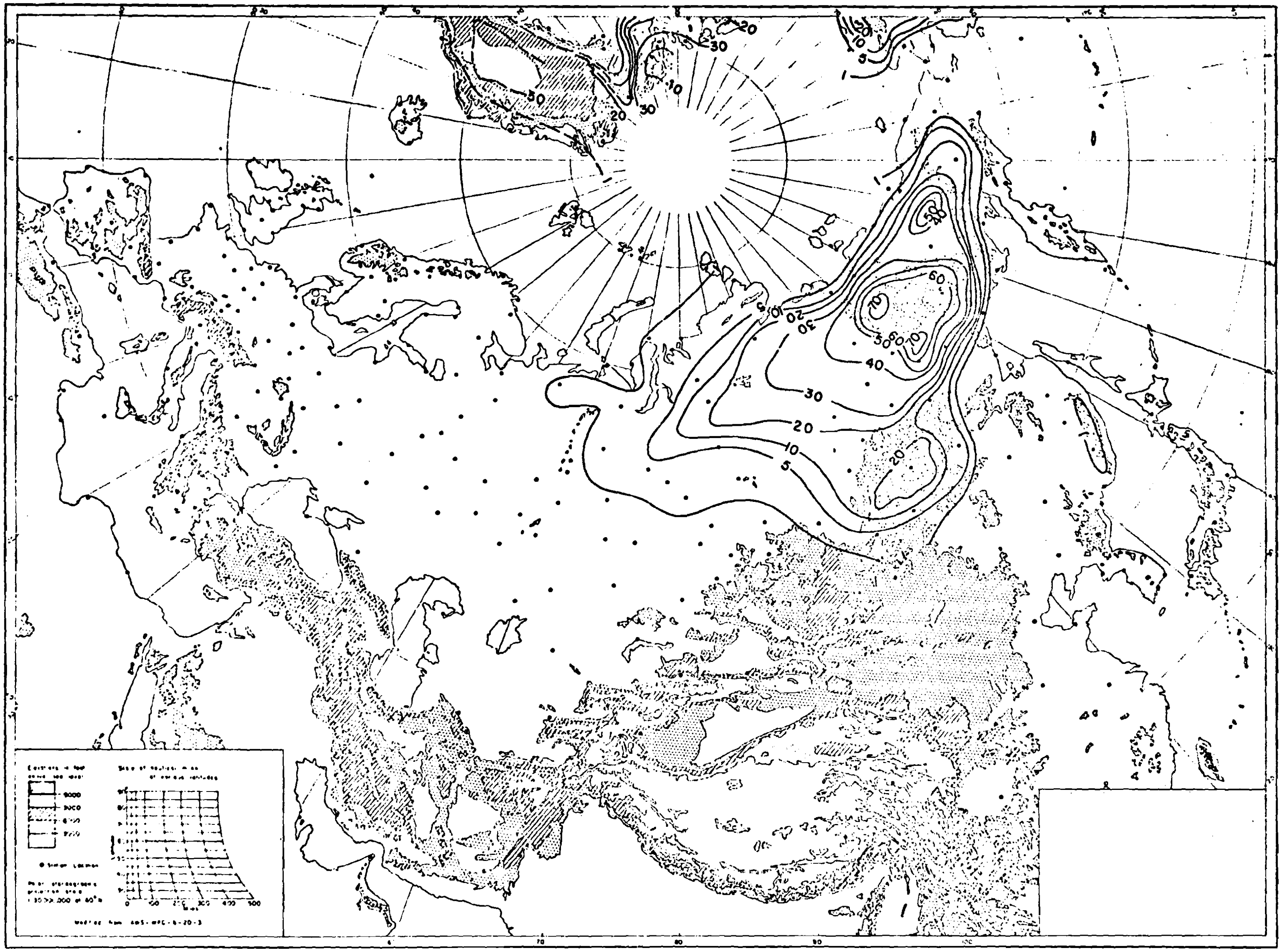

Figure 3-27. Percent Frequency of Temperatures Below –40° F–Eurasia in January (Ref. 32)

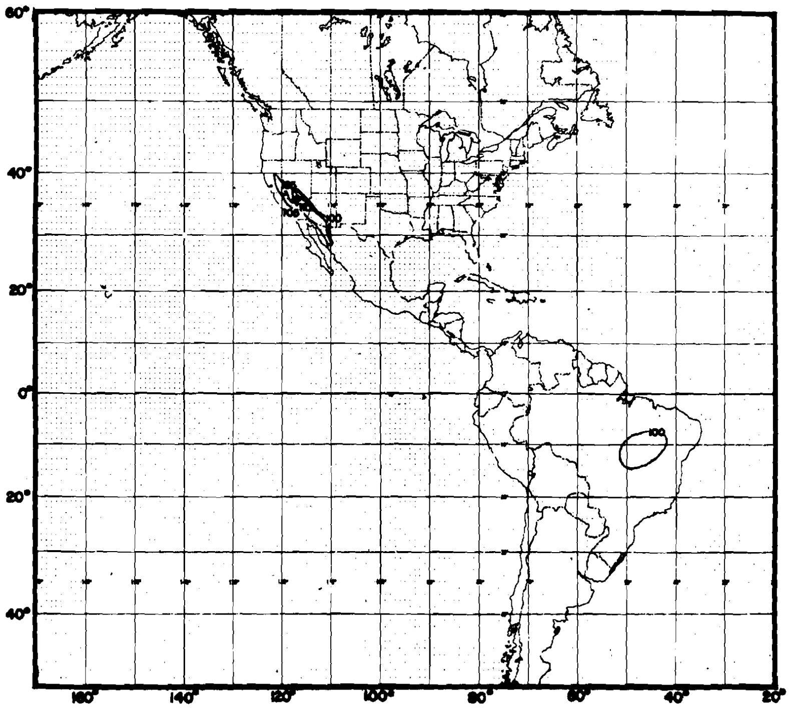

Figure 3-28. Temperature Equalled or Exceeded 5 Percent of Hottest Month, °F—Western Hemisphere (Ref. 64)

minimum temperature of −73.2°C (−99.8°F). Extreme minimum temperatures have been recorded at Vostok and Sovietskaya, and, to a lesser degree, at Komsomolskaya. All three of these stations in the cold central core experience temperatures below −80°C (−112°F). The absolute minimum temperature measured through 1962 was −88.3°C (−126.9°F), occurring at Vostok in August 1960. During August 1958, the absolute minimum recorded at Sovietskaya was −86.8°C (−124.2°F) and at Komosomolskaya, −80.8°C (−112.3°F). The absolute minimum temperature recorded for the South Pole is −80.7°C (−113.3°F), which occurred in July 1965 (Ref. 48).

3-2.4.2 HOT REGIONS*

The hottest part of the world is an area extending from northern Africa eastward to and including most of India. Within this area, large regions attain temperatures of 43.3°C (110°F) more than 10 percent of the time in the hottest month. In northwest Africa temperatures exceed 48.8°C (120°F) as much as 1 percent of the time in the hottest month.

Neither Australia nor South America has temperatures above 43.3°C (110°F) more than 1 percent of the time in the hottest month. Substantial areas in both continents have long periods with temperatures above 37.8°C (100°F) in the hottest month.

In North America, only a narrow strip of land in the Southwestern United States and in western Mexico is extremely hot by world standards. The center of this region has temperatures above 43.3°C (110°F) more than 1 percent of the time in the hottest month. This includes Death Valley, Calif., which has a record of 56.7°C (134°F) (10 July 1913), only 1 deg C (2 deg F) less than the world's record temperature.

In Figs. 3-28 and 3-29 the temperature that is equalled or exceeded 5 percent of the hottest month is mapped, and in Table 3-14, data on high temperatures for selected United

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*A general reference for this paragraph is Ref. 64.

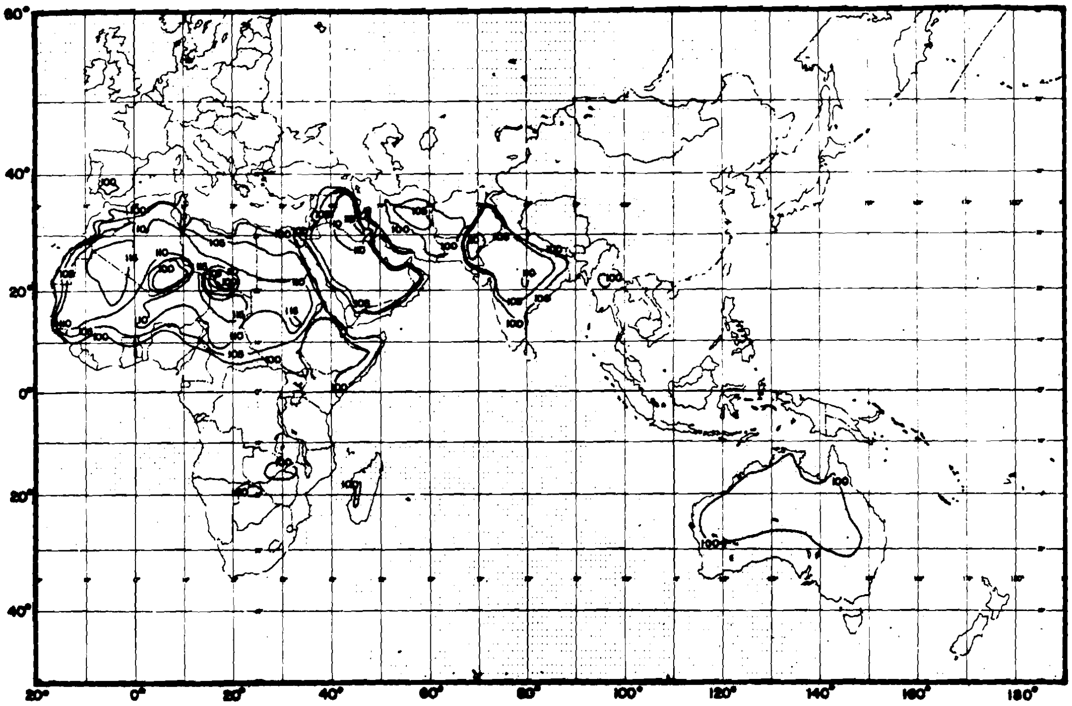

Figure 3-29. Temperature Equalled or Exceeded 5 Percent of Hottest Month, °F—Eastern Hemisphere (Ref. 64)

States stations are given.

The duration of very hot temperatures is of interest to the design engineer. In Table 3-15 the average duration is tabulated as a function of temperature range. Data were employed from only two locations, Death Valley, Calif., and Andimishk, Iran, in compiling this table.

Temperatures at or above 51.7°C (125°F) have been recorded in the Sahara in Algeria, Tunisia, Libya, and in the western Sahara (where a number have exceeded 54.4°C (130°F)), in Death Valley and other spots of the Colorado Desert in California and Arizona, and in the Jacobobad areas of India. Areas where such high temperatures occur with some regularity are uninhabited, and records of thermal conditions are, therefore, hard to find. In Death Valley, temperatures of 51.7°C (125°F) and higher occur on about 2 days in 3 yr, and usually last for 2 to 4 hr. It is emphasized that the temperatures cited are shelter shade temperatures taken 4 to 6 ft above the ground, and that equipment operating in direct sunshine will be exposed to temperatures 16.6 deg to 27.8 deg C (30 deg to 50 deg F) higher than the shade temperatures (Ref. 65).

3-2.4.3 SOIL AND WATER*

Soil temperatures, as noted in par. 3-2.1.2.2, are normally higher than air temperatures. Some examples of soil temperatures are shown in Tables 3-16 and 3-17. The maximum soil temperatures in areas with high levels of solar radiation can exceed air temperatures by more than 50 deg F.

Sea-surface temperatures for February and August, the coldest and hottest months, respectively, are given in Figs. 3-30 and 3-31. In the North Atlantic, the seasonal variation is approximately 10 deg F for a given location. Because of mixing and flow, temperatures of the oceans do not compare with the extremes of the soil but, where the water body is

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*A general reference for this paragraph is Ref. 66.

TABLE 3-14

TEMPERATURES EXCEEDED 1, 5, and 10 PERCENT OF THE HOURS DURING HOTTEST MONTH, ALSO MEAN AND MEAN RANGE, °F (Ref. 64)

	1%	5%	10%	$\bar{T}$	$\bar{T}_x-\bar{T}_n$
Station	Temp	Temp	Temp		
Amarillo, Tex.	99	95	92	81	27
Atlanta, Ga.	97	92	89	79	19
Bakersfield, Calif.	105	102	99	84	28
Birmingham, Ala.	99	94	91	80	21
Boston, Mass.	94	88	85	74	17
Brownsville, Tex.	95	93	92	84	17
Caribou, Maine	88	81	78	65	21
Death Valley, Calif.	123	120	117	102	29
Des Moines, Iowa	96	91	88	77	22
El Paso, Tex.	101	97	94	82	26
Fargo, N. Dak.	94	87	84	71	25
Fresno, Calif.	104	99	97	81	37
Goodland, Fla.	101	96	92	77	31
Houston, Tex.	98	94	92	83	18
Jacksonville, Fla.	98	94	91	83	19
Laredo, Tex.	105	102	99	88	23
Little Rock, Ark.	100	95	93	82	22
Miami, Fla.	94	89	88	82	14
Minneapolis, Minn.	95	89	86	73	24
New Orleans, La.	94	91	89	82	18
Oklahoma City, Okla.	101	96	93	81	22
Phoenix, Ariz.	111	107	104	91	27
Rapid City, S. Dak.	98	92	89	74	28
Sacramento, Calif.	103	97	93	77	36
Salt Lake City, Utah	99	94	91	76	31
Sault Ste. Marie, Mich.	87	81	77	65	22
Tucson, Ariz.	107	102	99	86	26
Washington, D.C.	97	92	89	78	18
Wichita, Kan.	105	98	95	81	23
Yuma, Ariz.	112	108	106	94	28

$\bar{T}$ = mean monthly temperature in hottest month

$\bar{T}_x$ = mean daily maximum temperature for hottest month

$\bar{T}_n$ = mean daily minimum temperature for hottest month limited in extent and shallow, water temperatures will approach those of the soil. In flowing water, the temperature varies widely and is a function of local geography and hydrology.

3-3 INDUCED TEMPERATURE ENVIRONMENT

Natural surface air, soil, and water temperatures are of primary importance but do not provide a complete description of the materiel temperature environment. The interiors of equipment, storage containers, shelters, and buildings can experience temperatures considerably different from the reported temperatures of the natural environment. The temperatures obtained in these circumstances depend to a considerable extent on the reflectivity of the exposed surfaces and on the thermal properties of items exposed.

If the surface has a low heat capacity and is inefficient in transferring heat to and from the interior, the interior temperature can be considerably different from that of the surface. Thus, the ordinary Dewar flask can maintain temperatures very much above or below the ambient because its surface reflects radiation efficiently and because the thermal transfer from the surface to the interior is

TABLE 3-15

AVERAGE DURATIONS OF VERY HOT TEMPERATURES (WITHIN GIVEN AMOUNTS BELOW THE MAXIMUM TEMPERATURE, 110°F OR HIGHER) (Ref. 12)

Deg F below maximum	Average no. of hours
0	2
1	3
2	4
3	5
4	6
5	7
6	7.5
7	8
8	9
9	9.5
10	10
11	10.5
12	11
13	12
14	12.5
15	13
16	13.5
17	14
18	14.5

TABLE 3-16

MAXIMUM RECORDED SOIL TEMPERATURES (Ref. 37)

Station	Temperature	
	°F	°C
Loango, French Equatorial Africa	180	82
Cairo, Egypt	155	68
Germany	154	68
Poona, India	167	75
Tucson, Ariz.	165	74
British Columbia, Canada	160	71
Nanking, China	147	64
Siikakangas, Finland	145	63

TABLE 3-17

GROUND SURFACE TEMPERATURES AND CONCURRENT AIR TEMPERATURES AT SELECTED ALASKAN STATIONS (Ref. 37)

Station	Ground temperature		Air temperature	
	°F	°C	°F	°C
Barrow	-32.3	-35.7	-47.8	-44.3
Big Delta	-39.4	-39.7	-44.4	-42.4
Wainwright	-36.5	-38.1	-34.0	-36.7
Nome	10.8	-11.8	7.0	-13.9
Fairbanks	18.9	- 7.3	- 8.0	-22.2

very low. A building with a reflective roof will have a cooler interior on a hot sunny day than one with an absorbent roof. Insulation of a building protects the interior from extremes of outside temperatures. On the other hand, a dark colored, largely metallic tank can experience very high temperatures under direct solar radiation. A large amount of empirical data has been accumulated on the temperatures experienced by military materiel. Some examples of high temperature are given in the figures and tables that follow.

Artillery ammunition exposed to direct solar radiation in an extremely hot region experiences temperatures 35 deg F above the ambient as shown in Fig. 3-32. However, when left in the storage containers, the ammunition temperature approximated that of the ambient. Fig. 3-33 shows average diurnal temperature cycles for antipersonnel mines both in the ground and in their storage containers in a hot desert environment. At Yuma, Ariz., where much temperature data representative of a hot region are obtained, the noon temperatures of various items of materiel are given in Fig. 3-34. Boxcars exposed to the sun at Yuma showed the temperatures given in Table 3-18. Inside a gasoline storage tank, the average weekly maximum and minimum temperatures over a 45-wk period fell within the ambient extremes as shown in Fig. 3-35.

In vehicles, hot temperatures can be a particular problem. The cockpit of an airplane, with the canopy closed, can reach 160°F as shown in Fig. 3-36. Other aircraft, at China Lake, Calif., showed the maximum temperatures listed in Table 3-19. In an M60 Tank, interior air temperatures of 140°F have been recorded as shown in Table 3-20.

Ammunition storage facilities obtain a large amount of insulation when covered with earth. Data on 11 magazines are given in Table 3-21. These data are based on a large number of measurements extending over as much as 6 yr.

In Fig. 3-37 temperatures are shown for an Army warehouse in which experiments were performed to assess the effects of insulation and ventilation. The control area was not ventilated but the test area was. The advantage of ventilation is apparent – a 10 deg F temperature reduction. These data – taken at Richmond, Va. – indicate the storage temperatures experienced on a hot day (maximum of 96°F outside air temperature) in a temperate climate.

The induced temperature environment – i.e., that determined by the properties of materiel and structures, by operational procedures, and by energy dissipation – will usually be high compared with the natural

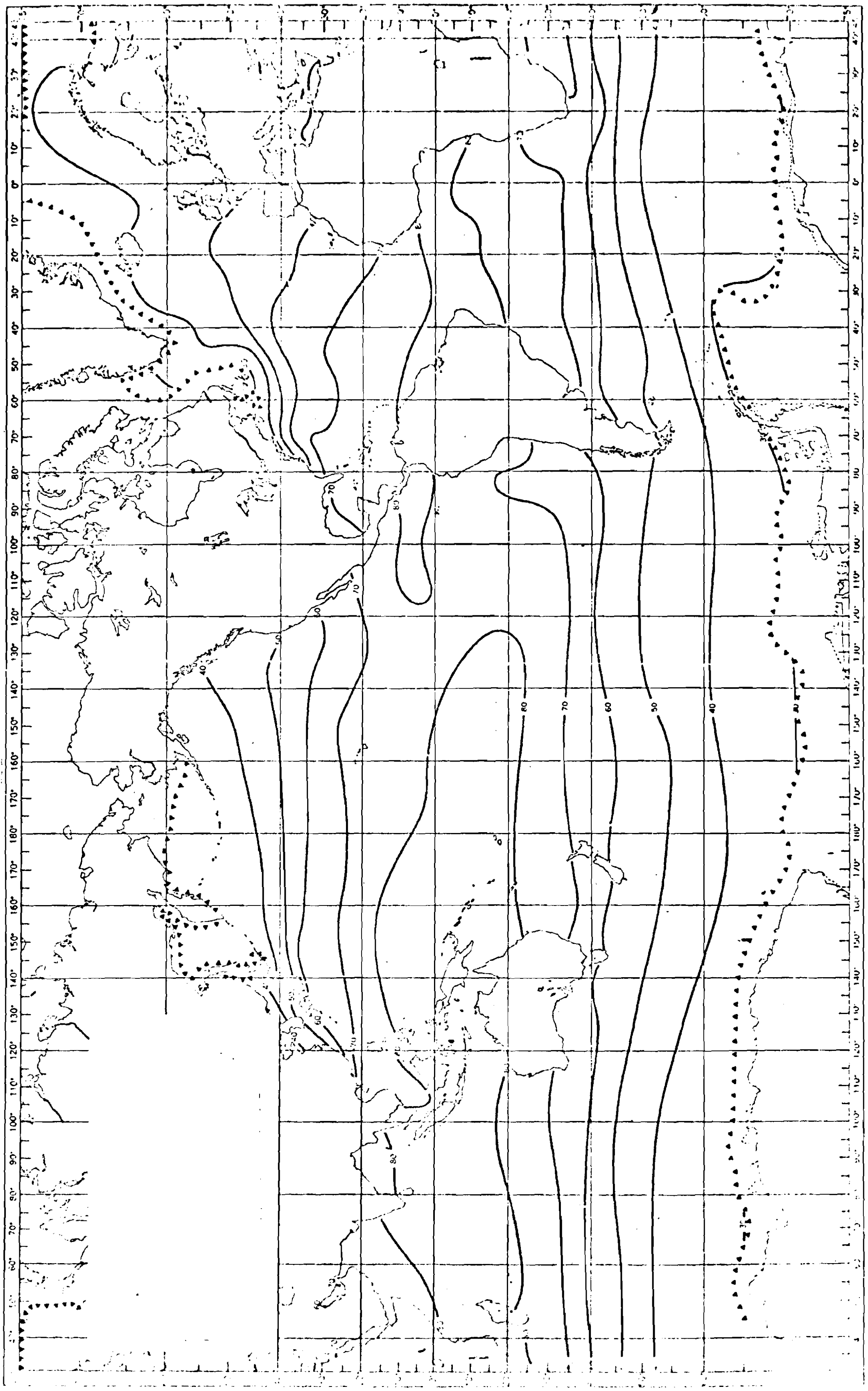

Figure 3-30. Mean Sea-surface Temperature, °F—February (Ref. 26)

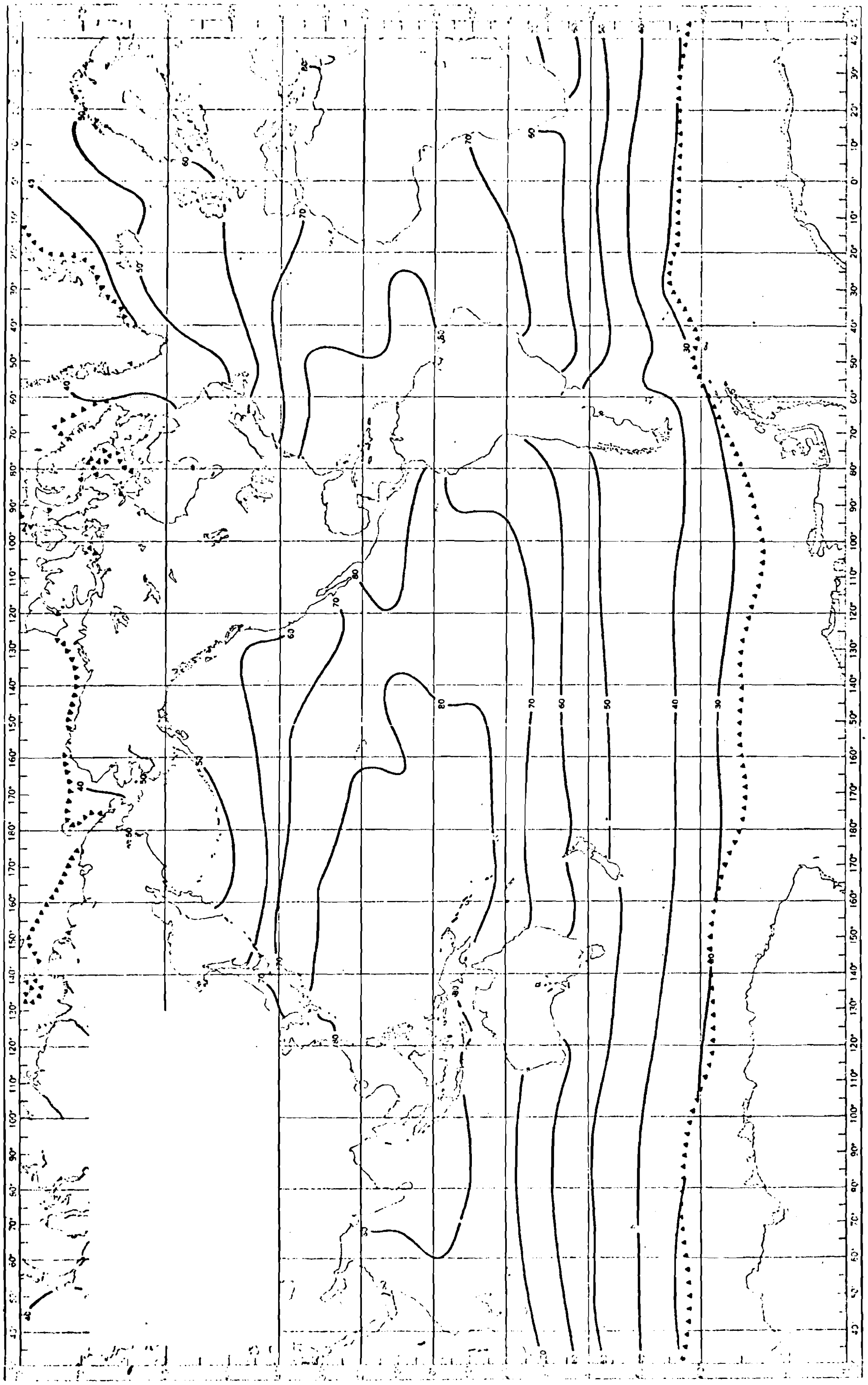

Figure 3-31. Mean Sea-surface Temperature, °F—August (Ref. 26)

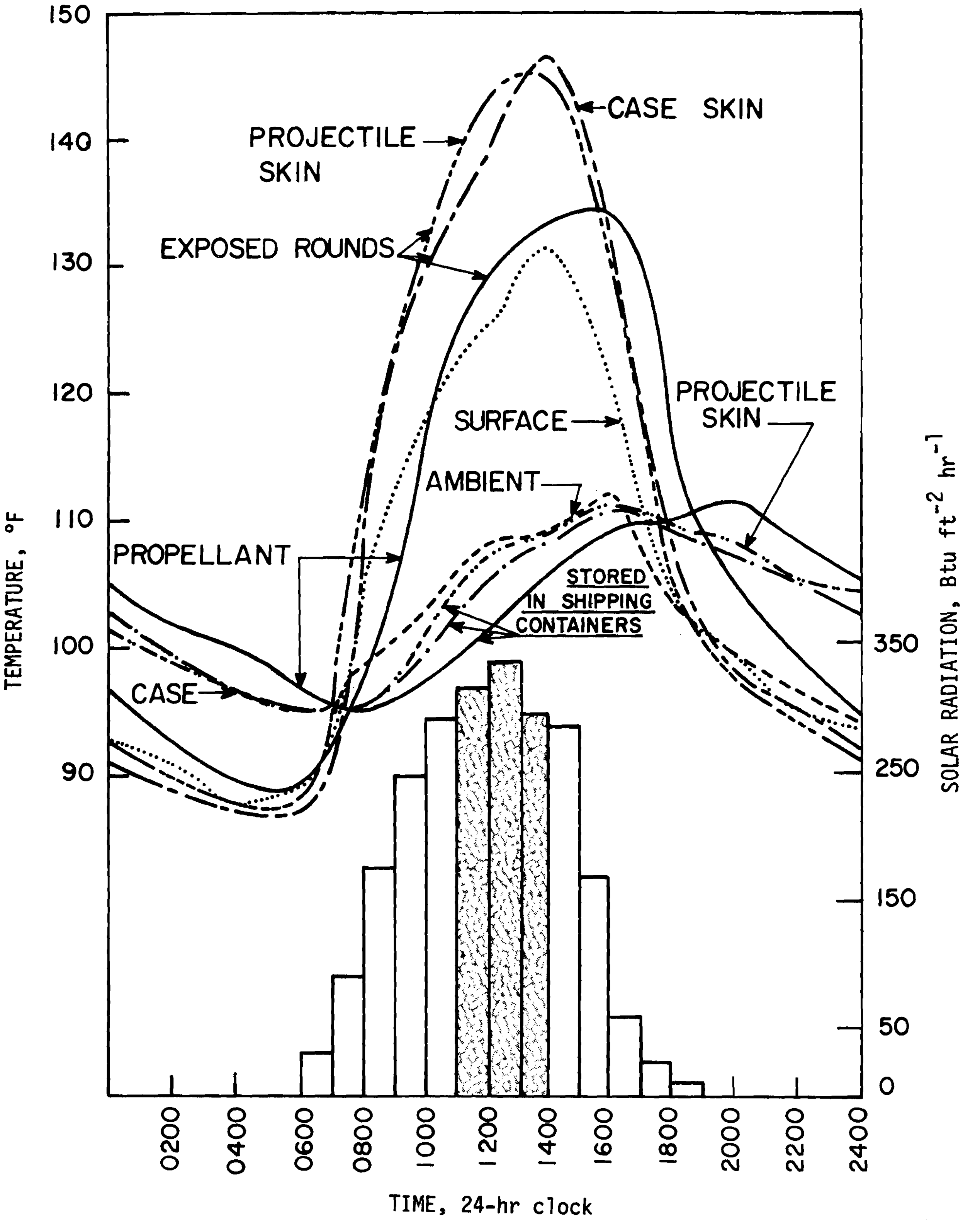

Figure 3-32. Temperature Conditions Encountered During Storage of 105 mm, HEP-T Cartridge (Stored in shipping container with exposure to direct solar radiation, 21 August 1961) (Ref. 67)

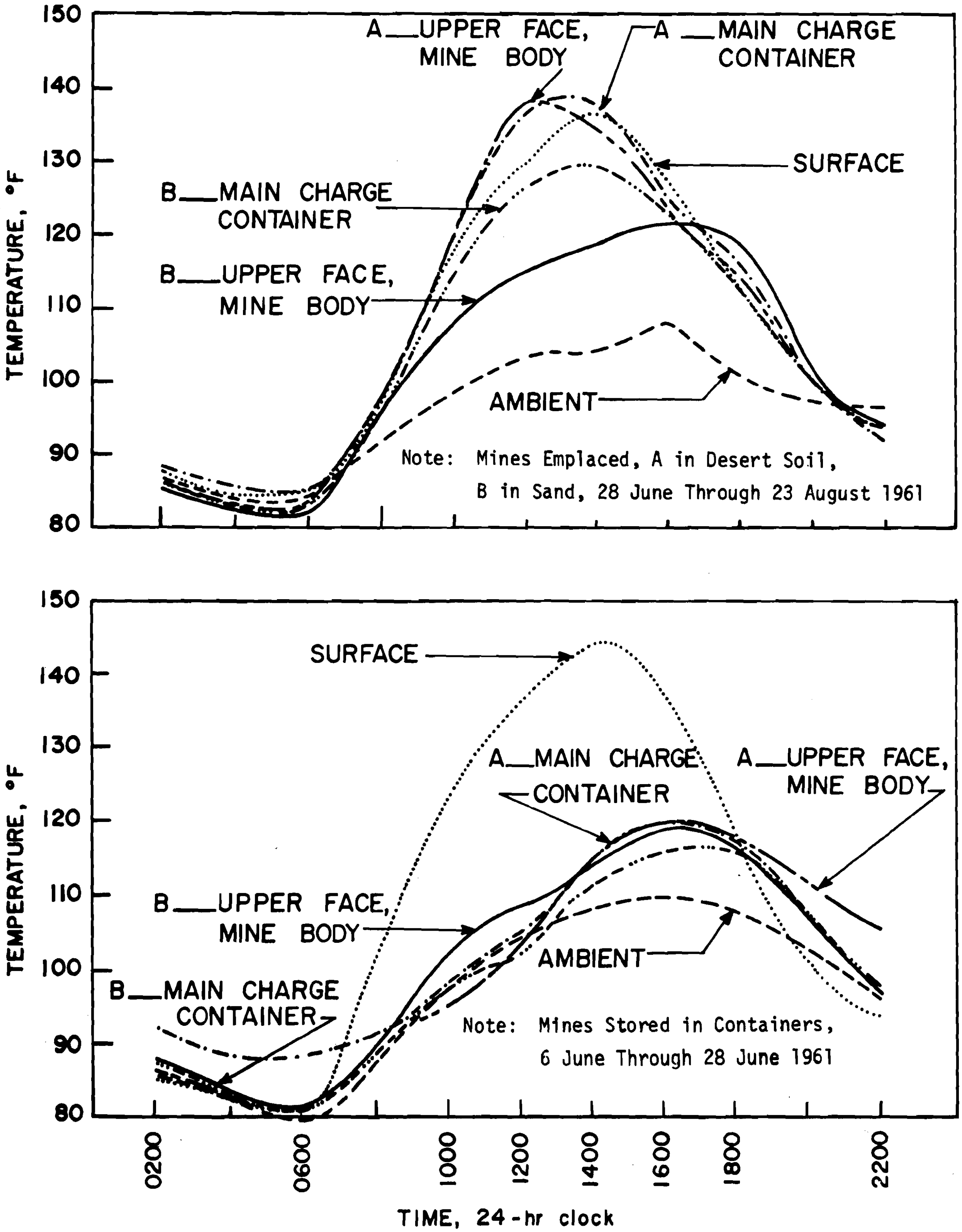

Figure 3-33. Average Daily Temperature Cycle During Emplacement and Storage of Antipersonnel Mine (Canadian "Elsie") (Ref. 67)

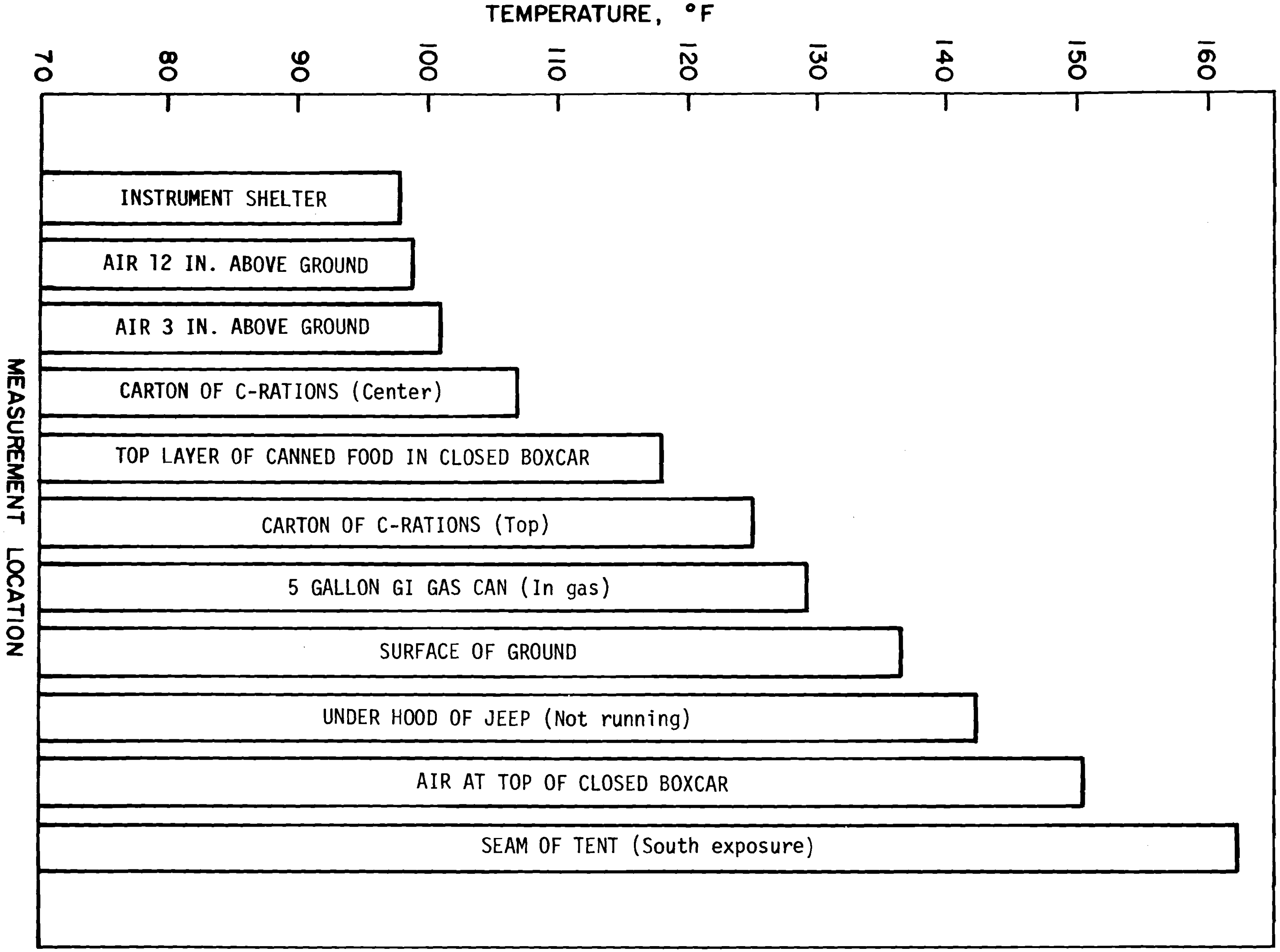

Figure 3-34. Temperatures Recorded at Noon on a July Day at Yuma, Ariz. (Ref. 68)

TABLE 3-18.

MAXIMUM TEMPERATURES IN STANDING BOXCARS AT YUMA, ARIZ., °F* (Ref. 57)

	Absolute maximum	Lowest daily maximum
Roof air	152 (11 Aug)	93 (30 Apr)
Top center carton	119 (15 Aug)	81 (30 Apr)
Food	113 (15 Aug)	79 (30 Apr)

*Measurement in cartons of canned vegetables where top center carton was about 5.5 ft from roof of boxcar

temperature environment. Insolation can and does heat objects above ambient. On the other hand, objects are seldom colder than the environmental extremes of cold temperatures because of the inherent thermal transfer process – air obtains its thermal energy from the ground, water, and other surroundings. However, on a given day, it is possible for interior temperatures to be lower than outside temperatures. This is most evident in the natural case observed in the Arctic where large regions have a permanent frozen layer under the surface soil and the temperature of water often remains very close to the freezing temperature.

3-4 MEASUREMENT AND INSTRUMENTATION

The NBS *Bibliography on Temperature Measurement* contains over 2,000 references for the period from 1953 through December 1965 (Refs. 72, 73, 74). This is cited in order to indicate the complexity of temperature measurement. A large number of special mensuration problems are associated with temperature – these problems are found in cryogenics, plasma research, combustion, space, and almost all other advancing technologies (Ref. 75). In limiting consideration to temperature as an environmental factor, it is possible to reduce but not to eliminate the complexity of the problems to be considered. The simple task of measuring air temperature on a sunny day can result in a wide range of values when untrained personnel are employed. The problem of observing, monitoring, and recording of temperatures in a variety of materials and substances throughout the earth emphasizes the need for careful consideration and refined techniques. Only a few of the more relevant topics associated with temperature measurement can be presented here.

If an accurate and rapidly responding thermometer is exposed to the air and the temperature is continuously recorded, it will often be found that in a period of 10 min, the temperature will vary by 2 deg F or more. Similarly, if the same thermometer is carried on a vehicle over a short distance, temperature variations of from 2 deg to over 20 deg F can be found in a distance of 2 mi or less. The observations are made in order to emphasize that the measurement of air temperature to an accuracy of greater than 1 deg F is not justified. Even for water temperatures, the temperature gradient with depth is so large that precision of greater than 1 deg F is not justified for routine observations. Soil temperature does not vary as rapidly so that accuracies of 0.1 deg F or better may be employed. When measuring the temperature of exposed materiel, the constancy of the

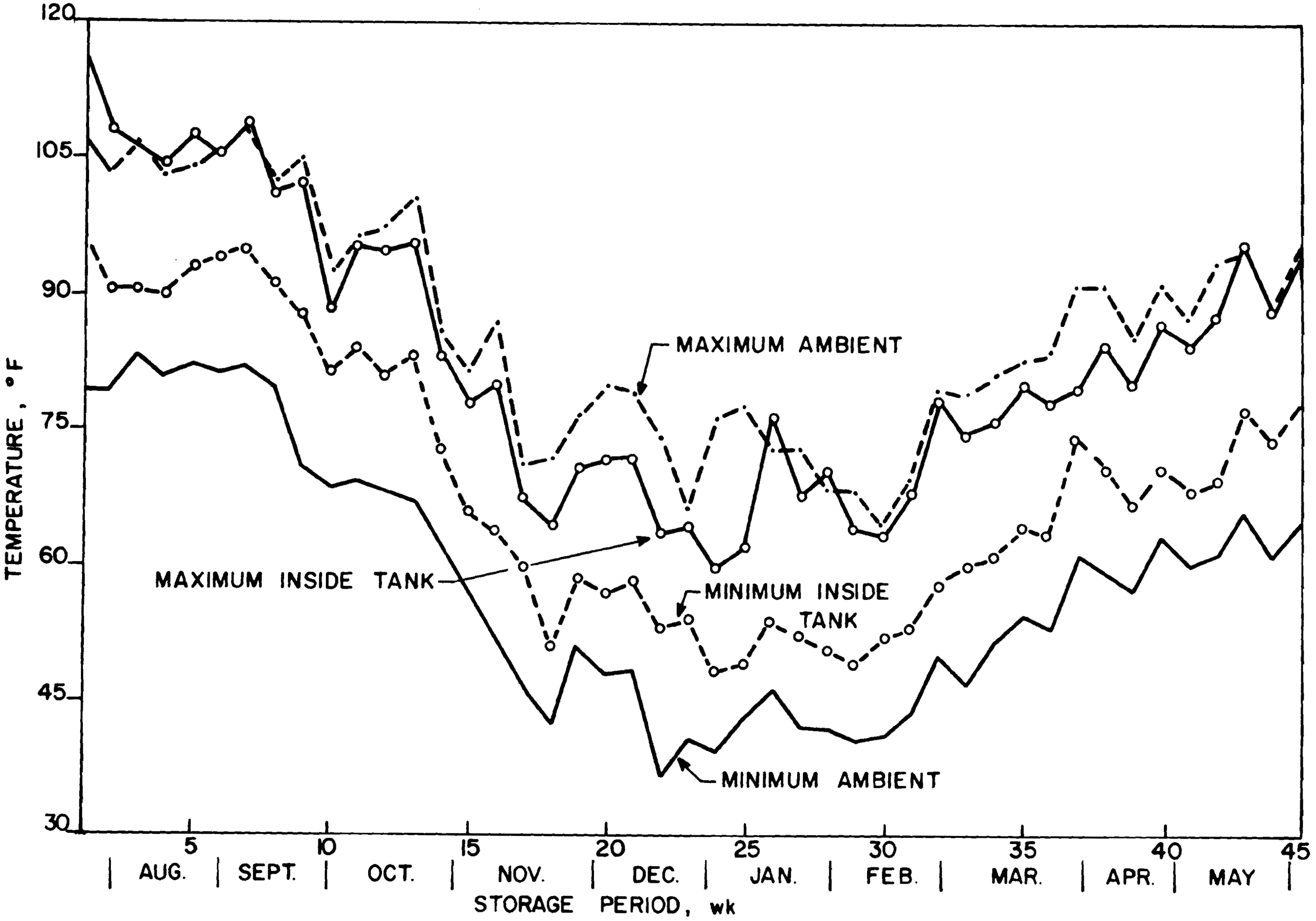

Figure 3-35. Average Weekly Maximum and Minimum Temperatures Inside a Storage Tank for Motor Gasoline (At Yuma, Ariz., 21 July 1958 to 2 June 1959) (Ref. 68)

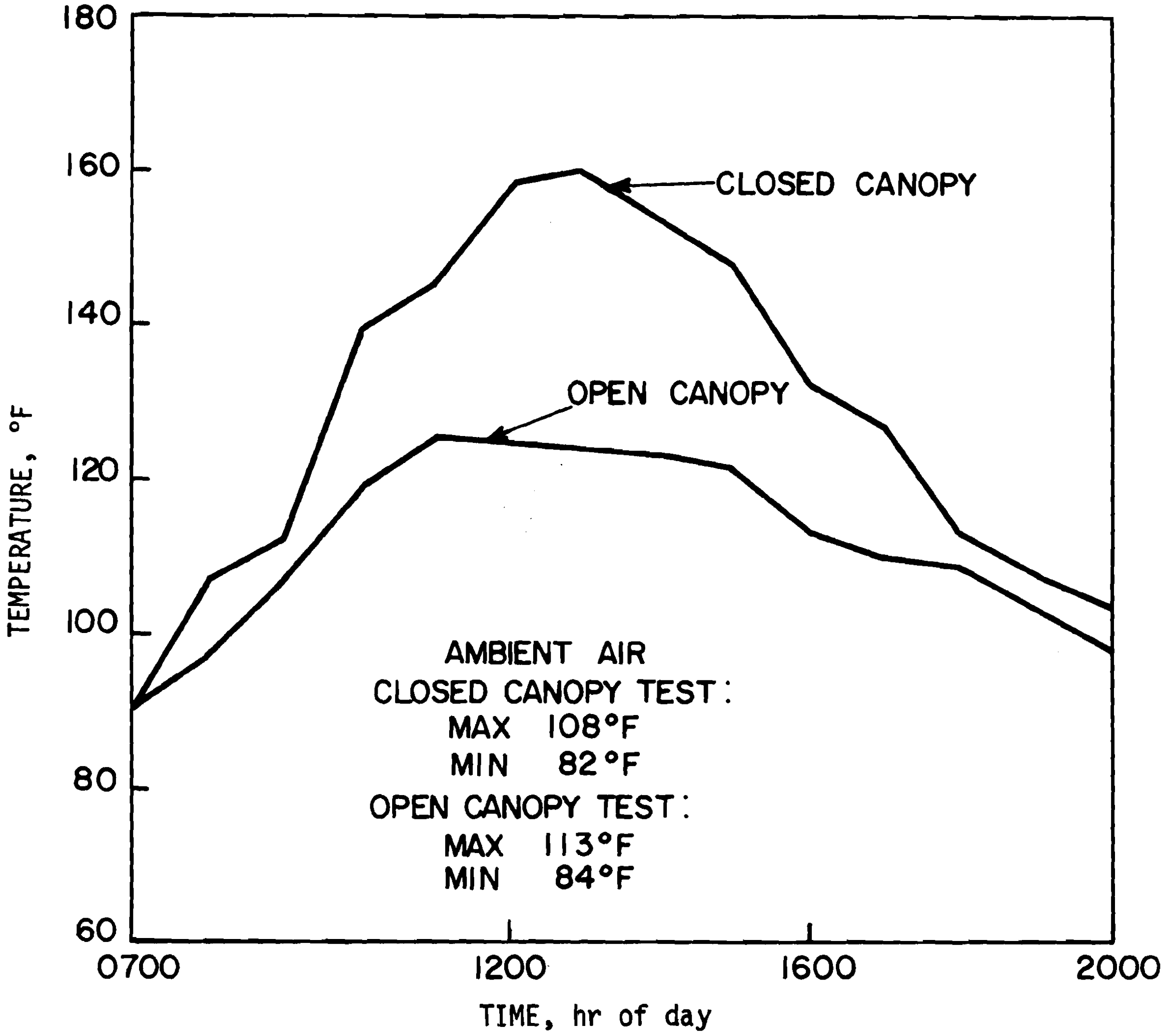

Figure 3-36. Open and Closed B47E Airplane Cockpit Temperatures at Yuma, Ariz. (Ref. 68)

temperature being measured should be considered before any accuracy requirement is specified (Ref. 76).

Changes in the physical characteristics or properties of matter resulting from temperature change serve as the basis for a wide variety of temperature measurement methods. The most widely used effect is the expansion and contraction of matter due to heating and cooling, respectively, and is exemplified by gas, liquid, and metallic thermometers.

However, the limitations of this type of instrument – for example, the necessity for contact and thermal equilibrium of the instrument with the medium being measured – have led to the development of alternate methods of temperature measurement.

These include measurement of radiation from the substance being measured, the propagation speed of sound waves through it, electrical or magnetic properties of the substance, and its spectroscopic properties. A majority of the properties of matter change with temperature, thus providing a variety of usable phenomena but also complicating the measurement. Each technique is best for some specific measurement; none serves well for all temperature measurements.

The following summary of underlying physical principles of temperature measure-

TABLE 3-19

DISTRIBUTION OF MAXIMUM LOCAL TEMPERATURES IN AIRCRAFT (DURING SUMMER TESTS AT CHINA LAKE, CALIF.) (Ref. 68)

Aircraft and date	Temperature, °F			
	Ambient	On instrument panel	Inside top of canopy	On cockpit floor
F-84, NOTS*				
19 July	109	168	155	140
19 August	106	167	145	134
18 July	111	167	153	140
17 July	108	167	159	137
16 July	107	165	151	136
15 July	107	164	153	134
12 August.....	107	164	149	135
13 July	101	163	152	132
6 August	106	163	150	135
7 August	108	163	150	135
20 July	105	162	157	133
20 August	105	162	144	131
8 August	105	161	147	136
A4D, NOTS*				
26 July	104	165	170	137
6 August	106	164	171	134
11 August	106	162	173	135
12 August	107	162	176	137
19 August	106	161	172	133
9 September .	101	161	171	135
A4D, El Centro				
18 August	119	162	183	152

*Now Naval Weapons Center, China Lake, Calif.

ment is presented in terms of the major physical effect involved:

(1) *Expansion*. Liquids, gases, and solids expand and contract with temperature changes. Liquid-filled, gas-filled, and bimetallic thermometers are the most frequently used applications of this principle. Liquid-filled thermometers using mercury and alcohol are most common. In gas thermometers, the increase in pressure is often employed to indicate the temperature. In bimetallic thermometers, the differential expansion of two metals bonded together is utilized. Deformation caused by the differential expansion is employed for temperature indication. Increases in stress occurring in a material when its length is held constant while its temperature increases are proportional to the temperature increase. Indirectly, the expansion of metals is also used to measure temperature through the expansion of an X-ray spot pattern of the crystal lattice.

(2) *Electrical*. The major electrical effect accompanying a temperature change is the change in conductivity of metals and semiconductors. The resistance of metals increases

TABLE 3-20

SURFACE TEMPERATURES OF AN M60 TANK EXPOSED TO SOLAR RADIATION (Ref. 69)

Location	Temp, °F
Outside air	115
Interior air	140
Exterior surface	150
Interior wall	140-145
Ammunition rack	130-135

with increasing temperature; that of semiconductors decreases with increasing temperature. Resistance thermometers, thermistors, and semiconductor thermometers utilize these effects. The thermoelectric effect wherein a voltage is generated at the heated junction of two dissimilar metals serves as the basis for the widely used class of thermometers known as thermocouples.

(3) *Optical.* Radiation thermometry or optical pyrometry is an application of the Stefan-Boltzmann Law, which states that the emission of total radiant energy from a body is proportional to the fourth power of its absolute temperature. Both visual and photoelectric optical pyrometers are highly accurate for measuring high temperatures. Infrared thermometry using sensitive detectors are being increasingly utilized in commercial and military applications. Advantages of optical techniques are that they can be used at a distance and do not require thermal equilibrium between the instrument and the substance being measured. They can be used equally well on static or moving objects. The rapidity of emission changes in response to temperature changes makes these techniques well suited to measurement of highly transient temperatures.

(4) *Acoustical.* The speed of sound is a function of temperature. In general, with increases in temperature, speed decreases in solids and liquids but increases in gases. This principle is the basis for ultrasonic thermometry. As temperature increases, the rate of change of sound velocity is greatest at low temperatures for gases, essentially constant for liquids, and maximum at high temperature for solids. Sound waves are sent either through a medium or through a secondary material in thermal equilibrium with the medium being measured. Material employed as secondary sources are either quartz crystals or thin wires.

(5) *Chemical.* Changes in chemical composition and the rate of chemical reaction as a result of heat changes serve as the basis of a variety of techniques for measuring temperature. Changes in color, texture, and shape are used as indicators of temperature change and temperature levels. The chemical changes in the substances employed may be permanent or reversible. Materials used in these techniques include liquid crystals, minerals, wax crayons, pellets, and paints. They are inexpensive but have limited accuracy and sensitivity.

3-4.1 TEMPERATURE MEASURING INSTRUMENTS

A variety of sensors and instruments have been developed for use in temperature mea-

TABLE 3-21

AMMUNITION STORAGE FACILITY TEMPERATURES (Ref. 70)

Storage locations	Magazine type	Time, yr*	N**	Number of maximum temperatures equal to or greater than		Maximum recorded temperature, °F
				90°F	100°F	
Naval Ammunition Depot, Oahu, Hawaii	Earth-covered	6	39,155	128	0	98
	Nonearth-covered	6	7,165	2,203	0	99
Naval Air Station Barbers Point, Oahu, Hawaii	Earth-covered	2	2,146	95	3	101
	Nonearth-covered	2	2,837	141	1	100
Naval Magazines, Guam	Earth-covered	3	6.739	35	0	98
	Nonearth-covered	3	679	471	79	104
Naval Air Station, Agana, Guam	Earth-covered	3	6,518	416	8	108
	Nonearth-covered	2	2,421	311	1	105
Naval Magazines, Republic of the Philippines	Earth-covered	5	9,100	661	1	100
	Nonearth-covered	2	140	69	56	110
Naval Station, Sangley Point, Republic of the Philippines	Earth-covered	1	3,479	476	1	101
	Nonearth-covered	1	383	8	0	98

*Length of time in complete calendar years

**Number of data points represented in the sampling

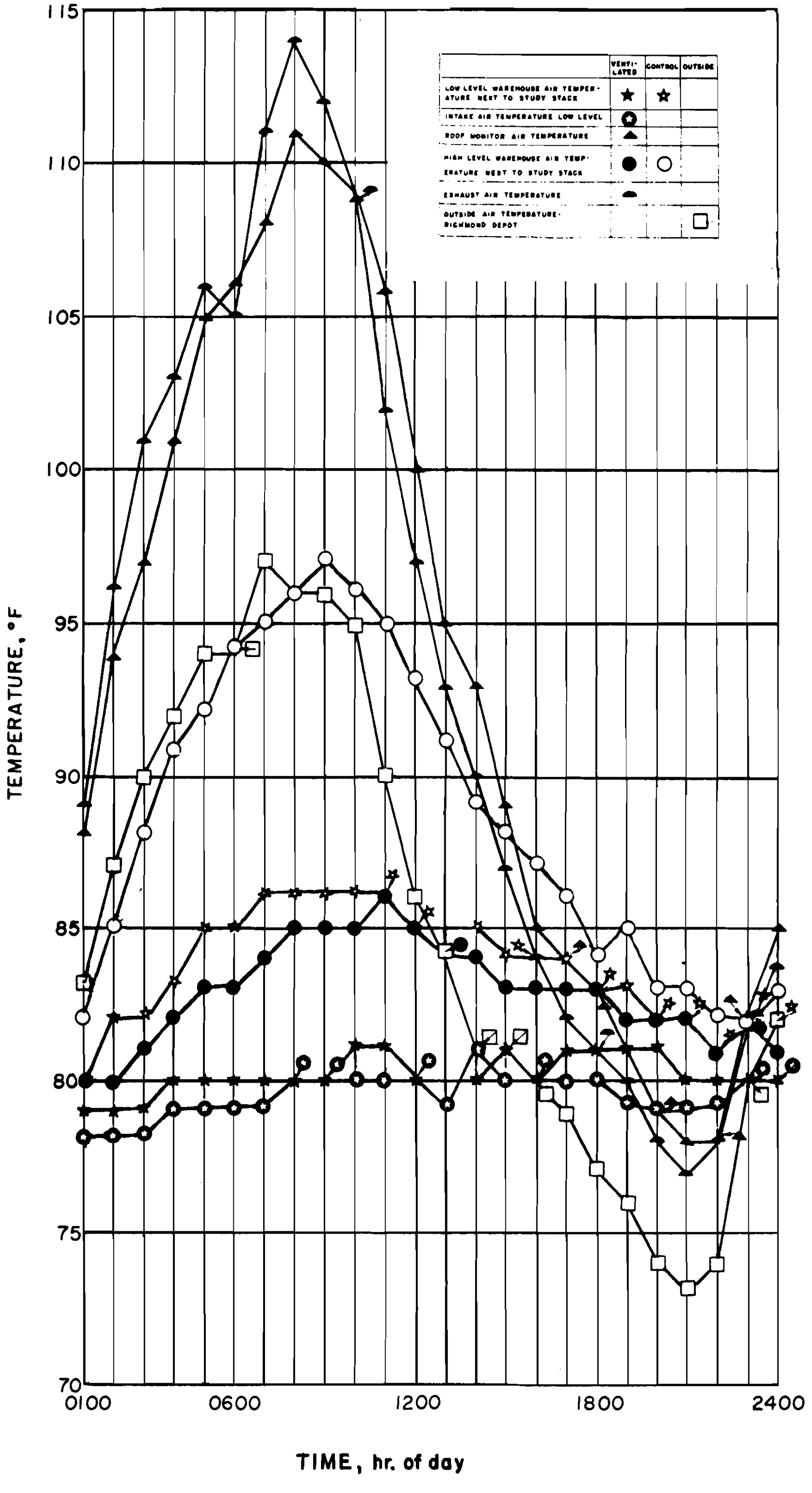

Figure 3-37. Warehouse Air Temperatures for Hottest Day, 1956 (Ref. 71)

surement. Sensors include liquid-in-glass thermometers, thermocouples, thermistors, pyrometers, infrared detectors, thermopiles, gas thermometers, and bimetallic thermometers. Instruments range from simple indicators to others that can provide a linear graph with time, a digital record, a digital display, a two-dimensional display with temperature proportional to brightness or color, or provide a graph of temperature as a function of another variable. Almost any desired precision can be obtained.

With respect to precision and to the amount of data, it is important to consider the usefulness of the data. As previously noted, measuring natural air temperature, for example, to a precision greater than 1 deg F is illogical; equally undesirable would be recording temperature at 1-s intervals in a weather station. For some purposes, e.g., evaluating the performance of a heat sink in an electronic assembly, higher precision in temperature measurement is desirable. Choosing the proper sensor and instrument for a given temperature measurement is essential.

The discussion that follows provides information on the common meteorological instruments as well as some designed for laboratory use and is based on several of the many excellent discussions of such instrumentation (Refs. 76, 77).

3-4.1.1 LIQUID-IN-GLASS THERMOMETERS

These thermometers are invariably used for routine observations in the laboratory and for air temperatures – including maximum, minimum, and wet-bulb temperatures. They include the common mercury-filled or alcohol-filled indicating thermometers. The mercury-filled thermometers are usually more accurate and maintain their accuracy better than those filled with alcohol. Mercury-in-glass thermometers indicate temperatures by virtue of the differential expansion of mercury and glass. Mercury thermometers, if prepared under carefully controlled conditions and carefully calibrated, can be quite accurate. Mercury freezes at –38.89°C (–38° F) and alcohol, at –117.3°C (–179.14°F), limiting the lower temperature to which these types should be used. The temperature range of liquid-filled thermometers is from approximately –117° to 1,204°C (–180° to 2,200°F). Some types are sensitive to changes as small as 0.006 deg C (0.01 deg F). In general the useful temperature range is in inverse ratio to sensitivity.

Maximum and minimum thermometers are a type of liquid-in-glass thermometer useful for obtaining daily average temperature. This is the standard method of the National Weather Service. On individual days, considerable difference may exist between the average of the hourly temperatures and the daily average.

The most common maximum thermometer is a mercury-filled glass-tube type with a fine constriction in the bore near the bulb. The remaining space in the tube is a vacuum. When the mercury in the bulb expands, it is forced past the constriction; when it contracts, the mercury that has been forced past the constriction remains there so that the maximum temperature reached will be indicated. This thermometer is reset by swinging it with the bulb down so the centrifugal force pushes the mercury past the constriction into the bulb.

Minimum thermometers are usually liquid-in-glass types, with ethyl alcohol (C_2H_5OH) used as the liquid. Pentane (C_5H_{12}) and toluol ($C_6H_5CH_3$) may also be used. A black glass dumbbell-shaped rod, called the index, is located inside the column of liquid in the bore of the thermometer and, as the temperature falls, surface tension at the top of the alcohol column pulls the index down. When the column rises, the alcohol flows past the index leaving it at the point of minimum temperature. The thermometer is reset by tipping the bulb end up until the index returns to the top of the column of alcohol.

When using the alcohol thermometer, care

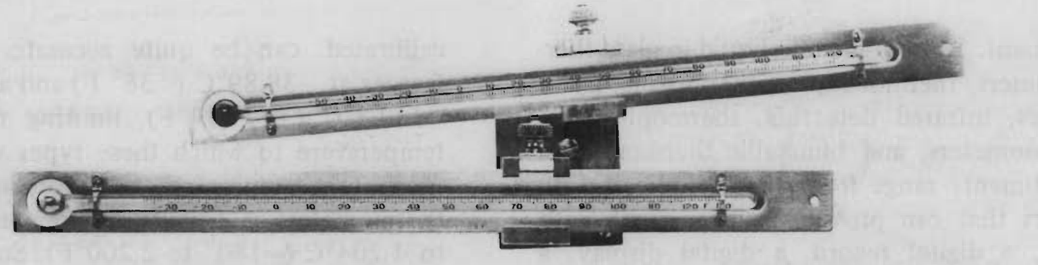

Figure 3-38. Maximum and Minimum Thermometers Mounted in the Operating Position

must be taken to insure that none of the fluid has evaporated from the surface of the liquid and condensed somewhere near the top of the thermometer. If this condition is not corrected, the top of the main column of liquid will be too low. Sometimes, when jarred, the column will separate, forming one or two bubbles in the main column, causing the top of the column to be too high. It may take from 5 to 10 min of tapping, a bath of crushed ice, or a salt-ice mixture to unite the segmented columns. Errors in the minimum reading may also result from vibrations or other disturbance of the instrument, which can cause the index to change position. Both maximum and minimum thermometers are exposed in an almost horizontal position; the maximum with bulb slightly higher than the top, the minimum horizontal. A mounted pair is shown in Fig. 3-38. Unless high ventilation and good radiation shielding are provided, errors of 1.7 deg or 2.2 deg C (3 deg or 4 deg F) can occur.

Another type of maximum and minimum thermometer (Six's), which uses glycerin ($HOCH_2 \cdot CHOH \cdot CH_2OH$), indicates both points on the same instrument (see Fig. 3-39). The glycerin bulb is attached at one end of a U-tube and an expansion chamber is at the other end. The U-tube is partially filled with mercury, which moves back and forth as the glycerin expands or contracts. One side is calibrated to read minimum temperatures, which decrease as one reads up the scale. Because of this, it is easy to make a mistake in reading since the maximum and minimum scales are read in opposite directions. Small steel indicators float on the mercury on each side of the U-tube. They are held at the highest point reached on either side by means of small springs. This thermometer is reset by drawing the steel indicators back to the level of the mercury with a magnet.

3-4.1.2 BIMETALLIC THERMOMETERS AND THERMOGRAPHS

The temperature-sensitive element of a bimetallic thermometer is an elongated strip made of two metals bonded together. The metals have different coefficients of expansion so that the strip deforms with a change in temperature. One of the materials used is generally Invar (an iron-nickel alloy), since it has a low coefficient of thermal expansion. The other is usually brass (for low temperature) or nickel (for higher temperature). Deformation is indicated by a pointer on a

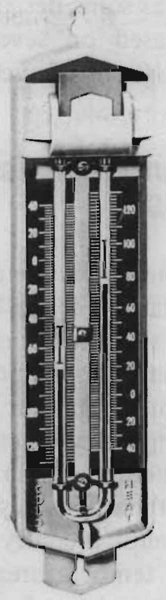

Figure 3-39. Maximum-Minimum Six's Thermometer

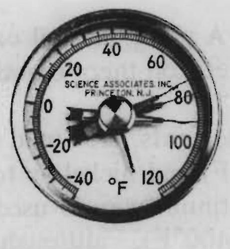

Figure 3-40. Bimetallic Maximum-Minimum Thermometer

temperature scale. Choice of exposure, so as to eliminate the effects of radiation, is important. A bimetallic thermometer that includes pointers indicating maximum and minimum temperatures is shown in Fig. 3-40.

When properly constructed and calibrated, a bimetallic thermometer may be accurate, but many of the inferior indicating thermometers of this type are unreliable. A bimetallic strip is often used as the sensing element in a thermograph such as shown in Fig. 3-41. If blowing snow crystals should fall on the bimetallic strip, erroneous readings may result, particularly when the ambient air is above freezing. A Bourdon tube, a bent, metal liquid-filled container of elliptical cross section which straightens out when the liquid is heated, is also used in thermographs. This type of thermograph is very convenient to use and is also accurate if shielded from radiation, rain, and snow.

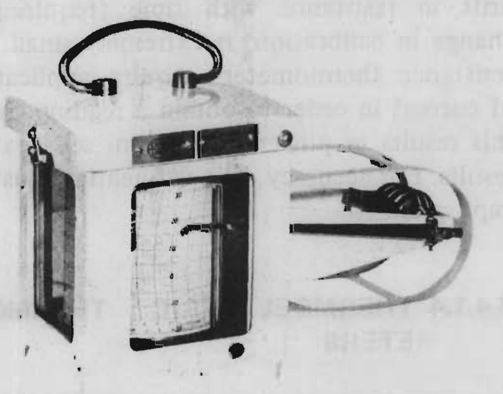

Figure 3-41. Thermograph Employing Bimetallic Coil as Sensor

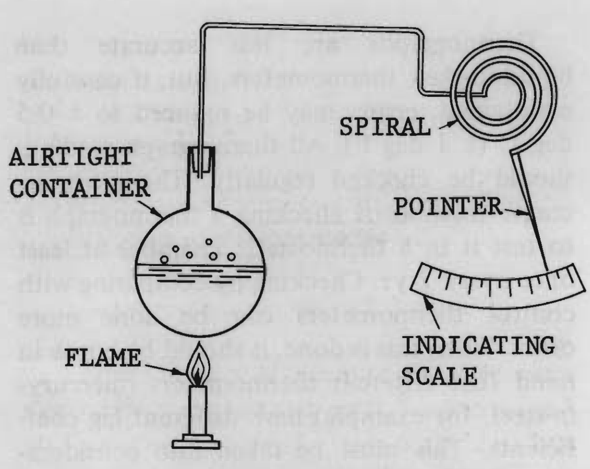

Figure 3-42. Operating Principle of Vapor Pressure Thermometer

Remote thermometers or thermographs are sometimes made with a sensitive element connected by capillary steel tubing to the recording mechanism. In this type, a bulb (the sensitive element) is filled with liquid, gas, or vapor, which expands when heated. The increased pressure is transmitted to the indicating or recording mechanism by means of capillary tubing. The pressure change is calibrated on a temperature scale. The principle of this is illustrated in Fig. 3-42. Considerable accuracy can be attained. Owing to the thermal mass of the bulb, the instrument is slow in responding to change and presents problems in radiation shielding. However, it is well suited to ground temperature measurements. A soil maximum-minimum thermometer using this principle is shown in Fig. 3-43.

Figure 3-43. Soil Maximum-Minimum Thermometer With Capillary Tube Connecting Sensor and Indicator

Thermographs are less accurate than liquid-in-glass thermometers, but, if carefully maintained, errors may be reduced to ± 0.5 deg C (± 1 deg F). All thermograph readings should be checked regularly. The most accurate method of checking a thermograph is to test it in a thermostatic chamber at least once every 2 yr. Checking by comparing with control thermometers can be done more often. When this is done, it should be borne in mind that different thermometers (mercury-in-steel, for example) have different lag coefficients. This must be taken into consideration by checking when the air temperature is not changing rapidly.

The temperature range of bimetallic thermometers is from –40° to 427°C (–40° to 800°F). Accuracy is usually ± 5 percent, although it can be as high as ± 1 percent.

3-4.1.3 RESISTANCE THERMOMETERS*

Electrical thermometers are of two types – resistance and thermoelectric. Neither of these types is widely used in weather shelters, but both are employed – chiefly in laboratories – for measurement of temperature gradients in small spaces or at remote points. For precision measurements, some form of potentiometer circuit is used; for less accurate work, an out-of-balance bridge circuit is used in the case of the resistance thermometer. The low voltage levels associated with these instruments sometimes gives accuracy problems due to electrical noise.

Resistance thermometers depend upon the change in electrical resistance with temperature. Most metallic resistance thermometers are made from one of three metals – platinum, nickel, or copper. Platinum is used for fundamental standards since it maintains its calibration for a long period. Nickel is satisfactory for secondary standards and, when a close linear relation between resistance and temperature is desired, copper is used. The sensitive element consists of a coil supported in air, or some other medium, and protected by a sheath. A platinum coil on a mica frame is used for precision thermometry.

Copper elements are used up to about 121°C (250°F) and nickel up to about 316°C (600°F). Platinum wire is used up to about 1315°C (2,400°F), although evaporation causes some zero drift in the readout above 538°C (1,000°F).

An upper limit for platinum is about 1,593°C (2,900°F) when the platinum wire is embedded in pure alumina to decrease the effects of contamination.

Semiconducting elements are used in thermistor sensors. Their useful range is from –45.6° to 316°C (–50° to 600°F). Materials used are generally oxides of nickel, iron, cobalt, copper, magnesium, or titanium. Their temperature coefficient of resistance is about 10 times that of metallic elements so that narrower temperature spans and greater sensitivity are obtained. Response time is on the order of milliseconds. Tolerances on nominal resistances can be kept to about ± 0.5 percent.

Diamond thermistor devices measure temperatures continuously and accurately from –129° to 343°C (–200° to 650°F). The only thermistor available that can sense over this wide range without discontinuities, the diamond thermistor, exhibits excellent repeatability, high stability, and fast response. The drift in resistance with time (requiring a change in calibration) is extremely small. All resistance thermometers require application of current in order to obtain a reading. Since this results in power dissipation, self-heating results. For accuracy, this self-heating must be kept small.

3-4.1.4 THERMOELECTRIC THERMOMETERS

A current flows in a thermoelectric circuit if it consists of two dissimilar metals and if the various junctions between these metals are not all at the same temperature. When only

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*General references for this paragraph are Refs. 77 and 78.

two metals are used, the total emf in the circuit is proportional to the difference in temperature of the reference and the measuring junctions. The reference junction is always kept at a constant temperature (e.g., in a container with melting ice). Thermocouple instruments are especially useful for differential measurements and can be made to have a lag coefficient of only 1 or 2 s. A thorough discussion of thermoelectric thermometry has been published by Roeser (Ref. 78).

Precision high temperature measurements are made with platinum and rhodium alloy (90 parts platinum to 10 parts rhodium). Copper and constantan (Cu-Ni alloy), affording a much larger emf per degree of temperature, are usually used for meteorological measurements. Iron and constantan, Manganin and constantan, and Chromel and Alumel are also used. Table 3-22 gives application information for the more common thermocouples and calibration voltages are illustrated in Table 3-23. Complete calibration tables are available from the manufacturers of thermocouples and from the National Bureau of Standards.

3-4.1.5 ACOUSTICAL THERMOMETERS*

The speed of sound in a medium is a function of temperature. Free-air temperatures, for example, are determined in one of the commonly used methods by using a short pulse of high-frequency sound generated by applying a voltage to a piezoelectric crystal. This is propagated through a fixed distance and received by an identical piezoelectric receiver, which generates a voltage that is amplified. The voltage, after being peaked, is fed back to the pulse generator, which causes a new pulse to be initiated. The time between pulses is the total time taken within the electrical circuit from the receiver to the outgoing pulse, which is constant, and the transmission time, which depends on temperature. The distance between transmitter and receiver can be arranged so that successively generated pulses possess a frequency that can be measured by ordinary instruments and read as temperature. Measurement is immediate and independent of solar radiation.

Quartz thermometry is based on the sensitivity of the resonant frequency of a quartz crystal to temperature change. The temperature range of natural quartz thermometers is −80° to 250°C (−112° to 482°F). Below −80°C (−112°F), synthetic quartz crystals are required. The quartz thermometer is considerably more linear than a platinum resistance thermometer: 0.05 percent of the span from −40° to 250°C (−40° to 482°F) for quartz compared to a typical figure of 0.55 percent for the same range for a resistance thermometer. Linearity of the quartz thermometer is superior to that of thermocouples and thermistors, which have a linearity that is approximately exponential. Usable resolution of quartz thermometers is about 0.0001 deg C for both absolute and differential measurements.

The quartz thermometer is equal to platinum resistance thermometers and thermocouple measuring systems with respect to repeatability, long-term stability, speed of response, self-heating, and probe interchangeability. Other characteristics are direct digital readout (no bridge balancing, or reference to resistance-temperature or voltage-temperature tables or curves), immunity to noise and cable resistance effects, no reference function, and good interchangeability between sensing probes. This instrument is, however, expensive (> $3,000).

Acoustical measurement techniques have been employed to measure temperatures of cryogenic gases, plasmas, molten glass, and solids over a temperature span from −456° to over 6,000°F.

3-4.1.6 RADIATION THERMOMETRY*

Thermometers based on the change in

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*General references for this paragraph are Refs. 77 and 79.

*General references for this paragraph are Refs. 77, 80, and 81.

TABLE 3-22

APPLICATION OF THERMOCUPLES (Ref. 78)

Type	Usual temperature range		Maximum temperature	
	°C	°F	°C	°F
Platinum to platinum-rhodium	0 to 1,450	0 to 2,630	1,700	3,100
Chromel-P to Alumel	-200 to 1,200	-300 to 2,200	1,350	2,450
Iron to constantan	-200 to 750	-300 to 1,400	1,000	1,800
Copper to constantan	-200 to 350	-300 to 650	600	1,100

TABLE 3-23

VOLTAGE-TEMPERATURE RELATION FOR DIFFERENT THERMOCOUPLES (Ref. 72)

Temp, °C	Voltage, mV (reference junction at 0°C)				
	90 Pt-10 Rh to Pt	87 Pt-13 Rh to Pt	Chromel-P to Alumel	Iron to constantan*	Copper to constantan
-200	-	-	- 5.75	- 8.27	- 5.539
-100	-	-	- 3.49	- 4.82	- 3.349
0	0.000	0.000	0.00	0.00	0.000
100	0.643	0.646	4.10	5.40	4.276
200	1.436	1.464	8.13	10.99	9.285
300	2.315	2.394	12.21	16.56	14.859

*The properties of iron-constantan vary with the quality of the material available. Materials must be selected and matched to a calibration table for accurate results.

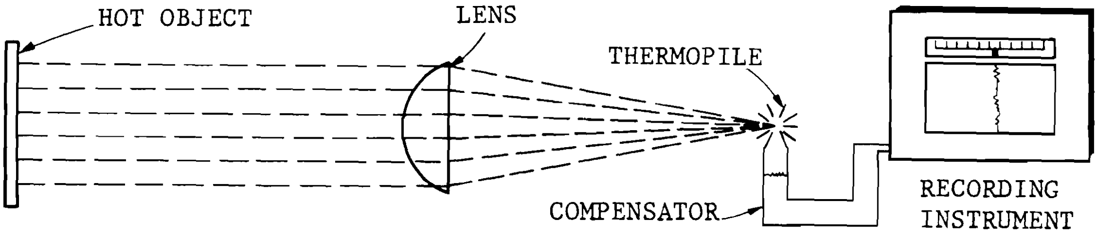

Figure 3-44. Principle of Radiation Pyrometer

electromagnetic radiation with temperature include pyrometers and infrared thermometers. Radiation pyrometers utilize different sensitive elements such as thermocouple junctions, thermopiles, thermistors, photovoltaic cells, and photoconductive or photoemissive cells. Two-color radiation pyrometers measure the relative intensities in two fractions of the electromagnetic spectrum, and their ratio provides a measure of temperature that does not require the emissivity of the substance to be known (emissivity is the ratio of the actual energy radiated to the theoretical maximum or blackbody level). The principle of a radiation pyrometer is shown in Fig. 3-44.

Optical pyrometers measure temperature by comparing the radiant intensity of an incandescent object with an adjustable, calibrated reference element. Balancing of intensities can be done either visually or by a photocell. The range of optical pyrometers is from 537° to about 4,500°C (1,000° to 8,000°F) and give readings to about ± 5.5 deg C (± 10 deg F). Those types in which the balancing is performed by the human eye can achieve a high level of precision ± 0.05 deg C (± 0.1 deg F) at 1,010°C (1,850°F).

An infrared thermometer measures the temperature of materials, hot or cold, moving or static, without physical contact through application of the principle that radiation from an object is proportional to the fourth power of the absolute temperature (Stefan-Boltzmann Law). Response to temperature change is instantaneous at any distance and changing intervening conditions normally have negligible effect upon the accuracy of measurement.

One type of infrared instrument consists of a sensing head with aiming sights and controls, amplifiers, and indicating meter. For continuous measurements, the sensing head may be bracketed or tripod mounted; an electrical output is provided to drive standard chart recorders and controllers. Operation of the instrument follows. Radiation from the selected target and from an internal, controlled cavity is alternately sensed by a thermistor bolometer detector. Because it is sensitive only to standard bandwidths of long wavelength radiation between 8 and 14 μm, it is capable of accurate measurement of temperature as low as −45°C (−50°F), far beyond the limits of usefulness of radiometric devices sensitive only to short infrared wavelengths. Temperature readings are shown directly on meter scales.

The infrared thermometer is sensitive to radiation in a spectral region in which water is highly emissive and the atmosphere is transparent; it can, therefore, look through the atmosphere to make accurate readings of water surfaces. Special calibrations can be made over a total span of from −45° to 1,100°C (−50° to 2,000°F); accuracy is independent of altitude or distance. Infrared thermometry is used extensively in airborne equipment for obtaining thermal profiles of terrain. Infrared radiometers are also used for satellite mapping of both land and water temperature patterns.

3-4.1.7 CHEMICAL KINETIC THERMOMETRIC DEVICES*

Pyrometric cones are slender trihedral pyra-

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*A general reference for this paragraph is Ref. 77.

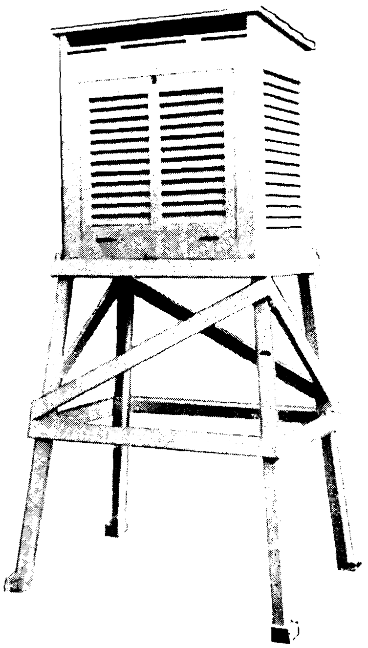

Figure 3-45. Standard Weather Instrument Shelter

mids composed of mixtures of minerals that soften and bend when heated. By suitably varying their composition, a series of such cones can be arranged to deform at uniform intervals between 300° and 2,000°C (500° and 3,600°F). They are widely used in the ceramics industry.

Certain mixtures of materials undergo permanent changes when exposed to increasing temperatures. Such mixtures, in the form of paints, pellets, and crayons are used to indicate temperature variations by changes in their color or texture. Temperature-sensing screws, an application of this method, contain a heat-sensing colored material inserted into the head. The material melts at a predetermined temperature. The usual range of these screws is from 38° to 537°C (100° to 1,000°F). This class of devices, although inexpensive, is generally not very accurate.

A form of liquid crystals, "cholesterics" (derivatives of cholesterol) exhibit color changes with slight changes in temperature. The overall temperature range in which they can be used is from –20° to 150°C (–4° to 300°F), but temperature color bands can be set with ranges as narrow as 2° or up to 150°C (3.6° or 300°F). Measurement is possible to 0.1 deg C (0.18 deg F). Their primary application is in thermal-gradient mapping; other applications include thermal imaging of heating elements, studies of air-jet impingement, mapping of electronic assembly temperatures, and nondestructive testing.

3-4.2 METEOROLOGICAL TEMPERATURE INSTRUMENTATION AND MEASUREMENT

3-4.2.1 SURFACE AIR TEMPERATURE*

The station temperature of synoptic meteorology is known as surface air temperature or standard instrument shelter temperature. In the United States and in other official meteorological offices throughout the world, the standard method of observation is by enclosure of meteorological instruments in the free air of a white-painted louvered box or Stevenson screen (Fig. 3-45) located about 4.5 ft (5.5 to 6.5 ft in Europe) above a close-cropped grass surface in the center of an open field with the door side poleward. The standard height of the thermometers is 4.5 to 6 ft. The latter figure is used where there is considerable snow.

The most rudimentary weather station (also known as a climatological station) has an instrument shelter with a calibrated thermometer for measuring the temperature one or more times per day. In almost every case, the station will also have both maximum and minimum thermometers, which are read at a set time each day. Many of these basic weather stations will also have a wet-bulb thermometer for measuring humidity and a bimetallic thermograph for recording temperatures. More sophisticated recording equipment will be found at major weather stations, which are now usually located at airports near major cities or at large military installations. The basic instruments are generally read to the nearest 0.5 deg C (1 deg F) but the more

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*A general reference for this paragraph is Ref. 4.

accurate instruments can be read to 0.05 deg C (0.1 deg F).

The standard maximum station temperature for a given day is measured with a mercury-in-glass thermometer; the minimum with an alcohol-in-glass thermometer; and the hourly values with a mercury-in-glass thermometer. The louvered box with double roof permits air circulation past the thermometer, and excludes direct solar and terrestrial radiation. It does, however, absorb and radiate heat, which causes a systematic deviation of the standard shelter temperatures from the free-air temperature.

Air temperatures are usually taken at standard fixed times by an official observer, but they may be taken continuously by automatic recorders. The time of reading varied from country to country for most early records, but today the hours of reading have been standardized by the World Meteorological Organization. Synoptic surface observations are taken at 0000, 0600, 1200, and 1800 hr Greenwich Mean Time (GMT). Upper air synoptic observations are made at the main synoptic times; however, when only two upper air observations can be made daily, they generally are taken at 0000 and 1200 GMT.

3-4.2.2 SOIL TEMPERATURE*

Many of the thermometers used to measure air temperatures have been adapted for use in measuring soil temperatures. The mercury-in-glass thermometer with stems bent for easy reading at the 5-, 10-, and 20-cm depths, are in common use. Small but appreciable errors may occur if the exposed part of the stem is in bright sunshine. For depths of 50 and 100 cm or more, thin iron tubes with thermometers suspended within them are sunk in the earth to the desired distance.

Another type of thermometer designed for soil temperature measurement is a thick-stemmed thermometer tube enclosed in a wooden case, which is driven into the ground to the desired depth. The scale of the thermometer protrudes above the soil surface. Commercial thermometers are available up to 96 ft in length. In addition to the usual errors inherent in the mercury-in-glass thermometers (parallax, for example), errors may result from exposure of the scale to sunshine, which heats the upper part of the thermometer; from pressure on the bulb, which may change its calibration; or from poor thermal contact between the bulb and the soil.

Thermographs have also been adapted to soil temperature measurement. Mercury-in-steel elements and bimetallic thermographs have been used by many investigators. Heat conduction down the capillary tube may lead to serious errors unless several feet of cable are buried at the bulb level. Serious corrosion problems have been reported when bulbs have been placed in clay soils.

The most widely used sensing element for continuous soil temperature measurements is the thermocouple. One recorder can be made to measure the temperature of the air and soil at many locations. The thermojunction can be made with a low thermal mass. Corrosion and electrical leakage may be serious problems. Remote indicating thermometers are also available for measuring soil temperature.

Resistance thermometers and bimetallic dial thermometers – with maximum, minimum, and current temperature dials – are also in general use, but should be checked often for mechanical damage.

When taking soil temperatures, the soil cover and the degree and direction of ground slope should also be recorded. The physical soil constants such as bulk density, thermal conductivity, and moisture content should be indicated as well as the level of the water table (if within 5 m of the surface) and the soil structure.

The two standards of exposure include bare soil and soil under a short grass cover, and they should be used simultaneously for com-

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*A general reference for this paragraph is Ref. 82.

parative purposes. The standard surface for representative areas should be at least 100 m^2 in size. Standard depths for soil temperature measurements are 5, 10, 20, 50, and 100 cm below the surface. Others may be made as required. When snow is present, the temperature in the snow cover should also be made. These measurements are made difficult by the small thermal mass of the snow. Further discussion of snow temperature measurement may be found in Chap. 8, "Solid Precipitation", of this handbook.

3-4.2.3 SEA-SURFACE THERMOMETERS*

The simplest method for obtaining sea-surface temperatures is to collect a canvas bucketful of surface sea water from the deck of a ship and determine its temperature using an ordinary mercury thermometer. Another convenient method is to lower a thermometer overboard in a perforated metal case (known as an armored thermometer) and obtain a direct reading. Some thermometers have wells surrounding the bulb that catch and retain sea water. These thermometers give variable results, however, depending on whether the sun is shining or a marked difference exists between the sea and air temperatures.

The best results are obtained by using an all-steel mercury thermograph. This instrument is made up of a steel, gas-free mercury Bourdon tube with rotating drum and pen, with a lead- or copper-coated steel bulb and capillary, which is installed in the condenser intake of a ship. One drawback to its use is the capillary length, which may run to 150 ft. Oceanographic thermometry is a complex subject that cannot be treated completely here. Publications of the U S Navy Hydrographic Office and other specialized reviews should be consulted for further information (Ref. 53).

3-4.2.4 ACCURACY REQUIREMENTS FOR METEOROLOGICAL INSTRUMENTS†

The maximum acceptable tolerances established by the World Meteorological Organization for the manufacturers of thermometers are shown in Table 3-24.

The tolerances for ordinary thermometers permit greater negative than positive errors because of the tendency of the zero of mercury-in-glass thermometers to rise slowly with time. Thermometers used for psychrometry should be provided with a correction certificate giving corrections to an accuracy of ± 0.1 deg C (± 0.18 deg F) for at least six points equally spaced over the range.

All thermometers should be checked against the "ice point" at least once every 5 yr. At synoptic stations the thermometers should be checked against a secondary standard instrument at intervals of 1 or 2 yr. Maximum and minimum thermometers must be checked frequently.

Through the use of an ice bath, the ice point may be realized conveniently to better than 0.01°C. A Dewar flask serves as a container for the ice, the melting of the ice being retarded by the insulating properties of the vessel. Ice shaved from clear cakes is mixed with distilled water to form a slush. Enough water is used to afford good contact with the thermometers, but not enough to float the ice. From time to time excess water is siphoned from the bath. Care is taken to prevent contamination of the ice and water. A small reading telescope with a magnification of 10 diameters aids in reading the thermometer indication and reduces parallax errors. Gently tapping the thermometer just before reading may prevent the sticking of a falling meniscus. On the other hand, too vigorous a tap will occasionally cause the mercury to rebound to an erroneously high reading (Ref. 83).

Where maximum and minimum or wet- and dry-bulb thermometers are used in pairs, they should be selected so as to minimize the differences in errors between the two thermometers. The tolerances in Table 3-25 are suggested for these differences.

It is more important for instruments to be

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*A general reference for this paragraph is Ref. 22.

†A general reference for this paragraph is Ref. 4.

TABLE 3-24

MANUFACTURING TOLERANCES FOR THERMOMETERS (Ref. 4)

		°F	Tolerance, deg	°C	Tolerance, deg
Maximum thermometers	above	0.4°	±0.36	-18°	±0.2
	below	0.4°	±0.54	-18°	±0.3
Minimum thermometers	above	0.4°	±0.54	-18°	±0.3
	from	0.4°	+1.08	-18°	±0.6
	to	-31°		-35°	
	below	-31°	±1.44	-35°	±0.8
Ordinary thermometers	above	32°	+0.18 -0.36	0°	+0.1 -0.2
	below	32°	+0.36 -0.54	0°	+0.2 -0.3
Change of error in an interval of 17 deg C (30.6 deg F)	above	32°	0.36	0°	0.2
	below	32°	0.54	0°	0.3

TABLE 3-25

TOLERANCES ON DIFFERENCES BETWEEN THERMOMETERS USED TOGETHER (Ref. 4)

Type	°F		°C	
	Range	Tolerance	Range	Tolerance
Maximum and minimum	-	0.54	-	±0.3
Wet and dry				
Above	32	±0.36	0	±0.2
Below	32	±0.18	0	±0.1

able to maintain a known accuracy over a long period of time than to have very high precision initially without being able to retain it for a long period under operating conditions. Simplicity and convenience of operation and maintenance are very important, because most instruments are in continuous use under a wide variety of environmental conditions and may be located far from good repair facilities. Sturdy construction is particularly desirable for instruments that are exposed to the weather for a long period of time.

In recording instruments, the motion of the working parts in most of them is magnified by levers that move a pen on a chart on a rotating clock-driven drum. Such recorders should be as friction-free as possible, in the bearing as well as between the pen and chart. Means for making daily time marks and adjusting the pressure of the pen on the chart must be provided, consistent with a legible trace. It is also essential that recording instruments be periodically checked against a standard control instrument. Regional standards should be checked once in every 10 yr. Choice of an instrument in which the drum but not the clock rotates will eliminate the danger to the clock since only the drum is removed to change the chart. The design of the clock should be such that it will fit all drums and recording instruments; clock rates should be synchronized so that the rate of revolution of the drum coincides with the time scale for the charts.

3-4.2.5 MEASUREMENT ERRORS*

Air temperature, as recorded in a shelter, may be in error by 1.6 deg C (3 deg F) or more due in part to the following: (1) thermometer error, (2) error due to difference between the temperature of the air in the shelter and the thermometer body, (3) difference in temperature between the air in the shelter and that outside, and (4) sampling error.

Mercury thermometers are highly stable and retain calibration well over long periods of time. The equilibrium between shelter air and the thermometer body is constantly being influenced by the radiative exchange between the shelter walls and the thermometer, which is due to shelter walls being heated by insolation during the day and cooled by radiation at night. The magnitude of the difference in temperature between the air in the shelter and that outside depends on how well the shelter is ventilated by wind. The error is minimized if the air at shelter height is in constant movement at moderate velocity. The error may be increased if rain falls on the shelter since the shelter air approaches its wet-bulb temperature and becomes cooler than the free air.

The sampling error is the difference between the air temperature at the spot where the measurement is made and the temperature over the area for which the reading is considered to be representative. In practice, the air temperature usually is required to be representative in a weighted or specialized manner, which simplifies the problem of obtaining representative temperatures. For example, a representative temperature for an aircraft flight is an average temperature for an airmass covering a million mi^2. On the other hand, an error frequently experienced in recording field test data is to use ambient air data from a station located several miles from the test, and to interpret the ambient air data as having some significance to the test. Test reports have no significance unless the air temperatures are taken at the site of test, or unless some evidence indicates that the temperature is representative of conditions at the site.

Air temperature frequently fluctuates as much as 1 deg or 2 deg C (2 deg or 3 deg F) in a period of 1 or 2 min at a given location; it varies greatly with altitude, particularly in the first 6 ft above the ground. It also varies laterally due to differences in terrain. Because of this, it is impractical to attempt to determine the air temperature to less than 0.56 deg

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*General references for this paragraph are Refs. 76 and 84.

C (1 deg F). Most instruments used for measuring air temperatures are, therefore, sufficiently accurate for the purpose, provided that they are properly exposed. Instruments capable of extreme accuracy do not provide better meteorological recording results than instruments accurate to only 0.56 deg C (1 deg F). Reports of air temperature measurements in the field to a higher resolution than this, except for heat-flow studies, only convey a false impression of accuracy.

In measuring air temperatures for design, test, or research purposes, the standard instrument shelter is not always sufficient since temperature at only one level is obtained. Large differences exist in air temperatures between the ground level and the region 4 to 6 ft above ground, a range that comprises the main environment of the erect soldier. Thus, in the desert the temperature 6 in. above the ground is frequently from 3 deg to 6 deg C (5 deg to 10 deg F) warmer than at shelter height; at the surface of the ground, 20 deg C (35 deg F) warmer. The temperature gradient is larger on calm, sunny days. With a wind of less than 1 mph on a sunny day in June, the temperature 0.5 in. above the ground was observed to be 33 deg F warmer than at 1 ft, 40 deg F warmer than at 8 ft. On cloudy, windy days the temperature gradient disappears. On clear, calm nights an inversion of temperature often causes the temperature of the air on the ground at sleeping-bag level to be many degrees less than the temperature recorded at shelter height. In addition to the distance above the ground, a considerable difference in temperature often occurs from place to place. This is quite pronounced where a considerable contrast in terrain exists. Small depressions or valley bottoms on clear cool nights are likely to be much colder than nearby ridges or higher ground. Large-scale inversions may increase the temperature in a relatively short distance on a hillside. Large-scale temperature gradients may also exist near large bodies of water. Consequently, when temperature tests are made, it is advisable to make the measurements at the immediate site of the test or operation. The variations that are possible or experienced in an area also should be kept in mind when design criteria are being established.

3-5 EFFECTS ON MATERIEL*

The physical properties of most materials, and the rate of most chemical reactions, are affected by temperature changes. Temperature also determines the impact of other environmental factors, but it is often practical, in designing for temperature effects, to treat temperature as a single environmental factor. The discussion that follows of temperature effects treats them from this point of view primarily, although a brief discussion of synergisms is given in par. 3-5.5.

With few exceptions, materials expand on heating and contract on cooling – different materials expand or contract at different rates. Since most materials do not heat or cool uniformly throughout their mass, the temperature gradients produce internal stresses that may cause rupture or permanent distortion. High temperatures may change the physical properties of materials permanently or temporarily, depending on whether such phenomena as precipitation, aging, or recrystallization occur. At high temperatures, tensile and compressive yield strengths are reduced. Effects of prior heat treatment of metals may be altered if the recrystallization point is exceeded. Stress alloying may occur in metals if heat causes plated coatings to diffuse into grain boundaries, changing the physical characteristics of the base metal. High temperatures may cause permanent deformation of metals in the form of creep.

The rate of chemical reactions increases with temperature; as a rule-of-thumb, the rate of chemical reactions will double for every 10 deg C (18 deg F) rise in temperature. Chemical changes may take place not only within a material, but also by reaction with other substances – e.g., oxygen, moisture, pollutants, contaminants, and soil. On exposure to high temperatures, many complexly

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*Much of the material in this paragraph is derived from Ref. 85.

structured organic materials undergo internal chemical changes such as rearrangement, polymerization, cleavage, and pyrolysis. Increases in temperature are also conducive to an increase in microbiological decay.

Table 3-26 lists some of the principal physical and chemical effects of high and low temperatures and the typical failures of material induced by these effects.

3-5.1 EFFECTS OF HIGH TEMPERATURES ON MATERIALS*

The heat that affects equipment or material performance is primarily derived from four sources, listed in order of increasing intensity:

(1) The ambient air

(2) Direct solar radiation

(3) Operation of equipment

(4) Supersonic aerodynamic flight.

Both the circumstances governing heat buildup and the location of the equipment being heated are significant. When equipment is operated on or near the ground, the most important heat sources are insolation and internal heat from power and motor sources. Internal heat sources can usually be anticipated and are generally offset by heat dissipation devices. External heat sources are not as easy to anticipate and compensate for, since so many variables affect surface temperature.

The following paragraphs deal primarily with the effects of heat derived from the ambient air and solar insolation (The effects of heat from operation of equipment and from aerodynamic flight relate primarily to the operation of major equipment items and are not covered here.):

(1) *Heat derived from ambient air.* Temperature extremes of the ambient air may cause serious malfunctions or failures in equipment. High ambient temperatures are often tolerable because many types of equipment generate considerable heat in operation and are, therefore, designed to dissipate excessive heat loads. The temperatures on the colder side of the range, however, may limit or preclude the operation and use of some items of ground equipment.

Varying ambient air temperature conditions cause equipment temperature to vary throughout the day at a somewhat lesser range than the maximum and minimum temperatures at a given location. The temperature attained by equipment in a specific environment depends upon its thermal inertia, packaging, exposure, and operational status. In addition, the heating effects of ambient air may be modified by wind, rain, humidity, and extent of ventilation.

The use of shade temperatures for design and testing purposes must be interpreted by the engineer in terms of the equipment life cycle in use, storage, and transit. Few items of equipment will experience only shade temperatures during their lives. Medical equipment, supplies, and canned foodstuffs are probably the best examples of materiel that are designed and tested for the shade temperature range. Since much equipment and materiel are operated in or exposed to direct sunlight, they must be designed to withstand temperatures that take into consideration the solar load.

(2) *Heat derived from insolation.* Absorption of direct solar energy increases equipment surface and compartment temperatures well above the ambient air temperatures. The heat load provided by solar insolation is particularly important to vehicles or equipment constantly used in the open and not protected by coatings or coverings. Depending on alignment, angle of exposure, color, composition of surface material, mass, shape, and surface smoothness, solar radiation will be reflected or absorbed in varying degrees. Once radiation is absorbed by surface materials, its effects on temperature depend on the thermal capacity and heat transfer characteristics of

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*General references for this paragraph are Refs. 12 and 85.

TABLE 3-26

PRINCIPAL EFFECTS AND TYPICAL FAILURE MODES INDUCED BY HIGH AND LOW TEMPERATURE

Temperature	Principal effects	Typical failures induced
High temperature	Thermal aging:	Insulation failure
	Oxidation	Alteration of electrical properties
	Structural change	
	Chemical reaction	
	Softening, melting, and sublimation	Structural failure
	Viscosity reduction and evaporation	Loss of lubrication properties
	Physical expansion	Structural failure
		Increased mechanical stress
		Increased wear on moving parts
Low temperature	Increased viscosity and solidification	Loss of lubrication properties
	Ice formation	Alteration of electrical properties
	Embrittlement	Loss of mechanical strength
		Cracking, fracture
	Physical contraction	Structural failure
		Increased wear on moving parts

TABLE 3-27

UPPER TEMPERATURE LIMIT FOR DIFFERENT TYPES OF RUBBER (Ref. 85)

Type	Highest usable temperature	
	°C	°F
Polysulfide	121	250
Natural	127	260
Buna-S	138	280
Butyl	149	300
Neoprene	157	315
Buna-N	171	340
Polyacrylic	175	350
Silicone	260	500

the skin and structure of the item. If, for example, the thermal capacity and heat transfer capabilities of a piece of equipment are high, absorbed heat will be stored in the material or distributed around the body with moderate overall temperature changes. If the thermal capacity is small, temperatures will rise more rapidly.

3-5.1.1 METALS*

The usual temperatures encountered by military equipment stored or operated in tropical or desert areas are not sufficiently high to cause malfunctions resulting from changes in mechanical properties of metals. However, metal surfaces exposed to direct sunlight may become too hot to handle, thus interfering with maintenance work. Tropical temperatures combined with moisture tend to accelerate corrosion processes.

Each pure metal or alloy has a characteristic coefficient of thermal expansion. The difference in expansion and contraction of dissimilar metals under extreme temperature conditions (e.g., arctic, desert) are sufficient to cause seizing, loss of contact, failure to meet tolerance requirements, and buckling.

3-5.1.2 NONMETALLIC MATERIALS

The effect of high air temperatures on nonmetallic materials is often one of accelerating some other destructive force rather than a degradation of mechanical properties from the effect of temperature alone. Prolonged exposure to high temperatures, e.g., storage temperatures of 71°C (160°F) or above, cause some nonmetallic materials to soften, flow, become gummy, or lose their adhesiveness. Nonmetallic materials that may be exposed to high air temperatures should be selected or designed specifically for high temperature operation.

The effects of high temperature on some nonmetallic materials during equipment operation are listed in the paragraphs that follow. Some of these effects occur when materials are exposed to high storage temperatures for prolonged periods of time (Ref. 86).

(1) *Petroleum products.* Lubricating oils evaporate or oxidize and form sludge. Hydraulic fluids evaporate, break down, and oxidize. Greases become thin, break down, and oxidize and their oil base evaporates

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*A general reference for this paragraph is Ref. 86.

causing the soap base to char under the increased frictional heat.

(2) *Rubbers*. Both natural and synthetic rubbers become gummy, take on a permanent set, and decrease in tensile strength. However, most natural and synthetic rubbers are unaffected by the high temperatures found under natural environmental conditions as shown in Table 3-27.

(3) *Organic materials*. Deterioration and long-range aging processes are accelerated. The strength of most organic structural materials used in materiel construction decreases. The heat distortion of most thermoplastics occurs below 95°C (203°F). Cellulose begins to deteriorate at about 100°C (212°F). Plastics in the Teflon* group resist temperature damage up to approximately 171°C (340°F).

3-5.2 EFFECTS OF LOW TEMPERATURES ON MATERIALS

Most engineering materials exposed to low temperatures show a substantial loss of useful structural properties. While wood, ceramics, and glass are virtually unaffected, metals, rubber, and plastics are subject to mechanical failure. Rubber materials usually lose flexibility and become hard and brittle. Many of the newer synthetic elastomers, however, retain flexibility down to extremely low temperatures. Most plastics harden and embrittle, and will fracture on shock loading or impact. Structural metals, particularly the steels, are subject to catastrophic brittle failure.

3-5.2.1 METALS†

The significant effect of cold environments on the mechanical behavior of metals is the tendency to induce brittle failure. With a temperature decrease, metallic materials actually become stronger, as reflected in higher measured yield strengths and ultimate tensile strength. On the other hand, most metals also develop lowered resistance to impact or shock loading and become dangerously brittle. The lack of toughness then becomes an overriding consideration, with an important governing factor being the so-called transition temperature range. This is the temperature below which a material behaves in a brittle manner (the mode of failure being primarily a cleavage mechanism), and above which it behaves in a ductile manner (the mode of failure being predominantly a shear mechanism).

The transition temperature depends on a variety of metallurgical and mechanical factors. The austenitic stainless steels, aluminum, copper, nickel, lead, silver, gold, and platinum group do not exhibit brittleness at any temperature (except when a second metallurgical phase is present). Most of the structural steel alloys (columbium, molybdenum, tantalum, tungsten, vanadium, and chromium) display abrupt ductile-to-brittle transitions. Titanium, zirconium, magnesium, beryllium, cobalt, zinc, and cadmium characteristically exhibit low temperature behavior similar to that of the structural steel alloys. An important exception is some high purity titanium alloys that display increased strength at low temperatures, with little sacrifice of ductility.

The fact that the transition temperature of a metal is below the environmental temperature provides no guarantee against brittle failure; the presence of notch-type defects increases the susceptibility of structural parts to low temperature failure. The effects of temperature and notches are additive, since notches can raise the transition temperature and notch-type defects and geometry changes can also initiate brittle fractures. Special care should be taken during design to eliminate or reduce notch-type defects such as keyways, holes, sharp fillets, threads, scratches, nicks, machining marks, corrosion pits, inclusions, tiny cracks, and discontinuities in equipment intended for extreme cold weather use, since such defects serve to concentrate stresses.

Nickel is very effective in reducing the transition temperature behavior of low carbon alloy steels. Alloys containing above 8.5

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*Teflon is a trademark of E. I. du Pont de Nemours and Co.

†A general reference for this paragraph is Ref. 87.

percent nickel are suitable for use at temperatures down to −195°F (−320°F). Titanium alloys also have considerable potential for low temperature applications, particularly an alloy composed of titanium, 5 percent aluminum, and 2 percent tin. With adequate control of impurities, this alloy possesses excellent high strength, accompanied by good toughness and ductility down to cryogenic temperatures.

3-5.2.2 NONMETALLIC MATERIALS*

The low temperature behavior of nonmetallic materials is discussed by material categories as follows:

(1) *Plastics*. The strength of plastics increases as temperature decreases, but the durability of nearly all plastics subject to shock decreases in cold environments. Many classes of plastics can be used successfully at temperatures as low as −40°C (−40°F) provided that they are not subject to shock loading. Polyethylene, a thermoplastic polymer, remains tough at temperatures as low as −73°C (−100°F). Only the fluorocarbon plastics (polytetrafluoroethylene (Teflon) and polychlorotrifluoroethylene (Kel-F†)) retain useful ductility at extremely low temperature. Engineering data on plastic properties at low temperatures are available (Ref. 88).

(2) *Rubber*. Cold adversely affects the serviceability of such rubber components as tires, inner tubes, cable, hose, bushings, and seals. The cold-temperature effects of greatest concern are changes in flexibility and compression-set characteristics, and the development of brittleness. Low-temperature changes in rubber are classed as visco-elastic effects, crystallization, vitrification, and effects associated with changes in properties of plasticizers.

Simple temperature effects are shown by loss of resilience, increase in stiffness, and increase in hardness. First-order transitions (crystallization) are time dependent and may require periods ranging from hours to months. They are accompanied by changes in hardness, volume, the coefficient of thermal expansion, and an increase in stiffness. Second-order transitions (vitrification) are exhibited by all elastomers and occur quite rapidly within a narrow temperature range. Rubber materials usually become unserviceable due to simple temperature effects well above the second-order transition temperatures. When rubber compositions are highly loaded with certain plasticizers, time effects not necessarily associated with crystallization may be evident. Low-temperature flexibility may be improved by the addition of selected plasticizers but this may be done at the sacrifice of other more desirable properties such as tear and abrasion resistance, and bondability.

Many low temperature rubbers do not possess adequate chemical resistance for use in hoses that convey fuels, hydrocarbon oils, hydraulic fluids, and lubricants. These fluids extract the compounds from the rubber that impart the original low temperature qualities. Table 3-28 shows low temperature characteristics of some elastomers.

(3) *Lubricants*. Commercially available engine and gear lubricants are useful down to at least −54°C (−65°F), and instrument greases to at least −73°C (−100°F). Solid film lubricants, based on molybdenum sulfide or polytetrafluoroethylene, can provide lubricity down to cryogenic temperatures. Some low temperature synthetic engine lubricants with good viscosity and lubricity characteristics may not be compatible with seals and bearing materials.

(4) *Other Materials*. Leather becomes stiff, and cracks and tears easily when placed under tension. Canvas and other heavy fabrics become inflexible and cannot be folded or unfolded without breaking or tearing. Glass and wood are not appreciably affected by low temperatures.

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*General references for this paragraph are Refs. 86, 87, and 88.

†Kel-F is a trademark of the 3M Company.

TABLE 3-28

RELATIVE LOW TEMPERATURE CHARACTERISTICS OF SOME ELASTOMERS (Ref. 87)

Type	Typical brittleness temperature		Temperature range for rapid stiffening	
	°C	°F	°C	°F
Neoprene	-40	-40	-12 to -29	10 to -20
Butyl	-46	-50	-18 to -29	0 to -20
Natural rubber	-54	-65	-29 to -46	-20 to -50
Styrene-butadiene	-59	-75	-46 to -51	-50 to -60
Polyurethanes	-68	below -90	-23 to -34	-10 to -30
Silicones (general purpose)	-68	-90	-54	-65
Fluorosilicones	-68	-90	-59	-75
Silicones (extreme low temperature)	-101	-150	-76	-105

3-5.3 EFFECTS OF TEMPERATURE ON COMPONENTS*

The composition of materials used in equipment will largely determine the extent of temperature effects on equipment performance, provided that sound design has been used. The discussion of temperature effects on materials also applies to equipment and components that contain these materials.

The design of equipment has much to do with its ability to dissipate heat buildup. In electronic equipment, the close proximity of heat generating components such as electron tubes, transformers, and resistors in confined spaces and enclosures can raise the temperature to failure levels. In hot climates the heat generating elements will tend to operate hotter, thereby compounding the deleterious effects of high temperature and hastening failure. Miniaturization, plus the increase in power output in electronic equipment, intensifies heat dissipation problems. In some cases, miniaturization results in heat dissipation ranging from 0.5 to 3.0 W in.$^{-3}$, with an average of about 1 W. Degradation is likely to occur when more than 0.5 W in.$^{-2}$ has to be removed by natural means for a 50 deg C (90 deg F) rise in temperature.

Classes of components which exhibit temperature effects and which are of concern in a variety of applications are discussed in the following subparagraphs:

(1) *Electronic, electrical, and electromechanical components.* Table 3-29 lists some of the principal failure modes of electronic and electromechanical components caused by temperature effects. The effects of temperature on the electrical properties of materials result in the component behavior described in the following:

(a) *Resistors.* Resistors employed in military equipment generally perform satisfacto-

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*General references for this paragraph are Refs. 85 and 86.

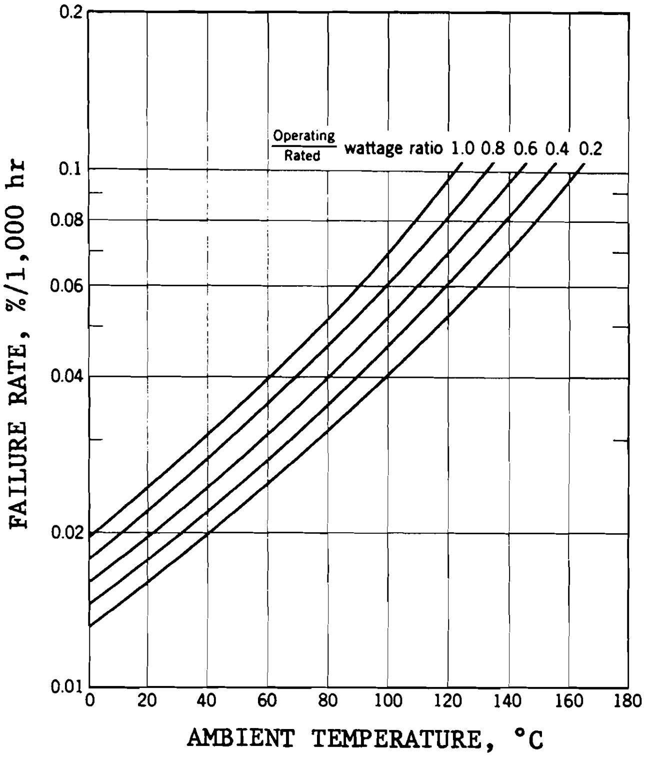
TABLE 3-29

THERMALLY INDUCED FAILURE MODES OF ELECTRICAL COMPONENTS (Ref. 90)

Component	Failure mode
Blowers	Shorts; lubricant deterioration
Capacitors	
Ceramic	Changes in dielectric constant and capacitance; lowered insulation resistance with high temperature
Electrolytic	Increased electrolyte leakage; shortened life; increased current leakage; large change in capacitance, increased series resistance with low temperature
Mica	Increased insulation resistance; aluminum ion migration; drift
Paper	Changes in capacitance; increased oil leakage; decreased insulation resistance; increased power factor
Tantalum	Electrolyte leakage; change in capacitance; insulation resistance; series resistance
Choppers	Decrease in phase angle, variation in dwell time
Circuit breakers	Failure to function
Clutches, magnetic	Hot spots in coil
Coils	Warping; melting; instability, change in dielectric properties
Connectors	
Standard	Fractures, dielectric damage
Interstage	Fractures, dielectric damage
Crystals	Drift, microphonics
Diodes	Change in voltage breakdown; increased current leakage; increase in opens and shorts
Gyros	Drift
Insulators	Epoxy cracking; ferrite separation, (arcing); moisture condensation (insertion-loss)
Joints, solder	Loss of strength
Magnetrons	Decreased life
Motors	Shorts; opens; deterioration of lubricants
Potentiometers	Increased noise; change in torque, linearity, and resistance; decreased insulation resistance with high temperature
Resistors	Increased resistance; opens; shorts
Resolvers	High breakaway voltage; shift in electrical axis; opens; shorts; deterioration of lubricants
Servos	Oil throwout; breakdown of grease; high breakaway voltage
Switches	Oxidation of contacts
Synchros	High breakaway voltage
Thermistors	Increased shorts and opens
Transformers	Reduced dielectric; opens; shorts; hot spots; malformation
Transistors	Increased leakage current; changes in gain; increase in opens and shorts
Tubes, electron	Shorts; temporary change in characteristics; formation of leakage paths; increased contact potential; gassiness; bulb fracture
Vibrators	Lag

rily at low temperatures, although large resistance variations in high-value composition resistors can be expected. High temperatures cause most resistors to fail rapidly. Both reversible and irreversible resistance changes take place.

In the temperature range of –55° to 25°C (–67° to 77°F), the resistance of wire-wound resistors usually varies less than 1 percent. Use of dissimilar metals for control shafts and shaft bearings of continuously variable resistors (potentiometers and rheostats) can



Resistor Rating in Watts	f_1
⅛	1.5
¼	1.2
½	1.0
1	0.9
2	1.2

Resistance Value in Ohms	f_2
Up to 100 K	1.0
100 K to 1 meg	1.2
1 meg to 10 meg	1.5
10 meg to 30 meg	2.0

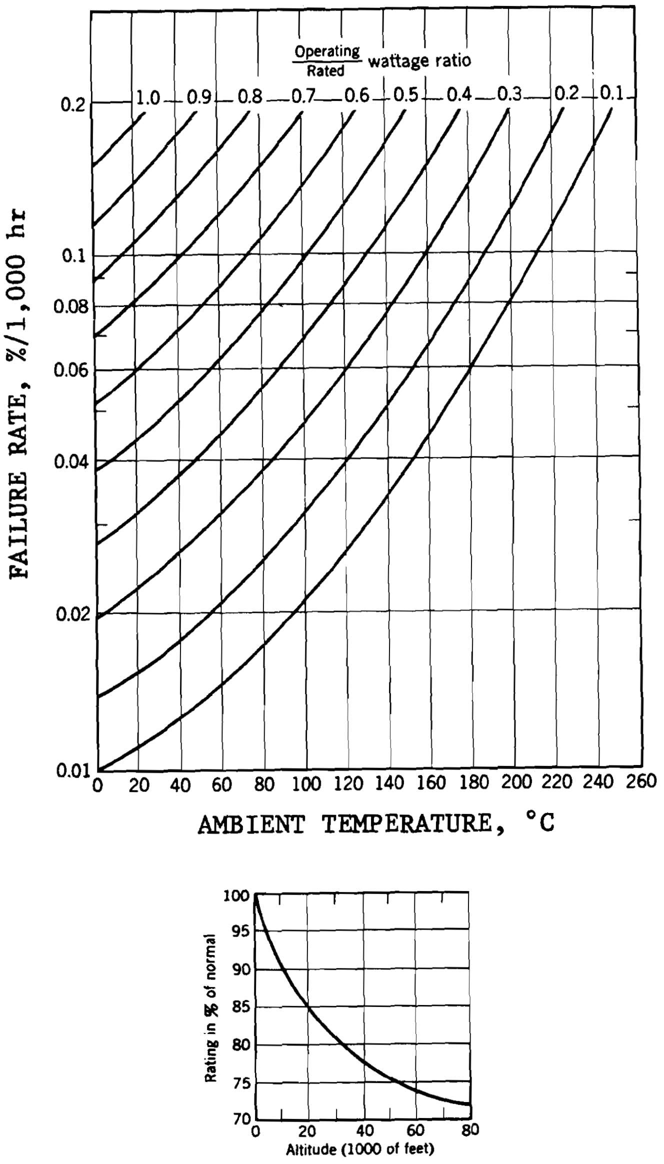
(NOTE. The final failure rate is obtained by multiplying the value read from curve by $f_1 \times f_2$ as given in the above tables.)

Figure 3-46. Failure Rates for Film Resistors (Ref. 89)

result in excessive tightness or looseness of shafts at low temperatures. Binding of the shafts can also result if proper lubricants are not used in the bearings. The torque required to rotate the movable arm of some units operated at −55°C (−67°F) can be more than 50 times as great as the turning effort needed at room temperature due to increased friction in the wiper arm surface. Temporary electrical discontinuity in variable wire-wound resistors, due to ice formation or hardening of the lubricant on the resistance element, has been reported at −55°C (−67°F).

Composition resistors show resistance variations of from 10 to 50 percent as the temperature varies from −67° to 25°F; numerous cracks in the plastic insulating tubes of certain fixed composition resistors develop which tends to shorten the life of the affected units. Variable composition resistors are subject to the same torque and discontinuity difficulties as the wire-wound resistors. In addition, high temperatures cause the lubricants used in all variable resistors to dry up, ooze out, or migrate from the bearings to other surfaces.

Failure rates as a function of temperature for film, wire-wound, and composition resistors are given in Figs. 3-46 through 3-48. A derating parameter is indicated that provides for improved performance.



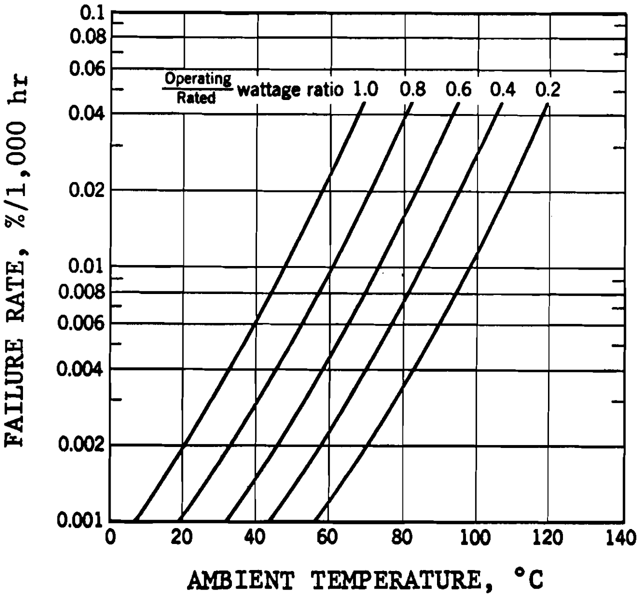
(NOTE. When using these power resistors in unpressurized airborne equipments, the nominal power rating should be derated in accordance with the graph shown to compensate for the lower density of the air.)

Figure 3-47. Failure Rates for Power Wire-wound Resistors (Ref. 89)

Since simple resistors of this type are dependent on heat sinking (by the way of its leads), the connection of parts in series can affect the equivalent rating of the parts used. Series strings without intermediate heat sinks will deteriorate the rating of the interior elements.

Additional failure rate factors come into play depending on resistor type and application data. For example, for deposited film resistors (Fig. 3-46), the failure rate is multiplied by $f_1 \times f_2$. Factor f_1 compensates for the different temperature rises that result when operating resistors of different wattage ratings at the same percent of their rated dissipation. Factor f_2 attempts to manifest the increase in failure rate with increased resistance values.

(b) *Capacitors*. Electrolytic capacitors ex-



NOTE 1. For variable composition resistors, add 0.010 to above values.

NOTE 2. For uninsulated composition resistors, use the above values directly.

NOTE 3. The values determined from curves (or values derived therefrom) must be modified as a function of resistance value if the ambient air temperature is 80°C or above.

Figure 3-48. Failure Rates for Composition Resistors (Ref. 89)

hibit large reductions in effective capacitance at low temperatures, the extent depending upon the electrolyte, type of foil, voltage rating, and manufacturing technique. The series resistance, and, consequently, the impedance, of electrolytic units increases greatly at subzero temperatures. Variations in reactance and resistance with temperature become greater at higher frequencies. Low temperatures result in two favorable effects – (1) the dielectric breakdown voltage increases, and (2) the DC leakage values show an extreme decrease. Storage of electrolytic capacitors at temperatures as low as –55°C (–67°F) results in no permanent harm and may even inhibit deterioration due to aging.

Oil-impregnated paper, air, and mica capacitors function well at cold temperatures, but wax-impregnated paper capacitors are subject to extensive cracking of the impregnate below –20°C (–4°F). This results in permanent changes in capacitance, insulation resistance, and AC losses, especially if moisture enters. In general, the properties of the capacitor become impaired, with the dielectric failing ultimately. Failure rates for paper capacitors as a function of temperature are shown in Fig. 3-49.

(c) *Transformers*. Transformers operate satisfactorily over the temperature range of –55° to 25°C (–67° to 77°F), provided that precautions have been taken in their design to prevent mechanical damage due to thermal contraction. Coil-winding resistance decreases with decreasing temperature. The DC resistance for copper wire of any gage at –55°C (–67°F) is about 70 percent of its value at 25°C (77°F). Cracking of potting compounds and terminal bushings can also occur, especially if the temperature drops rapidly. In general, high temperatures reduce the life of a transformer. Insulation deteriorates and the

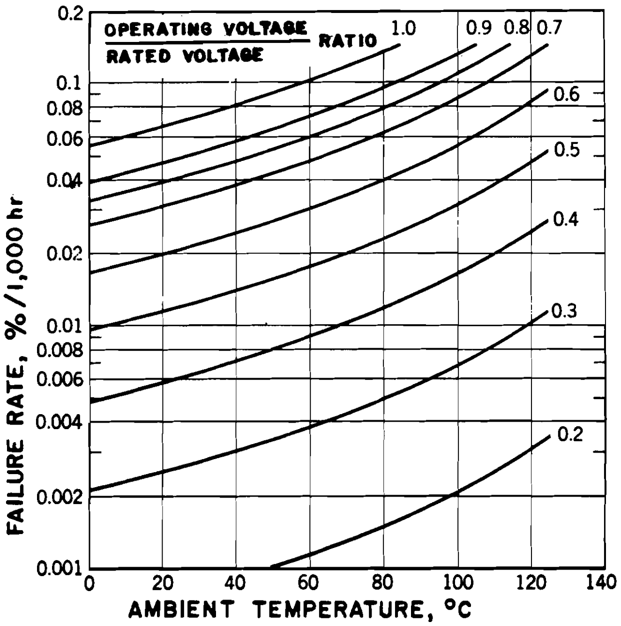


Figure 3-49. Failure Rates for Paper Capacitors (Ref. 89)

resistance of the windings increases, possibly resulting in changes in transformer characteristics.

(d) *Electron tubes*. Low temperatures have no serious effects on tubes. Below 0°C (32°F), tube cathode heating time takes longer. Also, if the condensed-mercury temperature in a mercury-vapor rectifier tube is below the minimum value of the operating range, arc-back can occur, which will damage the tube. Low temperatures can also cause tube basing cement to crack. High temperatures can result in grid emission and release of gas from other tube elements. Electrolysis of the leads through the glass envelope can also occur. As the bulb temperature increases, the life of a tube is markedly decreased. When condensation of moisture results from temperature cycling, the electrical impedance between tube elements decreases and the operating characteristics change.

(e) *Semiconductors*. Semiconductor devices with good circuit design give satisfactory performance at both subzero and elevated temperatures. Changes from room temperature operation can be compensated for. As the temperature rises, semiconductor devices become increasingly unreliable, but when this is taken into account by derating the device, semiconductors may operate as high as 200°C. This limit is largely determined by the rate of heat transfer from the active elements to the outside ambience.

(f) *Relays*. Relays perform their intended functions, provided that the mechanical problems encountered at low temperatures are taken into account. The decrease in winding resistance tends to alter relay operating characteristics, particularly if small or critical currents are involved, as is the case with sensitive relays. At low temperatures, operating (closing) margins are improved and nonoperating (release) margins are impaired. Variations in spring stiffness and magnetic properties can also change these characteristics. Ice formation on operating parts and contacts can cause trouble at low temperatures. In addition, lubricants and dashpot oils tend to congeal.

At high temperatures in sealed relays, outgassing of constituent materials with subsequent contamination of contacts can be a serious problem.

(g) *Magnetic and thermal circuit breakers*. Magnetic circuit breakers with silicone oil damping perform well at subzero temperatures. As the temperature drops, the time required for the breaker to trip due to overload or short-circuit conditions increases. Thermal circuit breakers are affected at reduced temperatures by the increased heat transfer away from the bimetallic actuating elements, with a resultant change in operating characteristics. The tripping time at temperatures near −55°C (−67°F) can be about double the time required at 25°C (77°F) for a given overload current. At high temperatures, both magnetic and thermal circuit breakers trip at lower currents than at room temperature. Thermal circuit breakers are affected more by high temperature than are magnetic types.

(h) *Switches*. Exposure to low temperature can cause the molded body or plastic wafers of a switch to contract and thus be stressed sufficiently to cause cracking. This is especially true in the proximity of attached metal parts, which may contract more severely or more rapidly than the phenolic, plastic, or ceramic body of the switch. A cracked body or wafer may allow entrance of moisture or other foreign matter that can cause a short circuit. The spacing of switch contacts, which may be a fraction of an inch, may decrease sufficiently to cause voltage breakdown or corona. The chemical actions to which switches may be subjected are accelerated by high temperatures. Reactions that take place slowly at normal temperatures may take place rapidly enough at high temperatures to impair switch operation. Insulation resistance between the switch contacts and ground may be thousands of megohms at room temperature, but at elevated temperatures it may decrease to as low as 1 megohm. Another effect of high temperature is the increased speed of corrosion of contacts and switching mechanisms. Corrosion or expansion of materials at high temperatures results in stuck toggles or jammed detents.

(i) *Electrical indicating instruments*. Most electrical indicating instruments operate satisfactorily at reduced temperatures; changes in indication may be less than 10 percent at −55°C (−67°F). Thermocouple- and rectifier-type meters normally have the greatest temperature errors. Low temperature can cause meters to read incorrectly by altering the properties of such basic meter movement parts as control springs, magnets, and coils, as well as range and function-changing accessories.

(j) *Rotating Devices*. Motors and dynamotors will start and operate satisfactorily at temperatures as low as −55°C (−67°F), provided that lubricants specially developed for low temperatures are used. In general, as the temperature is decreased from 25° to −55°C (77° to −67°F), the final operating speed is lowered and the input power increases somewhat. Generators become less efficient at low temperatures and have a higher voltage output because of the reduced resistance of the windings. On the other hand, the output voltage may decrease due to increased air-gap spacing as a result of metal shrinkage. Low temperatures change the electrical characteristics of resolvers, synchros, and gyros, with the most important effect being a decrease in accuracy. High temperatures cause lubricants to creep, ooze, or evaporate, leading to bearing failure. Commutators and sliprings deteriorate more rapidly, and winding resistance increases, lowering the output voltage of dynamotors and generators. Synchros, resolvers, and gyros exhibit a decrease in accuracy. In general, deterioration of insulation brings about ultimate failure of all rotating devices from an electrical point of view.

(2) *Mechanical components*. Mechanical components include such items as pumps, valves, hydraulic and pneumatic actuators, and shock and vibration isolators.

Differential contraction at low temperatures results in binding, fluid leakage, and pump and actuator difficulties. Entrapped moisture freezes, clogging metering orifices. Stiffening of vibration mounts at cold temperatures increases their natural frequency and thereby reduces isolation from the structure in which they are mounted. The performance of these components in large part depends on the materials used in their construction and the type of lubricants used.

Differential expansion due to temperature gradients causes binding of movable parts, loosening of joints, distortion of assemblies, and rupture of seals. Valves may bind or leak. Fuel leaks are aggravated by the cyclical use of fuels of different aromaticity at high temperatures, and occur in check valves, boost pumps, and selector valves.

3-5.4 EFFECTS OF THERMAL SHOCK

Sudden changes in temperature experienced by guided missiles and rockets, while going from a relatively low ground temperature to extremely high temperatures within a few minutes, produce the most outstanding example of thermal shock. Effects can vary from no damage to complete rupture of the vehicle, depending on the severity of the shock and the extent of the stresses created. Severe thermal shock is also associated with the effects of certain weapons – both conventional and nuclear – but these constitute a highly specific induced environment that is not included in this discussion. Other lesser examples of thermal shock can be found not only in aircraft rapidly passing between different temperature environments but also in diverse operations in the cold regions. Moving equipment from heated shelters to a –40°F outside environment is sufficient shock to cause some types of damage.

In rockets and missiles differential expansion with binding of mechanical parts and malfunctioning of metering devices can occur quickly, leading to system failure. High ram-air and skin temperatures lead to compartment heating as the heat is transferred from the hot skin. Since the capacity of air to absorb heat is directly proportional to its density, the heat absorption capability of the low-density air at high altitudes is inadequate to dissipate the skin heat attained. Compartment heating due to increased solar radiation is negligible below 100,000 ft, regardless of Mach number, since the heat flux due to radiation is never more than about 8 percent of that due to convection.

Perhaps an even greater hazard is posed by the extremely low temperatures –184°C (–300°F) that surround liquid oxygen or liquid hydrogen lines in liquid-fuel missiles; these temperatures can adversely affect nearby components and equipment.

3-5.5 EFFECTS OF TEMPERATURE IN COMBINATION WITH OTHER ENVIRONMENTAL FACTORS

The treatment of temperature as the sole environmental factor present is applicable when temperature is the dominant stress to be considered (e.g., thermal shock), and its aggravating effect on other environmental factors can be disregarded. Frequently, however, the effects of temperature are such as to promote the harmful activity of other environmental factors.

Among the more important environmental combinations of this type is that of high temperature and moisture. The combination of these two factors, for example, exposes nonmetallic materials to attack by a variety of insects and micro-organisms, facilitates the action of light in photosynthesis, and intensifies chemical decomposition processes. Warmth and wetness facilitate the development of flourishing and diversified gatherings of insects, molds, and fungi that destroy materials of vegetable or animal origin. Fabrics of cotton, wood, linen, some rayons, and leather goods are vigorously attacked. Wood is rotted by micro-organisms and eaten by termites and other wood borers. In view of this, material of a protein, fat, or cellulose origin should not be exposed to these conditions unless it is suitably protected. Metallic materials are subject to degradation by the increased rate of oxidation resulting from the combination of high temperature and moisture. Electrical equipment is particularly subject to damage, as are optical instruments, photographic films, and glued joints.

Other important temperature synergisms are presented in Table 3-30. The number of

TABLE 3-30

TEMPERATURE SYNERGISMS (Ref. 85)

Factor	High temperature effect	Low temperature effect
Humidity	High temperature tends to increase the rate of moisture penetration. The general deterioration effects of humidity are increased by high temperatures.	Humidity decreases with temperature but low temperature induces moisture condensation and, if the temperature is low enough, frost or ice.
Solar radiation	This is a natural combination that causes increasing effects on organic materials.	Low temperature will tend to reduce the effects of solar radiation, and vice versa.
Shock and vibration	Since both of these environments affect common material properties, they will intensify each other's effects. The amount that the effects are intensified depends on the magnitude of each environment in the combination. Plastics and polymers are more susceptible to this combination than metals, unless extremely high temperatures are involved.	Low temperature tends to intensify the effects of shock and vibration. It is, however, a consideration only at very low temperatures.
Low pressure	Each of these environments is dependent on the other. For example, as pressure decreases, outgassing of constituents of materials increases; and as temperature increases, the rate of outgassing increases. Hence, each tends to intensify the effects of the other.	This combination can accelerate leakage through seals, etc.
Fungus	A certain degree of high temperature is necessary to permit fungus and micro-organisms to grow. But, above 160°F (71°C) fungi and micro-organisms cannot develop.	Low temperature reduces fungus growth. At subzero temperatures, fungi will remain in suspended animation.
Acceleration	This combination produces the same effect as high temperature with shock and vibration.	This combination produces the same effect as low temperature with shock and vibration.
Salt spray	High temperature tends to increase the rate of corrosion caused by salt spray.	Low temperature reduces the corrosion rate of salt spray.
Sand and dust	The erosion rate of sand and dust may be accelerated by high temperature. However, high temperatures reduce sand and dust penetration.	Low temperature increases dust penetration.
Explosive environment	Temperature has very little effect on the ignition of an explosive atmosphere, but it does affect the air-vapor ratio which is an important consideration.	Temperature has very little effect on the ignition of an explosive atmosphere. It does, however, affect the air-vapor ratio which is an important consideration.
Ozone	Starting at about 300°F (150°C), temperature starts to reduce ozone. Above about 520°F (270°C) ozone cannot exist at pressures normally encountered.	Ozone effects are reduced at lower temperatures, but ozone concentration increases with lower temperatures.

likely combinations consisting of two or more environmental factors (including temperature) is quite large, as is the range of their different possible effects. It is, moreover, difficult to establish beforehand the extent of their combined effects, which frequently become evident only after they occur. The designer can minimize the effect of these limitations by being thoroughly familiar with the types of environmental factors likely to be encountered by the materiel under consideration, the frequency and extent of their occurrence, and their effects on materials.

3-6 DESIGN

The design of materiel to survive the stresses of natural and induced temperature environments is an important element of design engineering encompassing much more data and technique than can be treated here. Each item of materiel must be considered separately with respect to its ability to endure or to provide a useful function throughout the temperature range. Thus, only general aspects of design are treated.

Fig. 3-22 shows the climatic categories that have been selected to provide environmental guidance for the preparation of documents covering the design, development, testing, and procurement of Army materiel. They consist of eight categories (described in par. 3-2.4) that can be classified in four broad types – hot-dry, hot-wet, intermediate, and cold. The conditions that establish each of the eight climatic categories are summarized in Table 3-31, where the temperature, solar radiation, and relative humidity ranges quoted represent diurnal variations, as specified in AR 70-38 (Ref. 44), which has susperseded AR 705-15. Table 3-32 shows the diurnal temperature variation time sequence suggested for use in designing testing cycles for operational and storage conditions.

The neutralization of temperature stresses on materiel is a basic design consideration. The importance of adequate design in this area is illustrated by Tables 3-33 and 3-34, which show the high level of occurrences of temperature and temperature-related failures for selected military equipment, materials, and components. Since combination of temperature and humidity is a major source of materiel degradation, protective measures should be emphasized in the design of equipment likely to be exposed to their joint occurrence at high levels for any sustained periods of time.

The prevention and control of temperature stresses can be accomplished either (1) by adaptation to the thermal environment through the judicious selection of materials and choice of design configuration, or (2) by control of the immediate environment by modification of heat (or cold) levels through the use of temperature regulating devices. The first method is passive, the second active. In practice the two approaches are frequently combined.

The successful design treatment of temperature problems requires an understanding of applicable environmental and engineering subject matter. This includes (1) the intensity and extent of the environmental stresses to be encountered, (2) the nature of the temperature effects on the properties of the materials under consideration, and (3) imagination in the selection of materials and the choice of design configuration. Environmental stresses to be considered are ambient and/or internal (as in the case of equipment), and may occur either singly, in combination, or sequentially. The sequential aspect of temperature and humidity in combination is particularly important, since alternate warming and cooling can result in significant accumulations of condensation if sealing materials are unacceptably porous. (This problem is aggravated by pressure changes in aerodynamic flight; the result can be a cyclic process through which condensation is built up in sealed equipment by infusion of moist air at low altitudes and loss of dryer air, but not moisture, at high atltitudes). Temperature effects on materials that should be considered are changes in mechanical, electrical, chemical, thermal, and radiational properties. Choice of substitute materials and alternate design configurations

TABLE 3-31

TEMPERATURE, SOLAR RADIATION, AND RELATIVE HUMIDITY DIURNAL CYCLES FOR CONSIDERATION IN THE DEVELOPMENT OF MILITARY MATERIEL (Ref. 44)

Climatic type	Climatic category	Climatic conditions				
		Operational			Storage and transit	
		Temperature, °F	Solar radiation, Btu ft^{-2} hr^{-1}	Relative humidity, %	Temperature, °F	Relative humidity, %
A Hot-dry	1 Hot-dry	90 to 125	0 to 360	5 to 20	90 to 160	2 to 50
B Hot-wet	2 Wet-warm	Nearly constant 75	Not applicable	95 to 100	Nearly constant 80	95 to 100
	3 Wet-hot	78 to 95	0 to 360	75 to 100	90 to 160	10 to 85
	4 Humid-hot coastal desert	85 to 100	0 to 360	63 to 90	90 to 160	10 to 85
C Intermediate	5 Intermediate hot-dry	70 to 110	0 to 360	20 to 85	70 to 145	5 to 50
	6 Intermediate cold	-25 to -5	Negligible	High	-30 to -10	High
D Cold	7 Cold	-50 to -35	Negligible	High	-50 to -35	High
	8 Extreme cold	-70 to -60	Negligible	High	-70 to -60	High

TABLE 3-32

DIURNAL TEMPERATURE VARIATION TIME SEQUENCE (Ref. 44)

Climatic category		Hours								Temp, °F	
		0300	0600	0900	1200	1500	1800	2100	2400	Max	Min
Hot-dry	Operation	94	91	101	115	125	116	105	95	125	90
	Storage	94	91	117	150	160	142	105	98	160	90
Intermediate hot-dry	Operation	71	73	90	106	109	96	83	75	110	70
	Storage	71	73	117	135	145	135	100	75	145	70
Intermediate cold	Operation	-25	-25	-15	-5	-6	-13	-19	-24	-5	-25
	Storage	-30	-30	-28	-19	-13	-20	-26	-29	-10	-30
Cold	Operation	-50	-50	-45	-35	-35	-39	-45	-49	-35	-50
	Storage	-50	-50	-45	-35	-35	-39	-45	-49	-35	-50
Severe cold (North America)	Operation	-60	-60	-59	-51	-50	-53	-56	-60	-50	-60
	Storage	-60	-60	-59	-51	-50	-53	-56	-60	-50	-60
Extreme cold	Operation	-70	-70	-69	-61	-60	-63	-66	-69	-60	-70
	Storage	-70	-70	-69	-61	-60	-63	-66	-69	-60	-70
For coldest areas (Northern Hemisphere)	Operation within 5 deg F of -80°F for 24-hr duration										
	Storage within 5 deg F of -80°F for 24-hr duration										
Warm-wet (nonseasonal) forest	Operation constant at 75°F throughout 24 hr										
	Storage constant at 80°F throughout 24 hr										
Wet-hot category (open)	Operation	79	78	87	94	95	90	83	80	95	78
	Storage	94	91	117	150	160	142	105	98	160	90
Humid-hot coastal desert	Operation	86	88	97	100	100	96	92	89	100	85
	Storage	94	91	117	150	160	142	105	98	160	90

TABLE 3-33

DISTRIBUTION OF FIELD FAILURES OF MILITARY EQUIPMENT

Equipment type	Percentage of failures classified by environment						
	Temperature and humidity	Dust	Humidity	Radiation	Salt spray	High temperature	Low temperature
Electronic and electrical equipment	8.2	1.4	4.8	0.5	-	6.7	6.7
Lubricants, fuels, and hydraulic fluids		0.5	-	-	-	3.8	1.9
Metals	4.8	-	4.3	-	12.5	3.8	2.4
Optical instruments and photo equipment	2.4	0.5	1.4	-	-	-	-
Packaging and storage	4.3	-	4.3	-	-	-	-
Textiles and cordage	6.7	-	2.4	5.3	-	1.4	-
Wood and paper	5.8	0.5	1.9	-	-	1.0	-
Total	32.2	2.9	19.1	5.8	12.5	16.7	11.0

TABLE 3-34

LABORATORY FAILURE RATE OF ELECTRONIC PARTS (PERCENTAGE OF TEST SPECIMENS)

Item	Temperature humidity	Temperature extremes	Temperature cycling	Vibration	Shock	Salt spray	Life
Resistors, composition	3.65	-	0	0	-	-	3.21
Capacitors:							
Tantalum	14.0	18	-	4.5	0	-	28.0
Plastic film	24.0	-	28.2	11.1	-	85	21.6
Inductors	8.8	8	0	0	-	-	-
Paints, stored	21.9	-	0			12.5	-
Rectifiers, selenium	30.0	-	5	3.0	1.1	36.0	16.5
Relays	30.0	-	-	55.8	22.5	-	37.9
Connectors, multipole	18.1	-	5.1	1.9	8.0	11 2	-
Crystal units	5.3	4.25	-	1.1	0.22	8 4	-

should be consistent with maximum and minimum levels of applicable operating criteria.

In addition to the proper selection of materials, passive prevention and control methods include the following: (1) substitution of items to reduce the generation of heat (e.g., transistors in place of electron tubes, fluorescent in place of incandescent lighting); (2) utilization of insulation materials and techniques; (3) application of heat transfer principles (heat sinks and conduction paths); and (4) dispersion of heat buildups when heat dissipating devices such as blowers or fans are not called for. In electronic equipment, miniaturization increases the potential for overheating, which must be guarded against.

Active methods for controlling heat (or cold) levels consist of devices that change the level of heat present. This is done either by the forced dissipation of excess heat or by warming, and is accomplished by use of heat pumps and refrigeration units (which create artificial heat sinks), fan, blowers, and heaters. Heat transfer mechanisms use the processes of conduction, convection, radiation, and vaporization.

Through various qualification programs, a large variety of parts are available that are qualified for various temperature stress levels. These are specified in the voluminous military specification system. Reliability screening programs have resulted in a high level of assurance that a part is capable of meeting its specifications. Thus, if good design procedures are followed, materiel should operate satisfactorily in any natural temperature environment as well as the induced temperature environment of equipment. If it does not, it usually indicates either inadequate design or poor quality parts.

3-7 TESTING

A portion of materiel procurement costs is designated explicitly for testing; for some items this is a large, very expensive portion. Of the many types of tests very few do not include temperature as a specific parameter. Tests for endurance, aging, parameter variation, and other attributes as a function of temperature stress are among the most important classes of tests for any item of materiel – weapons, vehicles, clothing, electronics, or food.

A test is a procedure used to characterize an item. In a test, certain conditions exist or are applied, the item responds by exhibiting some type of behavior, and there is some observation or measurement associated with the behavior. Some of the important elements of a test are (Ref. 91):

(1) Response during the test
    (a) Reversible vs nonreversible responses
    (b) Aging vs nonaging
    (c) Degradation, drift, and failure
    (d) Modes and mechanisms
(2) Test conditions
    (a) Characterization
    (b) Simulative validity
    (c) Stress
    (d) Single vs multiple factors
    (e) Time-dependent conditions
(3) Measurements.

In Table 3-35 some of the many test names are classified indicating the variety of tests that can be and are accomplished. All of these can include temperature as a stress either singly or in combination with another factor. This illustrates the complexity of testing – only reference to the standard texts on testing can provide complete information (Refs. 91, 92, 93). In this discussion, testing of materiel for ability to survive temperature

TABLE 3-35

TEST CLASSIFICATIONS (Ref. 91)

Classification	Test names	
Specific purpose	proof life strength burn-in	go, no-go run-in failure mode functional/performance
General purpose	environmental reliability development engineering tolerance flight research feasibility	assurance specification storage evaluation acceptance quality control systems investigation
Severity of test conditions	overstress normal stress	accelerated high temperature
Test design	nonsequential sequential matrix factorial	probit random balance up-and-down split-the-difference
Method of analysis	linear discriminant hypothesis testing	sequential analysis maximum likelihood analysis
Method of test	content stress step-stress profile	random stress stress-to-failure progressive stress
Test population	sampling	100% screening
Level of assembly	material part component	subsystem system assembly
Degree of formality	formal exploratory	informal probe
Degree of destruction	nondestructive	destructive
Type of function	electrical structural	mechanical
Method of terminating test	time-truncated failure-truncated	stress-to-failure

stress is the only subject included with emphasis on temperatures in the ranges found in the natural environment.

AR 70-38 specifies that "Climatic considerations will be included in all RDTE* of Army materiel to provide safe and effective materiel for areas of intended use (operation, storage, and transit)" (Ref. 44). The same document further specifies that, "Testing in climatic chambers will be fully and creatively exploited prior to tests in the natural environment." Consistent with this guidance, environmental tests are utilized throughout the development and procurement cycle, and are conducted both in test chambers and at natural sites. Environmental tests are frequently a part of the major development engineering tests specified in AR 70-10, *Research and Development, Army Materiel*

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*Research, development, testing, and engineering.

Testing, December 1962. Their use, however, is not restricted to this area. They are also utilized in other programs such as special tests of materials and components and in production tests (early production and postproduction testing). The value of environmental tests derives largely from the fact that advance determination of the ability of materiel to withstand environmentally induced stresses contributes significantly to (1) shortening of development lead time, (2) avoidance of costly redesign and modification programs, and (3) achievement of materiel reliability within the bounds of established climatic criteria.

Environmental tests are commonly employed for the following purposes:

(1) Determine the ability of materials and proposed design configurations to withstand the effects of environmental stresses within the ranges established by applicable criteria and specifications. Stresses may originate as natural environmental forces or as induced phenomena such as the heat of equipment operation. The effects of environmental factors may be studied singly, sequentially, or in combination.

(2) Establish uniform test criteria and specifications applicable to producer and consumer test performance and acceptance testing.

(3) Maintain quality control during production.

(4) Evaluate reliability.

(5) Determine survivability and operability of material in field evaluation tests.

(6) Analyze equipment failure modes.

(7) Perform evaluations required by product redesign programs.

Environmental testing for temperature effects may be conducted either in the field or in test chambers. Climatic conditions adequate for valid field tests, however, are not always dependable, since frequently the desired climatic severity is not encountered. Because of this uncertainty, the effects of extreme conditions are often more efficiently determined by simulation techniques.

The use of chambers for testing permits evaluation of the environmental factor under carefully controlled conditions and variable levels of intensity. Frequently used standard temperature tests include constant high and low temperature tests, high and low temperature cycling tests, and temperature shock tests. The temperature ranges of tests should conform to criteria presented in AR 70-38, or as specified in MIL-STD-810, *Environmental Test Methods* (Ref. 94).

Tests are frequently characterized as accelerated or aggravated. Accelerated tests approximate natural conditions, but with a greater frequency, duration, or severity than occur in nature. Aggravated tests involve subjecting materiel to more extreme conditions than are found in nature.

3-7.1 TEST PROCEDURES

The basic source document for military environmental testing is MIL-STD-810. Its stated purpose is to "establish uniform environmental test methods for determining the resistance of equipment to the effects of natural and induced environments peculiar to military operations". Temperature test methods presented in detail are high temperature, low temperature, temperature shock, temperature-altitude, and temperature-humidity-altitude. Personnel engaged in Army environmental testing should refer to Methods 501 through 504 for detailed and specific guidance in the areas of procedures and standards. A discussion of temperature test procedures is presented as background material to be used in conjunction with MIL-STD-810 specifications.

The usual procedure in conducting temperature tests is to place the test item in a chamber that is already at or near the test temperature. This practice, however, can apply a thermal shock to the test item, and, if it is known to be detrimental, the exception should be noted and prior conditioning specified, or the item should be placed in the chamber at room temperature and be allowed to change its temperature along with the chamber temperature. Exposure time (measured from the time the test item is introduced into the environment until it is removed) and stabilization time (the time required for the innermost mass of a test item placed in a temperature environment to reach ± 2 deg F (1.1 deg C) of the specified temperature) should be clearly distinguished from each other.

Problems are often encountered in conducting temperature chamber tests due to the difficulty of simulating natural conditions in the chamber. Conditions causing some of these difficulties are too many test items in a chamber, thermal lag of chamber walls, wide variations in temperature within the chamber, inaccurate temperature controls, inadequate methods for determining temperature stabilization, and condensation and frosting of electrical contacts.

Most of the difficulties encountered in steady-state and cycling temperature tests apply to temperature shock tests. Normally, shock tests are conducted in two large chambers, one being at the specified high temperature and the other at the specified low temperature. The test item is removed from one chamber and placed in the other as quickly as possible. The problem of maintaining the temperature of both the test item and the chambers during the exchange, particularly if much mass is involved, is overcome by using chambers with volumes much larger than that of the test item.

Tests must be carefully planned. A satellite once toppled several feet from its mount onto a concrete floor during a high temperature test because the effect of temperature on the mount had not been considered.

The information required to conduct a proper temperature test should be specified when the test specifications are being prepared. The following data should be indicated:

(1) Test temperature

(2) Test temperature tolerances (a range of ± 10 deg F (5.5 deg C) is often recommended within the design criteria range)

(3) Exposure time (minimum and maximum exposure time should be specified when critical; a recommended tolerance time of ± 10 percent of the duration specified is reasonable)

(4) Type of protection needed (a jet of dry air at room temperature should be used to dry the connectors before additional tests are performed)

(5) Description of functional tests as well as temperature conditions and time intervals,

(6) Number of sensors to be used and how located

(7) Temperature of the test chamber at the time of introducing the test item.

A test chamber for a given test should be used only if it is capable of maintaining temperatures within the tolerances specified. It must have enough reserve power to take care of any cycling and thermal shock requirements when subjected to sudden changes in loads. Heat transfer in the chamber is accomplished primarily by convection, but radiation from chamber walls may be considerable, thus affecting the temperature distribution within the chamber. To minimize radiation effects, test items should be placed in the chamber as far as possible from the chamber walls. The ratio of chamber volume to the total volume of test items should be as large as practical. Test items should be spaced far enough apart to allow adequate air circulation. The allowable proximity of test items to chamber walls, or to each other, will also depend on whether the temperature test is steady-state or cycling. During temperature cycling tests, chamber walls act as radiators or heat sinks; if this influences the tests adversely, radiation shields or baffles should be installed. To provide a better distribution of conditioned air and reduce air gradients, forced air circulation is frequently necessary.

Chamber control instrumentation should be accurate, sensitive, and capable of quick responses to temperature changes. A chamber should have a minimum of one fully calibrated indication system. Continuous or periodic recording requirements should be noted in the test specification. The temperature indication should be representative of the condition in the chamber volume used. The temperature distribution measurement system should indicate whether corrective action is necessary, and if so, how much. Spot checks at frequent intervals are necessary to detect improper temperature control and to provide some measure of the stability of the test. Independent measuring devices should be used for spot checking.

The accuracy of the calibration of temperature control instrumentation is dependent on the following factors: an accurate transfer standard (a standard is the physical embodiment of a defined unit of measure under specified conditions); proper location of temperature sensors; and care in the handling and use of the transfer standard. Personnel should be experienced in the use of calibration instruments, interested in accuracy and precision, and possess the ability to attain the degree of precision required. A temperature sensor must be located where it is representative of the geometric center of the chamber volume; this is determined from initial temperature distribution measurements.

Standard thermometers should be used only for calibration functions. The accuracy of the calibration depends upon their stability; meticulous care should be taken in their use and handling so as not to stress, shock, or otherwise misuse them. Recommended standards in order of preference are platinum resistance thermometers, copper-constantan or platinum-rhodium thermocouples, and potentiometers. Resistance thermometers and thermocouple-potentiometer elements should be calibrated as a system. The tolerance should not exceed ± 1.1 deg C (± 2 deg F) during a 10-min interval.

Accuracy and immediate response are two requirements for close control and accurate indication. Accuracy is assured by periodic calibration. Instrumentation should be spot-checked between calibration intervals to insure stability and reliability. A rapid response is needed within the control system to maintain temperatures within test tolerances.

Temperature distribution within the chamber is usually measured by noting differences between a reference point and other points. This method permits plus or minus readings relative to the reference point; it thereby minimizes possible errors and simplifies data recording. The principle of the method is that one thermocouple junction is located at the point of reference and the second junction located at the point to be measured. The common point of the constantan leads should be in good electrical contact with each lead. The common point may be located at any convenient location either inside or outside of the chamber. Care must be taken to guard against short circuits. The readout system should be capable of measuring the small potentials generated by the thermocouples to ± 0.1 mV. The reference junction should be located as close as possible to the reference point and the temperature should be measured to ± 0.28 deg C (± 0.5 deg F) with a platinum resistance thermometer. A minimum of eight points in the eight corners of a square prism encompassing the chamber volume should be measured with respect to the reference point. Additional points located at the midpoints of the edges of the prism and/or at the center of the six prism surfaces can be added to provide a more complete picture of the temperature distribution. The points should be located far enough from the walls to reduce radiation effects, but close enough to obtain a valid picture of the temperature distribution. Thermocouples should be calibrated prior to use, and at the extremes of temperature to which they will be subjected. Both thermocouple junctions of a pair should be exposed to the same temperature environment. A rack to hold the thermocouples should be of a lightweight material with a low coefficient of heat conductivity and have a minimum effect on airflow patterns. Wooden dowels are suggested.

An operational check of the completed system can be made by creating a temperature differential between each measuring junction and its paired reference junction, then grasping each measuring junction between the fingers while observing a plus indication on the readout system. Readings should be taken after stabilization. The temperature of the control reference point should be recorded at the beginning and end of each series of tests.

Since some stabilization techniques give inconsistent or erroneous results, the following stabilization time technique is recommended. The thermocouple is placed inside the test item at the point that has the greatest thermal inertia. The item is then placed in a chamber preconditioned to the specified test temperature. The time taken by the thermocouple to reach within 1.1 deg C (2 deg F) of the specified test temperature is defined as the stabilization time. If this method is impractical, the stabilization time may be calculated from quantified analytical or computer heat-transfer studies.

When neither of these methods is practical, the following technique can be used to obtain stabilization time. Several thermocouples, which should be shielded from radiating surfaces of the test chamber and from direct air circulation, are installed in good thermal contact with the surface of the test item. The elapsed time for the surface temperature, as recorded by the last thermocouple, to reach within 1.1 deg C (2 deg F) of the chamber test temperature, multiplied by three, is defined as the stabilization time. A prototype model can be used for this determination.

All test items and temperature sensing elements within a chamber should be shielded against direct radiation from heating or cooling surfaces. Care should also be taken to see that frost does not form on exposed connectors, switches, and relays, particularly during shock tests.

High-pressure liquid carbon dioxide (CO_2), when allowed to expand rapidly, will partially sublime to the solid form and adhere to the test item surfaces and sensors, subjecting them to a temperature of −78.8°C (−110°F). This interferes with the test and gives unrealistic results. The carbon dioxide should be in the gaseous phase before it enters the test chamber; judicious use of baffles and a manifold with many small jets should be considered as possible safeguards against the accumulation of carbon-dioxide "snow".

3-7.2 TEST FACILITIES

AR 70-38 states that "Test sites will be selected which have the extreme climatic conditions specified for the eight climatic categories . . . insofar as possible." Three extreme climatic conditions (hot-wet, hot-dry, and extreme cold) account for a significant proportion of temperature-induced design problems. Geographical areas in which test sites exist for evaluation of these factors are, respectively, the Canal Zone, the western deserts of the United States, and the arctic and antarctic regions.

Tropical environmental effects are tested at the US Army Tropic Test Center, Ft. Clayton, C.Z. The combination of high temperature and high humidity at this site provides a suitable natural environment for the evaluation of ancillary problems due to salt, fungus, vegetation, and insects.

Test facilities in the Western United States for evaluating hot-dry conditions include the Yuma Proving Ground, Yuma, Ariz., and the White Sands Missile Range, N. Mex., plus associated facilities in Death Valley, Calif. These are conducted by the Navy at China Lake, Calif., and by the Air Force at Edwards Air Force Base and Death Valley. The U S Army Electronics Command maintains a proving ground activity at Ft. Huachuca, Ariz.

Extreme cold temperature effects studied at the U S Army Arctic Test Center, Ft. Greely, Alaska, and at Pt. Barrow. Other cold weather tests are conducted in Greenland and other installations.

Many temperature-induced design problems require an evaluation of the effects of temperature (singly or in combination with other factors) on materials to be used in the fabrication of components and equipment. Engineering considerations – such as thermal expansion and contraction, porosity, brittleness, electrical conductivity, and viscosity – can be studied effectively in test chambers, in which desired extremes can be maintained and conditions closely controlled. Because of this need, a great number of environmental test chambers are used by both industrial and Government establishments. An extensive listing of such facilities in the industrial sector has been compiled by the Institute of Environmental Sciences and is published under the title, *Facility Survey* (Ref. 95). Details on test chamber equipment include company name and address, type of chamber, manufacturer, chamber dimensions, and operating characteristics.

A similar compilation of test chambers, in U S Government activities, is the *Index of Environmental Test Equipment in Government Establishments*, Third Edition, prepared by the Shock and Vibration Information Center, Naval Research Laboratory (Ref. 96). Detailed information includes the type of chamber, operating characteristics, location, and governmental activity and facility. Governmental activities covered in the study are the Army, Air Force, Navy, AEC, NASA, and the Department of Commerce. A list of important performance characteristics of readily available commercial facilities and testing equipment is also included.

A summary of the type of temperature test chambers in Army facilities is presented in Table 3-36. Presentation of individual chamber characteristics is not feasible due to the extensive number of such units. Chamber specifics can be readily obtained by reference to the index.

The range of equipment currently in use to simulate temperature effects (singly or in combination with other environmental factors) is very large. Equipment varies in size from very small cabinets to very large climatic chambers. Two examples of these extremes are a small cabinet with dimensions of 12 X 13 X 11 in. and the climatic chamber at the Air Proving Ground Center, Eglin Air Force Base, Fla., with dimensions of 201 X 252 X 70 ft. The diversity of equipment presently in use – in terms of performance parameters, dimensions, and types of environmental effects simulated – precludes any comprehensive presentation of test chamber operating characteristics. The data presented in the paragraphs that follow, therefore, are of a representative nature only. For specific applications, chamber or cabinet availability, and capability to meet test requirements should be ascertained before final testing arrangements are made.

In general, temperature simulation equipment provides the capability of testing for temperature effects in combination with other environmental factors. The most commonly used temperature combinations are temperature-humidity, temperature-altitude, and temperature-altitude-humidity (other chamber combinations and their location in Army activities are shown in Table 3-36). Multieffect chambers, as a rule, have restricted temperature ranges. Temperature-humidity cabinets generally provide minimum temperatures in the range –101° to –73°C (–150° to –100°F), and maximum temperatures in the range 149° to 176°C (300° to 350°F). Some temperature-humidity chambers have a maximum temperature capability in the 204° to 315°C (400° to 600°F) range; these, however, are found less frequently. Higher temperatures are produced either in temperature ovens or in specialized chambers (a Lockheed Flame Chamber is capable of producing temperatures up to 1,538°C (2,800°F); the Battelle Memorial In-

TABLE 3-36

SUMMARY OF TEMPERATURE TEST CHAMBERS IN ARMY ACTIVITIES (Ref. 96)

Activity	Type of temperature test chamber
Aberdeen Proving Ground	
Ballistic Research Laboratories	T/A/H
Development and Proof Services	T, T/A, T/H, T/H/SD, T/V, T/S
Dugway Proving Ground	T, T/A/H, T/F/H, T/H, T/SD
Edgewood Arsenal	T/A/H, T/H, T/SD
Frankford Arsenal	All except T/A and T/A/V plus T/salt fog
Harry Diamond Laboratories	T, T/V
Jefferson Proving Ground	T, T/A/V
Picatinny Arsenal	T, T/A/H, T/H
Redstone Arsenal	T, T/A, T/A/H, T/F/H, T/H, T/H/C, T/S, T/SD, T/V
Rock Island Arsenal	T, T/A/H, T/H, T/O, T/V
Tobyhanna Army Depot	T/A, T/H
U.S. Army Aviation Materiel Laboratories	T/H, T/SD
U.S. Army Electronics Command	T/A/H, T/H, T/H/C
U.S. Army Mobility Equipment Research and Development Center	T/A/V, T/H, T/H/V, T/O
U.S. Army Tank-Automotive Command	T/H
White Sands Missile Range	T, T/A/H, T/H, T/H/C, T/SD
Yuma Proving Ground	T/H

Symbol	Type chamber	Symbol	Type chamber
T	Temperature, High-Low	T/H/SR	Temperature/Humidity/Solar Radiation
T/A	Temperature/Altitude	T/H/V	Temperature/Humidity/Vibration
T/A/H	Temperature/Altitude/Humidity	T/O	Temperature/Ozone
T/A/V	Temperature/Altitude/Vibration	T/S	Temperature/Sunshine
T/F/H	Temperature/Fungus/Humidity	T/SD	Temperature/Sand and Dust
T/H	Temperature/Humidity	T/V	Temperature/Vibration
T/H/C	Temperature/Humidity/Climate		

stitute's Pacific Northwest Laboratory in Richland, Wash., has vacuum-high pressure chambers capable of maximum temperatures of 3,010°C (5,450°F)). Chambers capable of producing minimum temperatures in the range −212° to −184°C (−350° to −300°F) are most often vacuum types used for space simulation tests.

The range of relative humidity provided by temperature-humidity chambers is highly variable. Most of the commonly used chambers, however, will be found to have a range falling in one of two classes whose order-of-magnitude limits are either 5-10 to 95-100 percent or 20-25 to 95-100 percent.

The dimensions of temperature chambers also differ widely. Most frequently used are cabinets with inside dimensions on the order of 3 X 3 X 3 ft to 4 X 4 X 4 ft. However, cabinets and chambers larger or smaller than these are not unusual, though walk-in chambers tend to be the exception. Dimensions of some of the larger Army walk-in type chambers are:

Installation and type	Dimensions, ft
(1) Aberdeen Proving Ground–cold room	41 X 23 X 14
(2) Dugway Proving Ground–high temperature desert chamber	21 X 21 X 13
(3) Edgewood Arsenal–cold room	30 X 30 X 10
(4) Picatinny Arsenal–temperature/humidity chamber	13 X 8 X 7
(5) Redstone Arsenal–temperature/humidity chamber	35 X 35 X 37
(6) Rock Island Arsenal–cold room	24 X 15 X 12
(7) Tobyhanna Army Depot–temperature/humidity chamber	15 X 18 X 10
(8) Frankford Arsenal–cold room	NA

3-8 SPECIFICATIONS

The following basic documents contain directives, standards, and specifications related to the design, test, and operation of Army materiel under varying conditions of temperature:

(1) MIL-STD-810, *Environmental Test Methods*, 15 June 1967; with Notice 1, 20 October 1969, and Notice 2, 29 September 1969

(2) Quadripartite Standardization Agreement 200, American-British-Canadian-Australian Armies Standardization Program, *Climatic Factors Affecting Design Criteria*, 18 March 1969

(3) AR 70-38, *Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions*, 5 May 1969.

Specifications for individual items of equipment, materials, and specialized test procedures are contained in the *Index of Specifications and Standards*, Department of Defense, 1969.

AMC publications bearing on environmental design and test procedures are listed in AMCP 310-1, *Index of Publications and Blank Forms*, Headquarters, U S Army Materiel Command, January 1973. Other sources of technical information and guidance relating to subject material in this handbook are indexed in the 310 Series of Department of the Army Pamphlets.

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CHAPTER 4

HUMIDITY*

4-1 INTRODUCTION

Humidity is the general term used in referring to the water vapor content of the air. Atmospheric air is a mixture of various gases, the principal ones being nitrogen, oxygen, argon, carbon dioxide, and water vapor. Suspended solid and liquid particles of natural and human origin—liquid water, solid water (ice and snow), dust, salt, smoke, etc.—are also present in varying amounts in the atmosphere; together they constitute the dispersed system termed atmospheric aerosol. The definition of humidity does not encompass the liquid water content of the air, only the vapor. Water vapor is colorless, odorless, and tasteless.

The humidity of natural air is of prime concern because of its pervasiveness in the military materiel environment. There are, however, a variety of situations in which the humidity in a restricted or closed environment is determined by other than natural processes and for which special consideration is required. These will be discussed in par. 4-4. Much of the background discussion of humidity in natural air applies equally to the closed environments.

Closely associated with humidity are other natural environmental factors which are discussed in the other chapters of this handbook, namely:

Chap. 3: TEMPERATURE

Chap. 7: RAIN

Chap. 8: SOLID PRECIPITATION

Chap. 9: FOG AND WHITEOUT

Chap. 14: MICROBIOLOGICAL ORGANISMS.

The relationship of humidity to these other factors is strong. Humidity is dependent on temperature, always accompanies rain, is associated with the solid precipitants, is necessary for and accompanies fog, and supports the growth of microbiological organisms.

With the exception of carbon dioxide and water vapor, particularly, the relative gaseous composition of the natural atmosphere remains essentially constant up to an altitude of about 25 km. Because of this, the composition of atmospheric air is given in terms of the gaseous constituents of clean, dry air, i.e., air with no aerosol or water vapor content. The principal constituent gases of the atmosphere so defined with their percentages by volume are nitrogen (78.084), oxygen (20.9476), argon (0.934), and carbon dioxide (0.0314) (Ref. 1). It can be seen that nitrogen, oxygen, and argon together comprise over 99.9 percent of clean, dry air (the same percentage value holds for the composition of air by mass). Because of the fixed composition of dry air, it is possible to regard atmospheric air for meteorological purposes as a variable mixture of dry air and water vapor. Such a mixture is characterized as moist air.

Although water vapor and carbon dioxide constitute only a small proportion of the atmosphere, the role they play in atmospheric phenomena is extremely important. Carbon dioxide is a strong absorber—therefore, a strong emitter—of longwave radiation (wave-

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*This chapter is based on a manuscript prepared by Mr. D. Hogue at the Earth Sciences Laboratory, U.S. Army Natick Laboratories, Natick, Mass.

TABLE 4-1

CRITICAL TEMPERATURES OF SOME ATMOSPHERIC CONSTITUENTS (Ref. 2)

Substance	Critical temperature	
	°C	°F
Water	374.2	705.6
Sulfur dioxide	157.5	315.5
Carbon dioxide	31.0	87.8
Oxygen	-118.4	-181.1
Nitrogen	-146.9	-232.4
Hydrogen	-240.2	-400.4
Helium	-267.9	-450.2

length greater than approximately 4 μm). Water vapor is also a significant absorber and emitter of radiation. Since the processes of evaporation and condensation are accompanied by the absorption and release of heat, changes in the amount and distribution of atmospheric water vapor are of fundamental importance in thermal processes of the atmosphere.

Substances that are in the vapor phase at temperature above their critical temperature are referred to as gases (the critical temperature of a substance is the temperature above which its vapor cannot be liquefied by pressure alone). The "permanent" gases of the atmosphere (nitrogen, oxygen, hydrogen, helium, etc.) have critical temperatures well below any temperature in the atmosphere and are correctly known as gases. The vapors of water and sulfur dioxide have critical temperatures above any temperatures found in the atmosphere and are correctly known as vapors, for meteorological purposes. The critical temperature of carbon dioxide is well within the range of ambient temperatures, so that it is found in the atmosphere as both a gas and a vapor. However, the amount of carbon dioxide in the atmosphere is so small (approximately 0.03 percent of dry air) that it cannot be liquefied, and can be regarded as a gas. The critical temperatures of some atmospheric constitutents are given in Table 4-1.

In par. 4-2, the terminology associated with humidity is discussed primarily in terms of the important thermodynamic processes. Basic data on these processes are also presented. The natural distribution of water vapor is described in par. 4-3 both in general terms and with relation to data on geographic distributions. This is followed by a brief description of humidity in confined spaces in par. 4-4 while par. 4-5 describes the measurement techniques associated with humidity. Effects of humidity, design guidance, testing, simulation, and specifications constitute the remainder of this chapter.

4-2 THERMODYNAMIC DESCRIPTION AND DEFINITIONS

Water vapor is a gas and as such its properties are described by the classical gas laws. This behavior is complicated by the phase changes of water vapor at natural temperatures such that solid and liquid forms of water coexist with the vapor.

Since the critical temperature of water vapor is higher than the air temperature encountered in the atmosphere, it should not, strictly speaking, be classified among the ideal or perfect gases, i.e., those gases whose physical properties are governed by the ideal gas law. However, experimental investigations have established that the differences between the physical properties of water vapor and those of an ideal gas are so slight that water vapor, for all practical purposes, can be regarded as an ideal gas, and its physical properties can be characterized by the equation of state for an ideal gas* (Ref. 3):

$$p = \frac{\rho}{M} RT \tag{4-1}$$

where

p = pressure, N m^{-2} **

ρ = density, kg m^{-3}

M = molecular weight, kg mol^{-1}

R = universal gas constant, 8.314 J mol^{-1} K^{-1}

T = absolute (kelvin) temperature, K

If a mass m of gas occupies a volume V, then $\rho = m/V$, which, when substituted into Eq. 4-1, gives

$$\frac{pV}{T} = \frac{m}{M} R = nR \tag{4-2}$$

where n is the number of moles of the gas. The right-hand side of this equation is constant for a given quantity of a gas so that

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} \tag{4-3}$$

The specific gas constant R' is obtained by dividing the universal gas constant by the molecular weight; thus, it has a different value for each gas or gas mixture.

The properties of both dry and moist air, as well as the atmosphere of the earth, follow the ideal gas law in the absence of condensation or evaporation.

The density of a gas (and thus of the various atmospheric mixtures) depends upon its pressure, temperature, and molecular weight. The specific volume ν and its reciprocal, density ρ, are obtained from the equation of state after p and T are measured:

$$\nu = \frac{1}{\rho} = \frac{RT}{pM} = \frac{R'T}{p} \tag{4-4}$$

Water vapor has a lower density than dry air ($\rho_v = 0.6222\ \rho_a$ where ρ_v is the density of water vapor and ρ_a is the density of air); the difference is insignificant at low temperatures, but should be taken into account at high temperatures and high humidities.

Numerous terms and parameters are used to describe and quantify the amount of water vapor in the air. The terminology and specifications that follow have been adapted from the World Meteorological Organization's *Guide to Meteorological Instrument and Observing Practices* (Ref. 4), MIL-STD-1165, *Glossary of Environmental Terms (Terrestrial)* (Ref. 5), and the *Glossary of Meteorology* of the American Meteorological Society (Ref. 6). The processes and equations are those found in many meteorologic texts (e.g., Ref. 3).

4-2.1 VAPOR PRESSURE

The vapor pressure e of water in the atmosphere is independent of the presence of other gases; i.e., it is the partial pressure due to water vapor. If an enclosure is maintained at a given temperature so as to confine a fixed volume over a water surface, the vapor pressure within the enclosure will come to a value that is dependent only on temperature and is known as the saturation vapor pressure. Below 0°C, the saturation vapor pressure over supercooled water, e_w, is different from that over ice, e_i.

Many tables of the saturation vapor pressure are available; the *Smithsonian Meteorological Tables* being one example (Ref. 7). Table 4-2 gives some of these data.

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*Also referred to as the perfect gas law; it has many forms.

**Units employed in this chapter are those of the International System of Units except where common practice has necessitated employment of others.

TABLE 4-2

SATURATION VAPOR PRESSURE OVER WATER AND ICE (Ref. 7)

Temperature		Vapor pressure, mb	
°C	°F	Over ice e_i	Over water e_w
100	212	--	1013.25
90	194	--	701.13
80	176	--	473.67
70	158	--	311.69
60	140	--	199.26
50	122	--	123.40
40	104	--	73.78
30	86	--	42.43
20	68	--	23.37
10	50	--	12.27
0	32	6.11	6.11
-10	14	2.60	2.86
-20	-4	1.03	1.25
-30	-22	0.38	0.51
-40	-40	0.13	0.19

Pressure is sometimes measured in terms of the height of a column of mercury, i.e., millimeters or inches of mercury. Since these readings are dependent on the local value of the gravitational constant, it is necessary to standardize them using a standard value of the gravitational constant. The value arbitrarily chosen by the International Committee on Weights and Measures is 980.665 cm s^{-2} but the National Weather Service and other meteorological services have used a value of 980.616 cm s^{-2} corresponding to the best value at a latitude of 45 deg and sea level (Ref. 7). It is important to note which of these values is used in pressure readings given in terms of the height of a mercury column. Better practice, accepted today, is to use millibar (mb) as the unit for pressure. A millibar is equal to 100 N m^{-2}.

The vapor pressure e is directly related to the mixing ratio r and the mole fraction N_v by:

$$\frac{e}{p} = \frac{r}{0.622 + r} = N_v \qquad (4\text{-}5)$$

with similar relations for the saturation vapor pressures:

$$\frac{e_w}{p} = \frac{r_w}{0.622 + r_w} = N_{vw} \qquad (4\text{-}6)$$

and

$$\frac{e_i}{p} = \frac{r_i}{0.622 + r_i} = N_{vi} \qquad (4\text{-}7)$$

where p is the total pressure and the other symbols are as defined in Table 4-3. The constant 0.622 is the ratio of the density of water vapor to the density of dry air at the

TABLE 4-3

TERMINOLOGY OF HUMIDITY

Symbol	Name	Dimensions	Unit
e	vapor pressure of water	force/area	newtons per square meter, Nm^{-2}
e_w	saturation vapor pressure of water over water		millibar, mb
e_i	saturation vapor pressure of water over ice		millimeters of mercury, mm Hg
p	pressure		inches of mercury, in. Hg
m_v	mass of water vapor	mass	gram, g
m_a	mass of dry air		grains, gr
T	temperature	temperature	kelvin, K
T_d	dewpoint temperature		
r	mixing ratio	none	gram per kilogram, $g\ kg^{-1}$
r_w	mixing ratio for saturated air over water		
r_i	mixing ratio for saturated air over ice		
M_v	molecular weight of water	mass/mole	gram per mole, $g\ mol^{-1}$
M_a	apparent molecular weight of air		
V	volume of vapor or air	volume	cubic meter, m^3 cubic foot, ft^3
N_v	mole fraction	none	none
N_{vw}	mole fraction in saturated water vapor over water		
N_{vi}	mole fraction in saturated water vapor over ice		
U_w	relative humidity over water	none	percent
U_i	relative humidity over ice		
s	specific humidity	none	gram per kilogram, $g\ kg^{-1}$
d_v	absolute humidity	mass/volume	gram per cubic meter, $g\ m^{-3}$
n_v	number of moles of water vapor	none	none
n_a	number of moles of air	none	none

same temperature and pressure, which is also equal to the ratio of the molecular weight of water to that of air. If the temperature is raised, the saturation water vapor increases; if the temperature is lowered, the saturation water vapor decreases. Below 0°C, two equilibrium conditions are possible depending on whether the water vapor is over ice or supercooled water.

4-2.2 RELATIVE HUMIDITY

The relative humidity over water, U_w, or over ice, U_i, is the ratio of the actual vapor pressure to the saturation vapor pressure, expressed as a percentage, i.e.,

$$U_w = 100\, e/e_w \tag{4-8}$$

$$U_i = 100\, e/e_i \tag{4-9}$$

Relative humidity can also be expressed in terms of mole fractions

$$U_w = 100\, N_v/N_{vw} \tag{4-10}$$

In all cases, the pressure and temperature of the unsaturated and saturated air are identical. When the atmospheric pressure is less than the saturation vapor pressure, the given definitions do not hold.

Relative humidity is a useful parameter provided that the temperature is also given. Caution must be exercised in its use, however, since supersaturation with respect to ice at temperatures below 0°C (32°F) sometimes occurs. Although National Weather Service practice is to adjust and reference all relative humidity measurements to water when the air temperature is above 0°C (32°F), and to ice when the air temperature is below 0°C (32°F), the World Meteorological Organization prefers that relative humidity at temperatures below 0°C (32°F) be evaluated with respect to water. Advantages ascribed to this procedure are that (1) hygrometers most responsive to relative humidity measure it with respect to water at all temperatures; (2) the majority of clouds at temperatures below 0°C (32°F) consist of water or mainly of water; (3) relative humidities greater than 100 percent are, in general, not observed; and (4) the majority of existing records of relative humidity at temperatures below 0°C (32°F) are expressed on a basis of saturation with respect to water.

The relative humidity expressed as a decimal fraction is known as the saturation ratio.

4-2.3 MIXING RATIO AND SPECIFIC HUMIDITY

The mixing ratio r in a system of moist air is the ratio of the mass of water vapor m_v to the mass of dry air m_a

$$r = m_v/m_a \tag{4-11}$$

while the specific humidity s is the ratio of the mass of water vapor to the total mass of air

$$s = m_v/(m_a + m_v) \tag{4-12}$$

For many purposes, the mixing ratio and specific humidity are approximately equal and are used interchangeably; the difference between them, even at high humidities, is less than the error in humidity measurements. The specific humidity is always less than the mixing ratio.

Referring to Eq. 4-5, it can be seen that the mixing ratio can be written

$$r = 0.622\, e/(p - e) \tag{4-13}$$

and the specific humidity

$$s = 0.622\, e/(p - 0.378\, e) \tag{4-14}$$

where r and s are dimensionless and e and p must be expressed in the same units. For approximation, since $p \approx 1{,}000$ mb and e is normally less than 50 mb, one may use

$$r = s = 622\, e/p, \text{ g kg}^{-1} \tag{4-15}$$

4-2.4 ABSOLUTE HUMIDITY

The absolute humidity (vapor concentration or vapor density d_v) of a mixture of dry air and water vapor is given by

$$d_v = m_v/V \tag{4-16}$$

with the usual units of grams per cubic meter (scientific) or of grains per cubic foot (engineering). This term is sometimes incorrectly applied to the pressure of the water vapor in the air.

Absolute humidity is not conservative with respect to adiabatic expansion or compression. The percentage ratio of absolute humidity to the absolute humidity at saturation differs inappreciably from relative humidity below 35°C (95°F).

In general, absolute humidity cannot be converted into vapor pressure, although it is comparable to vapor pressure for most purposes. However, when vapor pressure is measured in mm Hg and absolute humidity d_v in g m^{-3}, the following numerical relationship holds (Ref. 8):

$$d_v = \frac{1.06\,e}{1 + \alpha T} \tag{4-17}$$

where T is in degrees Celsius and $\alpha = 3.658 \times 10^{-3}$.

Thus, the numerical values of absolute humidity and vapor pressure differ little and, at T = 16.4°C (61.5°F) they are equal, for the measurement units specified for Eq. 4-17.

The absolute humidity is seldom employed in meteorology, but is used in physics and engineering when dealing with fixed volumes; it is particularly useful in the field of air conditioning (Ref. 9).

4-2.5 MOLE FRACTION

The mole fraction* N_v of the water vapor of a sample of moist air is defined as the ratio of the number of moles and water vapor to the total number of moles in the sample of moist air

$$N_v = \frac{n_v}{n_a + n_v} = \frac{r}{\frac{M_v}{M_a} + r} = \frac{r}{0.622 + r} \tag{4-18}$$

4-2.6 SATURATION AND SUPERSATURATION

Saturation of moist air at a given temperature and pressure occurs if its mixing ratio is such that the moist air can coexist in stable equilibrium (i.e., no change in the proportion of vapor and liquid or solid) with an associated condensed phase (liquid or solid) at the same temperature and pressure, the surface of separation being plane. Alternatively, saturation is the condition in which the partial pressure of any atmospheric constituent (usually water vapor) is equal to the maximum possible under the existing environmental conditions.

At saturation, the number of molecules returning to the liquid equals the number leaving it, and the vapor pressure in the air is then identical to the vapor pressure of the water surface. Water vapor molecules in the atmosphere occupy spaces among the atmospheric gases and exert pressure in all directions as other gases do. Since vapor pressure is independent of the pressure exerted by other gases, water vapor produces the same pressure when mixed with other atmospheric gases as it does alone.

Saturation can be produced in either of two ways: (1) if temperature and, hence, capacity remain unchanged, saturation can occur when sufficient vapor is added to the air; and (2) if temperature decreases sufficiently, capacity also decreases until it equals the actual water vapor in the air, thereby producing saturation. Of the two processes, saturation resulting from a decrease in temperature is the more common natural occurrence. At any given temperature, the saturation vapor pressure has a specific value, but changes rapidly with changes in temperature

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*The composition of dry air is frequently presented in terms of mole fractions of its constituent elements, expressed as percentages.

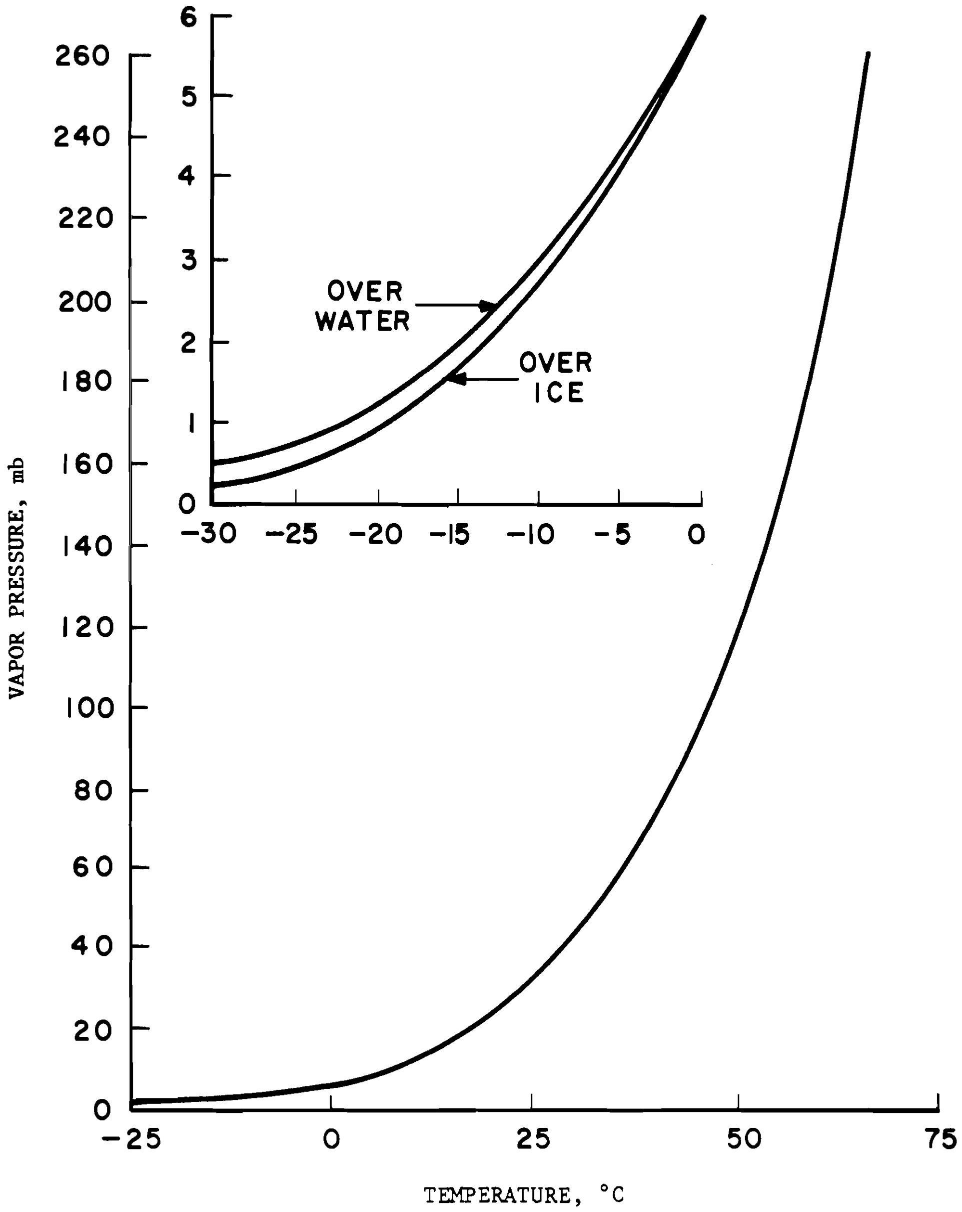

Figure 4-1. Saturation Vapor Pressure for Water (Ref. 7)

(Table 4-2 and Fig. 4-1). Although temperature determines the saturation vapor pressure level, temperature by itself is only one contributing factor to the actual quantity of vapor present.

The quantity of water vapor in a parcel of air can change only through the addition of vapor (evaporation, sublimation) or the loss of it (condensation, sublimation). However, the partial pressure of water vapor can change even when the amount of water vapor remains the same. Thus, in an airmass that rises to a higher elevation, the partial pressures of all gases, including water vapor, decrease because of the adiabatic expansion resulting from the upward movement of the air.

In the inset of Fig. 4-1, two curves of saturation vapor pressure are shown for subfreezing temperatures. The upper curve represents the saturation vapor pressure over supercooled water; the lower curve, saturation

TABLE 4-4

SATURATION MIXING RATIO OVER WATER r_w (Ref. 7)

Temperature, °C	Pressure, mb		
	1,000	900	800
40	49.81	55.83	63.49
35	37.25	41.66	47.24
30	27.69	30.92	34.98
25	20.44	22.19	25.74
20	14.95	16.65	18.79
15	10.83	12.06	13.59
10	7.762	8.633	9.725
5	5.495	6.109	6.878
0	3.839	4.267	4.802
-5	2.644	2.939	3.306
-10	1.794	1.993	2.242

vapor pressure over ice. Without the presence of supercooled water, direct sublimation of the excess water vapor would occur at temperatures below freezing. These curves are applicable to phenomena occurring generally in the upper atmosphere, but often in the lower atmosphere in winter, and in refrigerated spaces.

Supersaturation occurs when a given portion of the atmosphere (or other space) contains more water vapor than is needed to produce saturation with respect to a plane surface of pure water or pure ice. This state is unstable, but not uncommon in the atmosphere. Supersaturation usually occurs when saturated air is cooled, and condensation does not occur because of the lack of sufficient condensation nuclei.

Although supercooled water is prevalent in clouds down to about −15°C (5°F), the natural processes of condensation and evaporation in the atmosphere occur in such a way that appreciable supersaturation does not occur. (If ice crystals and water droplets coexist in a cloud, the tendency is for water vapor to sublime on the ice crystals. This includes the additional vapor due to evaporation from the water droplet surfaces.) Thus, for practical purposes it can be assumed that saturation is not exceeded.

Condensation and sublimation are not direct consequences of a state of saturation or even slight supersaturation. Laboratory experiments performed on extremely clean air have achieved supersaturation up to 700 percent before the start of condensation. These experiments demonstrate the need for suitable condensation nuclei in the atmosphere (Ref. 10).

The saturation mixing ratio is the mixing ratio of saturated air at a given temperature and pressure. It is denoted by the symbol r_w when the condensed phase is liquid, and by r_i when it is solid. The associated condensed liquid or solid phases refer to almost pure water and almost pure ice, some air being dissolved in both. Values of r_w are shown in Table 4-4.

Saturation deficit is the difference between the saturation vapor pressure at a given temperature and pressure, and the actual vapor pressure under the same conditions. It can be denoted by $(e_w - e)$ with respect to water, and by $(e_i - e)$ with respect to ice. It is also defined as the additional amount of water vapor in grams per cubic meter required to produce saturation in a given parcel of air at the same temperature and pressure.

4-2.7 DEWPOINT TEMPERATURE AND WET-BULB TEMPERATURE

4-2.7.1 DEWPOINT TEMPERATURE

The thermodynamic dewpoint temperature T_d of moist air at pressure p and with mixing ratio r is the temperature at which moist air, saturated with respect to water at the given pressure, has a saturation mixing ratio r_w equal to the given mixing ratio r. (When the moist air is saturated with respect to ice, the thermodynamic dewpoint temperature is known as the thermodynamic frostpoint temperature.) The temperatures so defined are identical with the definitions of the commonly used terms *dewpoint* and *frostpoint* (temperatures), i.e., the temperature to which a given parcel of air must be cooled at constant pressure and constant water vapor content in order for saturation to occur.

For a given dewpoint, there is only one saturation vapor pressure. Since the vapor content is just sufficient to saturate the air at the dewpoint, further cooling would produce condensation on a solid surface. Dewpoint is a convenient parameter, since it is expressed in the temperature scale, is as precise as vapor pressure, and can be readily converted to it. In saturated air, the dewpoint and air temperature are equal. A dewpoint temperature can be readily produced by forced cooling and can be determined readily by observation. This is true both above or below 0°C (32°F).

The dewpoint is the temperature at which condensation normally begins. When moist air is cooled to a point (above freezing) where its water vapor capacity is lower than the amount of vapor in the air, the excess water vapor changes to liquid water. It forms on cool surfaces, producing dew, and, on suitable condensation nuclei in the free atmosphere, forming clouds or fogs. If a sufficient number of hygroscopic nuclei are present, condensation may occur at temperatures above the dewpoint or before saturation vapor pressure is reached. In the lower atmosphere, an ample supply of condensation nuclei is always available, so condensation can be expected as soon as air becomes saturated.

Under certain conditions, when the air contains only a few small insoluble dust particles, condensation does not occur until vapor is cooled appreciably below its dewpoint. When the water content of the air is saturated at 0.01°C (273.16°K)*, its three phases—vapor, liquid, and solid—occur in equilibrium together and the vapor pressure is always 6.11 mb. Dewpoint and saturation vapor pressure equivalents for the liquid phase are shown in Fig. 4-2.

4-2.7.2 WET-BULB TEMPERATURE

Wet-bulb temperature is the lowest temperature to which air can be cooled at any given time by evaporating water into it at constant pressure, when the heat required for evaporation is supplied by the cooling of the air. This temperature is indicated by a well-ventilated wet-bulb thermometer. Since this measure shows increases in the vapor pressure by the addition of water vapor to the air and simultaneously shows decreases in the temperature of the air through its loss of latent heat, wet-bulb temperature is lower than the air temperature in unsaturated air but higher than the dewpoint temperature.

The temperature difference in degrees between dry-bulb temperature (air temperature) and wet-bulb temperature is called the wet-

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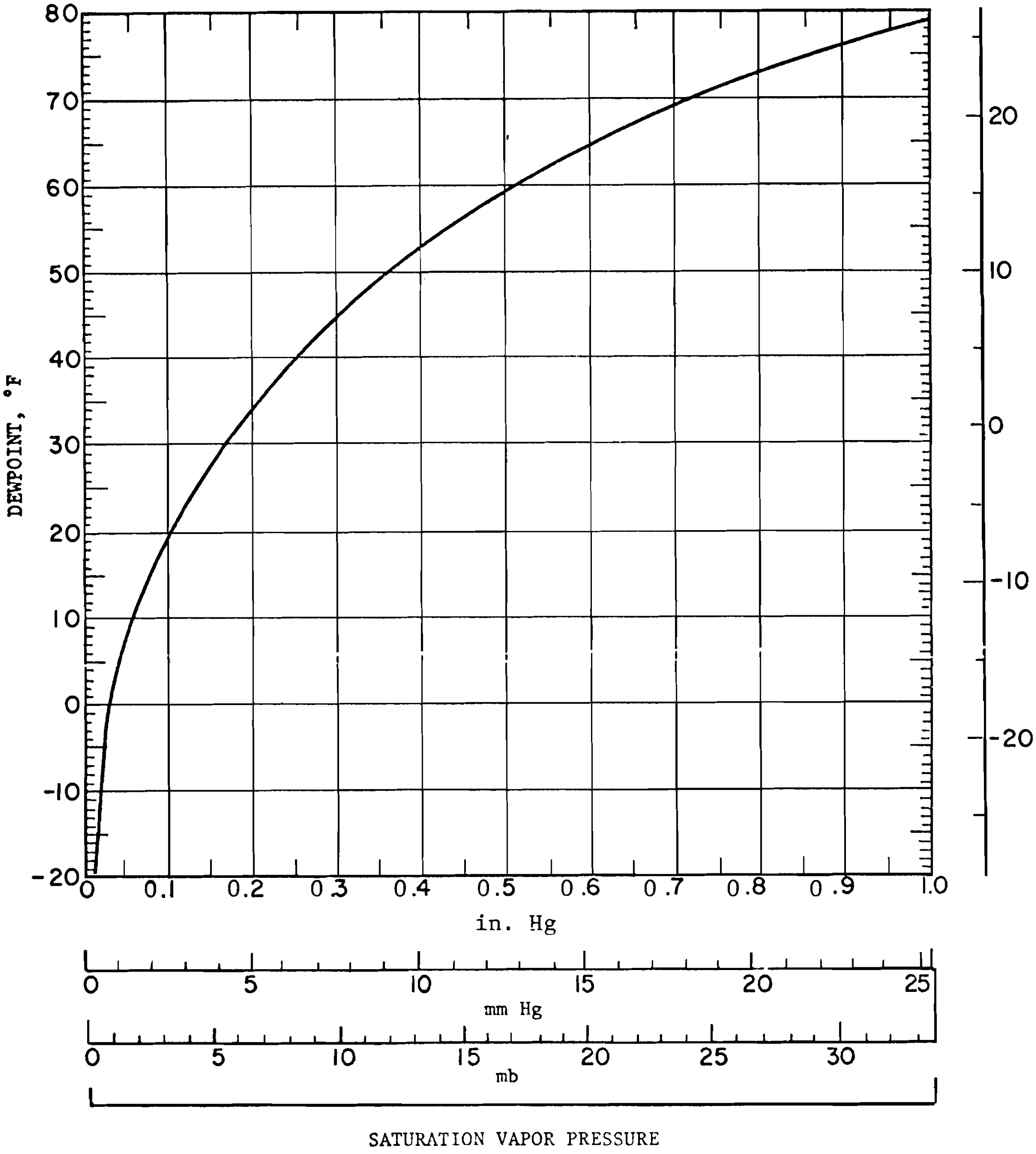
*This is the only point at which the three phases of water can exist in a state of equilibrium, and is known as the triple point of water. Equilibrium, in this context, means that the relative quantities do not change. The triple point of water is the fundamental fixed point of the internationally defined thermodynamic Celsius and the thermodynamic kelvin temperature scales (Ref. 4).



SATURATION VAPOR PRESSURE

Figure 4-2. Dewpoint-saturation Vapor Pressure Equivalents (with respect to water) (Ref. 11)

bulb depression. It depends on the temperature, humidity, and atmospheric pressure of the air.

The dry-bulb temperature, wet-bulb temperature, and wet-bulb depression are used in the determination of dewpoint and relative humidity. The vapor pressure deficit—the difference between the actual vapor pressure and the saturation vapor pressure—is tabulated in Table 4-5 as a function of wet-bulb depression for four wet-bulb temperatures. In Table 4-6, the relative humidity is given as a function of the wet-bulb depression.

4-2.8 LATENT HEATS AND PHASE CHANGES

The latent heat is the heat released or

TABLE 4-5

ATMOSPHERIC WATER VAPOR DEFICIT (Ref. 7)
VALUES OF ($e_w - e$) FOR p = 1,000 mb

Depression of wet-bulb, deg C	Wet-bulb temperature, °C			
	-10	0	10	20
0	0.0	0.0	0.0	0.0
1	0.6524	0.6600	0.6676	0.675
2	1.3048	1.3200	1.3352	1.350
3	1.9572	1.9800	2.0028	2.026
4	2.6096	2.6400	2.6704	2.701
5	3.2620	3.3000	3.3380	3.376
6	3.9145	3.9600	4.0055	4.051
7	4.5669	4.6200	4.6731	4.726
8	5.2193	5.2800	5.3407	5.401
9	5.8717	5.9400	6.0083	6.077
10		6.6000	6.6759	6.752
15			10.138	10.128
20				13.504

absorbed per unit mass in a reversible isobaric-isothermal change of phase. The latent heats of vaporization, condensation, fusion, and sublimation of water are of prime importance in atmospheric processes. Because the phase changes are reversible, the latent heat of vaporization is equal to the latent heat of condensation and the latent heat of sublimation is equal to the sum of the latent heats of vaporization and fusion. In all cases, latent heats are functions of the temperature. The latent heats of water are given in Table 4-7.

Basically, the latent heat of vaporization is associated with the fact that, as the temperature of a liquid increases, the kinetic energy associated with molecular motion also increases. Certain molecules—those with higher-than-average energy—are able to escape from the liquid and enter the vapor phase. Since only the higher energy molecules escape, the average energy of the remaining molecules in the liquid is less; thus, its temperature is lower. Heat has flowed from the liquid in the process of vaporization in an amount proportional to the quantity of liquid vaporized.

The energy removed from a water surface by evaporation and carried (often for great distances) as latent heat in water vapor is released during condensation. The latent heat of condensation is one of the main sources of energy in atmospheric processes. Heat acquired by vapor during evaporation has a cooling effect on the surface or the air sample from which the moisture is taken. Condensation, by releasing an equal quantity of latent heat, warms a surface or air sample. The amount of heat liberated by condensation can be considerable.

Evaporation of water is the process by which water is transferred into the gaseous state. The rate of evaporation is determined

TABLE 4-6

RELATIVE HUMIDITY FROM WET-BULB DEPRESSION (PERCENT) (Ref. 12)

Wet-bulb depression, deg C	Temperature, °C										
	40	35	30	25	20	15	10	5	0	-5	-10
1	95	95	94	94	94	94	94	93	93	93	92
2	90	89	89	89	88	88	87	87	86	86	85
3	85	85	84	83	83	82	82	81	80	79	79
4	81	80	79	78	78	77	76	75	74	73	73
5	76	75	75	74	73	72	71	70	69	68	67
6	72	71	70	69	68	67	66	65	64	63	61
7	68	67	66	65	64	63	62	61	59	58	57
8	64	63	62	61	60	59	57	56	55	53	52
9	61	60	59	57	56	55	54	52	51	49	48
10	58	56	55	54	53	51	50	48	47	45	44
11	54	53	52	50	49	48	46	45	43	42	40
12	51	50	49	47	46	45	43	41	40	38	37
13	48	47	46	44	43	42	40	38	37	35	34
14	46	44	43	41	40	39	37	36	34	32	31
15	43	42	40	39	37	36	34	33	31	30	28
16	40	39	38	36	35	33	32	30	29	27	26
17	38	37	35	34	32	31	29	28	27	25	23
18	36	34	33	32	30	29	27	26	24	23	21
19	34	32	31	30	28	27	25	24	22	21	20
20	32	30	29	28	26	25	23	22	21	19	18
21	30	28	27	26	24	23	22	20	19	17	16
22	28	27	25	24	23	21	20	19	17	16	15
23	26	25	24	22	21	19	18	17	16	15	15
24	25	23	22	21	19	18	17	16	14	13	12
25	23	22	21	19	18	17	16	14	13	12	11
26	22	20	19	18	17	16	14	13	12	11	10
27	20	19	18	17	16	14	13	12	11	10	09
28	19	18	17	15	14	13	12	11	10	09	08
29	18	17	15	14	13	12	11	10	09	08	07
30	17	16	14	13	12	11	10	09	08	07	07

by the temperature of the liquid and the relative humidity of the atmosphere over its surface; it is independent of the presence or absence of other gases. Evaporation is both dependent on and important in meteorological processes. Winds, carrying away moist air, increase the evaporation rate over water; over large bodies of water, vertical air motion is required. Fresh water evaporates about 5 percent more rapidly than sea water.

4-3 DISTRIBUTION OF ATMOSPHERIC WATER VAPOR

The water vapor contained in the atmosphere is the most dynamic of atmospheric constituents. It may condense or solidify forming a cloud, fog, or precipitant; its

TABLE 4-7

LATENT HEATS OF WATER (Ref. 7)

Temperature, °C	°F	Vaporization, cal g^{-1}	Fusion, cal g^{-1}	Sublimation, cal g^{-1}
-40	-40	621.7	56.3	678.0
-30	-22	615.0	63.0	678.0
-20	- 4	608.9	69.0	677.9
-10	14	603.0	74.5	677.5
0	32	597.3	79.7	677.0
10	50	591.7		
20	68	586.0		
30	86	580.4		
40	104	574.7		

concentration may increase by vaporization or sublimation from atmospheric or surface solid or liquid forms of water; it may travel great distances carrying with it considerable thermal energy; and it may condense, sublime, or absorb on any material with which it comes into contact. Generally, the changes in natural water vapor are physical although large quantities of water are added to the atmosphere by combustion processes and removed by biological processes, both of which involve chemical changes. The various cyclic processes in which water is involved—meteorological, biological, hydrological, and geological—are key to the existence of a habitable ecosphere. The atmosphere at any time contains only about 0.001 percent of the total water of the earth but this can constitute as much as 4 percent of the volume of the gases in the atmosphere.

The sources of atmospheric water vapor are, in order of importance:

(1) Evaporation from warm water bodies

(2) Evaporation from soil

(3) Transpiration of water vapor by plants

(4) Sublimation from snow and ice

(5) Combustion

(6) Expiration by animals.

Generally, the input of water vapor to the atmosphere decreases with altitude because of the general decrease in temperature. The decrease in atmospheric pressure with increased altitude does lower the boiling point of water, i.e., the temperature at which the vapor pressure and atmospheric pressure are equal. The boiling point decreases 1 deg C (1.8 deg F) for each decrease of 37 mb in air pressure. A pressure decrease of 37 mb corresponds to an increase in altitude of approximately 320 m at sea level but this correspondence is a function of temperature and pressure. Thus the passage of a low- or high-pressure meteorological disturbance can have a measurable effect on the boiling point.

Temperature is the primary control of water vapor content of the atmosphere. Warm air can, and usually does, contain more water vapor than cool air. In order for air at a given temperature to be saturated with water vapor, it must be exposed to sufficient moisture or water over a period long enough to allow equilibrium to be reached.

A change in temperature drastically alters the maximum amount of water vapor a mass of air can contain. These differences in the amounts of water vapor have important implications for design engineering. The highest temperature recorded at any station, about 55°C (131°F)*, produces a maximum possible water vapor content of approximately 100 g m^{-3}. The actual amount of water vapor present is a complex function of various atmospheric conditions. The highest dewpoint temperatures recorded are between 30° and 35°C (86° and 95°F), corresponding to water vapor content ranging from 30 to 40 g m^{-3}, and are usually associated with air temperatures below 40°C (104°F). The capacity of air to hold water vapor decreases rapidly as temperature decreases. At temperatures below about –40°C (–40°F), the amount of water vapor present in the atmosphere is negligible for most engineering purposes. The maximum amount of water vapor the air can contain at –40°C (–40°F) is about 0.1 g m^{-3}, and at –50°C (–58°F), only 0.04 g m^{-3}. Although the water vapor content of the air at low temperatures is extremely small, it is an important influence on the transmission of infrared radiation over long paths to and from the surface of the earth.

Water vapor acts as a highly important control on the temperature of the atmosphere, and has two far-reaching effects: (1) by absorbing longwave radiation from the surface of the earth, water vapor significantly limits the amount of cooling during the night; and (2) water vapor serves as a medium of heat transfer through the release of the latent heat of condensation. The latter process, whereby heat is transported from warmer to colder latitudes, is a major element in the heat balance of the earth.

4-3.1 GENERAL PATTERNS**

The distribution of water vapor in the atmosphere is exceptionally variable. Air can be practically dry or contain up to 4 percent by volume of water vapor. Under natural conditions, air always contains some water vapor. While only a small fraction of the water of the earth is stored as vapor at any one time, over long periods a vast amount of water in vapor form circulates in the atmosphere.

The distribution of water in the atmosphere is closely related to temperature conditions. The water vapor content of the air is higher in warm, moist areas where the capacity of air to hold vapor is also high. Since all water vapor originates at the surface of the earth, the availability of water in liquid or frozen form, plus conditions favoring its change to vapor, affect its distribution.

4-3.1.1 LATITUDINAL VARIATIONS

The mean latitudinal distribution of water vapor shows a marked decrease from the equator toward the poles as shown in Fig. 4-3. This pattern is closely related to seasonal temperatures and location. Except for some deserts, the correlation between atmospheric water vapor content and temperature distribution is generally good. The belts of maximum mean vapor pressure and maximum mean temperature shift northward during summer in the Northern Hemisphere and southward during summer in the Southern Hemisphere. This shift in temperature and vapor pressure levels is more extensive over the land masses north of the equator than over those south of the equator.

The poleward decreases in water vapor levels and temperature also correlate with a

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*Actually, 136°F has been observed in northern Africa but temperatures above 130°F are very rare.

**Discussion of the general patterns of atmospheric water vapor is contained in meteorological texts such as Refs. 13 and 14.

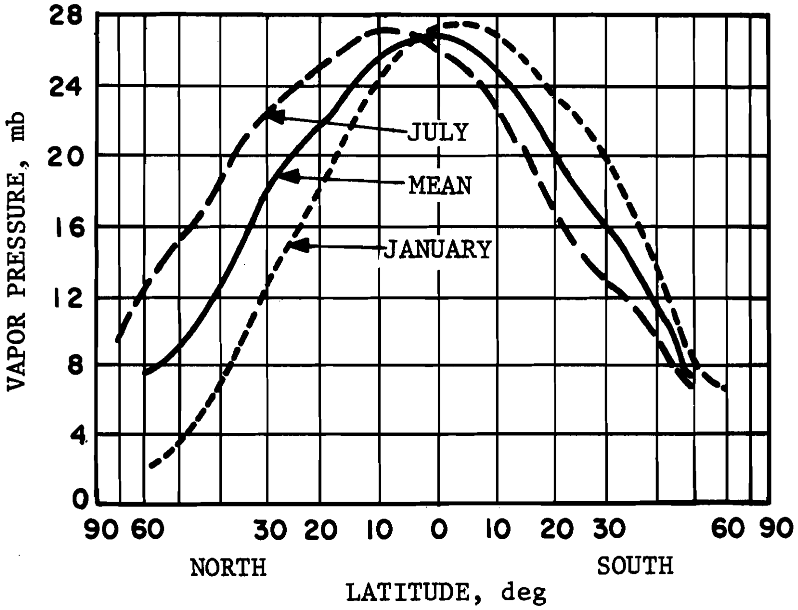

Figure 4-3. Mean Latitudinal Distribution of Water Vapor Pressure (Ref. 15)

similar decrease in latitudinal precipitation. Thus, precipitation averages 73 in. yr^{-1} in the equatorial belt of the Northern Hemisphere and 4.5 in. yr^{-1} in the polar zone.

Greater amounts of water vapor are also present during the summer than in the winter in the Northern Hemisphere. In winter, vapor pressures fall below 2 mb over large land areas in higher latitudes and over ice-laden polar areas. Those areas in which the mean vapor pressure exceeds 20 mb are distinctly humid all year, and constitute the major sources of atmospheric water vapor. In general, vapor pressure decreases rather rapidly with distance inland from primary source areas, since most of the water vapor lost inland by precipitation is not replaced by evaporation or transpiration.

Although the percentage content of water vapor in the atmosphere is always small, any appreciable variation in the local amount of water vapor has a significant effect on weather conditions and the environment. For example, water vapor is an important absorber of electromagnetic radiation, particularly in the long infrared wavelengths, and therefore has an important meteorological role as an absorber and emitter of radiant energy. In tropical latitudes, water vapor constitutes approximately 3 percent of the air by volume. In the intermediate latitudes, water vapor averages only 1 percent of the air by volume, varying from 1.5 percent in summer to 0.5 percent in winter. In high latitudes, the amount of water vapor in the air is negligible.

Landsberg (Ref. 16) states that, in general, an increase in temperature means a rise in absolute humidity and a decrease in relative humidity; a decrease in temperature has the opposite effect. Vapor pressure is significantly higher in deserts than on moist coasts in the Arctic. In the Sahara and California deserts, a vapor pressure of 13.6 mb is common and fairly characteristic of those latitudes. By contrast, oceanic latitudes between 60 and 70 deg N. have a vapor pressure of 4.08 to 5.44 mb. The air of deserts, therefore, contains about three times more water per unit volume than arctic maritime air.

Fig. 4-4 shows the approximate mean latitudinal distribution of relative humidity. Maximum relative humidities generally prevail at the equator and at latitudes 60 deg N. and S.; minimum relative humidities occur in the subtropical high pressure belts. On midlati-

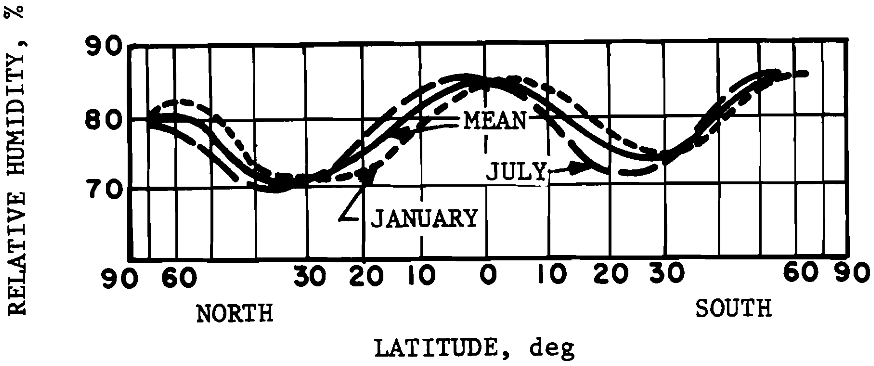

Figure 4-4. Approximate Mean Latitudinal Distribution of Relative Humidity (Ref. 15)

tude mountains, summer maxima in relative humidity tend to occur because of the strong convective flows of moist air upslope to cooler heights.

In the subtropical high pressure belts between latitudes 25 and 35 to 45 deg N. and S., the zonal distribution of mean relative humidity (Fig. 4-4) differs considerably from the general pattern of mean vapor pressure shown in Fig. 4-3. Although the desert air in these latitudes contains considerable water vapor, desert temperatures are characteristically high, and relative humidities are correspondingly low. By contrast, in arctic and subarctic regions, low temperatures produce high relative but low specific humidities. Thus, contrary to popular opinion, the lack of condensation and/or precipitation in these deserts is due to the large difference between air temperatures and dewpoints, not to the lack of water vapor in the air. The average relative humidity of marine air is usually near 80 percent; on the other hand, that of desert air is usually little more than 20 to 30 percent. In the lower and intermediate latitudes, relative humidity decreases with distance inland from the sea; in the high latitudes, the decrease in relative humidity away from the sea is slight.

Abnormally low levels of relative humidity occasionally occur in surface air and are most common in dry regions where broad fluctuations in temperature occur. In arid parts of the United States, relative humidity sometimes ranges down to about 3 percent, and in humid regions down to 10 percent. When the absolute humidity is low, a sharp rise in temperature can produce a similarly low relative humidity. The occurrence of foehns*, associated with cyclonic storms, can create extreme dryness on the lee side of mountain barriers. Unusually low relative humidities also occur as a result of marked downward settling of warming dry air from aloft.

4-3.1.2 VERTICAL DISTRIBUTION

According to Geiger (Ref. 17), water vapor, being lighter than air, almost always moves upward and can only move downward in special situations. The combination of higher temperatures at the evaporating surfaces of the earth restricts water vapor mainly to the lower atmosphere. Downward flow of water vapor is almost negligible—only 10 percent of the amount that normally passes upward to cooler altitudes. Except for minor losses by condensation** on surfaces during the cooler

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*Also spelled fohn; a warm, dry wind on the lee side of a mountain range. The warmth and dryness of the air is due to adiabatic compression upon descending mountain slopes. Foehns are associated with cyclonic-scale motions, being produced only when the circulation is sufficiently strong and deep to force air completely across a major mountain range in a short period of time. In different mountain regions foehns have a variety of names, e.g., the "Chinook" of the Rocky Mountains (Ref. 6).

**Almost all dew forms as water vapor streams upward from vegetation, soil, and other porous substances; vapor extracted from the atmosphere above such surfaces is generally slight, but is somewhat greater in arid areas.

TABLE 4-8

HUMIDITY VS ALTITUDE FOR U.S. STANDARD ATMOSPHERE (Ref. 18)

Altitude, km	Temperature, °C	Pressure, mb	Saturated atmosphere			Typical atmosphere				
			e, μb	d, mg m^{-3}	r, ppm	r ppm	e μb	d_v mg m^{-3}	U %	T_d °C
0	15.0	1013	17044	12830	10473	6300	10260	7718	60	7
2	2.0	795	7055	5559	5526	3800	4857	3823	69	- 3
4	-11.0	616	2644	2186	2669	1900	1882	1556	71	-15
6	-24.0	472	883	768	1163	900	683	594	77	-28
8	-37.0	356	257	236	449	270	154	142	60	-42
10	-50.0	264	39.3	38.2	92	37	15.7	15.3	40	-57
12	-56.5	193	17.2	17.2	55	17	5.3	5.3	31	-65
14	-56.5	141	17.2	17.2	76	10	2.3	2.3	13	-71
16	-56.5	103	17.2	17.2	104	9	1.5	1.5	9	-74
18	-56.5	75	17.2	17.2	142	13	1.6	1.8	9	-73
20	-56.5	33	17.2	17.2	196	18	1.6	1.6	9	-73

Key: e = saturation vapor pressure, d = saturation absolute humidity, r = saturation mixing ratio
r = mixing ratio, e = water vapor pressure, d_v = absolute humidity, U = relative humidity,
T_d = dewpoint temperature

TABLE 4-9

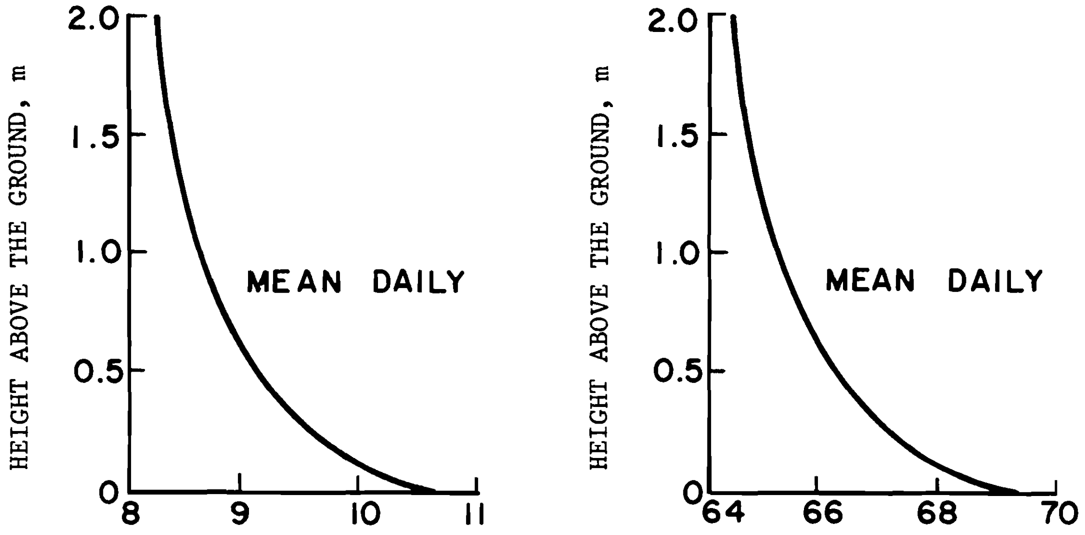
PRECIPITABLE WATER OF SATURATED ATMOSPHERE (Ref. 19)

Sea-level temperature		Precipitable water, in.
°C	°F	
28	82.4	4.15
20	68.0	2.08
0	32.0	0.33

hours of the day, a significant decrease in atmospheric water vapor content occurs only by precipitation. Water vapor often condenses into minute water droplets or ice crystals that remain suspended in the atmosphere and reevaporate. Falling precipitation may also evaporate before reaching the surface of the earth as it passes through dry layers of air in its descent.

Except for occasional "humidity inversions", both the amount of water vapor and its fluctuations decrease rapidly as altitude increases. Table 4-8 shows the computed decrease in humidity with increasing altitude for the U.S. Standard Atmosphere. The principal concentration of water vapor is within 2 km above sea level. Above 8 km, the water vapor content of the atmosphere is negligible.

The total water vapor content of an air column or of the atmosphere over an area is termed *precipitable water,* defined as the equivalent linear depth of water in a column of air if all the water vapor in the column were condensed. Measurements of precipitable water can be made accurately with an infrared hygrometer. The mean precipitable water in the United States in July averages about twice that for January, decreasing



(A) VAPOR PRESSURE, mm of Hg (B) RELATIVE HUMIDITY, %

Figure 4-5. Surface Humidity Variations (Ref. 17) northward and toward the central part of the Western States in both months.

The precipitable water contained in a saturated air column and in saturation-adiabatic* equilibrium show important differences controlled by temperature. Three examples are listed in Table 4-9.

The rate of decrease of atmospheric water vapor with altitude is normally more rapid within the first few meters above the surface of the earth. Fig. 4-5 shows an example of this decrease in the daily mean of vapor pressure and relative humidity; thermocouple pyschrometers were used. The rate of decrease holds equally well for both vapor pressure (expressed in mm Hg) and relative humidity. The humidity gradient is similar to that of temperature near the ground, since the rate of evaporation follows changes in temperature. The amount of water vapor will increase or decrease with corresponding changes in temperature, and condense if cooling causes saturation.

Starting at a short distance above the surface of the earth, the mean relative humidity increases at a slow rate up to the cloud zone, above which the air is drier. The decrease in the amount of water vapor with height above sea level, together with the normal decrease in temperature with altitude, appreciably reduces the controlling effect of temperature on relative humidity. Low humidities are more characteristic of the leeward side of higher mountains than of the windward side.

4-3.1.3 DIURNAL VARIATIONS

When the supply of moisture from soil, vegetation, or water surface is adequate but not excessive, vapor pressure and absolute humidity tend to parallel the diurnal variations in temperature, attaining their maxima in early afternoon and their minima near dawn. Other factors that influence the diurnal variation in humidity are evaporation, condensation, capillary transport of soil moisture to the surface, and the vertical transport of water vapor in the air by convection and diffusion.

In situations where the available moisture at the surface of the earth is small, and the vertical transport of air is well developed during solar heating each day, the diurnal variation in the amount of water vapor follows a different pattern. A rise in vapor pressure (and absolute humidity) occurs soon after sunrise as increased heat accelerates the evaporation of dew and later of soil moisture. In the late forenoon, vapor pressure starts to decrease because of the rapid vertical transport of water vapor and the lowered amount of available moisture at the surface of the earth. A gradual rise normally occurs before sunset because of diminished convection. The water vapor content of the air continues to decrease slowly until dawn due to the downward transport of water vapor and its condensation on the surface of the earth, and, occasionally, on particles suspended in the air near the surface.

Considerable local variation in humidity is produced by sea breezes and nocturnal winds. Occasionally, marked variations from the usual trend are caused by clouds and sunshine, changes in windspeed and direction, precipitation, subsidence, and airmass changes associated with the passage of fronts.

Relative humidity can vary considerably within a 24-hr period. Although influenced by absolute humidity, fluctuations in relative humidity are strongly dependent on temperature and usually constitute an approximate mirror image of it; i.e., the daily course of relative humidity is inverse to that of temperature. Maximum relative humidity usually occurs during the cooler morning hours, while minimum relative humidities are characteristic of warmer midday and early afternoon. However, relative humidity can increase appreciably within a short period of time, particu-

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*A saturation-adiabatic process is an adiabatic process in which the air is maintained at saturation by the evaporation or condensation of water, the latent heat being supplied by or to the air, respectively. The ascent of cloudy air, for example, is assumed to be such a process.

larly after rain, which subsequently increases evaporation.

Diurnal differences in relative humidity are greater in locations where large contrasts in temperature occur–such as mountainous areas, the dry tropics, and continental interiors. By contrast, such differences are relatively small over seas and most snow-covered areas.

Since it is directly related to vapor pressure, the dewpoint temperature normally rises after sunrise. In humid parts of the United States, such as the Northeast, the diurnal minimum of dewpoint occurs about dawn and the diurnal maximum in the afternoon, particularly during the cooler months when there is less turbulent mixing.

In mountainous areas of the Western States (and other places), diurnal mountain and valley breezes produce a vigorous vertical flux of water vapor. Because of the rapid upward transport of water vapor during periods of maximum heating, valleys have a decrease in dewpoint in contrast to an increase on summits.

In dry regions, minimum dewpoints are characteristic of the midday hours, with a maximum occurring in early morning. This is the reverse of the daily pattern of dewpoints characteristic of most humid regions.

4-3.2 GEOGRAPHIC DISTRIBUTION OF WATER VAPOR

Data on the naturally occurring concentrations of atmospheric water vapor are presented in a variety of forms due to the variability of water vapor concentration and to the variety of uses to which the data are put. For example, a manual providing engineering weather data for heating design, air-conditioning design and criteria, and for calculating energy use has been issued by the Department of the Air Force (AFM 88-8, Chap. 6), Department of the Army (TM 5-785), and by the Department of the Navy (NAVFAC P-89). In this manual, dry-bulb and wet-bulb temperatures are presented (Ref. 20). Data on a large number of locations throughout the world are provided. In Table 4-10, percent frequency of occurrence of specified relative humidity values at selected hours for midseasonal months is tabulated. These data indicate the diurnal extremes in relative humidity, which are also indicated by the representative daily variations shown in Fig. 4-6 for 10 representative U S cities. In Fig. 4-7 isopleth maps for the United States are shown for both mean relative humidity and for the maximum persisting 12-hr, 1,000-mb dewpoints.

A maximum *persisting* 12-hr dewpoint is the highest value that has been equalled or exceeded for 12 consecutive hours. A 12-hr persisting 1,000-mb dewpoint is the surface value reduced to 1,000-mb (approximately sea level) along a moist adiabat. This is approximately at the rate of 2.4 deg F, per 1,000 ft. Values on the maps may be readjusted to ground level by subtracting 2.4 deg F for each 1,000 ft of elevation. The original purpose of the dewpoint charts was to adjust past major rainstorms to maximum moisture, in making estimates of probable maximum precipitation in connection with the design of spillways of dams. Maps showing annual mean relative humidity and annual maximum persisting 12-hr 1,000-mb dewpoints are given in Figs. 4-8 and 4-9.

In Fig. 4-10 water vapor pressure levels are given for the world. The mean water vapor pressure for the month of maximum readings is given. For all areas except South America and Australia, the most humid month is July, whereas for those areas, it is January.

In a study of the simultaneous occurrence of high dewpoints and high temperatures, Dodd (Ref. 23) found that temperatures of at least 42.7°C (109°F) in combination with dewpoints at 23.9°C (75°F) and above are rare. When these extreme conditions occur concurrently, the limited data available indicate that they are most prevalent near the coasts of warm bodies of water–such as the Persian Gulf, Red Sea, or Gulf of California.

TABLE 4-10

RELATIVE HUMIDITY AT SELECTED U.S. LOCATIONS (Ref. 21)
(PERCENT FREQUENCY OF SPECIFIED RELATIVE HUMIDITY VALUES AT SELECTED HOURS FOR MIDSEASONAL MONTHS)

STATE and STATION	JANUARY												APRIL												JULY												OCTOBER											
	6 A.M.						3 P.M.						5 A.M.						3 P.M.						4 A.M.						3 P.M.						5 A.M.						3 P.M.					
	<30	<40	<50	≥50	≥70	≥90	<30	<40	<50	≥50	≥70	≥90	<30	<40	<50	≥50	≥70	≥90	<30	<40	<50	≥50	≥70	≥90	<30	<40	<50	≥50	≥70	≥90	<30	<40	<50	≥50	≥70	≥90	<30	<40	<50	≥50	≥70	≥90	<30	<40	<50	≥50	≥70	≥90
ALA. BIRMINGHAM	0	0	2	98	89	42	8	24	38	62	39	14	0	0	3	97	87	45	29	52	69	31	13	2	0	0	0	100	99	59	4	18	48	52	20	5	0	2	2	98	91	59	26	44	64	36	17	5
ARIZ. PHOENIX	2	4	9	91	71	29	42	68	82	18	8	3	3	12	42	58	19	3	81	90	95	5	2	0	3	14	37	63	20	3	66	89	95	5	2	0	1	15	50	50	9	3	89	97	98	2	1	0
CALIF. FRESNO	0	0	0	100	99	85	1	4	14	86	46	6	0	0	0	100	97	51	35	68	85	15	6	1	1	5	13	87	36	1	90	98	99	1	0	0	0	0	1	99	82	25	46	80	94	6	2	1
LOS ANGELES	1	6	11	89	69	28	7	17	29	71	31	9	1	3	5	95	90	33	1	4	13	87	33	2	0	0	0	100	99	26	0	1	3	97	22	0	1	3	6	94	87	44	7	9	12	88	46	0
SAN DIEGO	0	3	8	92	74	21	6	15	25	75	28	5	0	0	1	99	93	21	2	3	8	92	19	1	0	0	0	100	100	26	0	0	5	95	21	0	1	4	7	93	80	28	7	13	19	81	25	0
SAN FRANCISCO	0	0	1	99	96	68	1	4	9	91	58	6	0	0	1	99	97	45	1	3	7	93	46	1	0	0	0	100	100	70	1	2	10	90	20	0	1	2	3	97	95	59	6	14	24	76	33	0
COLO. DENVER	8	23	40	60	25	2	44	60	75	25	8	1	9	22	33	67	37	10	61	72	80	20	10	2	2	8	22	78	45	6	63	78	88	12	5	1	13	28	42	58	28	6	77	85	91	9	5	1
CONN. HARTFORD	0	1	2	98	65	26	1	9	32	68	32	10	0	0	3	97	82	46	17	33	54	46	26	11	0	0	0	100	99	66	4	22	50	50	15	3	0	0	1	99	93	60	6	27	46	54	19	6
D. C. WASHINGTON	0	1	9	91	52	23	6	31	50	50	18	6	0	1	11	89	58	24	25	53	67	33	17	6	0	0	1	99	88	21	5	39	67	33	8	2	0	0	1	99	84	36	13	35	57	43	16	3
FLA. JACKSONVILLE	0	0	1	99	91	57	13	21	44	56	13	3	0	1	2	98	89	51	20	39	58	42	10	3	0	0	0	100	100	53	0	6	22	78	28	8	0	0	1	99	98	65	1	11	26	74	30	5
MIAMI	0	0	0	100	87	40	4	9	32	68	10	3	0	0	0	100	87	29	1	7	32	68	16	3	0	0	0	100	99	48	0	1	3	97	30	4	0	0	0	100	98	59	0	1	11	89	36	5
TAMPA	0	0	1	99	92	67	7	9	41	59	10	1	0	0	1	99	90	53	10	31	48	52	7	2	0	0	0	100	100	77	0	2	16	84	26	4	0	1	1	99	98	80	1	7	33	67	22	6
GA. ATLANTA	0	0	0	100	82	46	9	23	33	67	33	14	0	0	3	97	72	30	31	53	72	28	13	3	0	0	1	99	94	50	5	21	47	53	20	3	0	1	2	98	85	46	11	32	56	44	19	6
HAWAII. HONOLULU	0	0	0	100	81	20	0	0	6	94	13	2	0	0	0	100	85	8	0	0	4	96	9	0	0	0	0	100	87	5	0	0	3	97	6	0	0	0	0	100	92	7	0	0	1	99	14	2
IDAHO. BOISE	0	0	3	97	83	28	1	3	12	88	48	14	0	3	8	92	50	10	45	76	87	13	5	1	1	18	44	56	9	0	88	99	100	0	0	0	2	10	22	78	34	8	41	73	85	15	4	1
ILL. CHICAGO	1	2	3	97	80	17	1	6	13	87	49	12	0	1	6	94	71	15	10	27	43	57	23	6	0	0	1	99	91	23	3	27	57	43	9	1	0	1	4	96	77	17	13	30	60	40	14	3
IOWA. DES MOINES	0	0	2	98	82	21	0	5	12	88	47	6	0	1	2	98	77	29	18	37	54	46	25	7	0	0	0	100	92	38	3	21	50	50	12	3	0	1	3	97	80	17	21	49	65	35	12	6
KANS. TOPEKA	1	1	4	96	71	21	4	18	43	57	21	4	0	1	3	97	74	25	26	42	55	45	19	7	0	0	2	98	87	45	15	34	55	45	16	5	1	1	4	96	77	32	30	52	71	29	11	3
LA. NEW ORLEANS	0	1	2	98	93	61	3	15	23	77	37	7	0	1	2	98	83	53	8	26	43	57	19	7	0	0	0	100	98	77	1	2	17	83	41	6	0	0	3	97	90	52	11	33	47	53	13	4
MASS. BOSTON	1	5	15	85	55	16	3	18	37	63	34	12	0	2	9	91	58	18	19	37	52	48	29	6	0	0	0	100	95	27	5	33	48	52	21	3	0	0	1	99	73	26	9	23	38	62	28	10
MICH. DETROIT	0	0	1	99	84	23	0	0	5	95	62	19	0	0	1	99	77	25	12	23	43	57	20	5	0	0	0	100	89	16	5	31	66	34	10	3	0	1	3	97	83	34	9	26	55	45	13	4
MINN. DULUTH	0	2	6	94	60	14	0	1	11	89	51	10	0	0	2	98	79	27	9	24	41	59	34	14	0	0	0	100	100	63	0	10	41	59	30	7	0	0	0	100	88	52	3	17	33	67	28	12
MINNEAPOLIS	0	1	1	99	81	14	0	1	10	90	45	5	0	0	3	97	71	24	20	37	50	50	21	9	0	0	0	100	94	35	0	28	61	39	11	1	0	1	2	98	75	32	12	37	60	40	13	4
MISS. JACKSON	0	0	1	99	92	58	8	21	34	66	35	12	0	0	0	100	90	50	17	40	62	38	17	3	0	0	0	100	98	68	1	14	49	51	19	5	1	1	2	98	93	48	31	53	68	32	14	3
MO. ST. LOUIS	0	1	2	98	76	23	2	12	30	70	35	14	0	0	1	99	72	20	16	42	62	38	17	5	0	0	1	99	75	22	14	40	64	36	9	2	0	3	8	92	76	22	20	52	69	31	13	6
MONT. BILLINGS	1	4	20	80	44	7	8	18	37	63	36	3	1	4	15	85	48	15	38	59	68	32	9	4	0	5	28	72	25	8	76	87	92	8	5	0	5	14	24	76	40	15	39	59	72	28	13	8
MISSOULA	0	0	1	99	87	37	0	1	6	94	54	11	0	1	6	94	70	21	49	69	80	20	8	3	0	0	2	98	61	15	66	82	90	10	3	0	0	0	1	99	84	39	18	46	65	35	11	1
N. J. NEWARK	0	1	4	96	61	28	1	9	30	70	34	10	0	1	5	95	64	15	19	36	53	47	20	7	0	0	0	100	84	26	5	43	65	35	13	2	0	0	1	99	82	37	7	30	55	45	19	2
N. MEX. ALBUQUERQUE	1	7	22	78	32	3	43	69	84	16	6	1	16	40	56	44	23	7	84	92	95	5	2	0	6	17	33	67	26	4	73	88	94	6	1	0	11	32	52	48	19	4	85	93	97	3	0	0
N. Y. ALBANY	0	0	1	99	75	21	0	6	17	83	33	8	0	0	1	99	80	29	17	41	58	42	18	7	0	0	0	100	95	58	3	32	62	38	11	5	0	0	0	100	90	54	5	20	48	52	19	5
BUFFALO	0	0	0	100	83	26	0	0	6	94	58	18	0	1	3	97	80	27	7	21	34	66	35	11	0	0	0	100	96	35	3	25	53	47	13	3	0	1	4	96	81	22	3	20	46	54	21	2
NEW YORK	0	0	8	92	44	19	1	15	38	62	29	8	0	1	8	92	62	18	15	31	45	55	20	8	0	0	1	99	75	15	5	37	58	42	14	1	0	0	1	99	67	21	6	25	49	51	21	1
N. C. RALEIGH	0	0	3	97	79	37	14	30	47	53	22	14	0	0	0	100	82	46	29	52	79	21	12	6	0	0	0	100	100	75	2	22	45	55	19	5	0	0	0	100	94	65	10	29	53	47	20	6
N. DAK. BISMARCK	0	0	0	100	83	6	0	0	2	98	55	1	0	0	0	100	89	32	20	34	49	51	21	6	0	0	0	100	90	42	9	37	67	33	6	3	0	0	4	96	82	34	20	46	62	38	15	3
OHIO. CINCINNATI	0	0	3	97	83	29	1	4	12	88	50	18	0	1	4	96	74	17	14	33	51	49	23	7	0	0	0	100	90	36	11	39	65	35	11	0	0	1	5	95	80	29	24	42	61	39	14	6
CLEVELAND	0	0	0	100	86	30	1	2	5	95	61	20	0	0	1	99	81	32	9	23	38	62	30	15	0	0	0	100	89	34	7	37	64	36	11	5	0	1	2	98	78	32	5	28	53	47	16	3
OKLA. OKLAHOMA CITY	0	0	8	92	71	28	15	38	52	48	27	13	0	1	9	91	64	25	30	53	64	36	18	4	0	0	0	100	96	44	1	15	46	54	19	5	1	6	11	89	69	26	27	49	68	32	11	6
OREG. MEDFORD	0	0	1	99	96	81	1	2	6	94	66	19	0	0	1	99	95	33	29	56	75	25	9	1	0	0	1	99	77	3	72	95	98	2	2	0	0	0	0	100	98	65	22	36	57	43	12	3
PA. PHILADELPHIA	0	3	8	92	64	30	3	13	32	68	28	9	1	1	4	96	70	22	18	43	63	37	18	6	0	0	0	100	91	37	9	41	64	36	11	2	0	0	1	99	90	36	9	31	57	43	13	3
S. C. CHARLESTON	0	0	1	99	89	56	9	21	46	54	21	6	0	1	2	98	86	57	20	37	60	40	16	3	0	0	0	100	99	91	0	1	9	91	33	8	0	0	1	99	95	80	2	13	28	72	24	6
COLUMBIA	0	0	1	99	88	50	14	35	56	44	19	7	0	1	1	99	87	49	34	58	72	28	13	6	0	0	0	100	99	61	4	23	50	50	12	1	0	0	1	99	96	65	14	38	59	41	12	6
TENN. KNOXVILLE	0	1	2	98	86	37	3	10	27	73	38	16	0	0	3	97	74	23	13	49	67	33	15	3	0	0	0	100	97	59	3	20	49	51	18	3	0	0	1	99	95	57	19	42	59	41	9	5
MEMPHIS	0	0	2	98	82	34	2	12	28	72	47	20	0	0	1	99	83	24	14	38	62	38	18	3	0	0	0	100	98	46	6	22	48	52	11	2	0	1	4	96	88	41	22	45	66	34	15	8
TEX. AMARILLO	1	6	21	79	39	6	51	68	76	24	9	2	9	20	33	67	41	15	61	76	85	15	5	1	0	1	11	89	55	22	46	66	79	21	3	0	1	6	18	82	47	15	58	72	83	17	8	5
BROWNSVILLE	0	3	7	93	88	65	9	15	23	77	29	4	0	0	1	99	95	48	4	12	22	78	13	1	0	0	0	100	100	52	0	1	20	80	3	1	0	0	0	100	94	43	5	11	34	66	15	3
DALLAS	0	1	5	95	73	30	18	39	48	52	25	10	0	1	4	96	76	25	27	40	55	45	19	3	0	0	0	100	85	14	1	34	66	34	10	1	1	1	6	94	75	29	26	53	72	28	11	5
EL PASO	7	20	41	59	30	8	58	71	81	19	9	0	32	56	70	30	11	2	90	93	96	4	1	1	1	9	24	76	33	3	60	83	91	9	1	0	8	34	59	41	17	3	79	90	95	5	2	1
GALVESTON	0	0	1	99	93	64	1	7	15	85	71	24	0	0	1	99	86	56	2	4	13	87	60	15	0	0	0	100	98	19	0	0	1	99	53	2	0	0	1	99	85	38	0	10	24	76	43	4
HOUSTON	0	0	3	97	87	65	9	21	28	72	39	15	0	0	1	99	88	63	9	22	35	65	24	7	0	0	0	100	100	78	0	2	19	81	21	3	0	1	2	98	90	54	17	31	47	53	18	5
SAN ANTONIO	0	3	9	91	71	46	28	40	53	47	29	12	1	3	8	92	81	41	28	43	60	40	18	6	0	0	0	100	95	32	7	64	89	11	4	2	0	3	6	94	78	40	34	60	80	20	8	2
UTAH. SALT LAKE CITY	0	1	4	96	79	26	1	6	21	79	35	6	3	6	17	83	46	11	45	64	79	21	9	3	2	8	29	71	24	3	77	89	93	7	3	0	4	9	17	83	42	6	51	79	89	11	5	1
VA. NORFOLK	0	0	4	96	73	35	6	18	39	61	28	12	0	1	2	98	76	36	11	33	52	48	17	4	0	0	0	100	97	52	0	7	33	67	25	7	0	0	1	99	86	49	4	15	30	70	34	7
WASH. SEATTLE	0	1	1	99	94	59	0	1	3	97	87	34	0	1	2	98	95	63	12	27	45	55	21	3	0	0	0	100	99	68	3	20	50	50	11	1	0	0	0	100	99	74	1	5	11	89	45	15
YAKIMA	0	1	2	98	91	44	0	4	11	89	58	16	0	1	6	94	71	6	66	88	92	8	2	0	0	0	3	97	65	3	77	94	97	3	1	0	0	0	0	100	92	46	22	50	74	26	7	1
WIS. LA CROSSE	0	0	2	98	79	14	0	3	10	90	44	7	0	2	5	95	77	26	19	34	48	52	29	12	0	0	0	100	98	67	0	16	51	49	23	5	0	1	4	96	78	34	13	38	65	35	12	2
P. R. SAN JUAN	0	0	0	100	85	28	0	0	2	98	35	0	0	0	0	100	95	27	0	0	5	95	42	3	0	0	0	100	100	41	0	0	0	100	62	3	0	0	0	100	99	68	0	0	0	100	59	4

THE HOURS SELECTED FOR THIS STUDY ARE THOSE CONFORMING MOST NEARLY TO THE AVERAGE NATIONAL DAILY MAXIMUM (EARLY MORNING) AND MINIMUM (3 P.M.) RELATIVE HUMIDITY.

IN THE COLUMN HEADINGS, THE SIGN < IS READ "LESS THAN," ≥ IS READ "EQUAL TO OR GREATER THAN." EXAMPLE: $\begin{array}{c|c} < & \geq \\ 50 & 50 \\ \hline 2 & 98 \end{array}$ IS READ: RELATIVE HUMIDITY OF LESS THAN 50% OCCURS 2% OF THE TIME, AND 50% OR HIGHER OCCURS 98% OF THE TIME. TIME IS LOCAL STANDARD.

THIS TABULATION IS BASED ON <u>CLIMATOGRAPHY OF THE UNITED STATES NO. 30 SUMMARY OF HOURLY OBSERVATIONS</u>; 5-YEAR PERIOD, MOSTLY 1949-54; TABLE E.

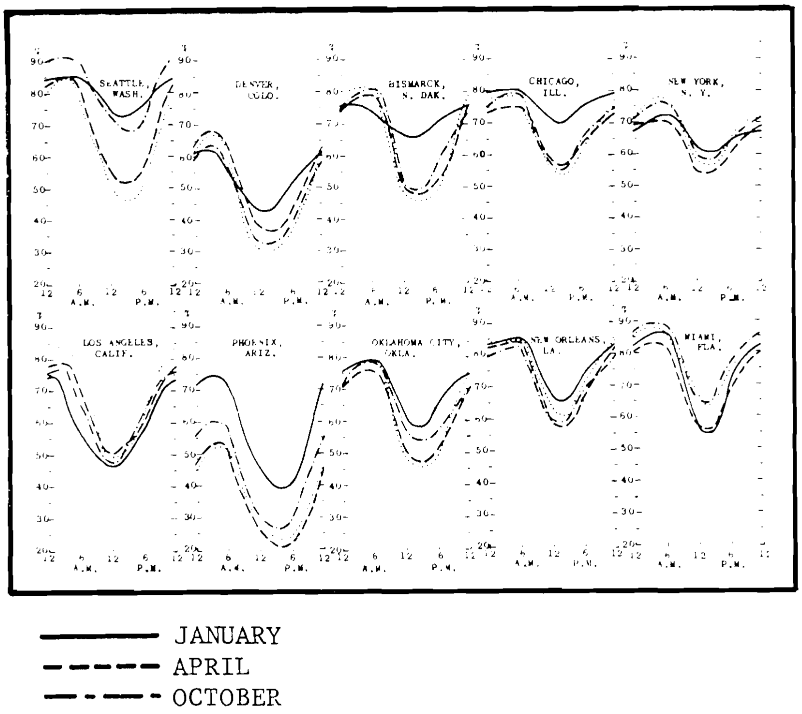

Figure 4-6. Mean Diurnal Humidity (Percent) for Midseasonal Months in 10 U.S. Cities (Ref. 21)

At Abadan on the northern coast of the Persian Gulf, dewpoints as high as 33.3° or 33.9°C (92° or 93°F) have been reported concurrently with temperatures of 42.7° to 45.5°C (109° to 114°F) at the port site, but their validity is questionable. In the period of record from 1946-1948 at Dhahran, Saudi Arabia, a few dewpoints of 26.6° to 28.9°C (80° to 84°F)* occurred with temperatures of 43.3° to 44.4°C (110° to 112°F).

In India's Ganges valley during the premonsoon period (May-June), the highest dewpoints at three stations ranged from 18.3° to 23.9°C (65° to 75°F) at temperatures of 42.7°C (109°F) or higher. Although higher dewpoints are associated with the monsoon season, temperatures are considerably lower.

In North Africa, summer temperatures are often extremely high, but mean dewpoints are lower than those in a number of other areas of high temperature-humidity stress.

In Fig. 4-11, maps are given on which are indicated the percentage monthly occurrence of high dewpoints. It should be noted that Figs. 4-11(A) and 4-11(B) give percentage frequency of occurrence of dewpoints at the 76°F level while Fig. 4-11(C) is for the 80°F level. The circular graphs on the maps are used to give monthly percentage occurrences of the indicated dewpoint temperatures. Additional data are in Ref. 24.

In comparing humidity-temperature conditions, it is important that humidity and temperature observations be made at representative sites and from standard heights (4.5 to 6 ft above the ground). The daily maximum and minimum temperatures of surfaces below this height are significantly higher (for maxima) and lower (for minima) than those of surfaces above this height. This produces an environment with greater diurnal ranges in temperature than that of standard shelter height, and most measures of humidity will

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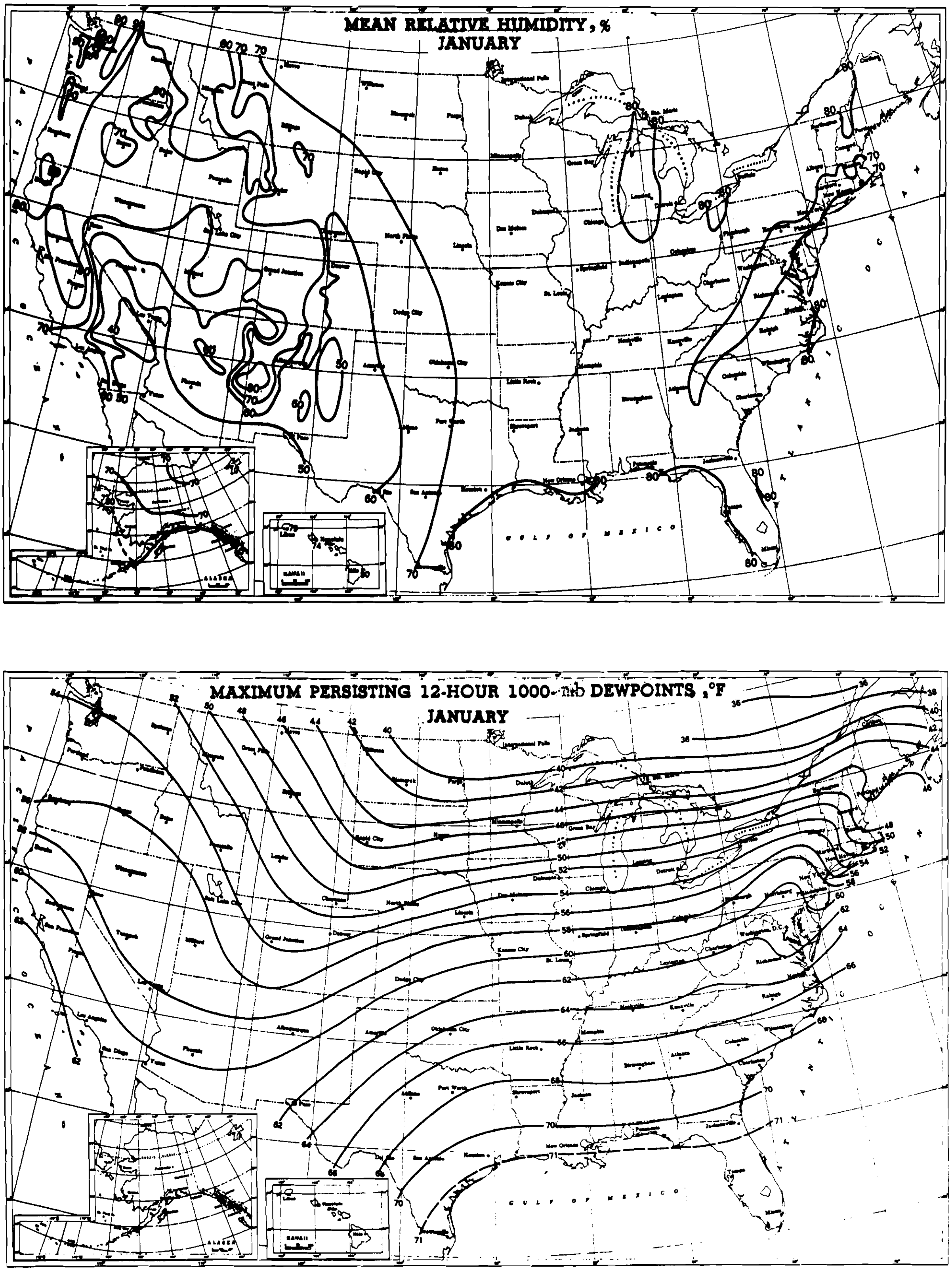
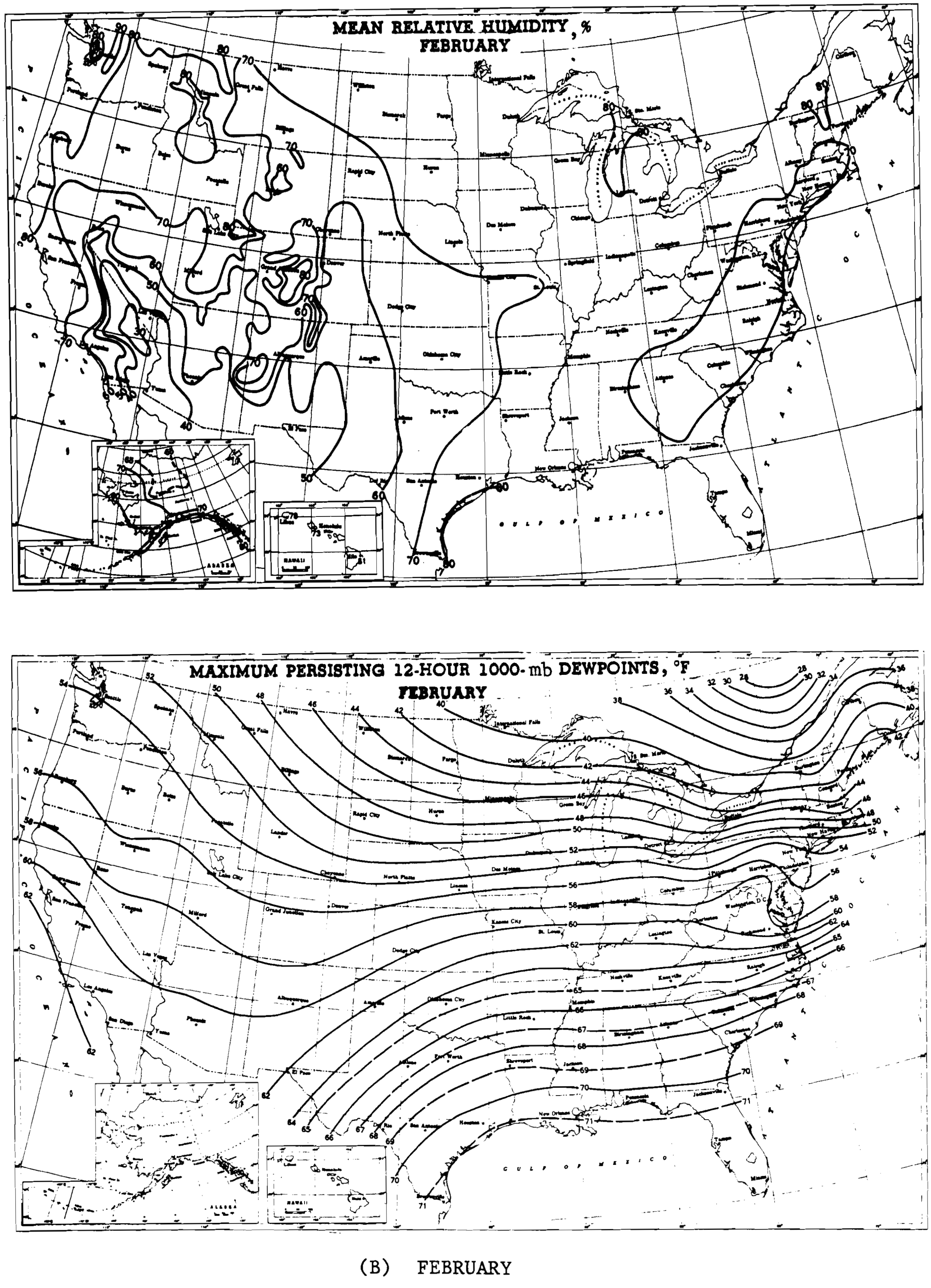
*This tabulation and others are based on temperature and dewpoint intervals of 2 deg F. Thus, two or more values must be given instead of a single value.



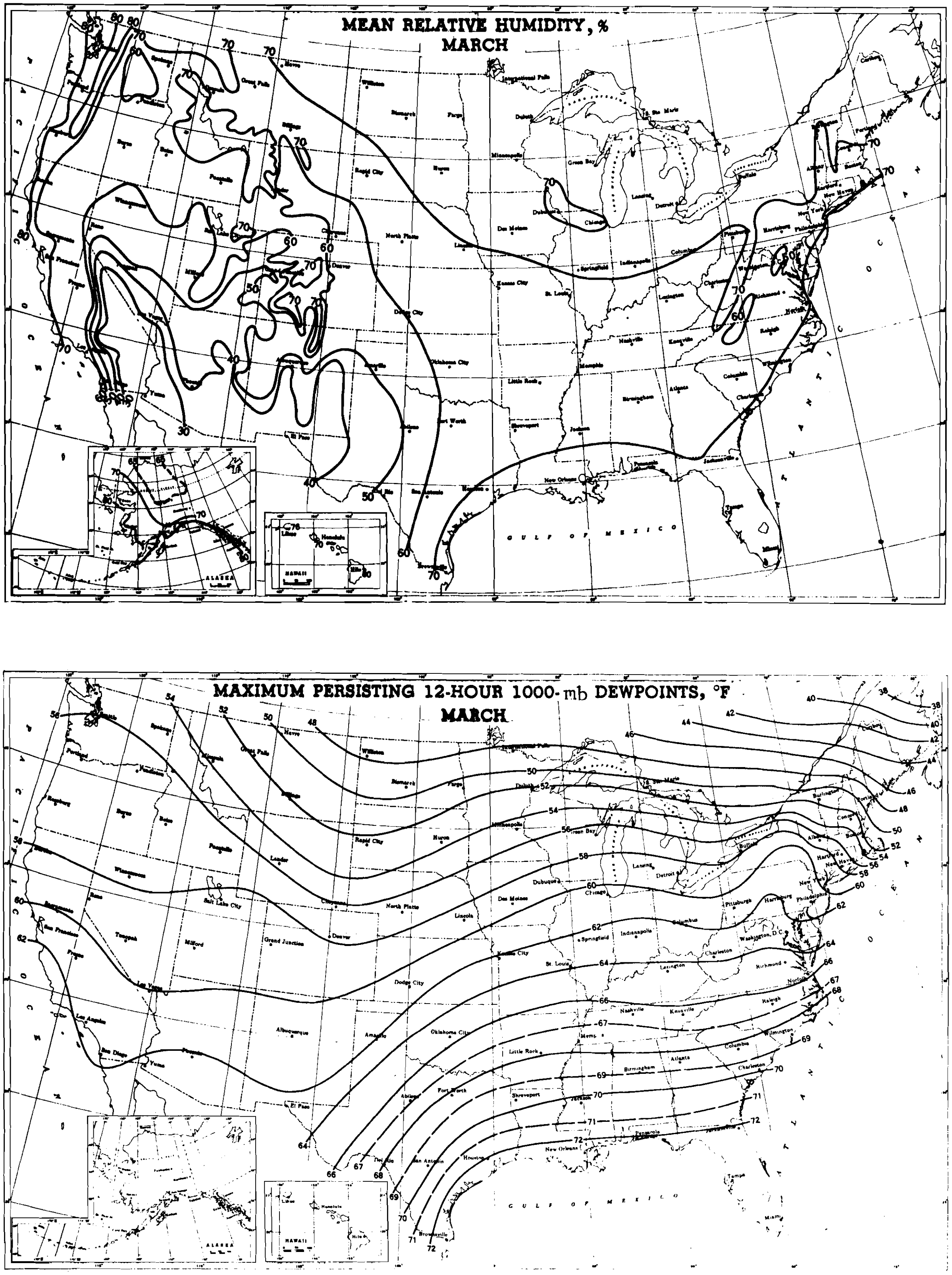
(A) JANUARY

Figure 4-7. Humidity in the United States (Ref. 21)



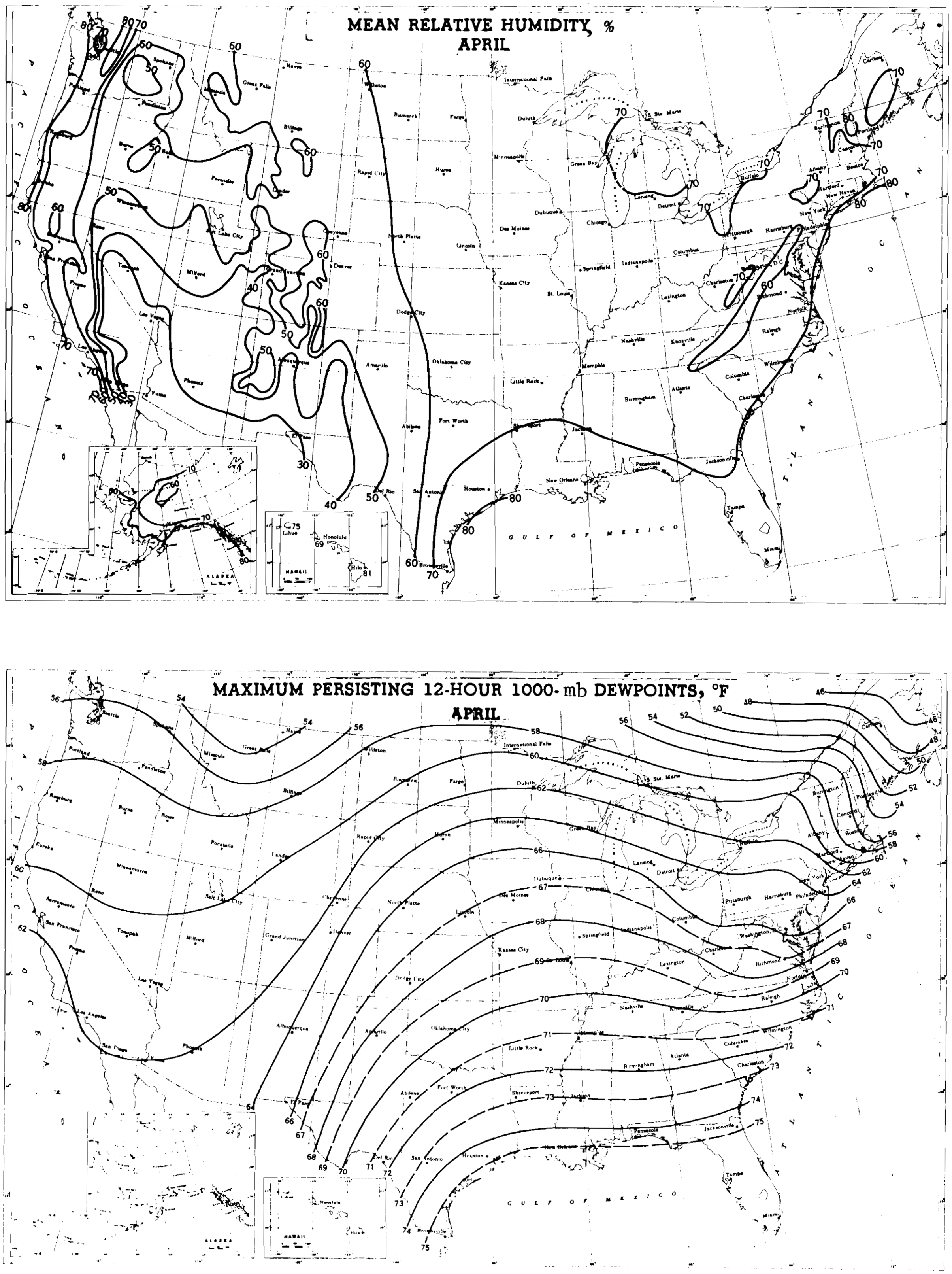
(B) FEBRUARY

Figure 4-7 (continued). Humidity in the United States (Ref. 21)



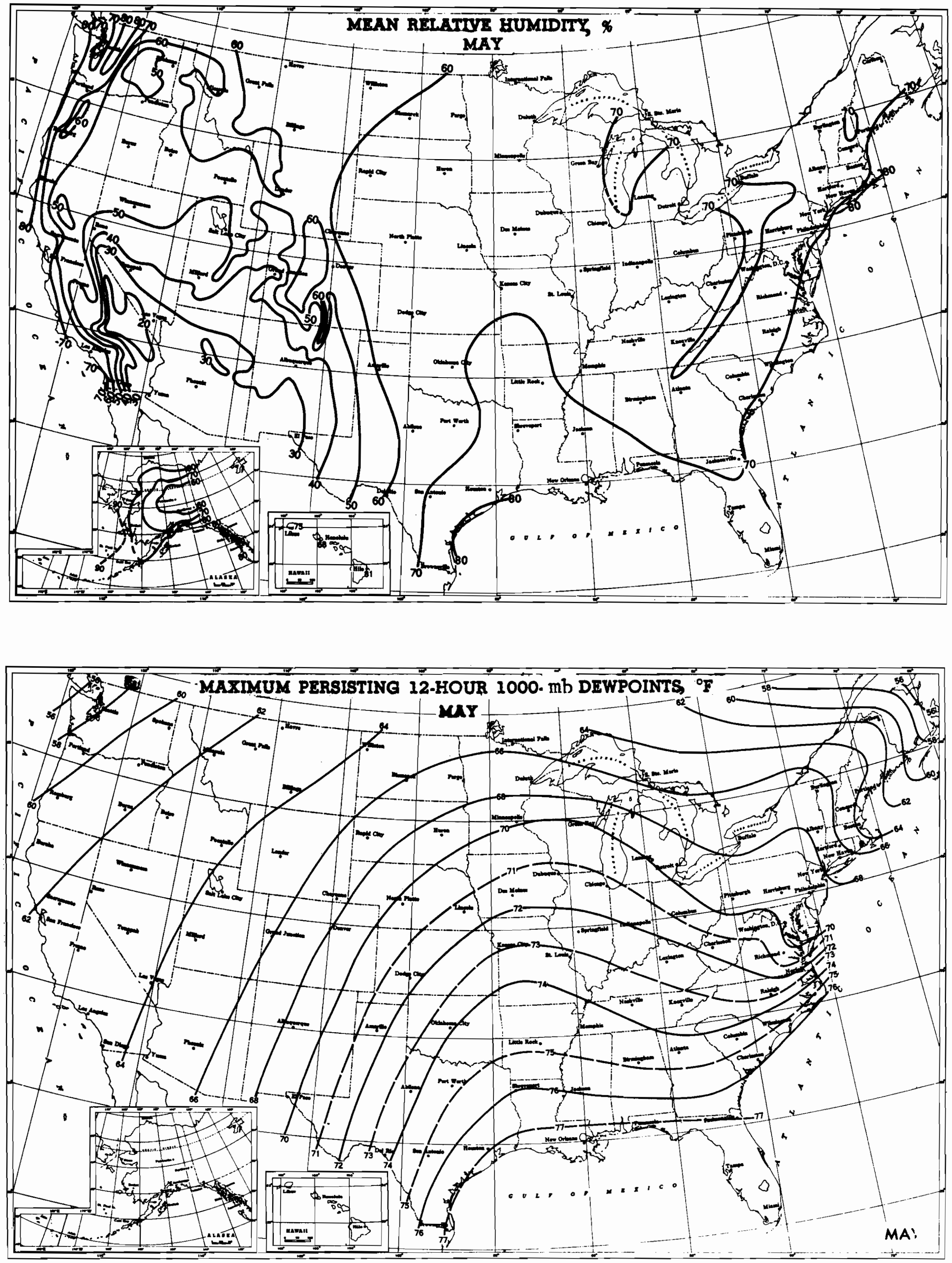
(C) MARCH

Figure 4-7 (continued). Humidity in the United States (Ref. 21)



(D) APRIL

Figure 4-7 (continued). Humidity in the United States (Ref. 21)

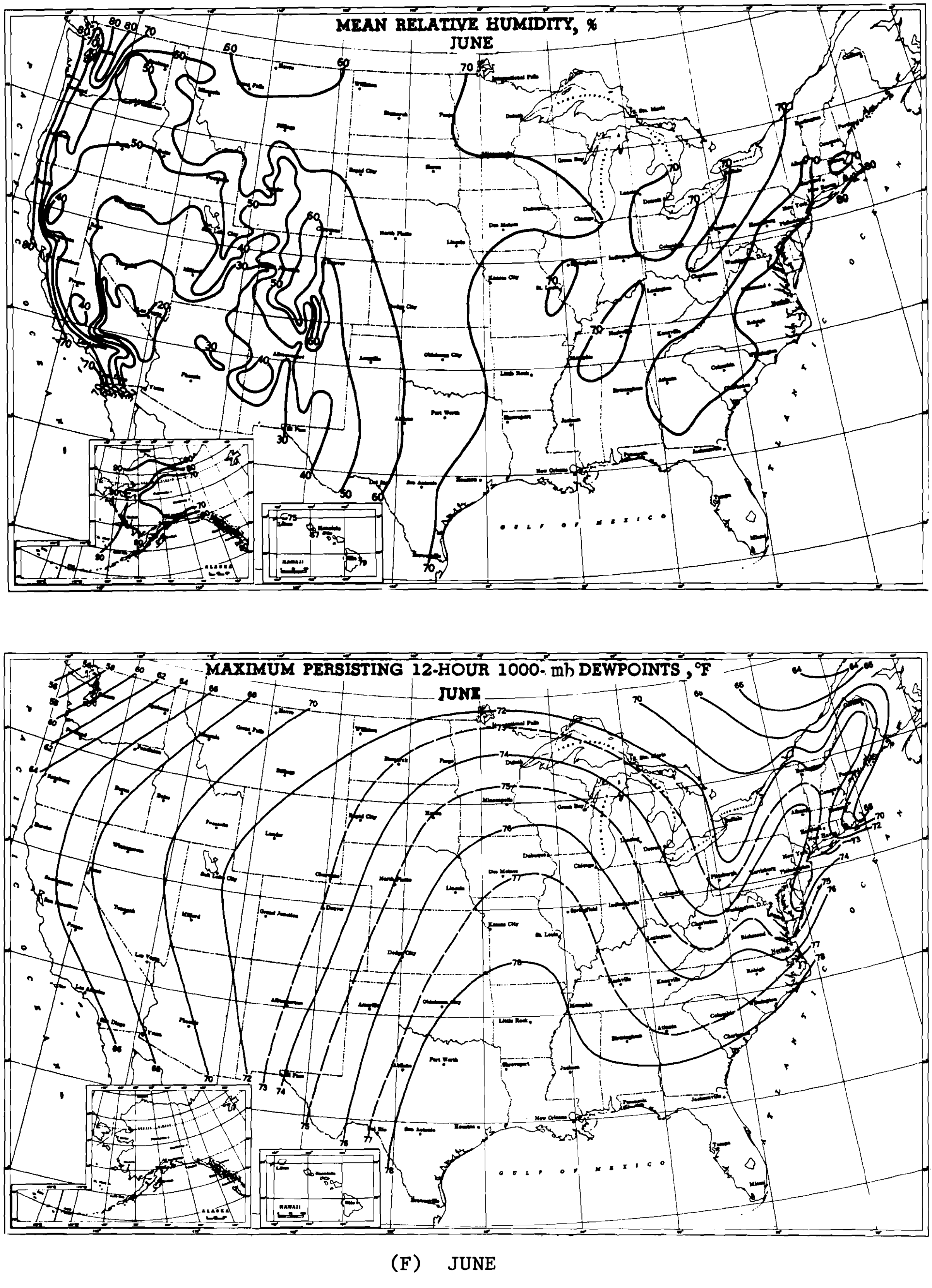


MEAN RELATIVE HUMIDITY, %
MAY

MAXIMUM PERSISTING 12-HOUR 1000- mb DEWPOINTS, °F
MAY

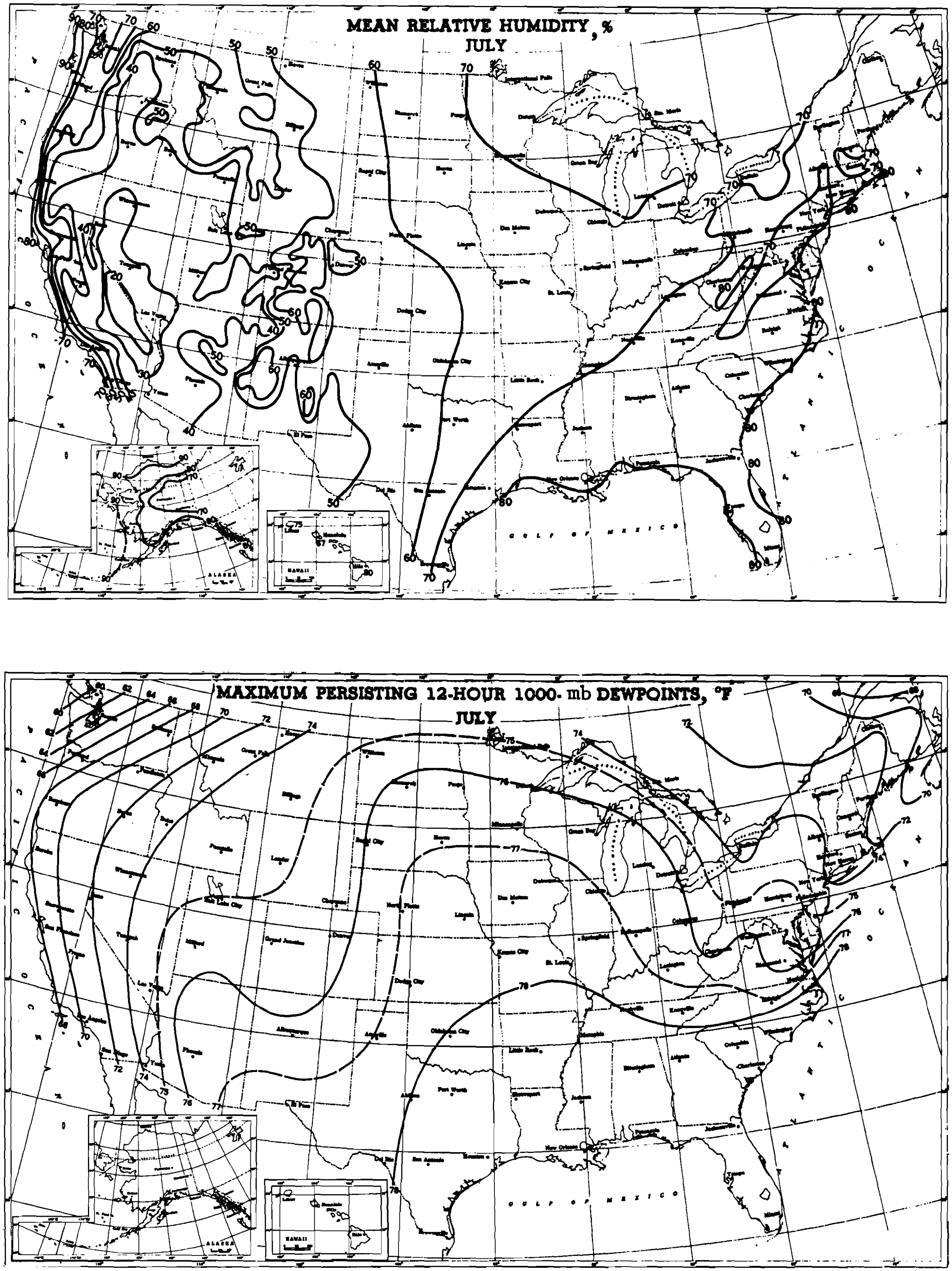
(E) MAY

Figure 4-7 (continued). Humidity in the United States (Ref. 21)



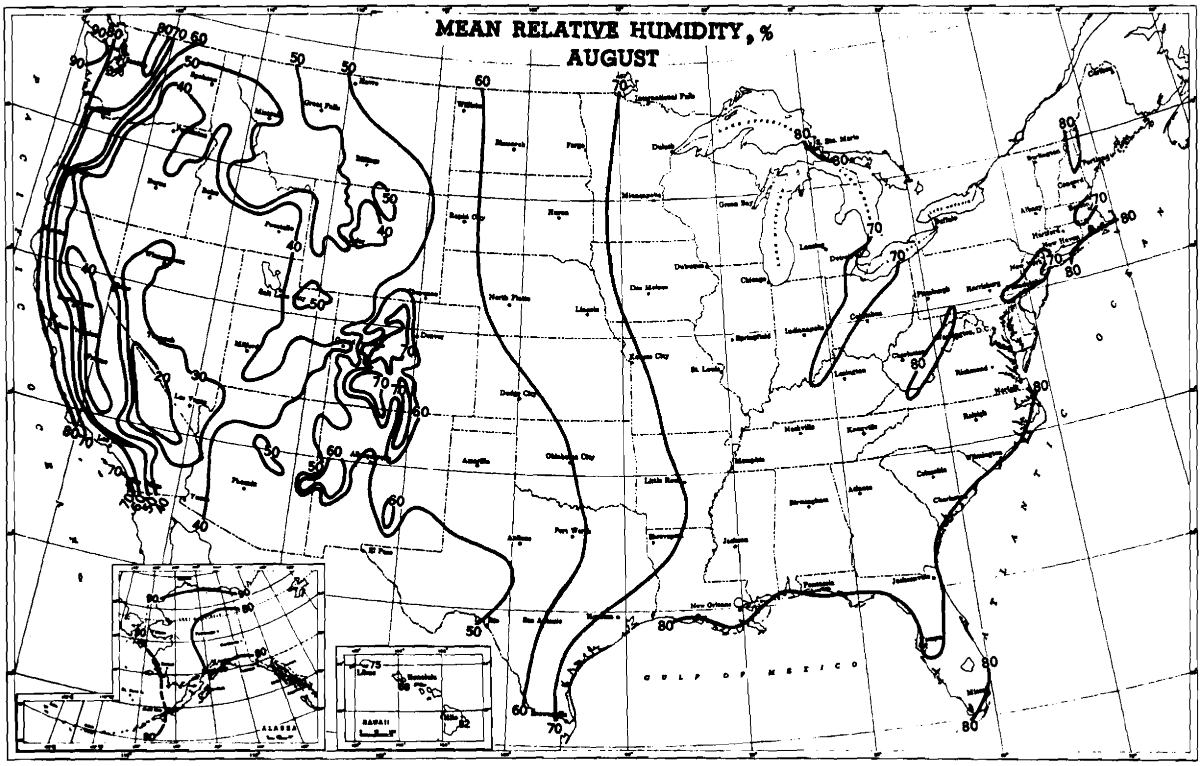
(F) JUNE

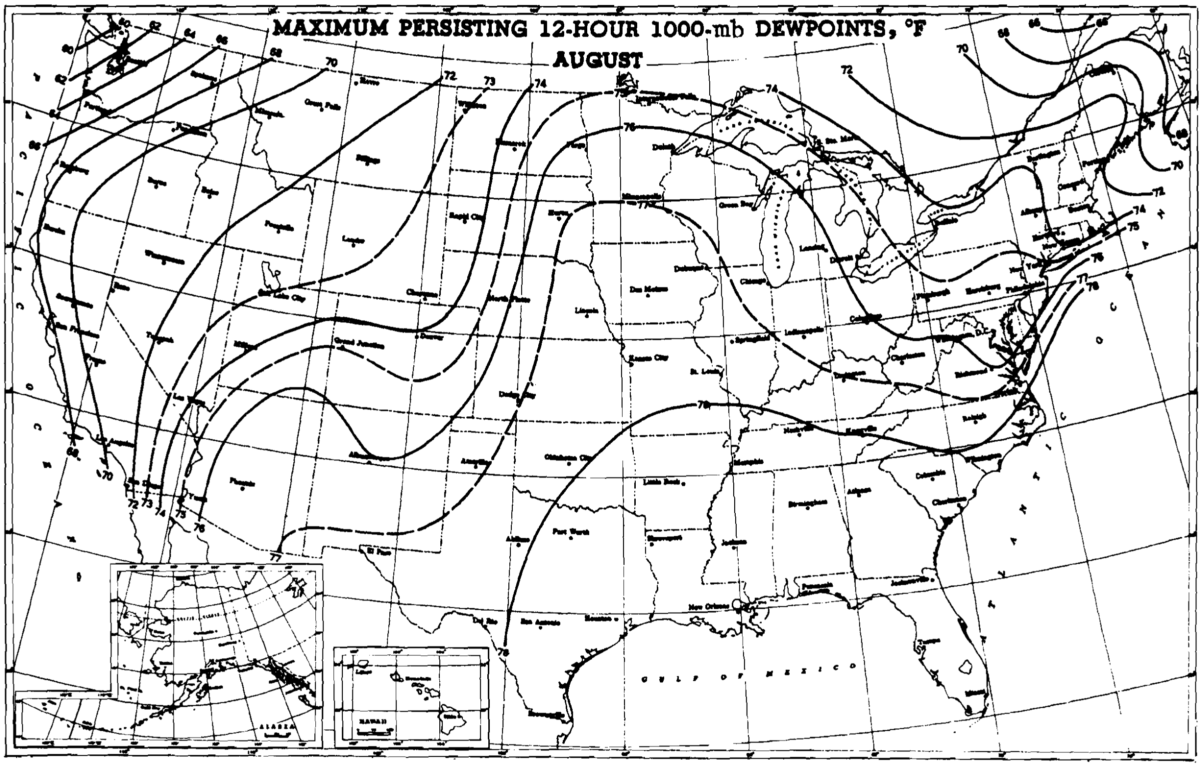
Figure 4-7 (continued). Humidity in the United States (Ref. 21)



(G) JULY

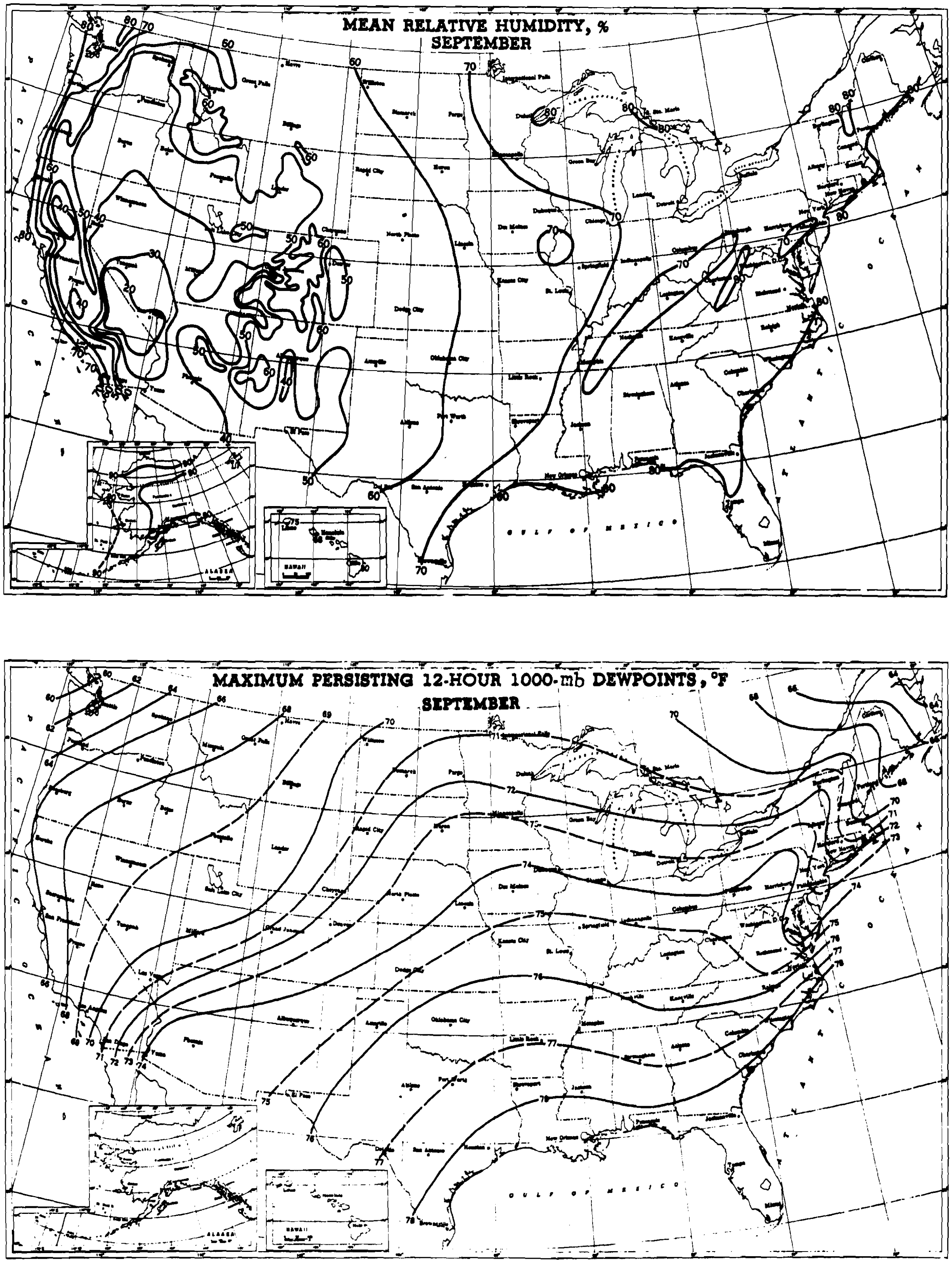
Figure 4-7 (continued). Humidity in the United States (Ref. 21)





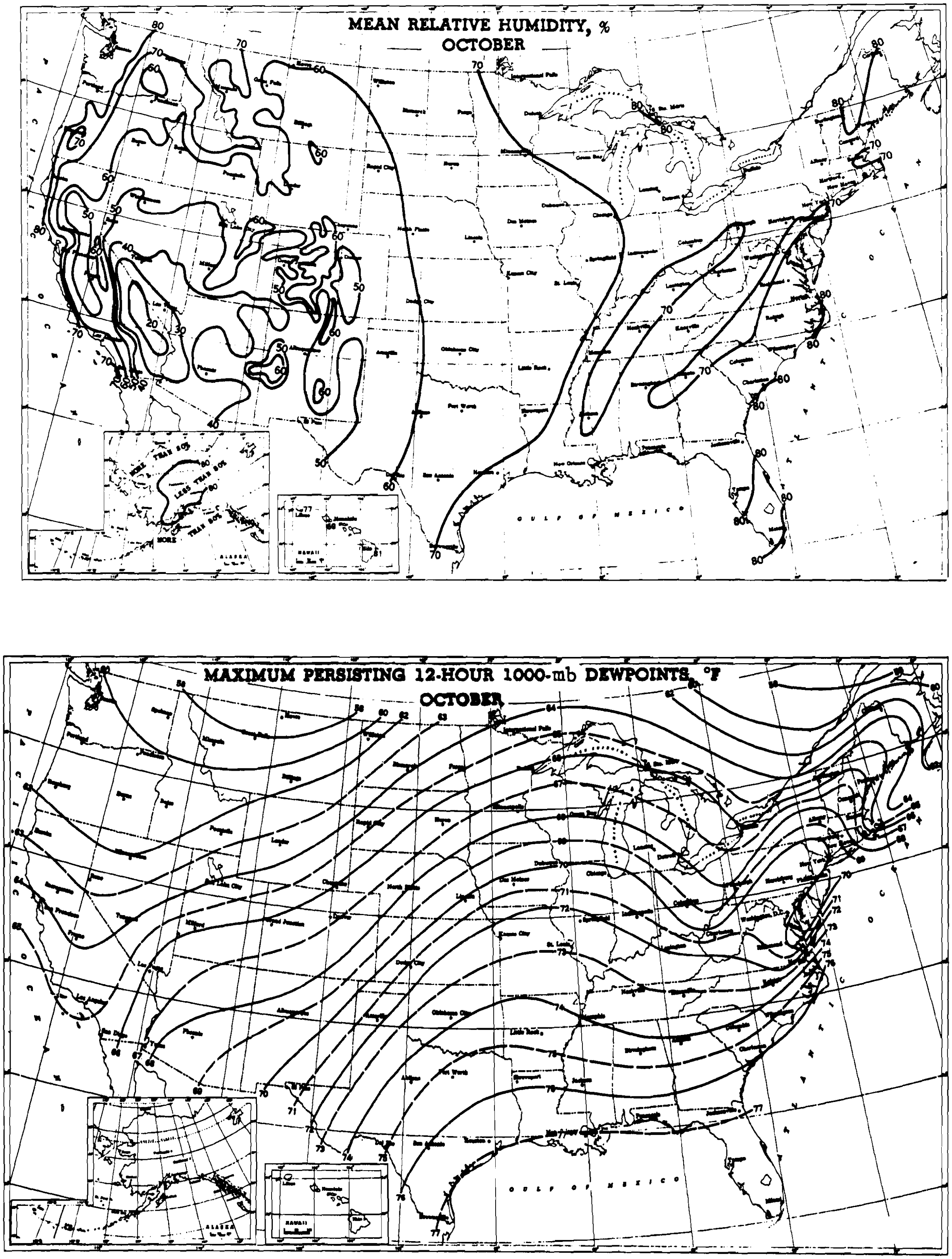
(H) AUGUST

Figure 4-7 (continued). Humidity in the United States (Ref. 21)



(I) SEPTEMBER

Figure 4-7 (continued). Humidity in the United States (Ref. 21)

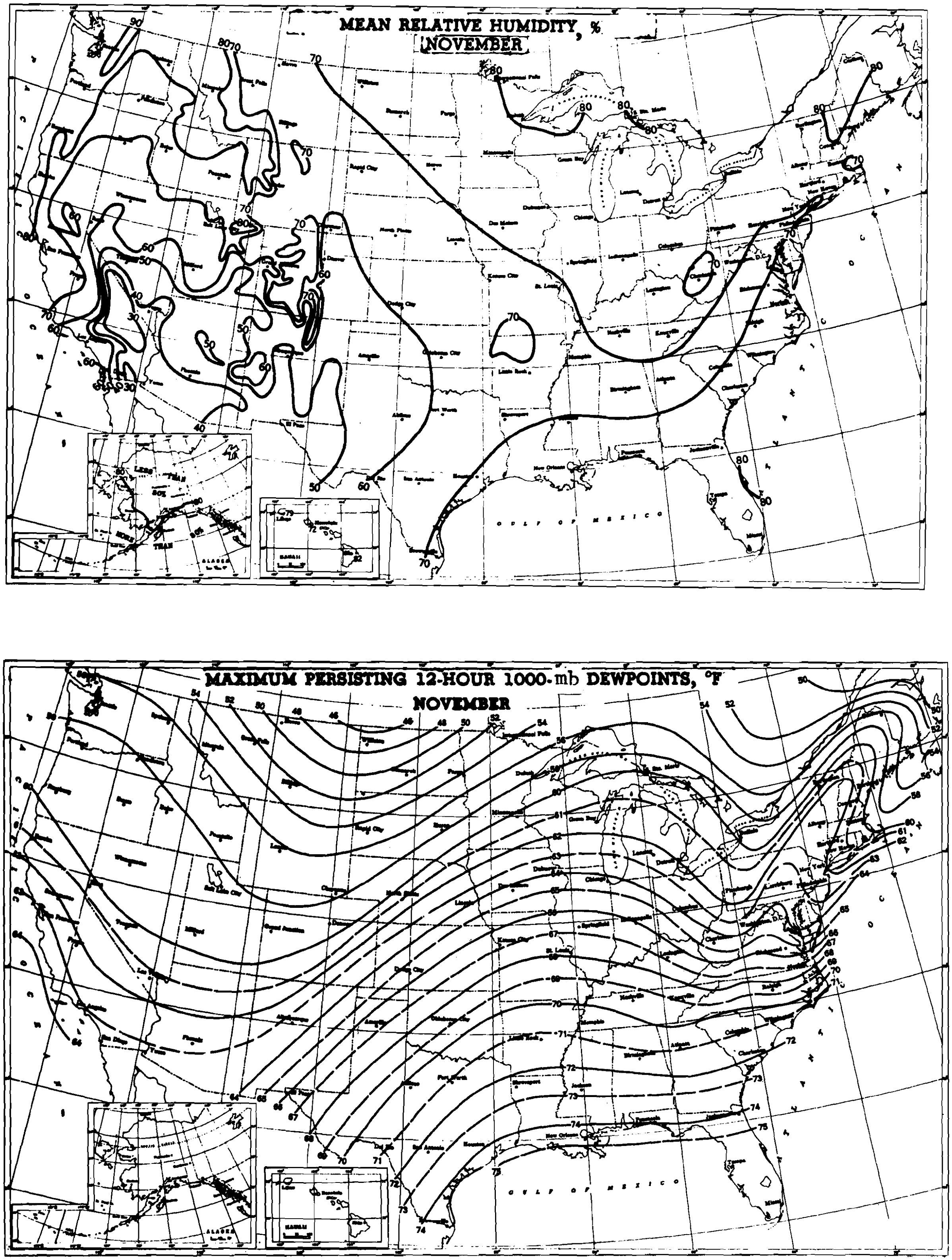


MEAN RELATIVE HUMIDITY, %
OCTOBER

MAXIMUM PERSISTING 12-HOUR 1000-mb DEWPOINTS, °F
OCTOBER

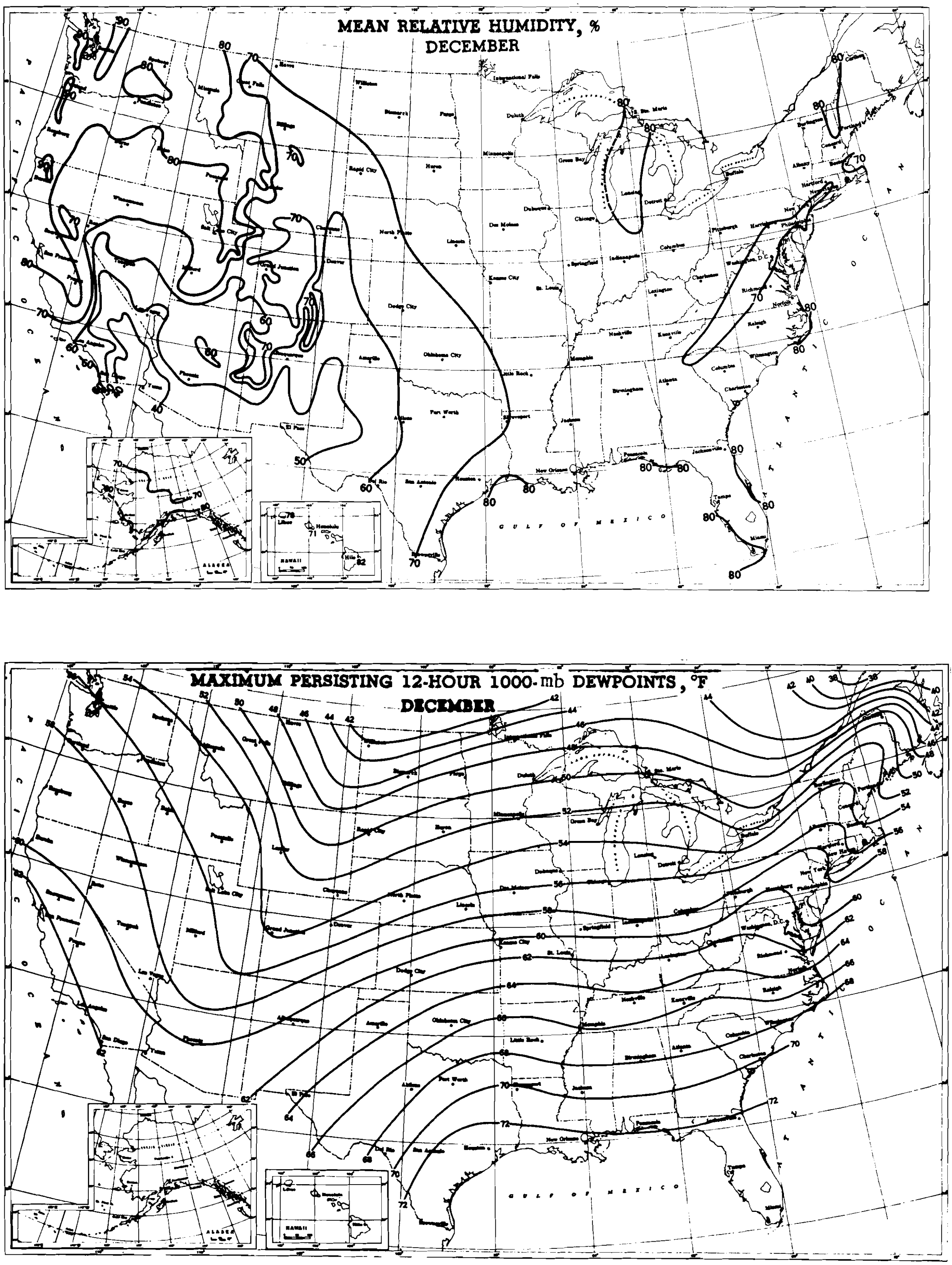
(J) OCTOBER

Figure 4-7 (continued). Humidity in the United States (Ref. 21)



(K) NOVEMBER

Figure 4-7 (continued). Humidity in the United States (Ref. 21)



(L) DECEMBER

Figure 4-7 (continued). Humidity in the United States (Ref. 21)

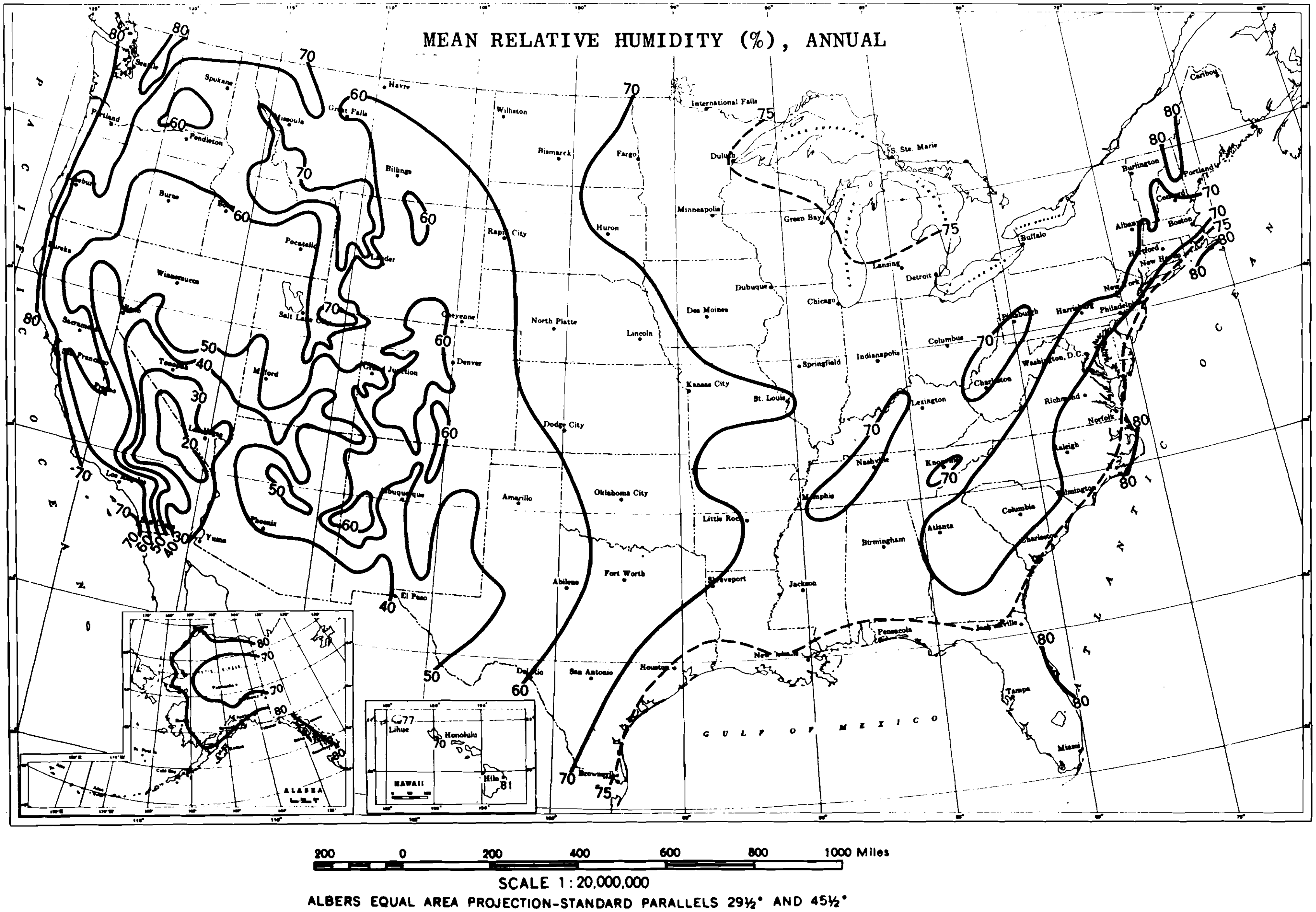
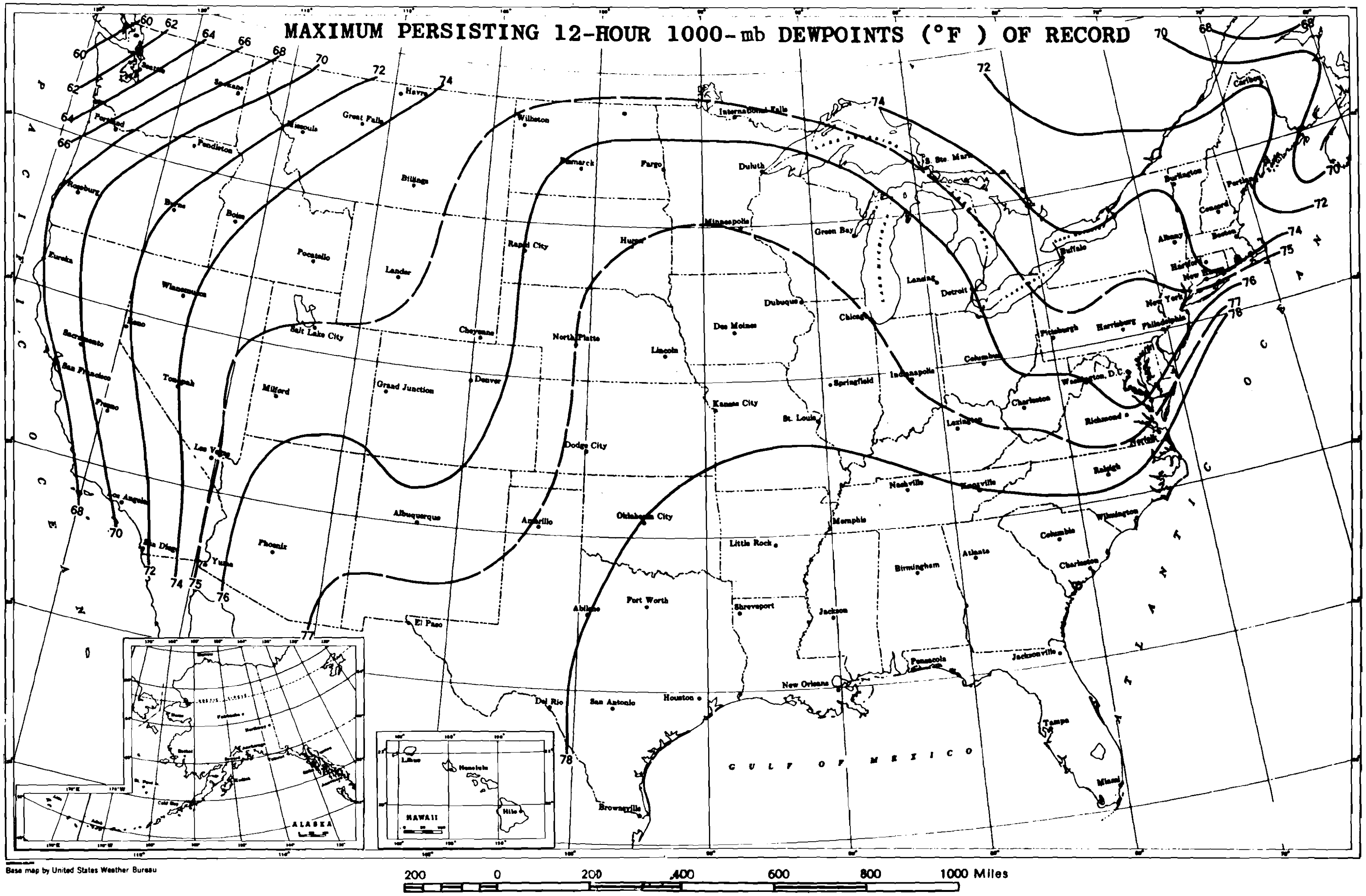


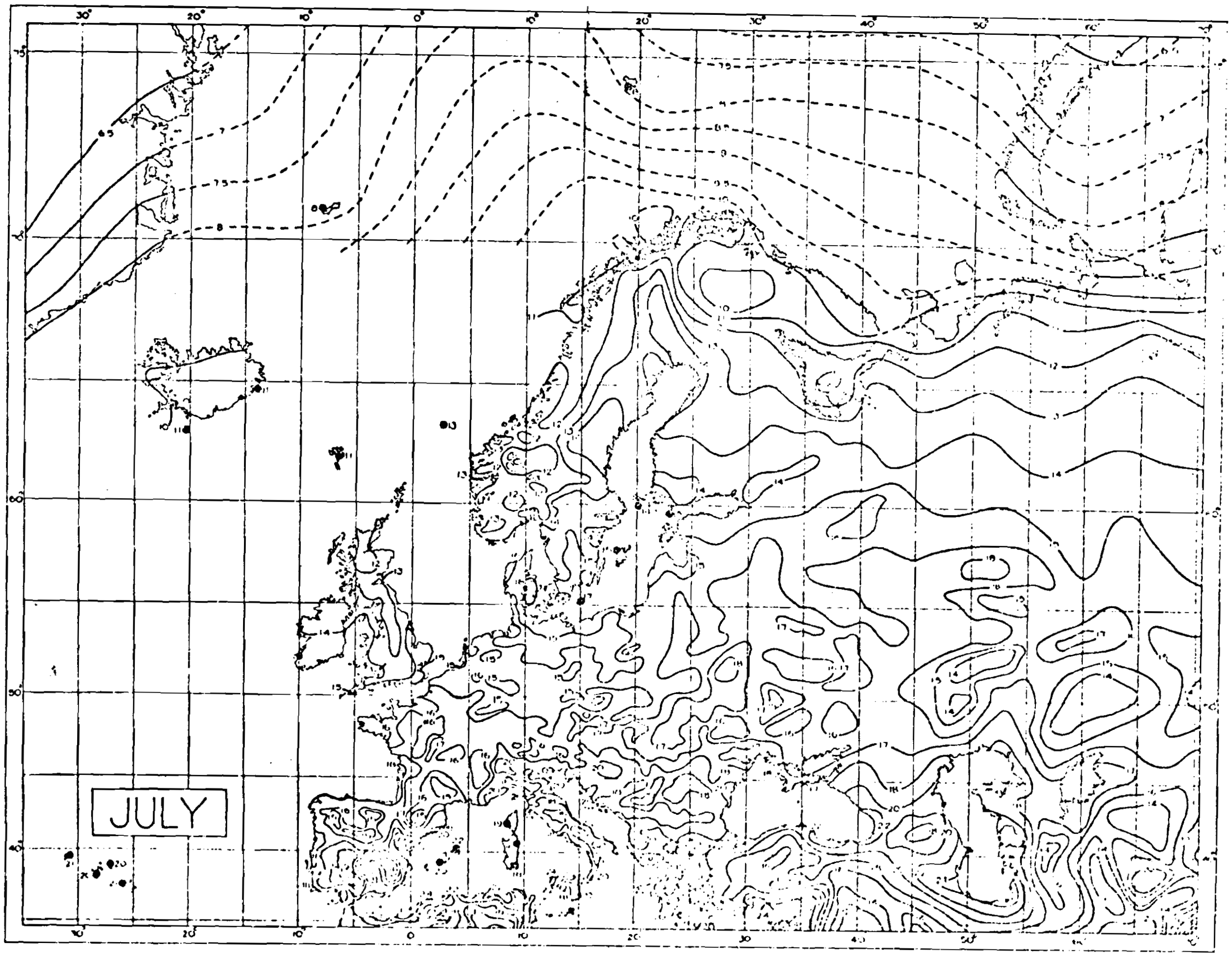
Figure 4-8. Mean Annual Relative Humidity in the United States (Ref. 21)



SCALE 1:20,000,000

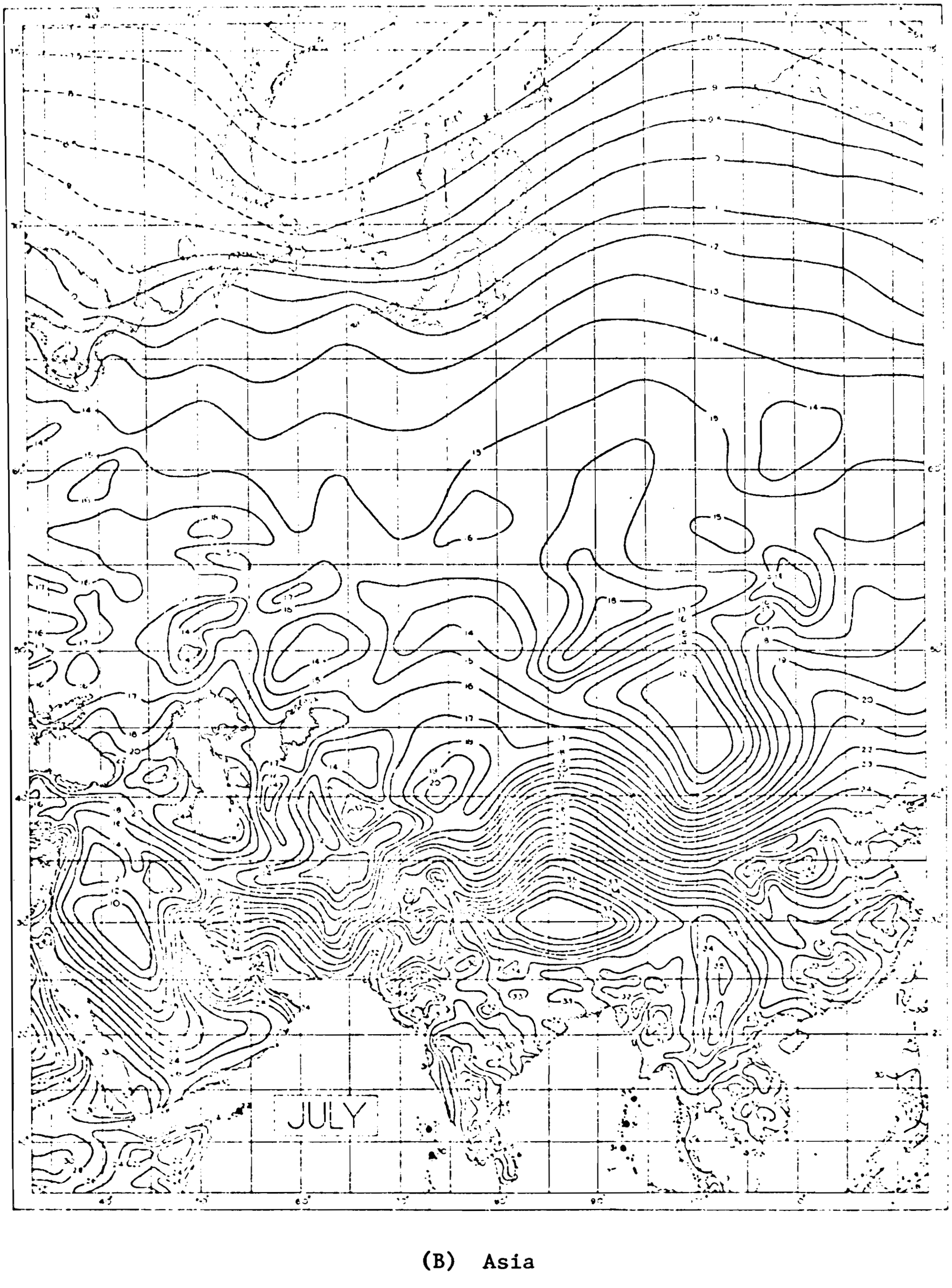
ALBERS EQUAL AREA PROJECTION-STANDARD PARALLELS 29½° AND 45½°

Figure 4-9. Maximum Dewpoints in the United States (Ref. 21)



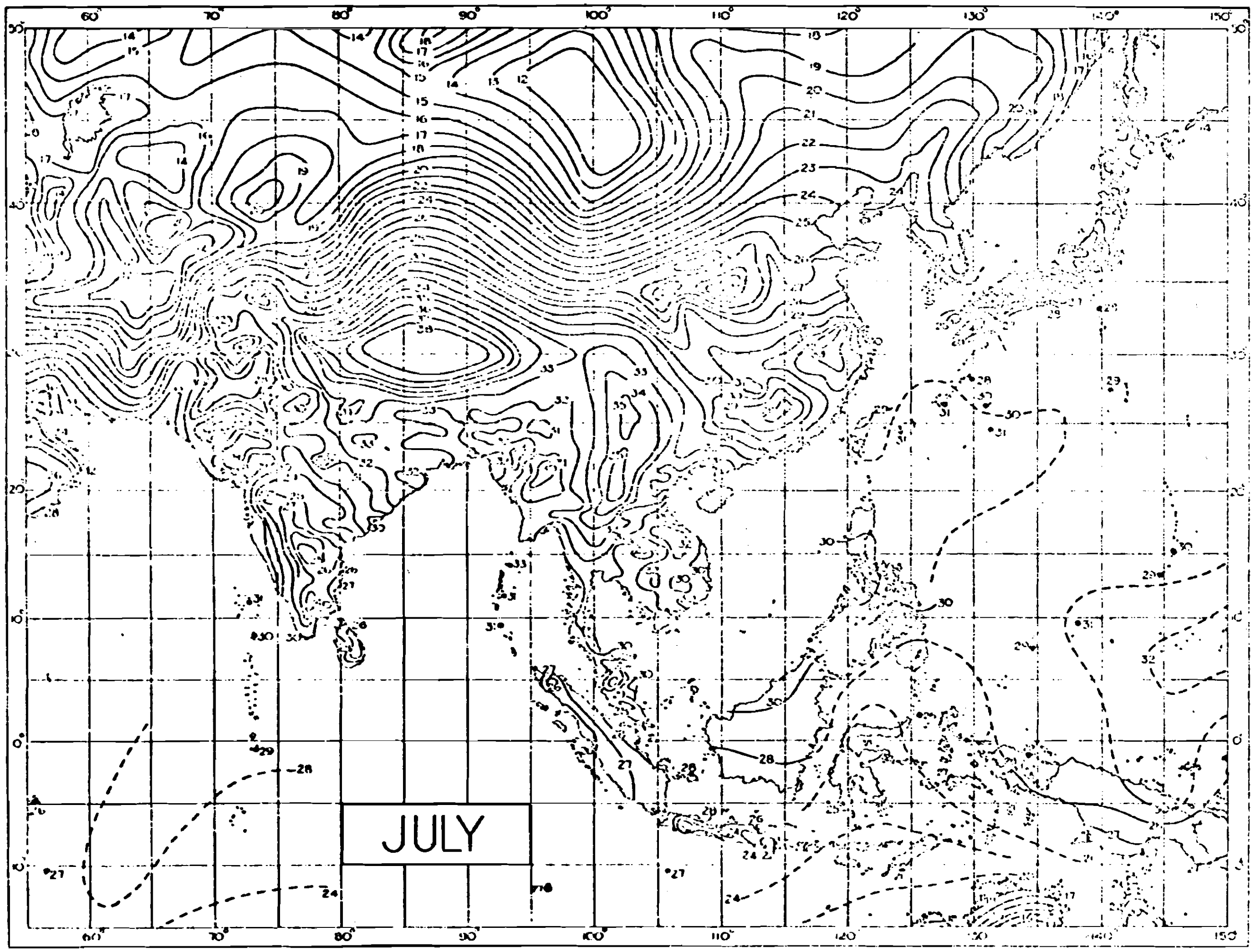
(A) Europe

Figure 4-10. Mean Water Vapor Pressure—Worldwide (for the month of maximum readings) (Ref. 22)



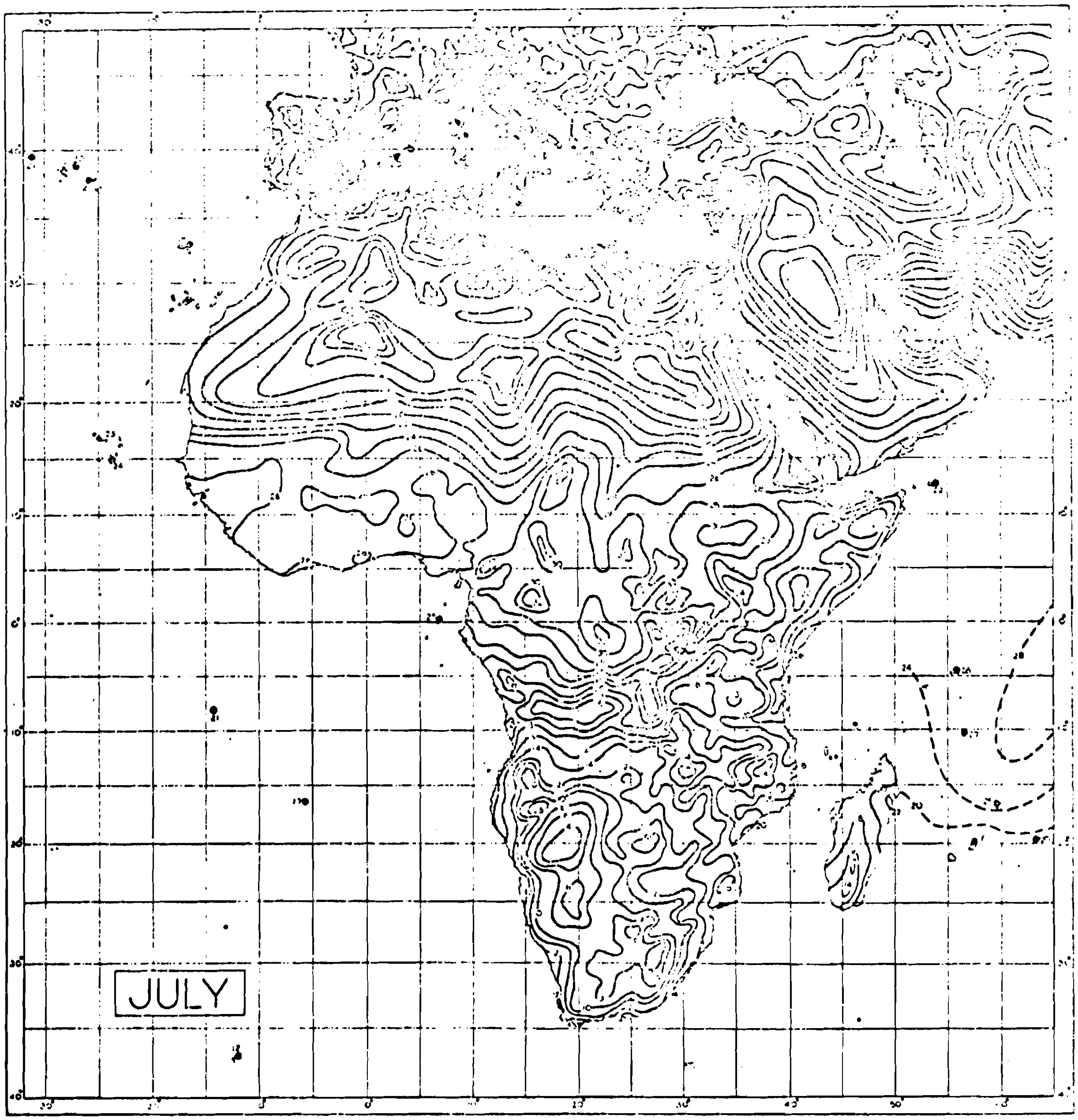
(B) Asia

Figure 4-10 (continued). Mean Water Vapor Pressure—Worldwide (for the month of maximum readings) (Ref. 22)



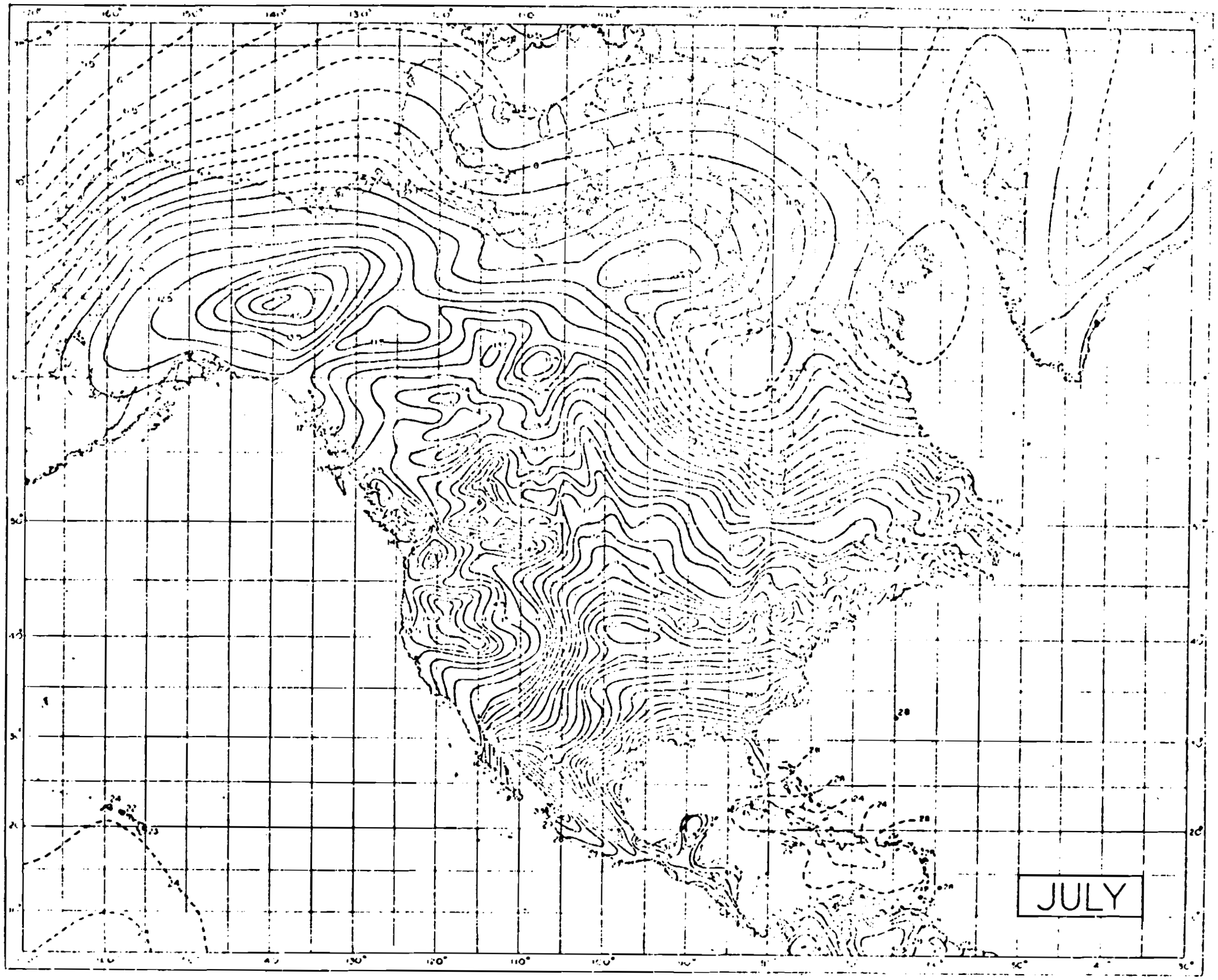
(C) Southern Asia Monsoon Region

Figure 4-10 (continued). Mean Water Vapor Pressure—Worldwide (for the month of maximum readings) (Ref. 22)



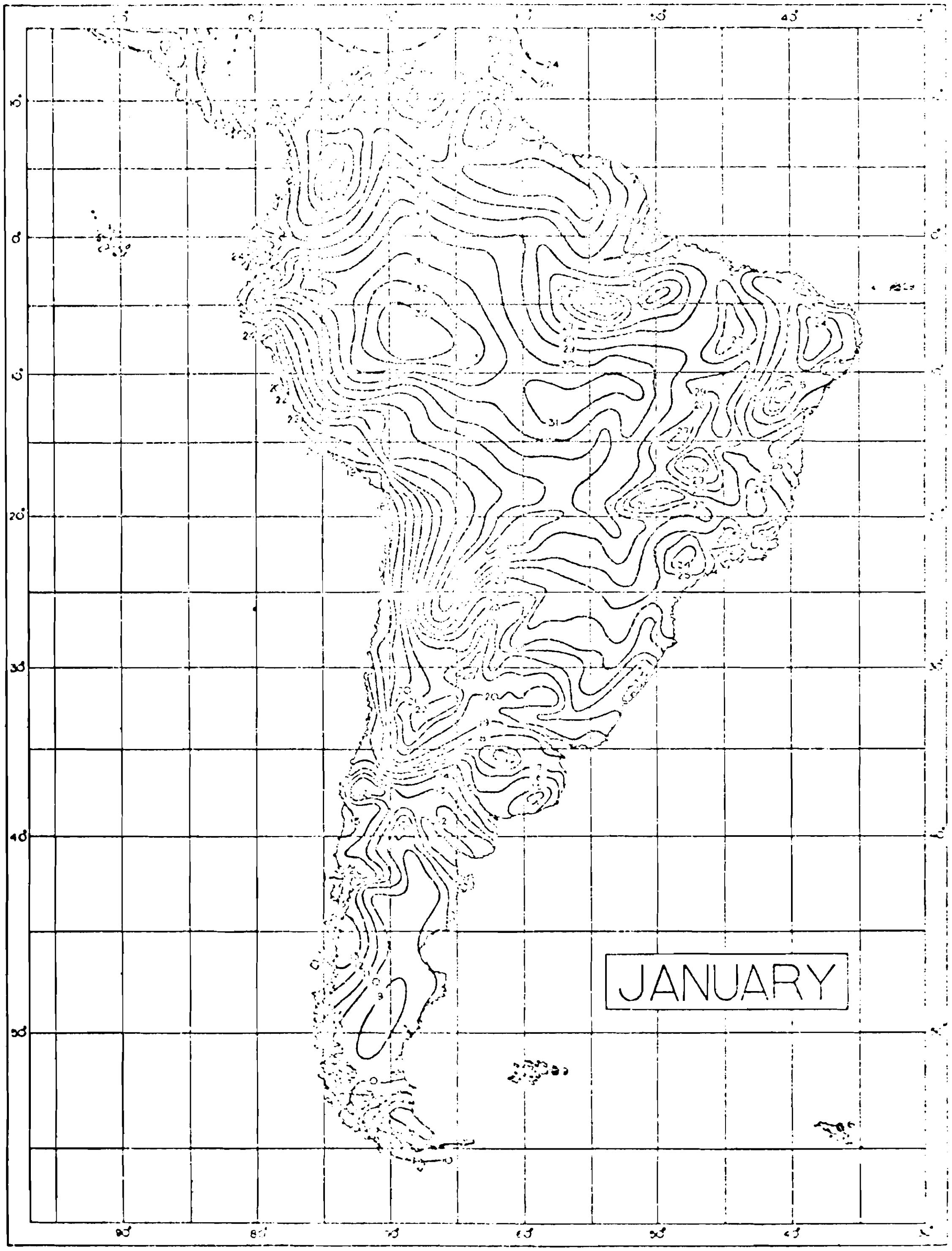
(D) Africa and the Mediterranean

Figure 4-10 (continued). Mean Water Vapor Pressure—Worldwide (for the month of maximum readings) (Ref. 22)



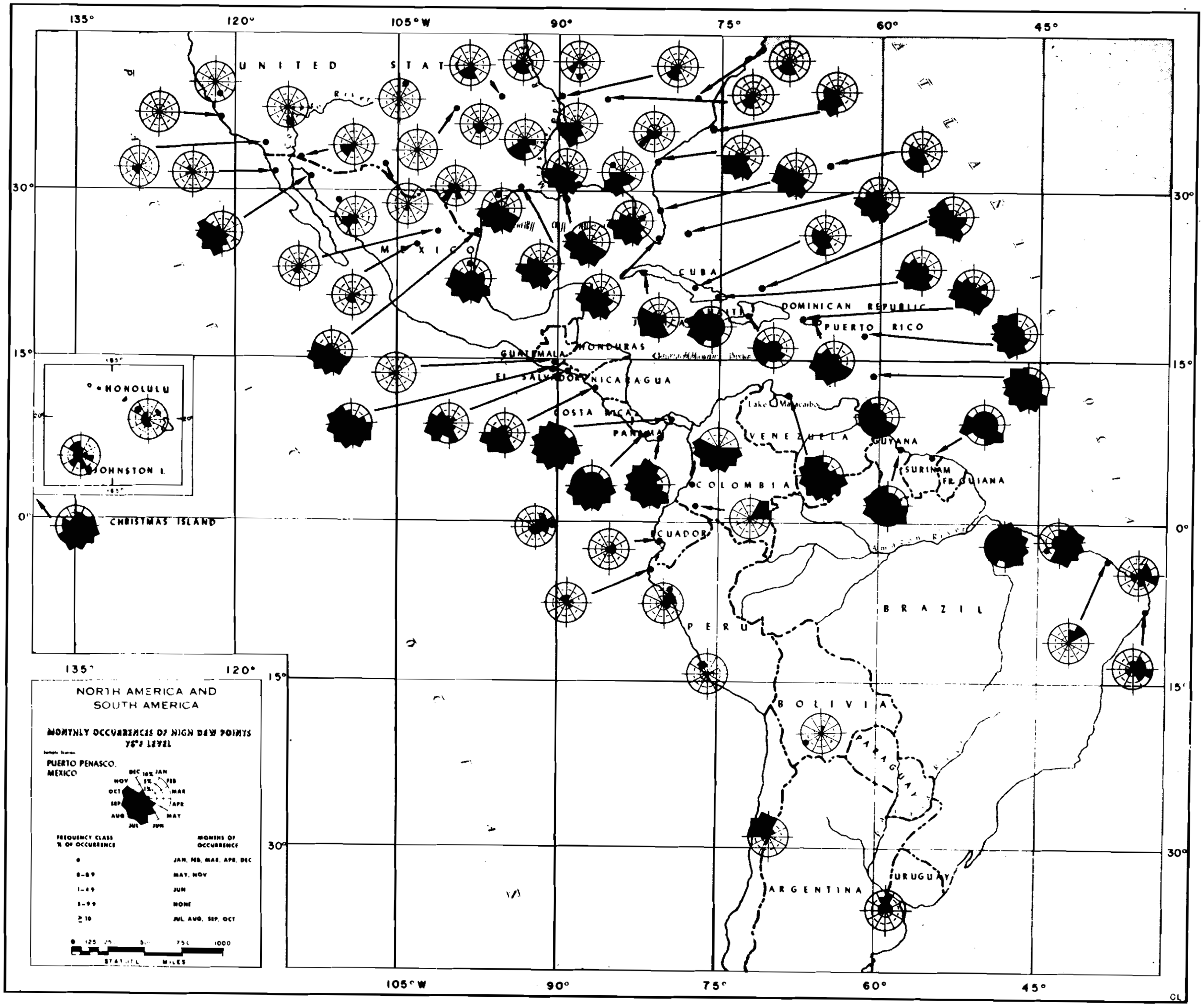
(E) North America

Figure 4-10 (continued). Mean Water Vapor Pressure—Worldwide (for the month of maximum readings) (Ref. 22)



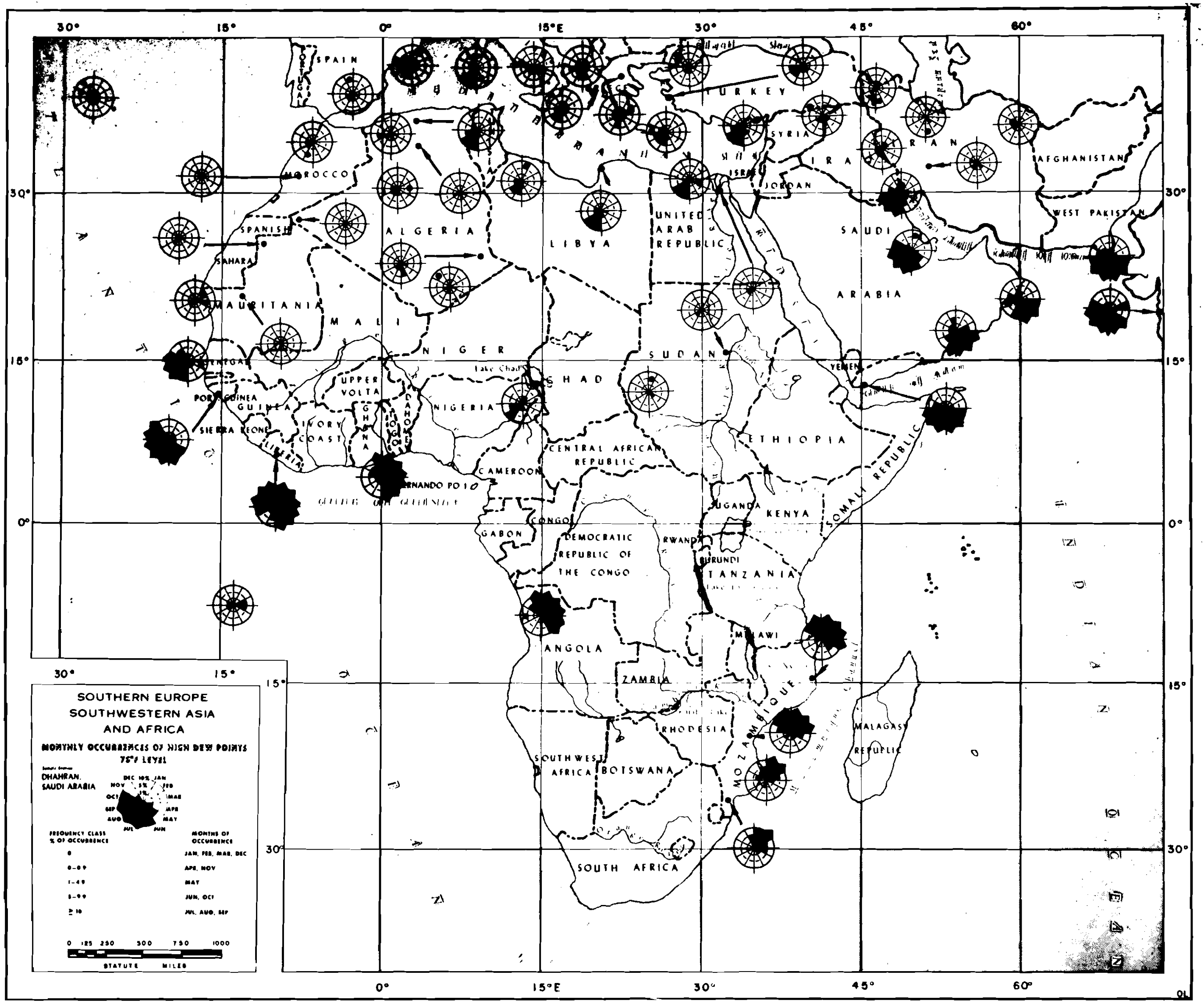
(F) South America

Figure 4-10 (continued). Mean Water Vapor Pressure—Worldwide (for the month of maximum readings) (Ref. 22)



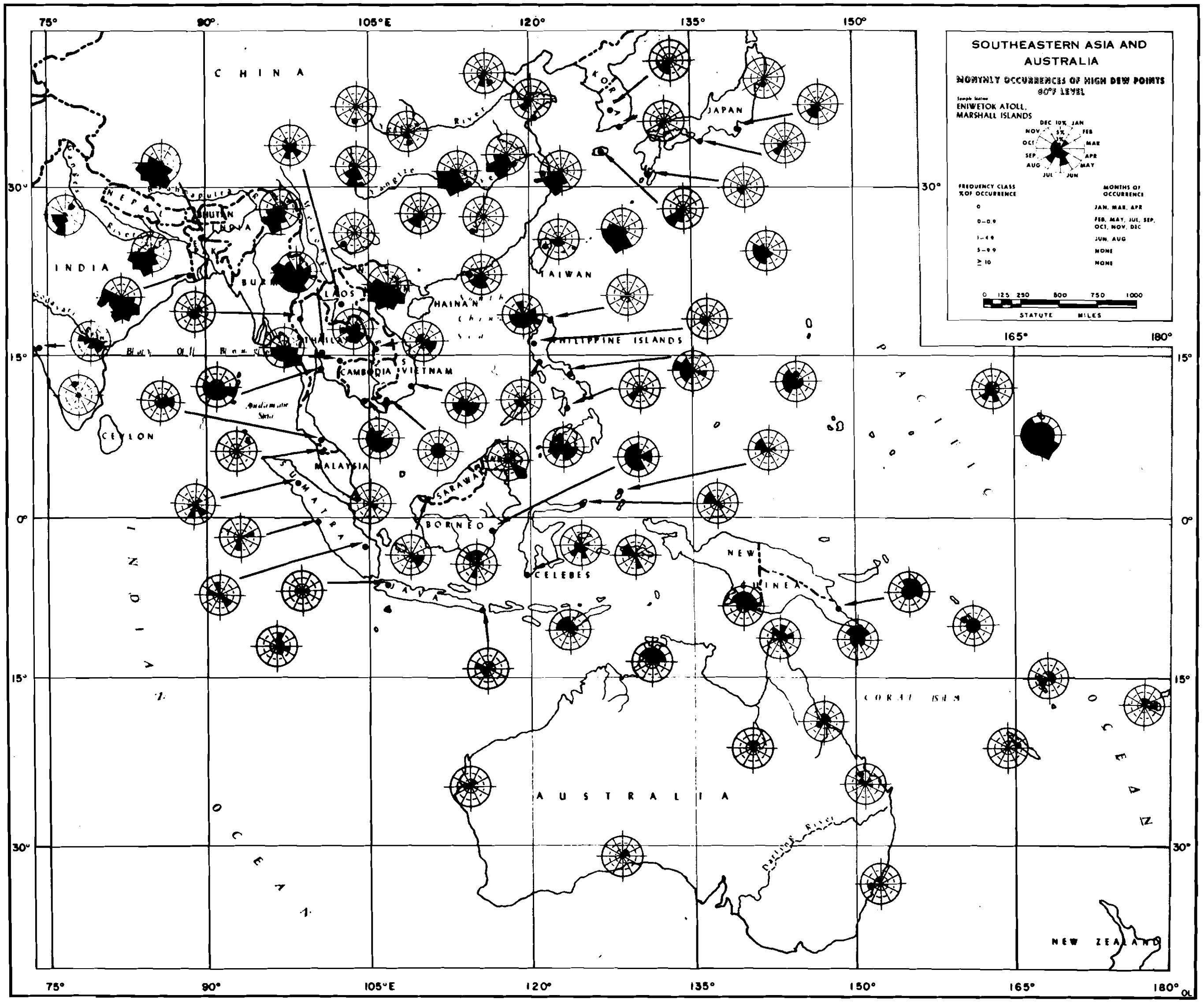
(A) North America and South America

Figure 4-11. Occurrence of High Dewpoint Temperatures (Ref. 24)



(B) Southern Europe, Southwestern Asia, and Africa

Figure 4-11 (continued). Occurrence of High Dewpoint Temperatures (Ref. 24)



(C) Southeastern Asia and Australia

Figure 4-11 (continued). Occurrence of High Dewpoint Temperatures (Ref. 24)

TABLE 4-11

RELATIVE HUMIDITY IN SEVERAL ENVIRONMENTS (Ref. 25)

Environment	Relative humidity, %	Temperature, °F
Truck	100	- 10°
Railway boxcar	95	95°
Covered storage	45	120°
Ship	95	40°
	95	90°
Aircraft	100	- 30°
	50	110°

reflect this. Provided that sufficient moisture is available, evapotranspiration from vegetation and exposed water or moist surfaces produces higher dewpoints than environments where ample sources of moisture are absent.

4-4 WATER VAPOR IN ENCLOSURES

Within buildings, vehicles, or other enclosures, the humidity is subject to different controls than it is in the natural environment. Examples include living quarters in which winter heating results in very low relative humidities due to the low absolute humidity of the cold natural air. In similar fashion, materiel that is stored in the open under a waterproof fabric is subjected to wide ranges of relative humidity as the temperature of the enclosed air changes. Similar conditions are encountered in railway boxcars, in unventilated field storage shelters, and even in tents where intense solar radiation may produce high levels of absolute humidity so that, with nighttime cooling, the dewpoint temperature is readily attained and condensation results. Relative humidity ranges for some enclosed environments are given in Table 4-11.

Humidity levels in an enclosed environment are determined by:

(1) Current and prior temperatures

(2) Amount of water within enclosure

(3) Circulation within enclosure

(4) Ventilation of enclosure

(5) Permeability of enclosure walls to water vapor

(6) Presence of absorbents or desiccants.

Although it would be possible to derive relations for the water vapor content of the air if given information on these parameters, it is usually more practical to measure the humidity level and to correct to the desired levels by use of humidifiers, dehumidifiers, desiccants, or other environmental control methods.

4-5 MEASUREMENT AND INSTRUMENTATION

Accurate measurement of humidity is difficult. While atmospheric temperature and pressure can be measured with a higher precision than is normally required, this is not so for humidity. Although there are many techniques for measuring humidity, no one hygrometer can be singled out as the "standard". The proper choice of hygrometer depends upon a number of considerations, each type having advantages and disadvantages. These include convenience, cost, suitability of instrument design, and the precision requirements of the measurements being made.

Four of the more practical methods may be classified as:

(1) Thermodynamic

(2) Use of hygroscopic substances

(3) Condensation

(4) Infrared absorption.

Discussion will be centered on a few of the more conventional measuring devices for each method, although the variety of modified devices vary greatly in complexity. A basic reference for humidity instrumentation is Middleton and Spilhaus (Ref. 26).

4-5.1 THERMODYNAMIC (PSYCHROMETRIC) METHOD

The most common type of hygrometer is a psychrometer. Many scientists consider this widely used instrument to be the best for general humidity measurement. It serves as a secondary standard for calibration of other types of hygrometers.

The psychrometer consists of two thermometers, one of which (the dry bulb) is an ordinary glass thermometer, while the other (wet bulb) has its bulb covered with a jacket of clean muslin that is saturated with distilled water prior to an observation. When the bulbs are suitably ventilated, they indicate the wet- and dry-bulb temperatures of the atmosphere.

In psychrometry the basic rationale is characterized by Penman (Ref. 27) as follows: "It is supposed that a volume of air at ambient temperature and humidity reaches the wet bulb and replaces an equal volume of air having the wet-bulb temperature and humidity, which will be cooler and wetter. The basic assumption implies that the loss of sensible heat (measured by the fall in temperature) is equal to the gain of latent heat (measured by the increase in water content)."

At a given temperature, the rate of evaporation from the moist muslin depends upon the amount of water vapor in the air passing over it. As relative humidity decreases, the rate of evaporation increases; cooling will also be greater. The difference between the higher reading (dry-bulb or ambient temperature) and the lower reading (wet-bulb temperature) is the wet-bulb depression.

The vapor pressure can be determined from wet- and dry-bulb temperatures by use of the expression (Ref. 7)

$$A = \frac{e_w - e}{p(T - T')} \tag{4-19}$$

where

e = water vapor pressure

e_w = saturation vapor pressure at temperature T'

T = air temperature (dry-bulb temperature)

T' = wet-bulb temperature

p = atmospheric pressure

A = empirically determined proportionality constant

For centigrade temperatures, the constant of proportionality has the value

$$A = 0.00660\,(1 + 0.00115\,T') \tag{4-20}$$

while for fahrenheit temperatures, the value is

$$A = 0.000367\left(1 + \frac{T' - 32}{1571}\right) \tag{4-21}$$

The units of e, e_w, and p must be the same and millibars have been most used in practice. Once e is determined, relative humidity (Eq. 4-8), mixing ratio (Eq. 4-13), and specific humidity (Eq. 4-14) can be determined and

Figure 4-12. Psychrometric Calculator

the dewpoint temperature is that temperature at which the vapor pressure *e* saturates as given in Table 4-2. For example, if *e* were found to be 16 mb, then the dewpoint temperature would be 14°C.

A variety of psychrometric tables, charts, slide rules, and nomograms are available. Some of the more presentative are:

Source	*Reference*
National Weather Service Psychrometric Tables	28
National Bureau of Standards Psychrometric Charts	29
National Weather Service Psychrometric Calculators, Nos. 11832 and 1184	
Air Conditioning Psychrometric Charts and Tables	30
General Electric Psychrometric Chart	9
Smithsonian Meteorological Tables	7
Hydrogrometric Chart	3
Jelineks Psychrometer–Tafeln	31

The National Weather Service psychrometric calculator shown in Fig. 4-12 consists of two circular plastic discs with an overall diameter of 11.25 in. and converts wet- and dry-bulb temperatures to relative humidity and dewpoint temperature. Temperature graduations are 0.5 deg F and relative humidity, 0.5 percent from 1 to 50 percent and 1 percent from 50 to 100 percent.

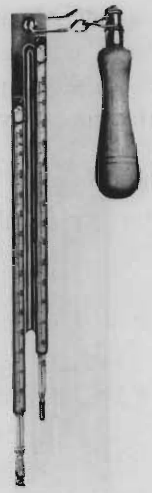


Figure 4-13. Sling Psychrometer

All psychrometers may be classified as nonventilated or ventilated types, the latter being more reliable. Of the ventilated types, the simplest and cheapest is the sling psychrometer shown in Fig. 4-13. It constists of two thermometers mounted in a frame that can be rotated about an axis at right angles to its length. Its wet bulb is moistened with pure water immediately before use. .The instrument, normally about 30 cm in length, is held by a handle and whirled at a specific rate (often of 4 rps). The sling psychrometer should be stopped smoothly in a vertical position. Readings of each thermometer must be taken very rapidly, and the same technique repeated until the wet bulb has reached a steady value. Ample space is essential for whirling the instrument, preferably out of direct sunlight. If observations must be made during sunny periods, the instrument should be whirled and readings made on the shaded side of the observer. Both bulbs of this or any other similar type instrument should be adequately shielded from direct radiation to insure accurate readings.

The Assmann psychrometer, an excellent instrument often used as a secondary standard

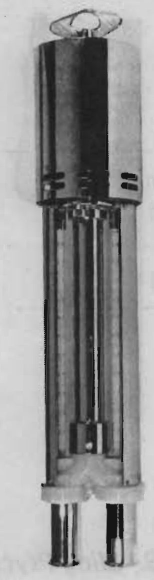


Figure 4-14. Assmann Psychrometer

in checking the performance of other types of hygrometers, is portable and automatically ventilated. Ventilation is induced by a fan (powered by a clock spring or electricity), which pulls air over each thermometer bulb through highly polished, double-walled metal pipes, which shield the bulbs from outside radiation. The Assmann psychrometer shown in Fig. 4-14 is designed for an accuracy of ± 1 percent RH and is constructed of two insulated-type thermometers employed as wet and dry bulbs. Air is forced past the bulbs at a rate of about 13 ft s^{-1} to insure proper ventilation. Radiation shields are included to minimize errors. Thermometer scale length is 6 in. and overall length is 11 in.

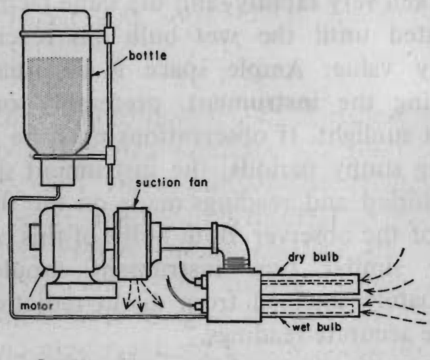


Figure 4-15. Forced Ventilation Continuous Feed Thermocuple Psychrometer

Figure 4-16. Standard Weather Instrument Shelter

After the wet bulb of the Assmann has first been moistened, the fan must run for up to 2 min to insure a steady wet-bulb temperature. Then both bulbs are read promptly. By using a psychrometric calculator or tables, accurate humidity readings can be obtained quickly.

Although the Assmann psychrometer can be used to obtain wet- and dry-bulb measurements in a wide range of environments, both indoors and outdoors, there are important limitations to its use. The instrument is unsuited for measuring humidity in extremely small spaces, or under conditions where the heat of its fan would introduce errors in the measurements. A psychrometer that is similar to the Assmann but which uses thermocouples as wet and dry bulbs is shown in Fig. 4-15.

For some purposes, a psychrometer may be kept and exposed in a standard weather shelter such as in Fig. 4-16. The psychrometer need only consist of two mercury-filled glass thermometers of identical construction mounted on a common back (a sling psychrometer without the wooden handle and chain). This instrument is hung from a hook in the mounting board about 7 in. from the right corner. A fan, mounted on the shelter, is operated by a crank to provide forced ventilation for the thermometers. This simple, sturdy arrangement is used by the National Weather Service.

TABLE 4-12

WET-BULB DEPRESSION FOR DRY AIR

Dry-bulb temperature		Wet-bulb depression for 0% relative humidity	
°F	°C	deg F	deg C
20	- 6.7	7	3.9
30	- 1.1	10	5.6
40	4.4	13	7.2
50	10.0	17	9.4
60	15.6	21.5	11.9
70	21.1	26.5	14.7
80	26.7	32	17.8
90	32.2	37	20.6
100	37.8	43	23.9
110	43.3	50.5	28.1

Computed from psychrometric chart in Ref. 9

A hand-aspirated psychrometer is also available for portable use. In this instrument, air is sucked over the sensing bulbs by means of a venturi tube and rubber bulb. Middleton and Spilhaus (Ref. 26) characterize this psychrometer as "excellent".

Since humidity is probably the most complicated weather element to measure accurately, observers should be thoroughly familiar with the more common sources of psychrometric errors. These are summarized as follows:

(1) Conduction of heat to the wet bulb

(2) Calibration errors in thermometers

(3) Pressure errors

(4) Radiation errors

(5) Incorrect psychrometric constant

(6) Muslin (or covering of ice on bulb) too thick

(7) Dirty muslin or impure water.

Conduction of heat down the wet-bulb stem may produce large errors when metallic thermometer bulbs or thermocouples are used, unless they are properly insulated from heat sources. However, conduction of heat into the wet bulb is relatively unimportant in glass thermometers. Although conduction has an effect on the value of the psychrometric constant and its variation with ventilation, psychrometric tables take this factor into account.

The accuracy of a psychrometer also depends upon the accurate calibration of its wet- and dry-bulb thermometers. They should be calibrated throughout their range and corrections made to readings before psychrometric tables are used. For a given dry-bulb temperature, the full range of relative humidity is obtained with a total wet-bulb depression (dry-bulb temperature minus wet-bulb temperature) as given in Table 4-12. Thus, at lower temperatures small errors in the wet-bulb temperatures produce large errors in relative humidity. For example, at a dry-bulb temperature of 30°F, a wet-bulb depression of 5 deg F corresponds to 50 percent relative humidity and a depression of 3 deg F, a 70 percent relative humidity. It is obvious that precise temperature measurements are required. On the other hand, at a dry-bulb temperature of 59°F, the difference between 50 and 70 percent relative humidity corresponds to a difference of 6 deg F in the wet-bulb depression.

Although an error in wet-bulb depression of 0.5 deg C (0.9 deg F) is not serious in summer (or during periods of relatively high temperature), it can result in an absurd reading in winter (during periods of low temperature). Thermometers should be read as accurately as possible at all times. The errors resulting from rounding off or from inaccurate temperature readings vary throughout the temperature range and are inversely proportional to temperature.

Errors from radiational heat exchange between the adjacent environment and the wet bulb are usually unrelated to ventilation speed. In most psychrometers, the radiation shielding of the wet bulb is at or near the ambient temperature. Thus, the need for radiational correction of the wet-bulb temperature is greatest during dry-warm conditions, when wet-bulb depressions are large. Bindon (Ref. 32) implies that theoretical means are inadequate to determine the effect of radiation on a specific psychrometer, so that empirical corrections must be employed.

Errors in measuring humidity caused by insufficient ventilation can be avoided by providing an air speed of 2.5 to 10 $m\ s^{-1}$. This is equivalent to whirling a 1-ft long sling psychrometer about 4 rps. The magnitude of errors produced by inadequate ventilation depends upon the humidity and temperature of the air, and increases in drier, colder air.

At above-freezing temperatures, significant errors can be minimized by frequent, careful checking of the muslin on the wet-bulb thermometer. The muslin cover should normally be changed weekly, but more often in places where the air contains a relatively high number of aerosols–such as salt, dust, or smoke. Any visible contamination of the muslin requires immediate replacement of this inexpensive item. Other precautions include washing the muslin thoroughly in soap and water, rinsing in distilled water, and avoiding contamination from hands. Great care must be taken to avoid contaminating the supply of distilled water. Any residue deposited either during evaporation or from the air affects the accuracy of wet-bulb readings. The muslin itself should be a thin, closely woven cotton fabric, and must tightly fit the wet bulb. A thick covering of ice on the wet bulb retards cooling of the bulb and should be removed by melting in distilled water.

The overall accuracy of a ventilated psychrometer of adequate design, when careful attention is given to the various sources of error, is on the order of 2 percent when temperatures are above freezing. At temperatures below freezing, errors will increase as the temperature lowers. Bindon notes that "the values of the psychrometric constant deemed valid for ventilated psychrometers and used in the compilation of various psychrometric tables in general use, do not differ from the so-called thermodynamic psychrometric constant by more than 1.9%" (Ref. 32).

The expected accuracy from nonventilated or normally ventilated psychrometers has to be estimated or determined by experimental comparisons with a standard. The results are usually less reliable than those from a ventilated type.

4-5.2 HYGROSCOPIC SUBSTANCES METHOD*

A number of organic substances of natural origin have been used to measure the water content of the air. Of these, only hair and

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*Middleton and Spilhaus (Ref. 26) given an extensive discussion of hair hygrometry.

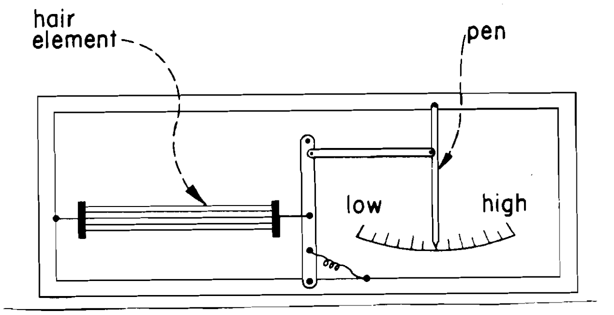

Figure 4-17. Schematic of Hair Hygrometer

goldbeater's skin* are used to any extent in scientific meteorology; the latter is superior primarily in its response to changing conditions, but is secondary in importance to hair. For nearly 200 yr, hair, particularly human hair, has been widely used in measuring relative humidity.

Although some of the more recent measuring devices are more accurate, sensitive, and responsive to changes in humidity, hair continues to be a practical, inexpensive sensor material in hygrometers, hygrographs, and hygrometric controlling devices. If accuracy requirements are not too stringent, the hair hygrometer or hygrograph is satisfactory for measuring intermediate humidities (20 to 80 percent) where temperatures are relatively steady and moderate, i.e., 0° to 30°C (32° to 86°F). The chief use of hair-activated instruments is for the control of rather than the measurement of humidity, i.e., controlling the relative humidity in an air-conditioned laboratory or building. Hair hygrographs have also been used in routine meteorological networks where their accuracy is checked periodically with a psychrometer. Hair and goldbeater's skin hygrometers are also useful in radiosonde measurements in the upper air.

The hair hygrometer consists of a suspended hair loaded with a small weight and attached to a pivoted arm. When the hair elongates, a pointer attached to the arm is moved along a scale indicating the relative humidity. Calibration is accomplished by adjusting the distance between the hair and pivot point. In a hair hydrograph, a pen arm is substituted for the pointer such that the deflection is recorded on a slowly moving graph as illustrated in Fig. 4-17.

Hair hygrometers may be well suited for use in one environment but worthless in another. With a change in relative humidity from 0 to 100 percent, the length of human hair will increase about 2.5 percent. The typical curve of natural hair elongation as a function of relative humidity is not linear, but simple mechanical linkages can produce a high degree of linearity. Between a relative humidity of 20 and 100 percent the relation is almost logarithmic but sensitivity decreases as the humidity approaches 100 percent. Table 4-13 shows the relationship between relative humidity and hair elongation.

Hair elongation is also affected slightly by temperature over the range in which hair is useful in hygrometry, elongation being about one-fifteenth as much per deg C as the mean change of length per 1 percent of relative humidity. A load on the hair-sensing element should not exceed 0.8 g per hair. A higher stress eventually produces a permanent change in length, which alters the calibration curve.

A hair hygrometer stored for several days in a humid environment, and subsequently exposed in a dry environment, will exhibit what is known as a "wet" curve; on exposure for an extended period in a very dry place, it will exhibit a "dry" curve during a period of increasing humidity. Under such conditions, the wet and dry curves show some important differences, but proper operation can be restored by periodic saturation of the hair-sensing element. For the most part, these errors in the calibration curve can be kept within acceptable limits for most meteorological surface measurements if instruments are exposed to normal daily and periodic variations in humidity.

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*A thin membrane from the intestine of an ox. Aside from some undersirable characteristics, goldbeater's skin responds more rapidly to changes in relative humidity than hair; it is used mainly in British radiosondes.

TABLE 4-13

EFFECT OF RELATIVE HUMIDITY ON THE LENGTH OF NATURAL HAIR (Ref. 33)

Relative humidity, %	Total change in length*, %
0	0.0
10	20.9
20	38.8
30	52.8
40	63.7
50	72.8
60	79.2
70	85.2
80	90.5
90	95.4
100	100.0

*The percent of change at low values of relative humidity seems to be well established, but that at medium and high values given by different authors differs considerably.

The response characteristics of hair are described by Davey (Ref. 34) as follows: "The speed of response of hair to changes in humidity depends on temperature, stress on the hair, and the relative humidity and direction of the change. Hair under light loading and adequate ventilation will have a time constant of approximately three minutes at room temperatures. The time constant gets longer the lower the temperature, and for all practical purposes hair no longer responds at −40°C (−40°F). Response is faster if the hair is under higher stress and is somewhat faster for increasing humidity than for decreasing humidity. Response is markedly slower at low relative humidity than at high relative humidity."

The use of hair bundles has proven less satisfactory than the use of single hairs in hygrometers. Since the expansion coefficients of individual hairs differ, the sensitivity of a bundle is limited to that of the lowest coefficient present; lag time is also increased. "Hasps" or two or more hairs having similar characteristics can be used successfully as a sensory element, provided that all sensory surfaces are well exposed to the environment.

Compared to normal hair and other humidity sensors, hair that has been preconditioned by compressing it between rollers responds much more rapidly to humidity changes. The calibration curves are distinctly more stable. Muller (Ref. 33) states that "rolling hairs to an elliptical cross section with a 1:4 ratio of dimensions increases the expansion coefficient of the hair by 40% over that of the natural product." A nearly linear relation between expansion and relative humidity results, and high humidity performance is greatly improved. Rolled hair is also superior in sensitivity and lag characteristics to goldbeater's skin.

Among the disadvantages of rolled hair is its lower elasticity; it has only about 20 percent of the tensile strength of the natural product. If calibration is to be maintained, the maximum load should not exceed 0.3 g per hair compared to 0.8 for natural hair.

When a hair hygrograph is used outdoors, it should be exposed in a standard weather shelter. Since ammonia causes rapid deterioration of hair, the instrument should not be used for long periods in the immediate vicinity of animal stables or near industrial plants using this gas. Hairs should be cleaned with a soft brush and washed with distilled water at frequent periods; they should never be touched by the hands.

Because of the occasional rapid changes in humidity, time marks should be made accurately on the hygrograph chart. In doing this, the pen arm has to be moved in the direction of lower relative humidity. If the hair hygrograph is used to supplement doubtful psychrometric readings in areas of low temperatures, precautions should be taken to keep snow or ice from forming on the hairs, which consequently alters the zero setting. If an instrument has been stored under very dry conditions for a long period, the calibration may be altered. The instrument can be restored to normal operation by keeping it in saturated air for an extended period before adjusting the zero setting.

The indicated readings on a hair hygrometer should be checked frequently against a psychrometer. It is important for a hygrometer to be calibrated periodically in a humidity chamber or in a room where approximately steady temperatures are maintained. If the hair sensory element has to be replaced, a complete recalibration must be made.

A good hair hygrograph that is properly serviced should record relative humidities at moderate temperatures with an error of about 3 percent or less. This error increases at low temperatures.

4-5.3 CONDENSATION METHOD (DEWPOINT HYGROMETER)

The dewpoint or frostpoint hygrometer combines high accuracy, fast response, and stable operation over a wide range; it has the ability to furnish automatic, continuous measurement of dewpoint or frostpoint temperatures in a great variety of environments (Ref. 35). Some versions of the basic instrument are used for calibrating other types of hygrometers. Some of the instruments are operated manually; others operate automatically.

The dewpoint or frostpoint principle is both simple and well known. The metal mirror of a hygrometer is cooled until the amount of dew or frost deposited on the condensation surface neither increases nor decreases as air from the sample passes over it. The temperature of the deposit in equilibrium is the dewpoint or frostpoint temperature of the air sample. Although various averaging techniques can be used to obtain the dewpoint or frostpoint temperature by an increasing and decreasing deposit obtained using an oscillating temperature, the highest accuracy is obtained if readings are obtained when the amount of the deposit remains steady. This becomes far more critical at very low temperatures, when the rate of frost formation is much slower than the rate of sublimation.

For successful operation, a practical instrument must include:

(1) A nonabsorptive, clean, polished surface for the dew or frost deposit

(2) A method for detecting changes in the deposit

(3) A device for controlling the temperature of the mirror surface

(4) A temperature sensor.

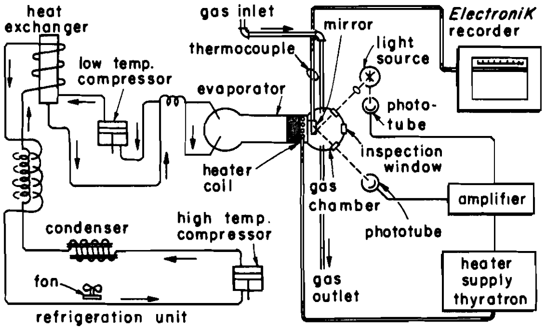

Figure 4-18. Schematic Diagram of Dewpoint Recorder

The essential components used in the basic dewpoint hygrometer are discussed by Paine and Farrah (Ref. 35). A schematic diagram of one is shown in Fig. 4-18.

The dew or frost deposit is usually detected by reflectivity, but alternative means of detecting a dew deposit include optical polarization phenomena, absorption of alpha or other radiations, and electrical conductivity of the surface of an ionic crystal (Ref. 36). The latter technique measures not the dewpoint but the condition of vapor saturation over a saturated solution of the salt. For reflectivity detection, a photodetector is used to detect either the decrease of specular reflection or the increase in diffuse reflection when dew forms. An important advantage of optical detection is its increased relative sensitivity at low temperatures when crystals of deposit become increasingly smaller. This is true only down to about −90°C (−130°F), where crystallization becomes unreasonably slow and the frost deposit becomes invisible.

The basis of dewpoint hygrometry is examined by Wylie et al. (Ref. 37), with respect to the factors that limit accuracy. He proposes that observations be made with dew or frost deposits on two or more substantially different surfaces. In areas having moderate amounts of soluble and insoluble pollutants in the air, the problem of keeping the condensation surface clean is important, especially when the air sample cannot be filtered properly. Initially, clean surfaces will deteriorate slowly, even if the air is efficiently filtered. Furthermore, with practically any known surface, it is possible to detect photoelectrically dewpoints or frostpoints that are well above a true reading. When the very slow rate of frost deposit at low temperatures and the inaccurate reading of visual dewpoint hygrometers with manual temperature control are considered, the chance of error is multiplied manyfold. Thus, results accurate to within 0.2 deg C (0.4 deg F) are likely to be obtained only with automatic temperature control and photoelectric detection at high humidity levels.

Although the visual hygrometer is less accurate and less reliable than automatic versions, there may be circumstances in which its use is justified. The visual instrument consists basically of a temperature-controlled specularly reflecting surface, a second, similar surface maintained dew-free for comparison, and a telescope for observation from a distance. It must meet some important functional requirements: it must receive the dew or frost deposit and make its detection easy; the temperature of the surface must be readily controllable and accurately measurable; the surface must be inert and mildly hydrophobic to facilitate receiving the deposit; and the surface must be clean and a deposit of moderate size used to insure that the deposit consists neither of hygroscopic dust particles nor is limited to water in scratches.

For a visual hygrometer, the conditions favoring the best view of the deposit are obtained with oblique, dark field illumination, and five- to ten-power optical magnification of good quality. The importance of an extemely clean surface can hardly be overemphasized, for hygrometer illumination and optics call attention to foreign deposits not evident to the unaided eye. Sensitivity of the surface is increased by differential ventilation of the surface, although this is not essential.

The time required for an observation varies greatly, depending on the skill of the observer, the design of the instrument, and the frost point to be observed (Ref. 36). The minimum time required for each observation may vary from at least several seconds to over 3 min.

Because so much skill is required to achieve the desired accuracy and speed in manual operation, considerable effort has been focused on making automatic measurements. By this method, the temperature of the surface is maintained at the dewpoint or frostpoint by continuous cooling and/or heating. The change to further cooling or heating is best accomplished photoelectrically.

Advantages of automatic operation are that a special observer is not required, and the speed of observation can be increased significantly. Brewer (Ref. 36) states that these increases are sometimes tenfold or more (at temperatures above 0°C (32°F), response times less than 0.1 s can be obtained). In addition, continuous indications can be obtained if the changes are slow enough to avoid temporary loss of control.

4-5.4 INFRARED ABSORPTION METHOD

Recently developed infrared hygrometers provide the means for measuring humidity in experimentation and for research in special areas where conventional methods fail or prove inadequate (Refs. 26, 38). Though the infrared approach is usable for most of the routine functions of the more common hygrometers, the higher costs of this method place a limitation on its use. Infrared hygrometers are readily justified in specific environments and applications where suitable data otherwise cannot be obtained. The most noteworthy case is that wherein measurements of water vapor content over long path lengths are desirable as opposed to the point measurement data obtained with the previously discussed instruments.

An infrared hygrometer is an optical instrument that measures absolute humidity by measuring the absorption of light in the near spectral region of an infrared water vapor absorption band. Basically, this instrument consists of a radiation source, optical filters for isolating selected wavelengths in the desired spectral region, and a method of measuring the attenuation of radiant energy caused by water vapor in the beam. The method consists essentially of measuring two close-by wavelengths of the near infrared spectrum (the 1.250 μm and 1.367 μm wavelengths have been used where the latter is in a water absorption region). One wavelength is in a suitable water vapor absorption band, the other is one for which relatively little absorption occurs. The ratio of energy between these measured wavelengths constitutes a measure of the total water vapor content in the optical path. A change of water vapor concentration in the sensing path changes the energy ratio and the indicated absolute humidity.

In practice, infrared hygrometry is accomplished with nondispersive infrared analyzers. These take a variety of forms and are also used for industrial process control, toxic and explosive gas analysis, and scientific investigations. Analyzers may measure a small enclosed gas volume or may be arranged to have an atmospheric absorption path of 1 mi or more in length. Remote infrared sources and detectors may be employed or, by use of a remote reflector, may be located at the same site (Ref. 38).

Noteworthy advantages of the infrared hygrometer include:

(1) Sensitivity is high at low water concentrations.

(2) Rapid response to changes in humidity is obtained at all water vapor concentrations.

(3) Sensitivity of the instrument increases as water vapor decreases.

(4) It can be used for short- and long-path measurements or for both simultaneously.

(5) It is contact-free, since measurements are made through the free, unconfined atmosphere without affecting any natural meteorological process.

(6) Accuracy and response are unaffected by wind or temperature conditions.

(7) In low-level, vertical profiles. All measurements can be made rapidly with the same instrument, thereby minimizing the errors possible when different instruments are used.

The short-path infrared hygrometer is used to monitor and control humidity in test-chamber experiments to determine the effects of relative humidity. Ranges in relative humidity for such tests have varied from 0.5 to over 95 percent. Periodic changes in vapor density in a chamber can be adjusted within a few minutes; not only can a humidity level be established on short notice, it can be held precisely to within 1 or 2 percent of the desired level.

Another application of the infrared hygrometer is in the measurement of water vapor diffusion through polyethylene films and other commonly used water vapor barriers in product packaging. The results are about as accurate, and much faster, than those obtained from the conventional gravimetric method.

A major asset of the infrared hygrometer is its ability to obtain an integrated value of humidity over large reservoirs in arid areas, over different types of vegetation, or over other large areas. Values provided by this instrument are important in measurements used for determining the danger of forest fires. According to Wood (Ref. 39), the infrared hygrometer is a sensitive indicator of the variations in humidity associated with airmass changes. Based on data he collected over a 9-mo period at Minneapolis, Minn., he concluded that changes in humidity proved to be a more sensitive indicator of frontal passages than did temperature. Accuracy of measurements is unaffected by periodic changes in atmospheric pressure.

In high latitudes, and at high altitudes, the infrared method can be used to obtain accurate measurements of water vapor density at temperatures below the freezing point. The method avoids the ambiguity of humidity measurements when taken over ice or supercooled water, since the total measurement sample is always in the gaseous phase.

In micrometeorological studies, the infrared system can be used to advantage in monitoring the sublimation rate over snow surfaces, thereby making it possible to relate the loss of snow directly to wind strength.

When used in airborne operations, the energy source and detector of the instrument can be mounted easily on the outside of an aircraft, with other components assembled on the inside.

4-5.5 CALIBRATION

Calibration for hygrometry is accomplished by establishing a known condition within an enclosure. This can be accomplished by (Ref. 26):

(1) Mixing of dry and saturated air

(2) Saturating air at a known temperature and then raising the temperature to obtain the desired relative humidity

(3) Saturating air at a selected high pressure so as to give known relative humidity at atmospheric pressure

(4) Employing the known equilibrium vapor pressure of solutions.

The latter method is particularly convenient since the relative humidity over solutions is relatively insensitive to temperature. In Table 4-14, relative humidities over glycerine solutions are given; in Table 4-15, those over saturated solutions of five different salts are tabulated (Ref. 40).

4-6 EFFECTS ON MATERIALS

The moisture content of materials is primarily determined by their interactions with humidity. Air serves as a vehicle that carries water vapor to surfaces on which it

TABLE 4-14

RELATIVE HUMIDITY OVER GLYCERINE SOLUTIONS (Ref. 40)

Relative humidity, %	Solution strength by weight in water, %	Specific gravity
10	95	1.245
20	92	1.237
30	89	1.229
40	84	1.216
50	79	1.203
60	72	1.184
70	64	1.162
80	51	1.127
90	33	1.079

may be condensed or absorbed. When condensation occurs, air goes into solution with the liquid and provides oxygen, hydrogen, and atmospheric contaminants that can lead to corrosion, dimensional changes, dielectric failure, etc. Almost any material exposed to water vapor absorbs water on or near its surface, the amount of absorption depending on the vapor pressure and the absorptive nature of the material. An increase in humidity forces moist air and condensed water vapor into porous materials, while a decrease in humidity acts to reduce the moisture content of the material. As periodic changes in vapor pressure occur, the amount of moisture in materials tends to equal that in the air as the result of a general equilibrium process. Water vapor frequently condenses on exposed surfaces as an invisible film before the surrounding air becomes saturated.

In some instances, moisture is essential to the useful properties of materials; more often, however, excessive moisture is a major physical and chemical agent of deterioration. The physical effects of changes in humidity are readily evident in the swelling and shrinking of wood, paper, textile fibers, and hydrophilic plastics. Excessive moisture causes a rapid deterioration and loss of physical strength of materials; it can destroy their utility, cause discoloration, and alter electrical and mechanical properties. The destructive effects of humidity are amplified as moisture conditions become more severe, particularly when high humidity is combined with high temperature.

Extremely low humidities are harmful to some materials, particularly organic materials such as wood, leather, glue, and fabrics, all of which can become brittle and less durable. Wood and paper become unusually flammable, constituting a major fire hazard. In many instances, low humidity allows the accumulation of a static electrical charge. This creates problems by producing electrostatic forces, generating ozone, contributing to dielectric breakdowns, and promoting the formation of dust deposits.

Adsorption is the adhesion of a thin film of liquid or gas to the surface of a solid substance; it is responsible for many harmful effects of humidity on materials and parts. Adsorption is an equilibrium process adjusting

TABLE 4-15

RELATIVE HUMIDITY OVER SATURATED SALT SOLUTIONS (Ref. 40)

Temperature, °C	°F	Relative Humidity, % Potassium nitrate KNO_3	Sodium chloride NaCl	Magnesium nitrate $Mg(NO_3)_2 \cdot 6\ H_2O$	Magnesium chloride $MgCl_2 \cdot 6\ H_2O$	Lithium chloride LiCl
0	32	97	76	54	34	19
5	41	96	76	54	33	16
10	50	95	75	53	33	14
15	59	95	75	53	33	13
20	68	94	75	53	33	12
25	77	93	75	52	33	11
30	86	92	75	52	32	11
35	95	90	75	51	32	11
40	104	89	75	51	31	11

rapidly to relative humidity. Three surface phenomena are classified as adsorption, each characterized by a different type of humidity damage (Ref. 41). The first type is the surface monolayer; its formation is directly dependent on the vapor pressure for constant temperature and is reversible. Surface monolayers of water cause an increase in electrical conduction of surfaces and can result in performance degradation of high impedance electrical and electronic circuits.

The second type of adsorption is characterized by a monolayer or multilayer of water on a highly porous surface. Such surfaces consist of many pores so that a considerable amount of time is required to establish equilibrium with the atmospheric moisture. Desorption of moisture from such surfaces also requires considerable time, additional thermal energy, and/or reduced pressure. Damage from this type of adsorption is generally similar to that of the first type, but will be of longer duration. With both types, damage is of a secondary nature, e.g., voltage breakdown. Paper is the most representative porous material exhibiting adsorption on a surface with many capillarylike passages.

The third surface process is chemisorption. In this, the binding forces are much greater, so that the process is reversible only by the addition of energy. Chemisorption involves chemical reactions and can cause changes of dimension, voltage breakdown due to decreased dielectric strength, and other physical changes. Return of the adsorbent to its original state is uncertain, even after prolonged drying out.

Adsorption of moisture does not necessarily result in visible effects–chemisorption may cause color changes–but condensation wherein droplets form is readily visible. Once liquid droplets form either in small numbers or such that the surface is completely covered with a liquid water layer, gross changes in the surface can occur. Surface moisture acts as a parallel conductor for electrical current and as a source of surface contamination. Only in the unlikely event that pure, distilled water comes into contact with a perfectly clean impervious surface whose solubility in the water is zero, will the surface moisture cause no degradation. Such ideal conditions, however, are almost never encountered. Surface contaminants range from those of human origin (oil and minerals from hands) to those normally found in the atmosphere, e.g., sulfur dioxide, lint. Moreover, condensed moisture tends toward equilibrium with its surroundings. Numerous processes of solution go into effect, involving the gaseous constituents of the atmsophere, as well as surface materials and contaminants. Galvanic action at the contact points of dissimilar metals also occurs, forming electrochemical cells that can result in corrosion.

For details of the analysis of surface moisture, and the application of the laws (Raoult's and Henry's law) used to describe this phenomenon, the reader is referred to Cook (Ref. 41).

4-6.1 METALS

Almost all metals exposed to clean, dry air become covered with an oxide film that inhibits further dry oxidation. Gold is a notable exception in that no oxide film forms on it. Silver and the so-called platinum metals (platinum, palladium, rhodium, etc.) show only a slight tendency to oxidize or tarnish when exposed to extremes of humidity. This relative freedom from corrosion enhances the use of these metals in electrical contacts, particularly those in which light pressures are exerted. These same properties make them superior metal-plating materials.

Under humid conditions, metallic materials absorb a layer of moisture before the ambient air is saturated. This layer thickens as vapor pressure increases, but never exceeds a few molecules in thickness.

For some metals, a critical relative humidity level exists, above which the rate of corrosion increases significantly. This critical level varies for different metals and metal alloys. At humidities above the critical level, the degree of corrosion of metals, e.g., the ferrous metals, depends mainly on the type and quantity of impurities in the metal and the air, including impurities in the form of gases such as ammonium sulfate and sulfur dioxide*. The humidity-induced solutions provide electrolytes for the electrochemical reactions of the corrosion process. The moisture film on metallic materials need not be visible in order to cause electrolytic corrosion. Exposure tests indicate that the major factor affecting metallic corrosion is the length of time the relative humidity exceeds a critical level. Mean relative humidity provides a less reliable indication of the corrosion rate in a given environment than does the duration of relative humidity levels above a critical level.

When water droplets form on metal, corrosion is most pronounced at the center of the droplet, where the concentration of oxygen is lowest and the amount of soluble impurities is greatest. Oxygen diffuses rapidly through thin layers of solution at the waterline of droplets.

The rate of corrosion of metals is related to the nature of the moisture deposition; e.g., by alternate wetting and drying, spraying, immersion, condensation, and precipitation. Thus, the corrosion of clean iron submerged in water at appreciable depths is practically nil due to the scarcity of oxygen. The alternate wetting and drying of a metal, however, results in rapid corrosion. Corrosion forms even more rapidly when thin layers of dew alternately condense and evaporate. Since some moisture is always present under natural conditions, most metals will oxidize. The rate of oxidation depends on the type of metal, the presence of corrosive elements in the microenvironment, and the severity of conditions.

Most metals are severely affected by very humid, hot environments. Ferrous metals may rust overnight, particularly when harmful contaminants are present. Galvanic corrosion, produced between dissimilar metals connected electrically by an electrolytic solution, can be very rapid. Examples include bolted or riveted joints, bearings, and slides. Connections between metals that are widely separated in the electromotive series often exist in electrical and electronic equipment. These cannot always be avoided; the result is major susceptibility of the equipment to galvanic corrosion.

The extent of galvanic corrosion depends largely upon the relative position of the metals in the galvanic series, the resistance in the electrolytic circuit, the relative sizes of the two metal components, and the extent to which the environment favors the corrosion process.

4-6.2 ELASTOMERS

The term "elastomer" includes the two major groups of materials known as plastics and rubbers (both natural and synthetic). Most elastomers in use are synthetic; both types are extensible and have a high molecular weight. In the course of manufacturing and processing, they are compounded with substantial amounts of additives to improve specific properties. The useful group properties of elastomers include (1) electrical resistance; (2) resistance to heat, light, moisture, insects, and atmospheric oxygen and ozone; (3) plasticity, elasticity, resilience, transparency, and ready formability, and (4) the ease with which colors may be added. No single elastomer, however, has all these properties.

4-6.2.1 PLASTICS

The physical deterioration of organic polymers is often manifested by warping and increased brittleness owing to loss of the plasticizer. Exposure to alternating levels of low and high humidity often causes shrinking and swelling in such hydrophilic plastics as nylon or cellulose acetate, thus accelerating the loss of plasticizer.

The chemical reaction of water with plastics is confined to types containing esters,

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*Additional discussion of corrosion is presented in Chap. 11 "Sal+ Salt Fog, and Salt Water," of this handbook.

amides, nitriles, acetals, and certain types of ketones. The process is accelerated by an increase in temperature and catalyzed by acidity. If the hydrolyzable groups comprise a vital part of the structural framework of the polymer, the chemical process seriously lowers the mechanical strength of the plastic. These include the polyesters, polyamides, and cellulose esters. In some groups composed entirely of carbon-to-carbon bonds, hydrolysis affects such properties of plastic as the dielectric constant, power factor, insulation resistance, and water absorption; it seldom affects the mechanical properties. Examples are polyvinyl acetate and polyvinyl nitrile.

In general, plastics with a low water-absorbing capacity have good dimensional stability and constant electrical properties when exposed to high and fluctuating humidities. Such plastics include polytetrafluoroethylene (PTFE), polyethylene, polystyrene, polymethyl methacrylate, and polyvinyl carbazole. Teflon*, a polyfluoroethylene resin, is unaffected by high humidity and absorbs no water.

Moisture dissolves impurities that may be in or on plastic, providing a conducting electrolyte. During a voltage stress, an electrolyte may conduct tiny surface arcs over an insulating plastic surface. These electrical arcs produce a mass of branched, sometimes interconnected, channels that can accelerate electrical failure.

By adding large amounts of hydrated fillers to polymers, highly resistant compositions have been developed among the many epoxies and polyester resins available.

4-6.2.2 RUBBER

As a deteriorative agent of natural and synthetic rubber, moisture is much less harmful than ozone, heat, oxygen, and light. Moisture contributes to permanent deteriorative changes in rubber when it combines with other harmful agents. The effects of moisture, therefore, must be assessed as those of a combinatorial agent. Moisture alone causes no significant lasting change in rubber. According to some authorities, the high humidity of the tropics has no important adverse effect on many of the natural and synthetic rubbers. Humid conditions have the beneficial effect of providing rubber moldings in the tropics with a protective shield against chemical changes induced by solar radiation, particularly in the ultraviolet wavelengths.

As with plastics, the chemical reaction of moisture is limited to organic rubber compounds containing hydrolyzable substances that are either part of the original composition or have been formed by oxidation. Organic compounds are generally susceptible to some chemical reaction with components of the environment. Hydrolysis can have serious effects on polyester rubbers, such as polyurethane and Vulcanprene. The chain-like cracking of polyester rubbers is partially attributed to hydrolysis insofar as these rubbers contain vulnerable hydrolyzable groups in their skeletal chain.

Where high and low humidities alternate, the danger of modifying the dielectric properties of rubber is less than where humidities and temperatures are consistently high. The prolonged diffusion of moisture into electrical components can weaken their insulating properties. The presence of moisture accelerates the deterioration of electrical properties already adversely affected by other climatic elements. Exposure of hard rubber to solar, radiation produces hydrogen sulfide. This dissolves in moisture and forms a conducting surface film, reducing its electrical resistance and contributing to eventual failure. The addition of large amounts of hydrated fillers to butyl rubber and some polyester rubbers improves their resistance to electrical surface cracking.

Polysulfide rubber has two outstanding characteristics: it absorbs little water and is exceptionally impermeable to water vapor. This makes it well suited as a material for gas-

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*Teflon is a trademark of E. I. du Pont de Nemours and Co.

proof diaphragms and the lining of storage tanks.

Silicone rubber, typical of all organosilicon oxide polymers, is characterized by extremely high water repellence, even at high humidities.

4-6.3 COATINGS

Humidity is a major environmental contributor to the breakdown of organic coatings, such as paint, varnish, enamel, and lacquer. In humid, hot regions, moisture is the most harmful factor in the deterioration of protective coatings. The effects of moisture on coatings may be mechanical, chemical, electrochemical, or any combination of the three. The potential extent of these harmful effects on coatings is determined by the chemical composition, permeability, thickness and continuity of the coating, and the nature of the substrate.

The ingredients comprising protective films are affected differently by the absorption or desorption of moisture. Many paint and varnish coatings swell on soaking and shrink on drying. Both processes tend to destroy adhesion to the substrate. When high humidities are repeatedly accompanied by rising temperatures, the expansion of humid pockets of air trapped between the substrate and the film produces blisters. These eventually break and peel off. Resins containing active hydroxyl (OH) and acid (COOH) groups are readily weakened by exposure in moist places.

When an organic coating serves as a semipermeable membrane, humidity may penetrate the coating by diffusion and reach the substrate. Moisture sometimes reaches the underside of coatings via a porous substrate, destroying or weakening adhesions and forming blisters. The addition of soluble pigments to paints also contributes to the formation of blisters. If the substrate is metal, its corrosion will accelerate the deterioration of a coating and contribute to the breakdown of components or materials. Water-soluble salts and other harmful soluble impurities that occur in semipermeable coatings are transported in moisture by osmosis through the coating to the substrate if the water vapor pressure remains high long enough. A corroding metal in contact with a painted panel will cause electrochemical action between them, greatly exaggerating the effect of simple osmosis.

The resistance of paints to moisture can be significantly improved by the proper application of resins like melamines, phenolics, vinyl copolymers of vinylchloride and vinylidene chloride, and other copolymers. The use of tung and dehydrated caster oils also retards the penetration of moisture. Silicone-insulating varnishes used on coils in hot-damp environments are highly resistant to moisture.

4-6.4 TEXTILES

Water vapor greatly increases the photochemical deterioration of cellulose, the basic substance in plant fibers. All fibers swell when moisture is absorbed, the amount of swelling depending on the type of fiber. Jute, unusually hygroscopic, can absorb 23 percent of its own weight in moisture. Cotton and flax are also highly absorbent; unlike jute, both are unusual in that they become stronger as moisture is absorbed.

Wool and silk, among the more widely used animal fibers, both swell and lose tensile strength as moisture is abosrbed. Wool absorbs moisture more readily than any other common fiber.

Manmade fibers are divided into semisynthetics and synthetics. The latter are processed from basic chemical elements, semisynthetics are made from fiber-forming material of natural origin. Of the semisynthetics, viscose rayon, similar to cuprammonium rayon in its characteristics, absorbs twice as much moisture as cotton, but retains only about half its tensile strength when wet. Cellulose acetate absorbs less moisture and has better wet strength than rayon. By contrast, casein fibers absorb moisture readily and have relatively little wet strength.

Synthetic (plastic) fibers, such as polyamides (nylon) and polyesters (Dacron*), are less absorbent than natural fibers; their mechanical properties are less seriously affected by high humidities. Polyacrylonitrile (Orlon*, Acrilan†) absorbs less moisture than the polyamides, but has less wet strength than the polyesters. Copolymers, including vinylchlorideacrylonitrile (Dynel‡), are only slightly absorbent, do not swell, and maintain good tensile strength. Polyvinylidene chloride (Saran§) absorbs almost no moisture, does not swell, and suffers no loss in wet strength.

4-6.5 WOOD

The physical properties of wood are readily affected by humidity. Changes in the moisture content of wood alter its strength, rigidity, dimensions, shape, electrical properties, and resistance to decay. Like all materials, wood tends to equalize its moisture content with that in the ambient air. During rising relative humidity, wood absorbs water, and as relative humidity decreases, wood gives up water. Even within the same board, the moisture content may show some striking contrasts. Where part of a board is exposed to a higher relative humidity, such as contact with a damp surface or location near a leaky pipe, the moist area of the board swells, warps and often twists, becomes slightly weaker, bends more easily, conducts electricity more readily, and decays at a faster rate. Sharp and frequent changes in the moisture content of wood produce internal stresses that may alter its properties. Different species of wood often differ greatly in their tendency to decay, warp, end-check, split, swell, or shrink in response to humidity stresses.

The adverse effects of humidity on wood normally increase greatly with appreciable increases in relative humidity and/or temperature. These conditions are highly favorable to increased activity by destructive micro-organisms. In many situations, a combination of environmental elements will have a larger influence on wood deterioration than will humidity alone, or periodic fluctuations in humidity, or the kind of wood being affected. The deterioration of untreated wood is extremely rapid at the surface of warm sea water, is less rapid at the surface of fresh water, and is practically nil well below a permanent mud surface. Wood decays much faster when continuously damp than when only occasionally exposed to high humidity. According to Greathouse and Wessel (Ref. 42), wood decays only when its water content exceeds 20 percent, based on the weight of the wood in an oven-dried condition.

In a humid environment, the sapwood is always affected as much as or more than the heartwood. In wood having a strong natural resistance to attack by harmful organisms, resistance occurs in the heartwood only. This results from natural preservatives in the wood. The distribution of a natural preservative in a single tree or board can vary considerably. Little is known about these preservatives.

Some important differences exist within and among wood species in their resistance to decay. Most such determinations are of an empirical nature, since suitable means of accurately measuring them are lacking. A comparison of the decay resistance of commonly used commercial woods of the United States is given in Table 4-16. These comparisons are based on observations and practical field experience; they are considered valid as a general guide for design and construction purposes.

Specific applications of wood should be made with full knowledge of such properties as weight, density, hardness, and fungus-resistant resins. For example, red cedar contains a resin that retards decay, and teak is dense, hard, heavy, and resistant to marine exposure; both woods resist the penetration of moisture and attack by harmful organisms for a long period.

4-6.6 PAPER

Ordinary paper loses its strength as soon as

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*Dacron and Orlon are trademarks of E. I. du Pont de Nemours and Co.

†Acrilan is a trademark of Monsanto Chemical Co.

‡Dynel is a trademark of Union Carbide Corp.

§Saran is a trademark of Dow Chemical Co.

TABLE 4-16

DECAY RESISTANCE OF SOME COMMON WOODS* (Ref. 42)

Good	Fair	Poor
Baldcypress	Douglas fir	Ash**
Catalpa	Honeylocust**	Aspen
Cedar	Larch, western	Basswood
Chestnut	Oak, chestnut	Beech**
Juniper	Oak, white	Birch**
Locust, black	Pine, eastern white	Cottonwood
Mesquite	Pine, southern yellow	Fir (true)
Mulberry, red	Sassafras	Hemlock**
Osage-orange		Maple, sugar**
Redwood		Oak, northern red**
Walnut, black		Spruce**
Yew, Pacific		Willow

*The species in each group are listed alphabetically, it being impractical to list them in order of relative decay resistance.

**These species may rate nearly as high in decay resistance as some of those in the next better group.

it gelatinous binder becomes wet or even moist. Paper—like wood, cotton, and linen textiles—consists mainly of a fibrous, organochemical substance called cellulose. Its natural binder will not tolerate soaking or intermittent wetting and drying regardless of how the fibers were processed. Even when no physical stress is applied to paper, high humidity speeds up the deterioration caused by acid gases, chemical reactions with solid contaminants, or fungal attack.

Paper can be made water-resistant or water-repellent only by the use of additives; e.g., waxes, rubber, chlorinated rubber, or neoprene. Additives prevent moisture from contacting the cellulosic fibers by strengthening the water-susceptible bonds of the fiber gel*.

Water-resistant paper differs from wet-strength paper in that the former has only a limited tolerance of humid or wet conditions. After a thorough soaking, wet-strength paper should exceed its dry strength by at least 15 percent*. In wet-strength papers, the use of good resins, like urea formaldehyde and melamine formaldehyde; provides an insoluble coating over the fibers and strengthens the bonds between fibers. Wet-strength paper endures rough usage; it resists deterioration when emersed in water, oil, and many other liquids; and it withstands washing in hot water with soap or cleaning in gasoline and other solvents.

Desirable characteristics in a paper are largely a function of the use to which it is put. The intended lifespan of paper ranges from short (tissue, paper bags, filter papers, etc.) to moderate (building paper, paperboard, paper fabrics, magazines) to indefinite (military archival records, important manuscripts). The considerations that enter into the selection of a paper are extremely varied.

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*A jellylike film that forms on cellulosic fibers during the manufacturing process; on drying, it serves as a cement to bond the felted sheet of fibers together at all points of contact.

*Standard suggested by the Plastics Committee of the Technical Association of the Pulp and Paper Industry (TAPPI).

Thus, the value of wet-strength war maps in the humid tropics can be readily appreciated. Wrapping paper needed in arid regions will differ greatly from paper serving as a partial vapor barrier for shipments to Southeast Asia. Long-lived paper, for use under ideal conditions, can be quite different from short-lived paper required under severe conditions.

4-6.7 OPTICAL PARTS AND ASSEMBLIES

High humidity often adversely affects optical instruments such as rangefinders, binoculars, driftmeters, cameras, transits, telescopes, and gyroscopic instruments. In areas of low temperatures or of short temperature contrasts, water vapor quickly condenses on glass and occasionally penetrates sealed optical units. The presence of liquid or frozen condensation on lenses, either inside or outside optical enclosures, greatly limits the use of such instruments or makes them worthless. If water vapor penetrates a sealed optical enclosure and condenses, moisture becomes at least partially trapped. Other factors, such as temperature or contaminants, contribute significantly to the breakdown of sealants.

High humidity, particularly in hot regions, can seriously affect glass by reacting chemically with it. Although glass is generally considered to be insoluble, technically, this is incorrect. Ordinary soda-lime-silica glass typically dissolves at normal temperatures at the extremely slow rate of about 0.0003 in. yr^{-1}. The rate of fogging of optical glass depends mainly on the composition of the glass, and on the procedures used to store glass-containing equipment in extremely humid, hot places. Visual dimming of comparatively stable types has been reported after 1-mo storage in very humid places. The visual deterioration of optical glass increases as the level of relative humidity increases, but there appears to be little correlation between visual deterioration and transmission. When alkaline and acid contaminants are present in addition to water, the etching process is further aggravated. Aside from its more direct effects on optical glass, high humidity is also harmful by supporting fungal attack.

In the presence of a moisture film, sodium ions of glass are among the most active agents in the deterioration process. These ions are exchanged with hydrogen ions of water, forming sodium hydroxide. This then attacks silica particles in glass. If the process continues long enough at high humidity levels, a layer of "silica-rich" glass may be deposited on the surface of optical glass. Such a deposit possesses optical properties different from the rest of the glass, with a consequent impairment of performance.

Electrical properties, such as the dielectric property or specific volume resistance, are little affected by high humidity. Nevertheless, adsorbed moisture film on a glass surface is likely to reduce its surface resistance, particularly when combined with contaminants.

4-6.8 OTHER MATERIAL CLASSES

Mineral oils comprised of various blends of hydrocarbons are used as insulants and coolants in electrical equipment. These oils, particularly those of low viscosity, absorb atmospheric moisture at a relatively rapid rate. A 7-day exposure of transformer oil to a relative humidity of 80 percent reduces its dielectric strength to 25 percent of its initial value. When insulating oils are polluted, their electrical properties are more rapidly affected by high humidity.

In glazed ceramics, the absorption of moisture is generally confined to the surface; in unglazed materials, however, much more condensation in capillary pores can be expected. For electrical purposes, unglazed materials have a lower surface insulating resistance.

Dummer and Griffin (Ref. 43) attribute more failures of conventional military ground equipment to humidity (under natural conditions of temperature and humidity) than to any other single environmental factor. A similar pattern of "highest" failures occurred during high temperature/humidity cycling tests of electronic equipment and parts in the laboratory. Although the cycling test results were not as clear cut (a number of electronic parts proved to be highly susceptible to shock, vibration, and salt spray), the data clearly indicate that humidity-induced failures are a major design problem.

The harmful effects of high humidity on metals are the source of numerous mechanical failures. Because of condensation, the zinc in carburetors and fuel pumps deteriorates rapidly; the products of corrosion often block the small orifices in these units. Rust in articulated metal assemblies, such as automotive brakes and gun trigger assemblies, hastens failure; proper maintenance, however, will greatly prolong the life of this type of mechanism.

Condensation problems are not restricted to very humid environments such as the tropics, but occur in extremely cold places as well. Although deterioration due to humidity effects is far less serious at low temperatures, moisture forming on electronic, electrical, or mechanical parts causes other problems. Water vapor quickly condenses on cold equipment that is brought into warm enclosures. If such items are exposed to low temperatures before evaporation of the condensation takes place, freezing of the moisture on metal parts can immobilize or hamper their free movement. Along most arctic coasts, the dense fogs prevalent in the spring and autumn intensify the problems due to condensation of moisture on metals. Under such conditions, condensation and corrosion aggravate the problems of high-voltage arc-overs and resistance leakage. Spark plug fouling due to condensation is a common problem in low temperature environments.

Moisture can condense in fuel tanks of vehicles or aircraft brought into a warm enclosure from the cold. Ice may then form in the fuel line when the vehicle is returned to the cold. This can be minimized by reducing the volume of air in the fuel tank (keeping the tank full) or by adding an antifreeze solution such as alcohol.

At low temperatures, the moisture in human breath will condense on almost any item and quickly freeze. Breathing on light and delicate equipment, therefore, poses major difficulties, particularly where condensation is likely to freeze on working metal parts. Moisture on exposed human skin will, under suitable conditions, freeze onto any metal objects that are touched, e.g., as when a slightly moist hand is removed from a glove and applied to a delicate metal device. The use of suitable gloves—made of pliable leather or wool, for example—will obviate the need for direct contact between the hands and cold metal. Painful and serious injuries can also result if bare hands touch very cold metal, a point to be observed in designing for maintenance.

Low humidity can adversely affect the performance of generators and electric motors. The effective sliding of graphite brushes on commutators and sliprings depends on a film of moisture for lubrication. Absence of such a film causes excessive friction, increased electrical losses, rapid brush wear, and higher operating temperatures. To counteract this effect, solid lubricants such as barium fluoride and molybdenum disulfide can be incorporated in the brushes.

In certain types of electric, electronic, and other precision equipment, desorption of moisture from insulants produces a marked improvement in their electric characteristics.

4-6.9 COMBINED ENVIRONMENTAL EFFECTS

The effects of environmental factors acting in combination or sequentially are difficult to identify and evaluate. Many of the difficulties arise from the scope and complexity of the possible combinations of reactions of items to the full range of stresses of a given environment. Environmental factors can be mutually aggravating, essentially independent, or nullify each other. The practical approach to the problem frequently consists of identifying those environmental factors harmful to a specific item, and then analyzing combinations of those stresses as they affect the item under consideration. Synergisms of humidity with other environmental factors are as follows:

(1) *Humidity and temperature.* The fundamental relationship between humidity and temperature has been examined elsewhere in this chapter. Cognizance of this relationship is of primary importance in designing for humidity stress and its effects on materiel.

Temperature change has a pronounced and instantaneous effect on relative humidity, but only a delayed effect on absolute humidity. Absolute humidity increases during periods of rising temperatures and increased evaporation; concurrently, relative humidity may be decreasing.

The relative humidity of ambient air is of special importance in problems related to swelling. High temperatures tend to accelerate the rate of moisture penetration. When both high temperatures and high humidities prevail for extended periods, conditions are particularly conducive to the occurrence of mildew, corrosion, and the decay of susceptible items.

Decreasing temperatures raise relative humidity until saturation occurs, but do not reduce absolute humidity unless condensation occurs. Condensation of water vapor in confined air is particularly harmful, since dissipation of trapped moisture by evaporation is frequently negligible. Low temperatures are conducive to frost and ice formation; in porous materials, the expansion of frozen moisture accelerates their deterioration, making them more susceptible to penetration by water vapor and liquid water. Low temperatures also induce brittleness in materials and cause cracks to form in places of stress. Such cracks provide additional avenues for the penetration of moisture.

(2) *Humidity and microbiological organisms.* Humidity facilitates the growth of micro-organisms, including harmful fungi. Fungi are simple plants having no stems, leaves, or flowers. Some fungous growth is readily evident to an experienced technician, an inexperienced investigator may encounter difficulty in distinguishing between fungous growth and the oxides of some materials, e.g., cuprous oxide.

Fungi can and do grow anywhere, provided that suitable nutrient material and sufficient moisture are available. There are tens of thousands of fungous species; many of them are harmful. With some important exceptions, a warm, humid environment favors the rapid growth of fungi. However, some species, such as *Aspergillus* strains, have survived a few hours at temperatures above 65.5°C (150°F) and below −84.4°C (−120°F) in laboratory tests.

Most organic materials are susceptible to direct fungous attack, which is made possible by humid conditions. Even oil deposited on sensitive components by human fingers will support fungous growth. Many harmful fungi secrete enzymes and acids that change other materials into soluble substances that can be assimilated. Some *Aspergillus* fungi can pit certain kinds of optical glass and some stainless steels. Since numerous harmful species of these organisms are normally present—particularly in hot, humid environments—the rate and extent of deterioration of organic materials and, to a lesser extent, the etching of some inorganic materials depend essentially on the humidity level, the nature of the nutrient material available to these organisms, and the protective measures utilized.

(3) *Humidity and salt spray.* Although high humidity tends to lower salt concentrations, it appears to have no impact on the corrosion action of saline solutions. However, the occurrence of salt spray at any concentration greatly accentuates the corrosion of steel and alloys of aluminum and magnesium.

(4) *Humidity and vegetation.* The evaporation of moisture from vegetation adds to the vapor content of ambient air but lowers the air temperature, thereby increasing the relative humidity. Consequently, vegetation increases the rate of decomposition of natural and manmade materials. The relatively greater

water vapor pressure in and above vegetation has an important bearing on the penetration of moist air into porous materials. The higher humidity near irrigated surfaces, whether soil or vegetation, is particularly striking when compared to arid areas. An absence of vegetation is often characterized by extremely low relative humidities, especially during the warmer hours of the day. Such an environment has an adverse, drying effect, particularly on pliable organic materials.

(5) *Humidity and vibration.* Humidity, in combination with vibration such as that produced by stationary engines and motors or in transportation equipment, tends to accelerate the general breakdown of materials. Electrical and electronic components are particularly vulnerable to the combined effects of humidity and vibration. The effects of these two environmental factors are greatly aggravated when alternate freezing and thawing are experienced. Stress cracks expand when subjected to vibration, freezing, or both.

(6) *Humidity and impurities.* The corrosion of metals depends primarily on the composition of the atmosphere, with impurities playing a major role and humidity acting as a catalyst. Above the critical humidity for a given metal, the severity of corrosion is closely related to the type and concentration of impurities present. Impurities may be present in a gaseous, liquid, or solid state. Solids have diverse dissolving characteristics that range from the nonsoluble to the soluble. The presence of ample moisture in combination with a variety of impurities constitutes a major problem in many storage and operational areas. The problem is basically a complex chemical one. Isolating the relative importance of either humidity or a particular impurity is a difficult task. Obtaining meaningful corrosion data for determining scientific factors is usually involved.

The corrosion process itself sometimes introduces additional harmful substances. Other considerations include temperature, the relative concentration of impurities (singly or in combination) in solution, the tolerances of different metals, and solar radiation. According to Hazard (Ref. 44), an industrial atmosphere is five to ten times more corrosive to metals than a rural one, and twice as corrosive as a humid atmosphere. However, comparable statistical data on the effects of humidity and impurities on a worldwide or even a continental basis are grossly inadequate or nonexistent.

(7) *Humidity in transportation and in storage.* Important fluctuations in temperature, and consequently in humidity, often occur during the shipment of equipment, repair parts, munitions, and other materiel through significantly different environments. This applies in varying degrees to all forms of transportation, but in particular to ocean transportation in which the environment of the vessel cargo space is not artificially controlled. Air over extensive tropical waters has a large capacity to absorb water vapor. Tropical maritime air, as a result, has high absolute and specific humidities. Thus, when a vessel is loaded in such an environment, a considerable quantity of humid air is at least partially trapped when the holds are closed. As the vessel proceeds through cooler water in higher latitudes, or across a cool ocean current, the air temperature in the holds may be lowered to the dewpoint, causing condensation to form on both cargo and bulkheads.

The extent of damage to materiel caused by humidity and/or other agents dependent on humidity will be determined largely by an understanding of potential problem areas and the extent of precautionary action taken. Basic protective measures include the use of dehumidifiers, ample ventilation, suitable moisture-resistant coatings on the more susceptible components, and moisture-resistant packaging. The possible deposition of salt nuclei on materiel and the accentuating effect of condensation must also be considered. A storm at sea greatly increases the salt nuclei count of the air being circulated into the holds of a ship.

A lack of ventilation in hot, humid storage areas can cause earlier than normal failure because of the greater humidity stress in overcrowded storage places and perhaps poorly designed shelters. Because failure of a single component can make a piece of vital equipment useless, a greater margin of safety is needed for those items likely to be seriously damaged by humidity while stored in unsuitable places or for prolonged periods.

4-7 DESIGN

4-7.1 CLIMATIC DESIGN AREAS

AR 70-38, *Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions* (Ref. 45), shows that most of the eight climatic categories used specify the joint occurrence of extreme temperature and humidity. Three of the eight designated climatic categories (wet-warm, wet-hot, and humid-hot) are based on combinations of high temperature and high humidity. A fourth category, hot-dry, is based on a combination of high temperature and very low humidity. Of primary concern in this chapter are categories 1 (wet-warm), 2 (wet-hot), and 3 (humid-hot coastal desert) in which high humidity produces a greater stress than temperature. These three categories occur mainly in low latitudes, at low elevations, and often near warm seas. The wet-warm and wet-hot categories are delimited on the basis of a modified Koppen classification.

The wet-warm category is characterized by the persistence of relative humidity above 95 percent and a nearly constant temperature of 23.9°C (75°F) for periods of 1 day or more. Wet-warm conditions occur under the forest canopy of heavily wooded tropical areas, most typically in tropical rain forests. The dense canopy of these forests interrupts the frequent and intense rainfalls, causing prolonged dripping and tree runoff to the underlying ground. The canopy also severely limits the drying effects of solar radiation and wind. These combined conditions beneath the vegetation cover produce a remarkably persistent humid environment. In some areas these conditions may occur on several days during any month of the year; in other areas wet-warm conditions are seasonal and less frequent, due to the gradual latitudinal migration of tropical rains. Although temperatures are not extreme in wet-warm areas, the constant high humidity imposes a major stress on materiel which is adversely affected by excessive absorption of moisture and often results in permanent damage to many items.

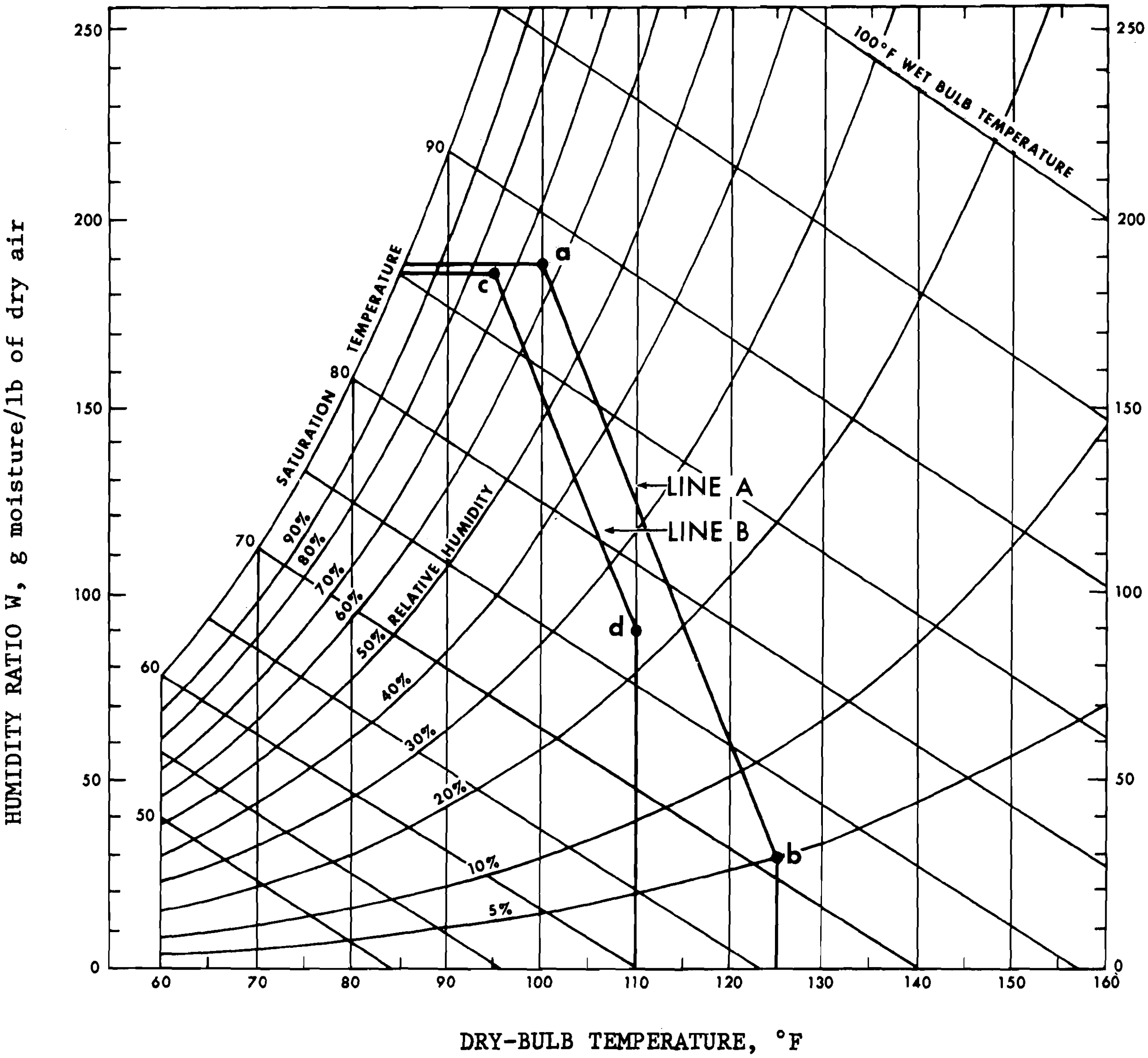
The wet-hot category applies to open areas in tropical regions, which are characterized by temperatures of 25.5° to 35°C (78° to 95°F) in combination with relative humidities of 75 to 100 percent, strong solar radiation, and frequent light-to-gentle winds. In some parts of the wet tropics, wet-hot conditions are experienced during most months; in other areas these will occur only during a pronounced rainy reason. This type of condition places a severe stress on materiel that is subject to malfunction or deterioration when exposed to moderately high temperatures and high humidities for extended periods of time.

Humid-hot coastal desert conditions are limited to fringe areas adjacent to bodies of water with a high sea surface temperature, such as the Persian Gulf and the Red Sea. A temperature of 37.7°C (100°F) concurrent with a relative humidity of 65 percent are specified as the extreme condition for category 3. Equivalent values for dewpoint and wet-bulb temperature are, respectively, 30°C (86°F) and 31.6°C (89°F).

4-7.2 SIMULTANEOUS OCCURRENCE OF HIGH TEMPERATURE AND HIGH HUMIDITY

Fig. 4-19, from AR 70-38 (Ref. 45), is a psychrometric chart that shows the relationships between temperature and atmospheric water vapor content at different levels of relative humidity. The chart contains two lines (A and B), which illustrate combined high temperatures and high humidities, the extreme climatic conditions.

These lines are described in AR 70-38 as follows:



(Psychrometric Chart Based on a Barometric Pressure of 29.92 in. Hg)

Point	Extreme Temperature and Relative Humidity Combination of Climatic Category
a	3, Humid-Hot Coastal Desert
b	4, Hot-Dry
c	2, Wet-Hot
d	5, Intermediate Hot-Dry

Figure 4-19. Simultaneous Occurrence of High Temperature and High Humidity (Ref. 45)

(1) *Line A* shows the most extreme combinations. Point *a* on this line 37.7°C (100°F) dry-bulb temperature and 64 percent relative humidity, is the extreme condition for category 3, humid-hot coastal desert. Point *b* on this line, 51.6°C (125°F) dry-bulb temperature and 5 percent relative humidity, is the extreme condition of category, 4, hot-dry. The conditions represented by line *A* are limited in extent and frequency of occurrence.

(2) *Line B* shows high temperature and humidity combinations that represent less extreme conditions, but are more widespread over the land surface of the earth, and occur more frequently during the year. Point *c* on this line, 35°C (95°F) dry-bulb temperature and 74 percent relative humidity, is the extreme condition of category 2, wet-hot. Point *d* on this line, 43.3°C (110°F) dry-bulb temperature and 23 percent relative humidity, is the extreme condition of category 5, intermediate hot-dry. Therefore, line *B* represents the extremes of concurrent high temperature and high humidity conditions for the intermediate and wet-hot categories.

4-7.3 PREVENTION AND CONTROL

Harmful humidity effects are basically caused by unwanted moisture penetration and accumulation. Penetration by moisture can be either in the form of water vapor (and subsequent condensation) or liquid water (after condensation), or both. Prevention and control of humidity-induced damage rests, essentially, on methods designed to prevent the intrusion and/or accumulation of moisture, and those involving the selection of materials that are impervious to, or minimize, moisture-induced degradation. Specific applications are constrained by the type of item and materials used, the nature of the effects guarded against (i.e., electrical, mechanical, or chemical), and the level of component reliability required. Prevention and control measures applicable to various classes of material are (Ref. 46):

(1) *Mechanical items.* Use of proper finishes for materials, use of nonabsorbent materials for gasketing, sealing of lubricated surfaces and assemblies, and use of drain holes for water run-off.

(2) *Electronic and electrical items.* Use of nonporous insulating materials, impregnation of cut edges on plastic with moisture-resistant varnish or resin, sealing of components with moving parts, perforation of sleeving over cabled wire to avoid the accumulation of condensed water, encapsulation or sealing, and use of only pure resin as a flux.

(3) *Electromagnetic items.* Impregnation of windings with moistureproof varnish, encapsulation, or hermetic sealing, avoidance of the use of commutators, provision of long creepage distances, and use of alumina insulators.

(4) *Thermally active items.* Use of nonhygroscopic materials, hermetic sealing where possible.

(5) *Finishes.* Avoidance of porous, corrosion-prone, or water-soluble finishes, as well as very thin "flash" plating.

(6) *Materials.* Avoidance of hygroscopic or porous materials; impregnation with wax, varnish, or resin on all capillary edges.

True hermetic sealing will eliminate failures due to humidity, salt spray, fungus, and rain. True hermetic sealing is a process that includes vacuum drying by evacuation to the micron range, outgassing, quantitative leak testing, flushing with pure dry nitrogen, and back-filling with an inert gas. Among the gases used for filling hermetically sealed components or units are nitrogen, helium, nitrogen-helium tracer, dry air, hydrogen, and halogenated compounds (Ref. 43).

The proper choice of materials is among the most important means for minimizing humidity-induced deterioration and failure, particularly that due to galvanic corrosion. Since corrosion cannot be avoided entirely or predicted in some instances, design consideration is generally oriented to controlling its effects. If the contact of dissimilar metals cannot be avoided, coatings or compatible plating should be used. Unless electrical contact between dissimilar metals is necessary, insulation should be utilized; if complete insulation is not feasible, the application of paints, plastics, or other coatings may prove effective. Where the potential corrosion area of a metal is relatively large, corrosion becomes less concentrated and, therefore, less destructive. In such cases preventive measures may not be needed. Because many related factors affect galvanic corrosion, materials for specific applications should be tested in corrosive environments when adequate data are unavailable to assess their susceptibility to this type of deterioration.

A number of commonly used materials undergo degradation in humid environments, or when used with other materials in the presence of moisture. Examples of materials requiring design cognizance of such properties are (Ref. 43):

(1) *Cadmium.* Cadmium or cadmium plate manifests a rapid formation of bulky, white, nonmetallic corrosion products when packaged or confined in a damp atmosphere without air circulation in the presence of acidic organic vapors. Such vapors are derived from drying aids used in paints, impregnated fabrics, organic electrical insulation, and many resins and waxs. High temperature and high humidity aggravate the process. This effect is potentially important in the design of watertight but not hermetically sealed units.

(2) *Silver.* Silver migrates through certain plastics and across the surface of some ceramics under the influence of an applied voltage and high humidity. The result is a drastic decrease in the dielectric breakdown strength of the plastics, and in the electrical surface insulation of the ceramics.

(3) *Mercury.* Mercury-aluminum amalgams rapidly form bulky, white corrosion products when exposed to damp atmospheres. These formations can occur in minutes. The mercury in many fungicides increases the probability of occurrence of this combination. Fungicides containing mercury should not be used near selenium oxide rectifiers, since chemical reaction of the oxide to metallic selenium may occur. Mercury or mercury salts in contact with some stressed metals may cause severe cracking known as stress-corrosion cracking.

(4) *Brass.* Stress cracking similar to that caused by mercury results from ammonia and nitrogen-bearing materials such as amines. Observed failures have been attributed to the fact that nylon in contact with moisture may yield amino compounds.

(5) *Wood.* Damage to lumber, timbers, or wood products can be minimized or prevented by proper seasoning and storage practices. Treated wood products often deteriorate more rapidly in moist storage areas than they do after being put into service. Untreated wood molds if it is damp from being green or from having become damp after drying; fungi quickly form on or beneath the wood surface, causing discoloration that limits usefulness of the wood. Unless green wood is properly seasoned, serious shrinking, checking, warping, twisting, and rapid decay can be expected. Thus, green lumber and timbers should either be kiln-dried or air-dried before being used or stored.

Seasoned lumber, timber, or wood products should be kept as dry as possible when stored in humid, warm areas. Storage should be under a nonleaking roof. Sheds with open sides permit the free circulation of air. However, in moist environments, enclosed buildings containing stored wood should be heated or provided with forced ventilation to prevent the buildup of relative humidity and the formation of condensation.

The use of wood preservative extends the useful life of wood, particularly under damp conditions. A good preservative is highly toxic to micro-organisms and termites, chemically stable, resonably permanent, safe to handle, and harmless to any wood or metal that may be attached to wood impregnated with it. Ideally, it should be cheap and readily available. For some applications, it may be important that a preservative not swell wood, that it leave surfaces clean, provide good adherence for paint, be free from staining or bad odor, and be moisture repellent.

Oil and water are commonly used as solvents in the application of preservatives. Oil-borne preservatives are more effective and more commonly used, but also more expensive; they include wood oils, lignite-tar oils, water-gas tars, and such byproduct oils as coal-tar creosote, creosote/coal-tar solutions, and creosote-petroleum solutions. Some of the better known toxic chemicals include the chlorinated phenols and copper naphthenate. In extremely moist or wet environments, the best preservative for the protection of general outdoor, unfinished structural timbers against fungi, insects, and marine borers is coal-tar creosote. It has a strong toxicity, low water solubility, low volatility, ease of application, and good depth penetration. It is generally available and has a relatively low cost when purchased in large quantities. However, creosoted wood has an objectionable odor, and sometimes irritates the skin of personnel handling it. Creosoted wood cannot be satisfactorily painted, and may contribute to fire hazards. Foods that absorb odors should not be stored nor used near creosoted wood. Information on wood preservatives and specifications are given in Federal Specifications TT-W-556a (coal-tar creosote), TT-W-566a (creosote/coal-tar solutions), and TT-W-568 (creosote-petroleum solutions). Similar information on preservatives is also available from the American Wood Preservers' Association.

Water-repellent preservatives, usually oil solutions of chlorinated phenols, combine a moderate degree of water repellency with decay and insect deterrents. Preservatives in this group act by retarding the rate of water absorption, not by preventing it. They are useful in protecting wood from frequently changing humidity conditions and brief contact with water. Thus, they tend to eliminate the adverse effects of extremely humid or dry conditions of short duration.

Waterborne preservatives are cheap, readily available, nonflammable, and have the advantage that they add little weight to the wood to which they are applied (due to evaporation of the water from wood). The dry surface also remains relatively clean. One disadvantage in their use is wood swelling from the large amount of water absorbed, which requires drying. Federal Specifications in the "TT-W" series cover preservatives in this group.

According to Greathouse and Wessel (Ref. 42), ordinary paints, varnishes, and stains are of little value in protecting untreated wood against fungous damage. The protection provided by the toxic chemicals added to coatings is limited by the depth of penetration, absorption, and life of the coating. Moreover, when such coatings are applied to structures, generally only exposed surfaces are coated, further limiting their effectiveness.

Fluctuations of high relative humidity, particularly in warm environments, contribute appreciably to the breakdown of glued wood joints and plywood laminations. This usually results from two concurrent actions, although either one alone can cause such damage. The first action is the softening of the glue from hydrolysis, which results in a loss of strength. The second action is the amount of mechanical stress exerted as the wood undergoes differential changes in dimension with changing moisture content. According to Brouse (Ref. 47), "The magnitude of the mechanical stress developed depends on the extent of the moisture changes, how far the extremes of moisture content depart from that of stock at the time the glue sets, the density and shrinking characteristics of the species of wood involved, and—in the case of plywood—the thickness of the laminations." It should be borne in mind, however, that excessive drying of glued wood joints may weaken them sufficiently to produce failure when subjected to normal use.

4-8 TESTING AND SIMULATION

Environmental tests are widely used to optimize the development and performance of materiel. Guidance in their application is to be found in numerous Army publications, such as AR 70-38 (Ref. 45) and AR 70-10, *Research and Development, Army Materiel Testing* (Ref. 48). The most immediate use of environmental tests is for determining the suitability of materials, combination of materials, and proposed design configurations relative to a given set of environmental stresses. They are also used for such purposes as determining test critieria and specifications, evaluating reliability, maintaining quality control during production, and evaluating test procedures and results, e.g., natural environment testing versus laboratory simulation.

Environmental tests may be conducted either in the field under natural conditions or in the laboratory under simulated conditions. Laboratory tests are frequently uncharacteristic of actual conditions found in the natural environment. This is the case with *accelerated tests* (natural conditions are made to occur with a greater frequency, severity, and/or duration than are found in nature).

Limitations on the use of field tests arise from the undependability of adequate environmental stress, the time factor, inconvenience, and cost. Advantages in the use of chambers lie in the close control attainable and in the experimental flexibility allowed by accelerating and/or aggravating the factors being studied. However, the results of laboratory testing of humidity stresses must be evaluated with caution, since the effects on material when exposed to natural conditions are often at variance with the effects achieved by chamber testing.

Table 4-17 shows the results, cited in Dummer and Griffin (Ref. 43), of comparison tests conducted by the Royal Radar Establishment, England, and the Tropical Testing Establishment, West Africa, to determine the relationship between the effects of standard artificial tropical test conditions and those of a natural tropical (i.e., hot-wet) climate. Test exposure was in a chamber for 84 days, with the temperature varied cyclically from 20°C ± 5°C to 35°C ± 1°C (68°F ± 9°F to 95°F ± 1.8°F); the upper temperature was maintained for 12 hr and the lower for a minimum of 5 hr each day. The minimum relative humidity throughout was 90 percent. The natural conditions were those associated with tropical rain forest areas, mean temperatures varying between 20° and 36°C (68° and 97°F), mean relative humidity between 70 and 90 percent, and an annual rainfall in excess of 100 in.

These results should not be accepted as fully representative, since they are for an 84-day test whereas in the United States a 28-day test is believed to more accurately correlate with experience in the field. The 28-day test is specified in MIL-STD-810 (Ref. 49).

4-8.1 TEST CHAMBERS

Numerous factors influence the design of a humidity test chamber. These include size, range of values (minimum, maximum, and duration), steady or cyclic requirements, reserve capacity to maintain tolerances, period of anticipated use, control equipment, and cost. Detailed information on the anticipated relationships among humidity, weather elements, and terrestrial factors should be known. Since some environmental elements are difficult to isolate from humidity, their relative importance must be established.

The objective or objectives of the test should be precisely formulated, and the nature of the test should conform to the environment in which the item will be used, e.g., geographical location, indoors or outdoors, and altitude. AR 70-38 furnishes general criteria, but specific adaptations should be made where called for.

All construction materials used within a humidity chamber should be highly resistant to corrosion. The inner lining must be completely impermeable to penetration by water

TABLE 4-17

COMPARISON OF FIELD AND LABORATORY TESTS ON ELECTRONIC COMPONENTS (Ref. 43)

Component	Storage		
	Tropical base depot, 12 mo	Jungle undergrowth (sheltered), 12 mo	Artificial, 84 days
Sealed potentiometers	Good (slight fungus)	Slight rusting, fungus	Fair (corrosion and rusting)
Nonsealed potentiometers	Good	Fairly good (stiffening of spindles and slight corrosion)	Very poor (heavy corrosion, stiff movement)
Wire-wound potentiometers	Good (slight stiffening of movement)	Fair (increase stiffening of spindles, slight corrosion)	Very poor (heavy corrosion, stiff movement)
Molded Bakelite valveholders	Good (very slight corrosion of pins)	Fairly good (slight corrosion)	Poor (pins badly corroded)
Multipin plugs and sockets	Good	Poor (corrosion of magnesium shell, locking rings "solid")	Very poor (severe corrosion, rings "solid")
Nonsealed Bakelite toggle switches	Good (all actions normal)	Bad (all failed after 6 mo)	Very bad (all failed after 80 days)
Ceramic wafer switches	Fairly good (distortion of phenolic pillars caused one ceramic mounting to crack on one sample)	Fairly good (distortion of phenolic pillars caused ceramic mounting to crack on two samples)	Fairly good (distortion of phenolic pillars caused ceramic mounting to crack on two samples)
Telephone relays	Good	Fairly good (some zinc corrosion)	Poor (frames badly corroded)
Paper (metal tubular) condensers	Fairly good (rubber seals bulging)	Fairly good (slight corrosion, rubber seals bulging)	Poor (heavy corrosion of aluminum cases, seals bulging)
Molded mica condensers	Good	Good (slight fungus)	Good

vapor to protect the surrounding insulation, since any gain or loss of heat will be reflected immediately in the relative humidity. This is very important, since tests in environmental chambers deal with relative humidity rather than water vapor content (absolute humidity). Sloping ceilings should be so constructed as to prevent condensation from dripping on test items; otherwise, a small polyethylene tent without sides can be easily fabricated to protect items from dripping water. The floor of the chamber should be pitched so that any accumulations of water can easily drain.

Adequate consideration must be given to the chamber cooling system. The cooling coil temperature should not be significantly below the lowest dewpoint desired, since otherwise condensation will lower the capacity of the coil to maintain the desired conditions, particularly during temperature-humidity cycling. Ample reserve power is required if drastic and rapid fluctuations in conditions are part of a test program. Some multipurpose chambers have dual coil systems; a Freon coil for low-temperature testing, and a water coil for cooling in humidity testing.

The selection of relative humidity controls for environmental chambers necessitates a careful analysis of the air-conditioning system requirements. These requirements generally call for narrow control tolerances and a capability for rapid changes in airflow. The velocity of air near the test specimen must be kept low (under 150 fpm) in a humidity chamber.

Humidity chambers are usually controlled by means of automatic recording and controlling instruments. The wet-bulb and dry-bulb comparison method (or an equivalent method) provides an indication of temperature and humidity within the chamber. As pointed out in par. 4-5.1, a small change in wet-bulb temperatures results in an appreciable error in relative humidity; at room temperature, for example, a variation of only 0.6 deg C (1 deg F) in wet-bulb depression results in an approximate difference of 4 percent in relative humidity. Temperature, therefore, must be measured and controlled accurately, and kept as constant as possible. In actual practice, the design of temperature tolerances immediately surrounding the test specimen within narrower limits than those specified in a sound precautionary measure against unanticipated loads on the system.

Test conditions should be maintained uniformly throughout the chamber if possible or, as a minimum, they should be kept within specified tolerances. A forced-circulation air-conditioning system requires proper baffles to provide sufficient circulation without excessive air velocity. The chamber should be vented to the atmosphere to prevent an increase in pressure, which affects humidity. Although condensation on walls and ceiling does not necessarily adversely affect the humidity environment, the same amount of water must be added to the air intake to compensate for the loss by condensation. According to MIL-STD-810, *Environmental Test Methods* (Ref. 49), "Steam or distilled, demineralized, or dionized water having a pH value between 6.0 and 7.2 at 23°C (73°F) shall be used to obtain the specified humidity." Formation of condensation on chamber walls and ceiling can be eliminated by maintaining the temperature of those surfaces at the dry-bulb temperature, or at least above the dewpoint.

The simulation of humidity conditions is conducted in a wide variety of environmental test chambers and test cabinets. Many of these chambers have combined environmental factor capability, some of which are temperature/humidity, temperature/altitude/humidity, temperature/fungus/humidity, temperature/humidity/solar radiation, and temperature/humidity/vibration. Listings of facilities in industry and Government are contained, respectively, in the following publications:

(1) *Facility Survey* (Ref. 50), published by the Institute of Environmental Sciences

(2) *Index of Environmental Test Equipment in Government Establishments* (Ref.

51), prepared by the Shock and Vibration Information Center, Naval Research Laboratory.

These documents provide detailed information on chamber type, operating characteristics, location, and activity (Government agency or company). The number and range of such chambers preclude enumeration here. A summary listing of environmental chamber types in Army facilities is presented in Chap. 3, "Temperature", of Part Two of this handbook.

Chambers and cabinets with humidity test capability over a wide range of sizes and operating characteristics are available. Equipment ranges in size from small cabinets to large walk-in facilities; small-to-medium cabinets are the most commonly used.

For specific applications, cabinet or chamber size and operating characteristics should be clearly ascertained, particularly if high-intensity stresses are to be applied. As a rule, multieffect chambers have restricted ranges, although even these will cover any range of natural ambient temperature-humidity conditions. In general, temperature-humidity cabinets provide temperatures in the −101° to −73°C (−150° to −100°F) low temperature range, and high temperatures in the 149° to 176°C (300° to 350°F) range. Some temperature-humidity chambers have a maximum temperature range of 204° to 315°C (400° to 600°F), although these are less common. The range of relative humidity provided by temperature-humidity chambers is quite variable. Most of the commonly used chambers have an upper limit of 95 to 100 percent relative humidity; the lower limit is most often on the order of 5 to 10 percent or 20 to 25 percent relative humidity (Refs. 50, 51).

4-8.2 TEST PROCEDURES AND EVALUATION

MIL-STD-810 (Method 507) provides five standard procedures for high humidity and high temperature chamber testing. Each procedure involves different cyclic exposures of a test item to exaggerated fluctuations and durations of humidity and temperature.

In each procedure an item is installed in a test chamber in a manner to simulate service usage and to prevent condensate dropping on it. Some test items should be operated or checked prior to testing to determine the adequacy of installation within the chamber and for possible damage in handling. No realignment, readjustment, repair, or replacement of a test item should be undertaken once a test cycle is started, except for movement of some of the operational controls indicated in equipment specifications. In each procedure initial measurements are taken and compared with findings obtained during and immediately after each test. Before taking measurements, each procedure provides that accumulated moisture may be removed by turning the test item upside down or by shaking; wiping of external surfaces is permitted only in one of the procedures. After measurements following the last cycle are taken, the test item is conditioned and adjusted for optimal performance according to the requirements of the particular procedure. The test item is then operated to obtain the final results of the humidity test.

Simulated laboratory tests, it should be repeated, are not synonymous with field conditions, particularly when time is a major factor in chemical reactions. Corrosion rarely occurs on exposed metal without the presence of some form of moisture; it results when metals react chemically with moisture mainly at or above critical levels of relative humidity. When the moisture on a metallic surface contains appreciable impurities in solution, the corrosion process progresses at a faster rate. Atmospheric impurities in a test chamber can be identified, measured, controlled, and introduced at known rates, but the types and amounts of impurities encountered under field conditions are decidedly more varied. Harmful impurities vary greatly with location and changes in weather. Fungi also contribute to increased chemical reaction of various materials.

Data from accelerated tests are useful in obtaining preliminary estimates of the effects that natural conditions and usage will have on materiel. Such data, however, should be used carefully since the compression of the time factor may not correlate with the increase in the stress factor. In addition to the time factor, in corrosion processes, synergistic effects that occur in the natural environment can seriously distort attempts to correlate the results of uncontrolled field tests with those of controlled chamber testing.

4-8.3 TEST RANGES

Locations utilized for testing humidity effects should have the extreme climatic conditions specified for the climatic categories as given in AR 70-38. Particular attention must be paid to seasonal variations in humidity patterns, since these can be quite marked. An example of this is the change that occurs near the end of June at the Yuma Proving Ground, Ariz., from a low to a high humidity environment due to the seasonal incursion of humid air from the Gulf of Mexico.

The effects of high temperature and high humidity are tested at the U.S. Army Tropic Test Center, Ft. Clayton, C.Z. This site also provides a suitable environment for the evaluation of humidity in combination with other environmental factors such as salt, fungus, vegetation, rain, and insects. The extremely high rate of salt deposition in this area enhances its value as a site for testing corrosion phenomena.

Considerable latitude exists in the choice of sites for humidity testing, since (1) numerous geographical areas provide the sustained high average temperature-humidity levels required by the time aspects of such tests; and (2) the facilities required are of a modest nature, being essentially storage or exposure structures.

4-8.4 SPECIFICATIONS

The following basic documents contain directives, standards, and specifications related to the design, test, and operation of Army materiel under varying climatic and induced humidity conditions:

(1) MIL-STD-810, *Environmental Test Methods*, 15 June 1967, with Notice 1, 20 October 1969, and Notice 2, 29 September 1969.

(2) Quadripartite Standardization Agreement 200, American-British-Canadian-Australian Armies Standardization Program, *Climatic Factors Affecting Design Criteria*, 18 March 1969.

(3) AR 70-38, *Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions*, 5 May 1969.

(4) Specifications for individual items of equipment, materials, and specialized test procedures are contained in the *Index of Specifications and Standards*, Department of Defense, 1969.

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CHAPTER 5

PRESSURE*

5-1 INTRODUCTION AND DEFINITIONS

Atmospheric pressure is defined as "the pressure exerted by the atmosphere as a consequence of the gravitational attraction exerted upon the column of air lying directly above the point in question" (Ref. 1). The dimensions of pressure are force per unit area, or energy per unit volume. The force is a result of the collision of gas molecules upon the pressure-measuring instrument, and it is also equal to the weight (mass times gravitational acceleration) of the air in a column of unit area extending from the measuring point to the top of the atmosphere.

The atmosphere exerts this pressure equally in all directions at any point on all exposed objects. It is not normally perceived since the objects usually exert an equal but opposite force.

At sea level, the standard atmospheric pressure is defined to be 1,013.25 millibars (mb) (14.7 lb ft^{-2}) although any measured pressure may differ from the standard (Ref. 2). As altitude increases, the mass of the air above a point decreases and consequently the pressure decreases. Near 5.5 km ($\approx$18,000 ft) altitude, the atmospheric pressure is reduced to about one-half of its standard sea-level value; near 16 km ($\approx$52,500 ft), the pressure is about one-tenth of the standard sea-level value; and near 31 km ($\approx$101,700 ft), the pressure is about one one-hundredth of the sea-level value.

Environments of atmospheric pressure, other than ambient, are created by man for various reasons. Aircraft cabins are pressurized for high altitude operations. "Clean rooms" maintain a pressure above ambient conditions. Vacuum tubes, although being replaced by miniaturized circuits, operate more efficiently in the absence of ordinary air at atmospheric pressures. In creating these artificial pressure environments, some precaution must be taken to insure that the forces on the enclosures created by the pressure differentials do not become great enough to induce malfunctions and/or hazardous conditions.

Except for new forms of transportation that may be adopted in the future for specialized research programs and for missiles or rockets, Army materiel is exposed to atmospheric pressures that occur below 16 km. Hence, this chapter considers primarily the effects of pressure on materiel operating at or below that altitude.

Man's natural habitat is in the portion of the atmosphere where the higher pressures are found. Thus, his materiel is less likely affected by extremes of high pressure than by reduced pressure.

Because pressure decreases with increasing altitude, the effects of reduced pressure and an increased altitude are often erroneously considered synonymous. Atmospheric density and temperature decrease with altitude. Fractional changes in pressure induce a smaller but nearly equal change in density and an even smaller change in temperature. Hence, the effects attributed to a reduced pressure may be due to a decreased density or temperature. For example, the thermal conductivity, heat absorption capability, and the dielectric

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*Material presented in this chapter is partially extracted from an original manuscript prepared by Pauline E. Riordan, Environmental Criteria Branch, Engineer Topographic Laboratories, Fort Belvoir, VA.

strength of the air decrease as the atmosphere density decreases with increased altitude.

The composition of the atmosphere up to about 90 km remains in constant proportion as the total pressure decreases, so the partial pressure exerted by each constituent must also decrease with increasing altitude in proportion to the total pressure decrease; e.g., the partial pressure of oxygen at 5.5 km is approximately one-half of its sea-level value. The density of each gas is also reduced. Since oxygen is required to support combustion, materials that are dependent upon combustion and man's capability to function at high altitudes are affected by the reduced available oxygen.

The principal effects of pressure per se upon materiel result not from the magnitude of the pressure but upon its gradient or differential. The gradient produces a force causing the air to move from a higher pressure toward a lower pressure. This force can cause leakage, or even explosion or implosion of sealed containers, and produce atmospheric winds. The greater the pressure gradient, or the more rapidly the pressure is changed, the greater the chance for damage to materiel.

Pressure is a force per unit area and, according to international convention (Ref. 3), it should be reported in units of newtons per square meter ($N\ m^{-1}$) or pascals (1 pascal = 1 $N\ m^{-2}$). However, other systems of units are more common and their usage is dependent upon the discipline of the reporter.

The first atmospheric pressure measurements are attributed to Torricelli, who, in 1643, devised the principle of the barometer (par. 5-3.1) using water instead of mercury (Ref. 4). Rather than computing the pressure, it is convenient and equivalent to report the height of the liquid in the column with an identification of the liquid. Among the units used to report pressure in that manner are millimeters of mercury (mm Hg), centimeters of mercury (cm Hg), and inches of mercury (in. Hg). The first two are commonly used in scientific laboratories throughout the world. The latter is a popular reporting unit in countries using the English measuring system. Another unit, the torr, is sometimes reported and is equivalent to 1 mm Hg at a temperature of 0°C. Mercury is commonly used as the fluid because it is a high density liquid ($\approx$13.5 $g\ cm^{-3}$) at environmental temperatures, whereas water is less dense ($\approx$1 $g\ cm^{-3}$) and changes phase.

When expressing pressure as a force per unit of area, derived units, other than $N\ m^{-2}$, are most frequently reported. Atmospheric pressures are usually reported, among meteorologists, in units of millibars (mb) (1 mb = 10^{-2} $N\ m^{-2}$, or 10^{-3} bar). Other units of varying use are dyne cm^{-2}, pound force per square foot (psf), and pound force per square inch (psi). Gage pressure, such as vehicle tire pressure, is usually reported as pounds per square inch, gage (psig). Regardless of the units used, gage pressure indicates the pressure in excess of the ambient pressure.

For some purposes, the term "atmospheres" is used to indicate pressure. One atmosphere of pressure equals the standard sea-level atmospheric pressure. Table 5-1 gives the conversion factors for the various pressure units.

5-2 THE NATURAL PRESSURE ENVIRONMENT

From a thermodynamic viewpoint, the atmosphere is primarily a mixture of ideal, diatomic gases, which for practical purposes obey the ideal gas law,

$$p = \frac{\rho}{M} RT,\ \mathrm{N\ m^{-2}} \qquad (5\text{-}1)$$

where

p = pressure exerted by the gas, $N\ m^{-2}$

ρ = gas density, $kg\ m^{-3}$

T = kelvin (absolute) temperature, K

TABLE 5-1

PRESSURE UNITS CONVERSION FACTORS

Given \ Desired	$N\ m^{-2}$	mb	in. Hg	mm Hg	lb-f $in.^{-2}$ (psi)	lb-f ft^{-2} (psf)	atm	dyne cm^{-2}
1 Newton per square meter =	1	10^{-2}	2.953×10^{-4}	7.501×10^{-3}	1.450×10^{-4}	2.089×10^{-2}	9.869×10^{-6}	10
1 Millibar =	10^{2}	1	2.953×10^{-2}	7.501×10^{-1}	1.450×10^{-2}	2.089	9.869×10^{-4}	10^{3}
1 Inch of mercury at 0°C =	3.387×10^{3}	3.387×10^{1}	1	2.54×10^{1}	4.913×10^{-1}	7.072×10^{1}	3.342×10^{-2}	3.387×10^{2}
1 Millimeter of mercury at 0°C =	1.333×10^{2}	1.333	3.937×10^{-2}	1	1.934×10^{-2}	2.784	1.316×10^{-3}	1.333×10^{2}
1 Pound (force) per square inch =	6.895×10^{3}	6.895×10^{1}	2.035	51.71	1	144	6.805×10^{-2}	6.895×10^{4}
1 Pound (force) per square foot =	4.788×10^{1}	4.788×10^{-1}	1.414×10^{-2}	3.591×10^{-1}	6.944×10^{-3}	1	4.725×10^{-4}	4.788×10^{2}
1 Atmosphere =	1.01325×10^{5}	1.01325×10^{3}	2.992×10^{1}	7.60×10^{3}	14.70×10^{1}	2.116×10^{3}	1	1.01325×10^{6}
1 Dyne per square centimeter =	10^{-1}	10^{-3}	2.953×10^{-5}	7.501×10^{-4}	1.450×10^{-5}	2.089×10^{-3}	9.869×10^{-7}	1

Multiply given units by appropriate factor to obtain desired units.

Definitions: 10^{-3} bar = 1 mb 10^{-1} cm Hg = 1 mm Hg

1 torr = 1 mm Hg   1 pascal = 1 $N\ m^{-2}$

R = universal gas constant, 8.31434 J mole^{-1} K^{-1}

M = molecular weight, kg mole^{-1}

For the first 90 km of altitude, the relative composition of the atmospheric gases (Table 5-2) remains constant except for a decrease of water vapor and an increase of ozone with altitude. (See Chap. 4, "Humidity", and Chap. 12, "Ozone", in this handbook for definitive discussion of these constituents.) Dalton's law of partial pressures states that the total pressure exerted by a mixture of gases in a given volume at a given temperature is the sum of the pressures exerted when each gas occupies the same volume at the same temperature. Therefore, for dry air (no water vapor content) the total atmospheric pressure P* is given by the equation of state

$$P = \rho R_d T \tag{5-2}$$

TABLE 5-2

COMPOSITION OF CLEAN, DRY AIR NEAR SEA LEVEL (Ref. 2)

Constituent gas and formula	Content, percent by volume	Content variable relative to its normal	Molecular weight*
Nitrogen (N_2)	78.084	-	28.0134
Oxygen (O_2)	20.9476	-	31.9988
Argon (Ar)	0.934	-	39.948
Carbon dioxide (CO_2)	0.0314	†	44.00995
Neon (Ne)	0.001818	-	20.183
Helium (He)	0.000524	-	4.0026
Krypton (Kr)	0.000114	-	83.80
Xenon (Xe)	0.0000087	-	131.30
Hydrogen (H_2)	0.00005	?	2.01594
Methane (CH_4)	0.0002	†	16.04303
Nitrous oxide (N_2O)	0.00005	-	44.0128
Ozone (O_3)	Summer: 0 to 0.000007 Winter: 0 to 0.000002	† †	47.9982 47.9982
Sulfur dioxide (SO_2)	0 to 0.0001	†	64.0628
Nitrogen dioxide (NO_2)	0 to 0.000002	†	46.0055
Ammonia (NH_3)	0 to trace	†	17.03061
Carbon monoxide (CO)	0 to trace	†	28.01055
Iodine (I_2)	0 to 0.000001	†	253.8088

*On basis of carbon-12 isotope scale for which $C^{12} = 12$.
†The content of the gases marked with a dagger may undergo significant variations from time to time or from place to place relative to the normal indicated for those gases.

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*p indicates the pressure exerted by an individual gas.
P indicates the total pressure exerted by a mixture of gases.

where $R_d = R/28.9644 = 0.28705$ J g^{-1} K^{-1} is the "gas constant" per mole for dry air. In the presence of water vapor, the total pressure may be written (Ref. 5) as

$$P = \rho R_d T(1 + 0.61\, r) \qquad (5\text{-}3)$$

where

r = water vapor mixing ratio (grams of vapor per gram of dry air)

ρ = density of the mixture, g m^{-3}

In an equilibrium state (no net vertical accelerations), the rate of change of pressure with altitude z is given by the hydrostatic equation

$$\frac{dP}{dz} = -\rho g \qquad (5\text{-}4)$$

where g = acceleration due to gravity ($\approx$9.80 m s^{-2} at sea level)

The hydrostatic pressure at any altitude is obtained by integrating the hydrostatic equation, provided the pressure at one altitude and the density distribution between the altitudes is known. The temperature, rather than the density, is commonly measured in the atmosphere. Substitution of the equation of state into the hydrostatic equation eliminates the density from the equation, giving

$$\frac{dP}{P} = -\frac{g}{R_d T}\, dz \qquad (5\text{-}5)$$

If an average temperature T can be determined for the layer, the expression

$$\frac{P}{P_o} = \exp\left[-\frac{g}{RT}(z - z_o)\right] \qquad (5\text{-}6)$$

defines the relationship of pressure, altitude, and average temperature of the layer. From these equations, two facts are established:

(1) pressure decreases exponentially with increasing altitude, and

(2) pressure decreases faster with altitude when the average temperature is cold than when warm.

Dynamic pressure, caused by vertical acceleration of the air, never exceeds 1 percent of the ambient hydrostatic pressure even in severe thunderstorms (Ref. 6) and for this discussion is inconsequential. Pressure forces resulting from horizontal winds are discussed in Chap. 10, "Wind", of this handbook.

5-2.1 STANDARD ATMOSPHERE

As noted, the distribution of pressure with altitude depends upon distribution of temperature with altitude above the measuring point. To define the "normal" structure of the atmosphere, numerous "standard atmospheres" have been proposed. The two principal ones currently in use, the ICAO Standard Atmosphere (Ref. 7) and the U S Standard Atmosphere, 1962 (Ref. 2), are in substantial agreement below 16 km. The standard sea-level pressure and temperatures are 1,013.25 mb (29.92 in. Hg) and 15°C (59.0°F), respectively. The standard temperature decreases at a constant rate of 6.5 deg C/km ($\approx$3.5 deg F/1,000 ft) from sea level up to 11 km ($\approx$36,000 ft) and then remains at a constant temperature of −56.5°C (−69.6°F) up to 20 km ($\approx$66,000 ft). These standards are the basis for transposing pressure measurements to altitude when using altimeters or when simulating high altitude conditions in the laboratory. The dependence of pressure upon altitude in the U S Standard Atmosphere, 1962, is shown in Fig. 5-1.

The standard atmosphere represents an approximation to the average annual distribution of pressure about the world. Since the temperatures at various altitudes and the average sea-level pressure vary with latitude and season, supplementary standard atmospheres or reference atmospheres have been developed (Ref. 8) to describe these situations. Properties of these atmospheres up to 16 km are presented in Table 5-3. The distributions of pressure at various altitudes in the warmest and coldest of these reference

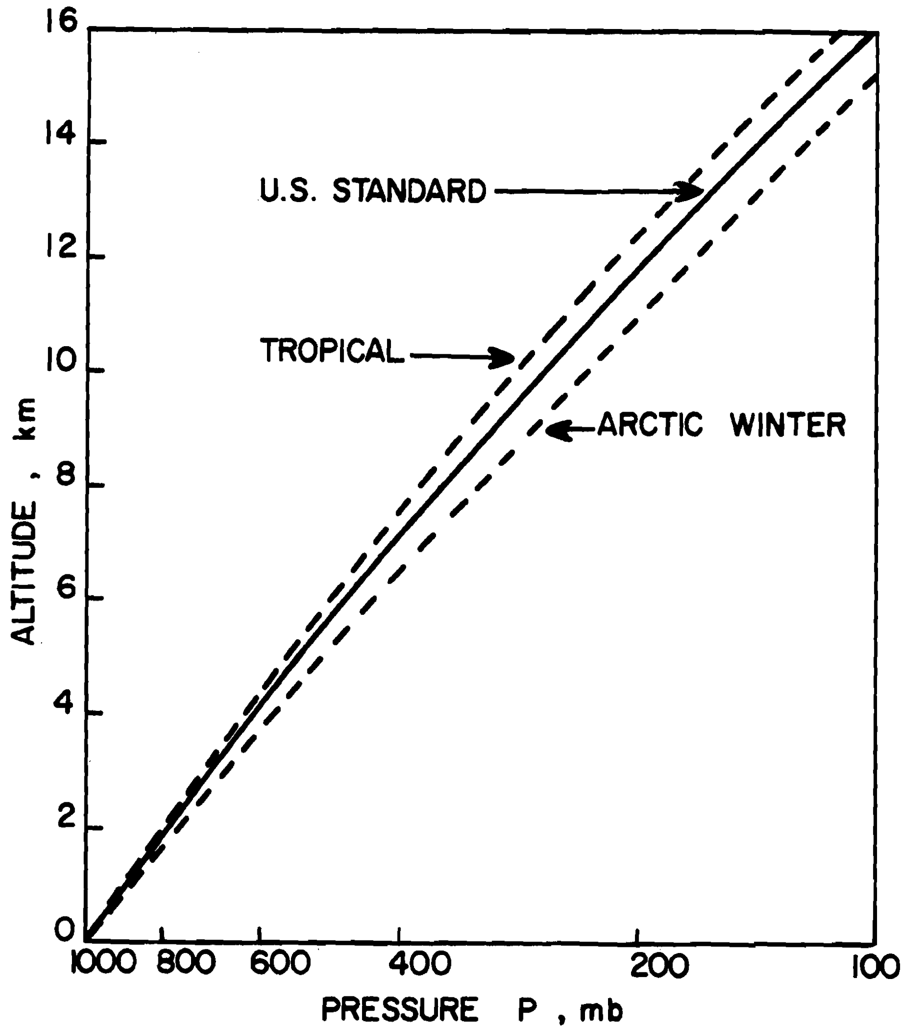


Figure 5-1. Pressure at/vs Altitude in the U.S. Standard Atmosphere and Extreme Supplementary Atmospheres

atmospheres are also shown in Fig. 5-1.

If the average temperature of an air column between two altitudes is warmer than standard, the pressure difference will be less than standard. Conversely, if the air column is colder than standard, the pressure difference will be greater than standard. Thus, the pressure will be higher than standard with a colder-than-standard column of air, and lower with a warmer-than-standard column of air. However, the pressure differentials at sea level are normally less than 5 percent of the standard value.

5-2.2 PRESSURE REPORTS

In conjunction with civil and military aircraft operations, several terms relating to pressure are used. All pressure terms are defined in terms of the station elevation, which is normally 10 ft greater than the maximum height of the runway above mean sea level (Ref. 9). Standard terminology includes the following four terms (Ref. 9):

(1) *Station pressure.* "The atmospheric pressure at the assigned station elevation."

TABLE 5-3

PROPERTIES OF SUPPLEMENTAL REFERENCE ATMOSPHERES TO 16 km (Ref. 11)

Geom alt, km	Temp, K	Pressure, mb	Density, kg m^{-3}
(A) Tropical, 15 deg N.			
0	299.65	1,013.25	1.1666
1	293.66	904.13	1.0644
2	287.68	804.79	0.9689
3	283.65	714.75	0.8757
4	276.98	633.21	0.7951
5	270.31	559.27	0.7199
6	263.63	492.40	0.6501
7	256.96	432.10	0.5855
8	250.29	377.92	0.5258
9	243.63	329.33	0.4708
10	236.96	285.89	0.4203
11	230.30	247.21	0.3739
12	223.64	212.86	0.3316
13	216.98	182.45	0.2929
14	201.32	155.64	0.2578
15	203.67	132.11	0.2260
16	197.02	111.55	0.1972
(B) Subtropical, 30 deg N., January			
0	287.15	1,021.00	1.2328
1	284.16	906.59	1.1072
2	281.15	803.78	0.9934
3	274.70	711.25	0.9006
4	268.20	627.39	0.8142
5	261.72	551.76	0.7340
6	255.24	483.67	0.6599
7	248.76	422.54	0.5916
8	242.29	367.86	0.5288
9	235.81	319.06	0.4713
10	229.34	275.63	0.4187
11	222.87	237.16	0.3707
12	216.40	203.15	0.3270
13	213.66	173.44	0.2828
14	211.08	147.81	0.2439
15	208.50	125.18	0.2101
16	205.91	106.71	0.1805

TABLE 5-3 (Continued)

PROPERTIES OF SUPPLEMENTAL REFERENCE ATMOSPHERES TO 16 km (Ref. 11)

Geom alt, km	Temp, K	Pressure, mb	Density, kg m^{-3}
(C) Subtropical, 30 deg N., July			
0	301.15	1,013.50	1.1592
1	293.67	904.64	1.0661
2	288.17	805.04	0.9686
3	282.68	714.84	0.8776
4	277.19	633.11	0.7937
5	271.71	559.36	0.7159
6	266.23	492.92	0.6443
7	259.27	433.04	0.5814
8	252.30	379.13	0.5232
9	245.33	330.68	0.4694
10	238.35	287.29	0.4198
11	231.39	248.58	0.3742
12	224.42	214.14	0.3324
13	217.46	183.59	0.2941
14	210.50	156.65	0.2592
15	203.54	132.95	0.2275
16	203.15	112.48	0.1929
(D) Midlatitude, 45 deg N., January			
0	272.15	1,018.00	1.3010
1	268.65	897.34	1.1621
2	265.15	789.75	1.0365
3	261.65	693.76	0.9230
4	255.67	608.13	0.8282
5	249.67	531.32	0.7411
6	243.69	462.75	0.6614
7	237.70	401.64	0.5886
8	231.71	347.33	0.5222
9	225.73	299.28	0.4619
10	219.75	256.84	0.4072
11	219.16	219.91	0.3496
12	218.66	188.25	0.2999
13	218.16	161.09	0.2572
14	217.67	137.80	0.2206
15	217.17	117.84	0.1890
16	216.67	100.75	0.1620

TABLE 5-3 (Continued)

PROPERTIES OF SUPPLEMENTAL REFERENCE ATMOSPHERES TO 16 km (Ref. 11)

Geom alt, km	Temp, K	Pressure, mb	Density, kg m^{-3}
(E) Midlatitude, 45 deg N., July			
0	294.15	1,013.50	1.1919
1	289.65	902.20	1.0795
2	285.15	801.59	0.9757
3	279.16	710.43	0.8846
4	273.17	628.06	0.7998
5	267.17	553.62	0.7211
6	261.18	486.63	0.6487
7	254.70	426.40	0.5830
8	248.22	372.35	0.5225
9	241.73	324.02	0.4669
10	235.25	280.90	0.4159
11	228.77	242.55	0.3693
12	222.30	208.58	0.3269
13	215.83	178.57	0.2882
14	215.65	152.51	0.2464
15	215.65	130.25	0.2104
16	215.65	111.25	0.1797
(F) Subarctic, 60 deg N., January			
0	257.15	1,013.50	1.3723
1	259.15	887.82	1.1928
2	255.94	777.48	1.0577
3	252.74	679.81	0.9366
4	247.74	593.23	0.8339
5	240.94	515.83	0.7457
6	234.14	416.74	0.6646
7	227.34	385.31	0.5904
8	220.55	330.85	0.5226
9	217.15	282.90	0.4538
10	217.15	241.79	0.3879
11	217.15	206.66	0.3315
12	217.15	176.63	0.2834
13	217.15	150.99	0.2422
14	217.15	129.07	0.2070
15	217.15	110.33	0.1770
16	216.56	94.31	0.1517

TABLE 5-3 (Continued)

PROPERTIES OF SUPPLEMENTAL REFERENCE ATMOSPHERES TO 16 km (Ref. 11)

Geom alt, km	Temp, K	Pressure, mb	Density, kg m^{-3}
(G) Subarctic, 60 deg N., July			
0	287.15	1,010.00	1.2198
1	281.75	896.01	1.1042
2	276.34	792.94	0.9971
3	270.94	700.07	0.8984
4	265.54	616.43	0.8077
5	260.14	541.40	0.7244
6	253.14	473.96	0.6519
7	246.14	413.42	0.5849
8	239.16	359.18	0.5231
9	232.16	310.76	0.4663
10	225.17	267.71	0.4142
11	225.15	230.03	0.3559
12	225.15	197.71	0.3059
13	225.15	169.95	0.2630
14	225.15	146.09	0.2260
15	225.15	125.58	0.1943
16	225.15	107.97	0.1671
(H) Subarctic, 60 deg N., Winter Cold			
0	257.15	1,013.50	1.3723
1	259.15	887.82	1.1928
2	255.94	777.48	1.0577
3	252.74	679.81	0.9366
4	247.74	593.23	0.8339
5	240.94	515.83	0.7457
6	234.14	446.74	0.6646
7	227.34	385.31	0.5904
8	220.55	330.85	0.5526
9	217.15	282.90	0.4538
10	217.15	241.79	0.3879
11	217.15	206.66	0.3315
12	217.15	176.63	0.2834
13	216.16	150.94	0.2433
14	215.16	128.84	0.2087
15	214.17	109.97	0.1789
16	213.17	93.78	0.1533

TABLE 5-3 (Continued)

PROPERTIES OF SUPPLEMENTAL REFERENCE ATMOSPHERES TO 16 km (Ref. 11)

Geom alt, km	Temp, K	Pressure, mb	Density, kg m^{-3}
(I) Subarctic, 60 deg N., Winter Warm			
0	257.15	1,013.50	1.3723
1	259.15	887.82	1.1928
2	255.94	777.48	1.0577
3	252.74	679.81	0.9366
4	247.74	593.23	0.8339
5	240.94	515.83	0.7457
6	234.14	446.74	0.6646
7	227.34	385.31	0.5904
8	220.55	330.85	0.5226
9	218.15	282.95	0.4519
10	220.14	242.18	0.3832
11	222.14	207.58	0.3255
12	224.14	178.17	0.2769
13	224.15	153.05	0.2379
14	224.15	131.47	0.2043
15	224.15	112.94	0.1755
16	224.15	97.03	0.1508
(J) Arctic, 75 deg N., January			
0	249.15	1,013.50	1.4167
1	252.16	884.16	1.2221
2	250.88	772.13	1.0719
3	245.37	672.74	0.9549
4	239.87	584.31	0.8485
5	234.36	505.83	0.7518
6	228.86	486.40	0.6643
7	223.36	375.20	0.5852
8	217.86	321.37	0.5139
9	214.90	274.35	0.4447
10	214.40	233.98	0.3802
11	213.90	199.51	0.3249
12	213.25	170.08	0.2778
13	212.45	144.90	0.2376
14	211.65	123.38	0.2031
15	210.85	104.99	0.1735
16	210.05	89.29	0.1481

TABLE 5-3 (Continued)

PROPERTIES OF SUPPLEMENTAL REFERENCE ATMOSPHERES TO 16 km (Ref. 11)

Geom alt, km	Temp, K	Pressure, mb	Density, kg m^{-3}
(K) Arctic, 75 deg N., July			
0	278.15	1,012.50	1.2646
1	275.55	895.02	1.1290
2	272.94	790.20	1.0067
3	268.37	696.71	0.9030
4	261.86	612.49	0.8141
5	255.35	536.67	0.7317
6	248.85	468.62	0.6558
7	242.35	407.78	0.5860
8	235.85	353.49	0.5221
9	229.35	305.25	0.4636
10	226.66	262.61	0.4036
11	227.66	225.98	0.3458
12	228.65	194.61	0.2965
13	229.65	167.70	0.2544
14	230.15	124.69	0.1887
15	230.15	107.52	0.1628
16	230.15	92.73	0.1436

(L) Arctic, 75 deg N., Winter Cold			
0	249.15	1,013.50	1.4167
1	252.15	884.16	1.2211
2	250.88	772.13	1.0719
3	245.37	672.74	0.9549
4	239.87	584.31	0.8485
5	234.36	505.83	0.7518
6	228.86	436.40	0.6643
7	223.36	375.20	0.5852
8	217.86	321.37	0.5139
9	214.39	274.33	0.4458
10	212.89	233.79	0.3826
11	211.39	199.04	0.3280
12	209.89	162.30	0.2810
13	208.40	143.83	0.2404
14	206.90	122.05	0.2055
15	205.40	103.45	0.1754
16	203.95	88.01	0.1503

TABLE 5-3 (Continued)

PROPERTIES OF SUPPLEMENTAL REFERENCE ATMOSPHERES TO 16 km (Ref. 11)

Geom alt, km	Temp, K	Pressure, mb	Density, kg m^{-3}
(M) Arctic, 75 deg N., Winter Warm			
0	249.15	1,013.50	1.4167
1	252.15	884.16	1.2211
2	250.88	772.13	1.0719
3	245.37	672.74	0.9549
4	239.87	584.31	0.8485
5	234.36	505.83	0.7518
6	228.86	436.40	0.6643
7	223.36	375.20	0.5852
8	217.86	321.37	0.5140
9	216.57	274.44	0.4415
10	219.37	234.62	0.3726
11	222.15	201.02	0.3152
12	222.15	172.42	0.2704
13	222.15	147.89	0.2319
14	222.15	126.84	0.1989
15	222.15	108.80	0.1706
16	222.15	93.75	0.1470

(2) *Sea-level pressure.* "A pressure value obtained by the theoretical reduction of station pressure to sea level. Where the surface of the earth is above sea level, it is assumed that the atmosphere extends to sea level below the station and that the properties of the hypothetical atmosphere are related to conditions observed at the station." The method of computation is given in Ref. 10.

(3) *Altimeter setting.* This is "that pressure value to which an aircraft altimeter scale is set so that it will indicate the altitude above mean sea level of an aircraft on the ground at the location for which the value was determined." This is also the pressure that would be experienced at sea level if a column of air from the station elevation to sea level increased in temperature at a rate of 6.5 deg C km^{-1}

(4) *Pressure altitude.* This is "the altitude, in the standard atmosphere, at which a given pressure will be observed. It is the indicated altitude of a pressure altimeter at an altimeter setting of 29.92 in. Hg and is therefore the indicated altitude above the 29.92 constant-pressure surface."

5-2.3 PRESSURE DISTRIBUTION

The distribution of pressure at sea level and at altitude is important to the diagnosis and prediction of weather. Current practice is to display the sea-level pressure distribution by constructing smooth isolines of constant pressure, called isobars, at regular increments (4 mb) of pressure. The distribution of pressure aloft is shown by the altitude of selected pressure surfaces–850, 700, 500, 300, 200, and 100 mb–at intervals of 60 m (≈200 ft).

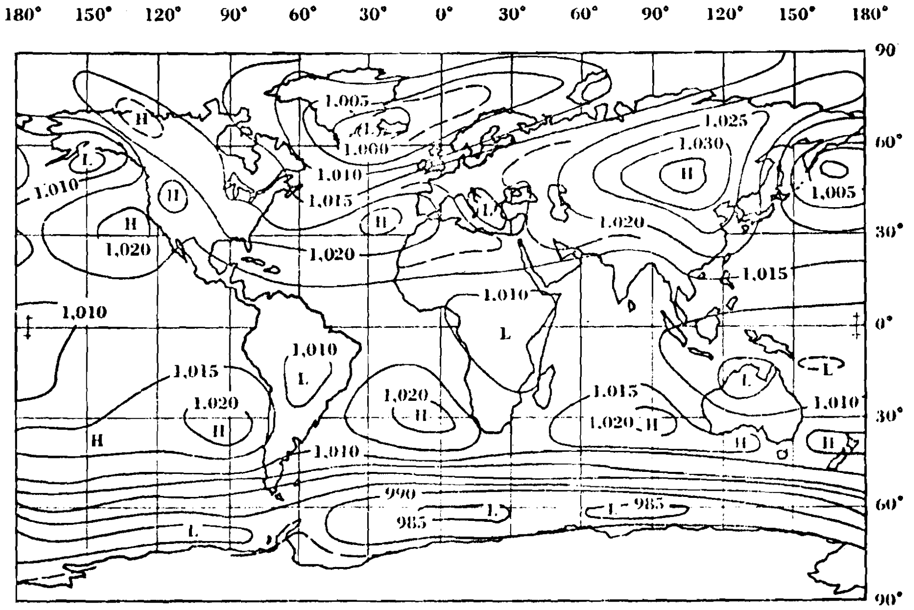


Figure 5-2. Annual Average Sea-level Pressure in Millibars

At sea level the isobars appear to form cells of high and low pressure. Fronts—lines delineating air masses of differing temperature and/or humidity characteristics—lie in the troughs of low pressure separating high pressure cells.

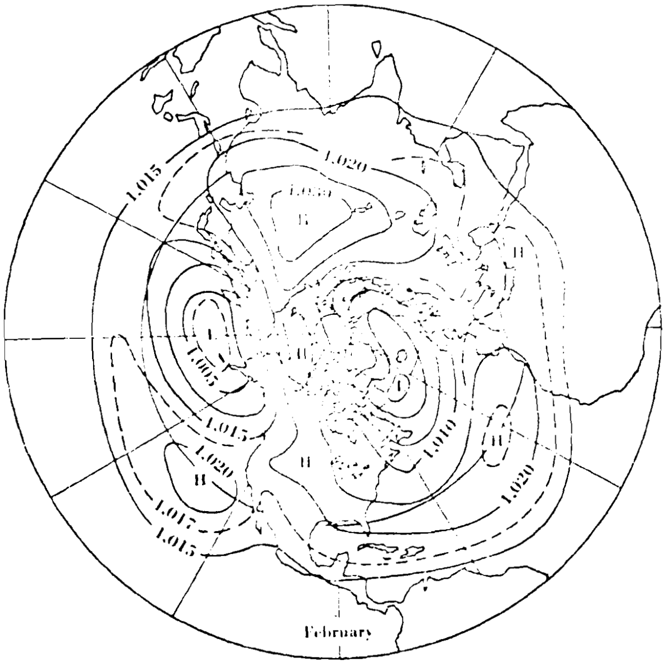
Aloft, the pressure height patterns generally lose their cellular nature and appear as successive troughs (low pressure heights) and ridges (high pressure heights) of a wave-like pattern about the earth. The axes of the troughs and ridges slope upward toward cold and warm air, respectively, and away from their direction of propagation.

5-2.3.1 SEA-LEVEL PRESSURE

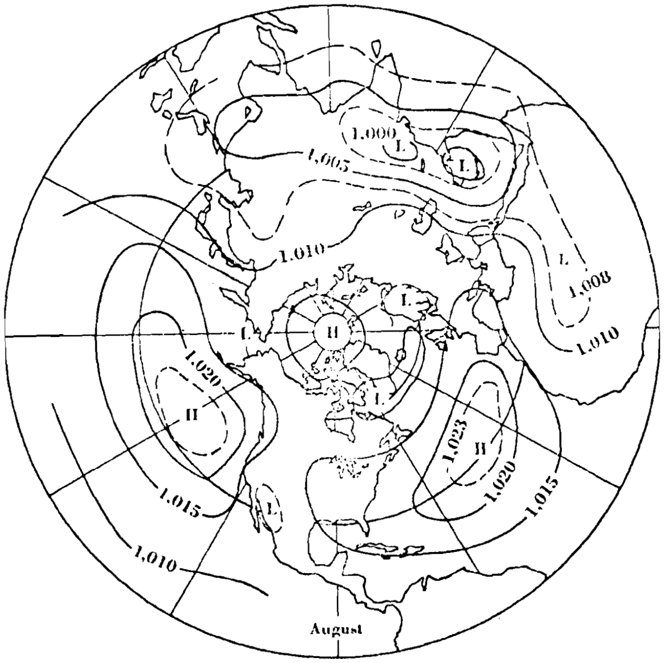
The distribution of pressure at sea level is largely dependent upon the latitude, the season, and the geography of the measuring location. Solar activity and solar and lunar tidal action produce secondary effects on differing time scales. Pressure changes are caused by the redistribution of air masses by high altitude winds and, to a lesser extent, by the heating and cooling of air near the surface of the earth.

The annual average distribution of pressure at sea level is shown in Fig. 5-2. The general trend is for lower pressures to occur near the Equator (the doldrums), higher pressures near 30 deg latitude (the subtropical high), lower pressures near 60 deg latitude, and higher pressures near the poles of each hemisphere. Because the larger landmasses of the Northern Hemisphere distort the pattern, it is more evident in the Southern Hemisphere. Over ocean areas, the highs are higher and lows are lower, on the average. Over continental areas, the pressure systems, although sometimes quite intense, are more variable on a daily and seasonal basis. Outside the tropics, the greatest fluctuation in pressure from its average occurs in the middle latitudes (30 to 60 deg) in the Northern Hemisphere, e.g., over continental areas.

Seasonal changes distort the annual pressure distribution (Fig. 5-3). In the summer hemisphere (Fig. 5-3(B)), the pressure gradients are weaker (isobars are farther apart) and the pressure belts are displaced poleward by approximately 5 deg of latitude. The intensity of the moving pressure systems is less and daily changes are smaller. The continental regions are warm as compared to oceanic regions. In continental regions of very dry air, low pressure centers called thermal lows are



(A) In February



(B) In August

Figure 5-3. Mean Sea-level Pressures in February and August, in Millibars

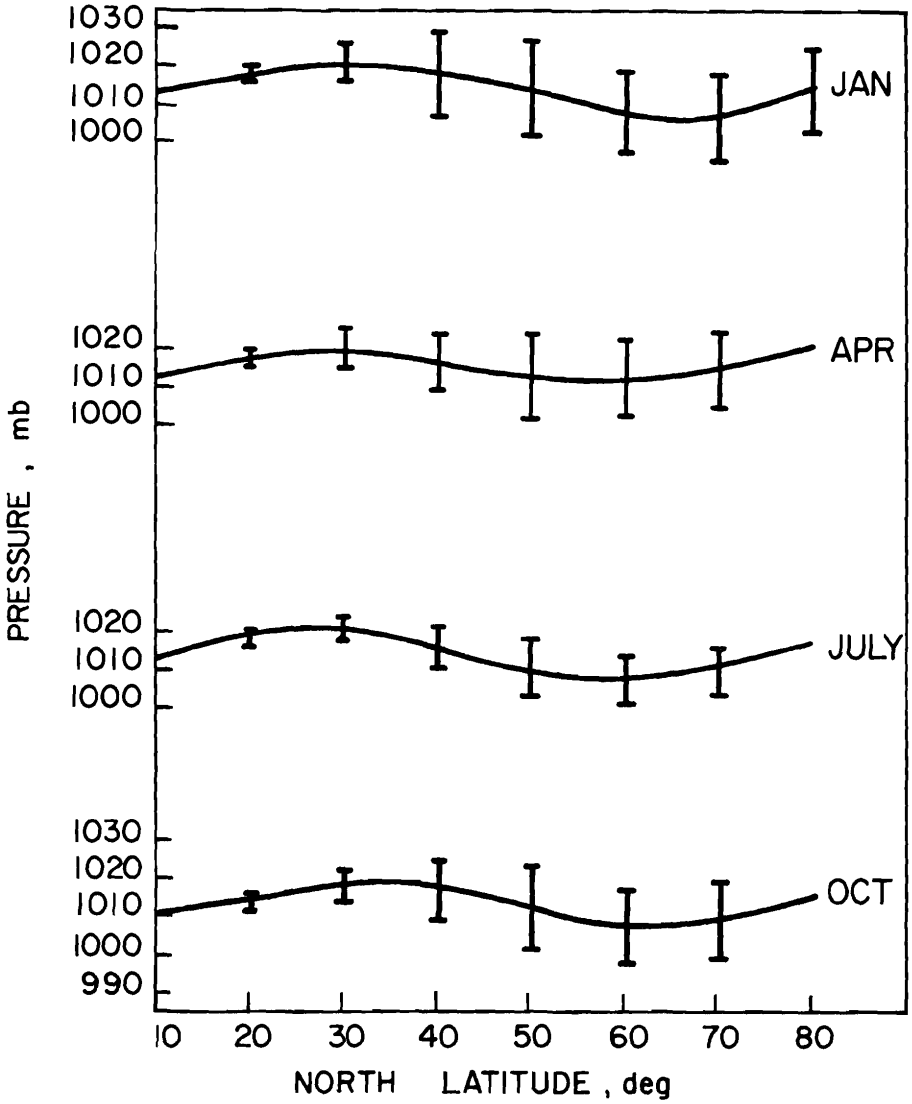


Figure 5-4. Mean Monthly Sea-level Pressure and Standard Deviation of Daily Pressure Values, Long. 70 deg W. to 65 deg W. (Ref. 11)

observed near the surface because solar heat effectively warms the air to a depth of several thousand feet. This thermal effect, apparent through the desert areas of the world, is strong enough to dominate the effects of latitudinal changes at the surface, but seldom extends above 3 km.

In the winter hemisphere (Fig. 5-3-(A)), the pressure gradients are greater, the pressure belts are displaced equatorward from their average positions, the contrast of airmasses is greater, and pressure systems move faster giving greater daily ranges of pressure (Fig. 5-4). In the northernmost continental regions, the dry air near the ground becomes quite cold, creating large high pressure areas over Siberia and northern Canada. Because of the greater landmasses in the Northern Hemisphere, these pressure systems are more pronounced than in the Southern Hemisphere. Intense low pressure centers develop when surface low pressure systems with cold air aloft move offshore over warm ocean water, and they tend to follow the warm Gulf Stream and Kuroshio currents northeastward. This persistent pattern of low pressure centers perpetuates the intense Icelandic and Aleutian low centers of the northern oceans.

In addition to the daily changes of pressure caused by moving pressure systems, a semidiurnal oscillation of the atmosphere is induced by solar and lunar tidal forces (Ref. 4). The amplitude of the oscillation is about 3 mb at sea level at the Equator and decreases with increasing latitude. The maxima occur near 1000 and 2200 hr local time, and the minima near 0400 and 1600 hr.

5-2.3.2 PRESSURE DISTRIBUTION WITH ALTITUDE AND LATITUDE

Above 3 km, the cellular pattern of pressure gives way to a series of troughs and ridges superimposed upon a general Equator-to-pole slope of the pressure surface. In the mean, the magnitude of the slope of a pressure surface is almost negligible in the tropical latitudes, increases through the midlatitudes, and decreases toward the poles.

At any altitude, the range of measured altitude about the standard value is small, but increases as the pressure decreases. Fig. 5-5 shows the latitudinal dependence of the altitude of selected pressure surfaces. As the pressure decreases, the latitudinal slope of the mean pressure surface increases in all latitudes until dT/dz becomes positive or only slightly negative. Since the wind velocity is approximately proportional to the pressure gradient (e.g., the slope of the pressure surface), windspeeds increase with height to the tropopause (See Chap. 10, "Wind", for more details). The height of the tropopause decreases from near 16 km in the tropics to 8 km in polar regions (Ref. 8). Above the tropopause, the slope of the pressure surface with latitude decreases less rapidly and windspeeds decrease.

As at the surface, the pressure gradients at all altitudes are reduced in the summer but increase during the winter. Troughs and ridges generally propagate eastward but usually at a speed less than the windspeed. In the summer, there are normally three principal troughs about the hemisphere whereas wintertime situations have 4 to 5 principal troughs. The increased intensity and propagation speeds of the troughs combine to give faster moving, more frequent, and more severe weather systems.

5-2.3.3 PRESSURE EXTREMES

Extreme values of pressure reduced to sea level are listed for the world and North America in Table 5-4. The lowest reported pressures occur within the eye of tropical storms (called hurricanes in the Western Hemisphere, typhoons in the Eastern Hemisphere and tropical cyclones in the countries bordering the Indian Ocean) having windspeeds greater than 64 kt. It is estimated that a pressure reduction of 100 mb may occur within a tornado, but no measurements have confirmed that value (Ref. 13). Fig. 5-6 shows the barograph trace recorded as a tornado passed overhead. Other extremes of low pressure occurring with the wintertime systems in the Aleutian and Icelandic lows are listed in Table 5-5.

Exceptionally high sea-level pressures are found with the wintertime, continental high pressure system over Siberia, USSR, Alaska, and northern Canada. The extremes and 1 percent exceedance values are listed in Tables 5-4 and 5-5. Of the subtropical high pressure cells, the one in the Pacific Ocean attains higher pressures than its counterpart in the Atlantic.

Extremes of station pressure are principally due to the altitude of the station. High altitude stations, those 1.6 km above mean sea level (MSL), routinely record pressures lower than those encountered in typhoons or hurricanes. In the Dead Sea basin, 392 m (1,286 ft) below MSL, standard atmospheric pressure would be about 1,060 mb or comparable to the maximum sea-level pressure observed in North America.

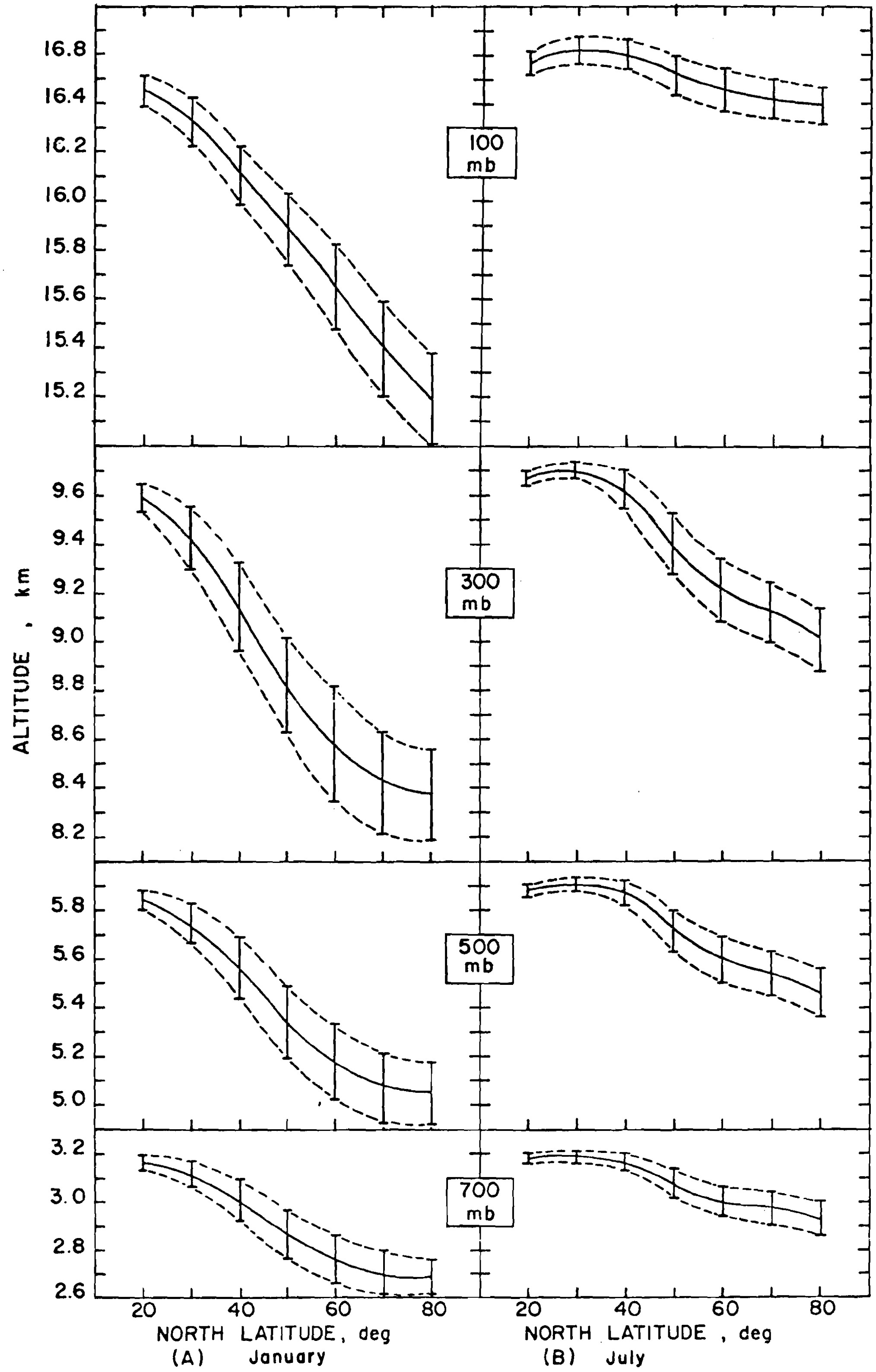


Figure 5-5. Mean Altitude and Standard Deviation of Daily Altitudes of Selected Pressure Surfaces in January and July (From data in Ref. 11)

TABLE 5-4

PRESSURE EXTREMES (Ref. 12)

	Pressure		Location
	mb	in. Hg	
HIGH			
World	1,083.8	32.005	Agata, Siberia, USSR
Canada	1,067.3	31.51	Medicine Hat, Alberta
United States	1,063.3	31.40	Helena, Mont.
Alaska	1,062.2	31.36	Bethel
LOW			
World	877	25.90	19 deg N., 135 deg E. (Estimated by aerial reconnaissance in eye of Typhoon Ida)
	886.6	26.18	S.S. Sapoerea, 460 mi east of Luzon, Philippine Republic
United States (hurricane)	892.3	26.35	Matecumbe Key, Fla.
United States (extratropical)	954.9	28.20	Canton, N.Y. Block Island, R.I.

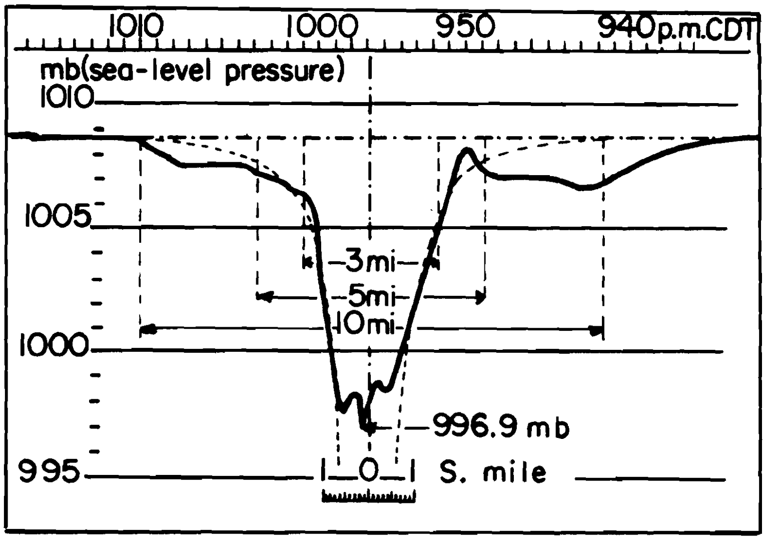


Figure 5-6. Barograph Trace During a Tornado Passage (Enlarged; Dashed Line Represents a Theoretical Pressure Trace Within a Tornado. Distances are in Statute Miles.) (Ref. 14)

5-3 MEASUREMENT AND INSTRUMENTATION*

The instruments most commonly used to measure pressure are the mercurial barometer and the aneroid barometer. Both use the weight of the air as the means of determining the pressure. The hypsometer, less frequently used, relies upon the change in boiling temperature of liquids with pressure changes.

5-3.1 MERCURIAL BAROMETERS

The mercurial barometer is based upon the Torricelli principle. In its simplest form, a glass tube closed at one end is filled with mercury and immersed in a cistern of mercu-

TABLE 5-5

SEA-LEVEL PRESSURES EXCEEDED 99 PERCENT AND 1 PERCENT OF THE TIME IN JANUARY (Ref. 12)

Location	Pressure, mb	Pressure, in. Hg
	Exceeded 99% of time	
Aleutian low	973	28.73
Icelandic low	955	28.20
	Exceeded 1% of time	
Siberian high	1,055	31.15
Pacific high	1,037	30.62
Canadian high	1,041	30.74

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*An in-depth discussion of this subject is found in *Meteorological Instruments* by W. E. K. Middleton and A. F. Spilhaus (Ref. 15), which is the primary source for this paragraph.

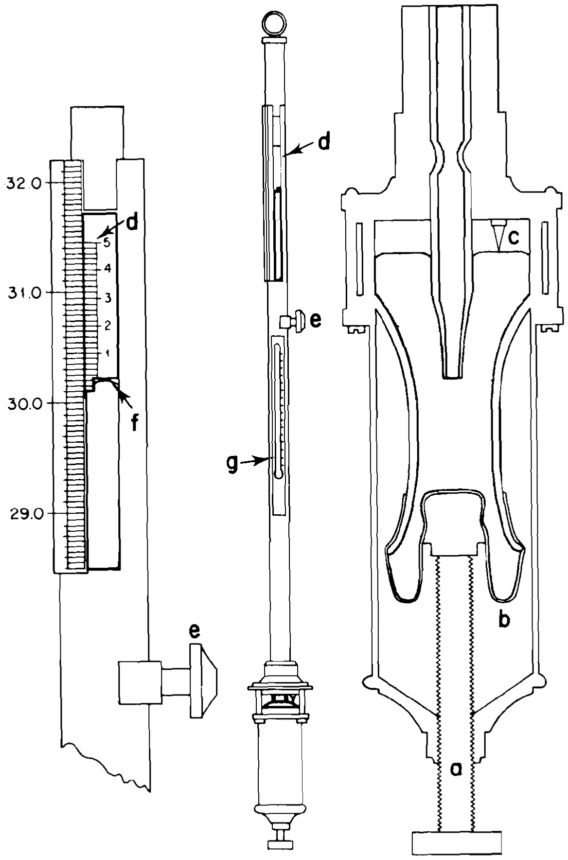

Figure 5-7. Schematic Drawing of a Fortin Mercurial Barometer: (center) the entire barometer, (right) the barometer cistern, and (left) the vernier scale. The level of the mercury in the cistern is adjusted by a screw (a) pressing on a leather bag (b) so that the top of the mercury meniscus just touches the index pointer (c). The sliding vernier (d) is adjusted by a thumbscrew (e) until the slide bottom is at the same level as the top of the mercury meniscus (f). The reading from a thermometer (g) is used to correct the height of the mercury column. (Ref. 16)

ry. The level of mercury in the tube decreases, creating a vacuum on the closed end, until the weight of the mercury column equals the weight of air in a column of equal cross-sectional area. (The area or depth of the mercury pool does not affect the height of the mercury column, nor does the area of the tube.) Knowing the density of mercury ρ, the acceleration due to gravity g, and the measured height of the mercury column h one can then compute the atmospheric pressure P.

$$P = \rho g h \tag{5-7}$$

However, ρ is dependent upon the temperature and g changes with elevation and position on the earth. Therefore, g and ρ must be corrected to standard values (lat 45 deg N. and sea level for g; density at 0°C for ρ) in order to determine the pressure. Frequently, instead of reporting pressure in force per area units, the corrected height of the mercury column is reported.

The most common type of mercurial barometer (the Fortin-type) has a variable volume cistern which is adjusted so that the reservoir of mercury is raised or lowered until its surface is just in contact with an ivory point. The height of the mercury column is read on the attached vernier scale (Fig. 5-7).

The Kew-type mercurial barometer is less common and has a fixed volume of mercury. An increase (decrease) of pressure causes the height of the column to rise (fall), and the level of the mercury in the cistern to fall (rise) slightly. Thus, a unit change of pressure brings about less-than-a-unit change of the height of the mercury column. The scale markings are precorrected for this change.

The Fortin-type barometer is the more portable of the two types, but requires two readings (the ivory point and the scale), whereas the Kew, though less portable, requires only one reading (scale). The Fortin type is usually used to calibrate installed barometers of either type, because of its portability. Either type gives an accurate measurement, but both must be plumb when in use.

Other types of mercurial barometers are available but are not common.

5-3.2 ANEROID BAROMETERS

The aneroid, or elastic, barometer uses the deformation of the surface of a thin, evacuated, metallic diaphragm to measure atmospheric pressure. A strong spring, inside or outside the diaphragm, prevents the excess pressure from crushing the chamber. An arm attached to the diaphragm or to the spring moves in response to changes in pressure and may be used as a pointer or as a lever to move a pointer across a dial to indicate the pressure. Precision aneroids have multiple diaphragms to amplify the motions. A pen arm may be substituted for a pointer to provide a continuous record on a strip chart. Such a device is called a barograph. Very sensitive barographs are called microbarographs.

All aneroid barometers sense pressure changes rather than absolute pressure and, using a mercurial barometer, must be calibrated initially and periodically thereafter to insure accuracy. As the aneroid barometers are independent of a fluid, they are lightweight and highly portable. They do respond slightly to temperature changes because of the expansion and contraction of the construction material.

Altimeters, either aircraft-type or handheld, are aneroid barometers calibrated to indicate altitude instead of pressure and are based upon the decrease of pressure with an increase in altitude in a reference atmosphere.

5-3.3 HYPSOMETER

A hypsometer is a device for measuring pressure by calculating the boiling point of a liquid. A liquid begins to boil at the temperature at which the equilibrium vapor pressure of gas phase equals the external pressure upon the liquid. For most gases, especially water vapor, the equilibrium vapor pressure depends only upon the temperature. Therefore, by using measurements of the boiling temperature and proper tables, one can determine atmospheric pressure. The accuracy of the hypsometer increases with increasing altitude. Fig. 5-8 shows the equilibrium vapor pressure of pure water as a function of the boiling temperature. The boiling point of water decreases about 1.0 deg C (1.8 deg F) for each 300 m (1,000 ft) increase of elevation.

5-3.4 MANOMETER

A manometer measures pressure differences by balancing the weight of a liquid in a tube against the pressures at either end of the tube. A mercurial barometer is one kind of manometer. A more common manometer consists of a U-shaped tube, partially filled with a liquid (water), with one end open to the air and the other end connected to the point of measurement. The pressure differential is indicated by the difference of heights of the liquid in the U-tube and is computed by the hydrostatic equation.

5-3.5 STRAIN GAGE

A strain gage barometer operates on the same principle as the aneroid barometer; however, an electrical conductor is attached to the diaphragm. The changes of stress on the conductor cause a change in its resistance. Hence, the pressure changes produce a proportional voltage change.

5-4 EFFECTS ON MATERIEL

Many tests of materiel have reported effects on performance due to reduced air pressure. Often the reduction of pressure is to simulate conditions at different altitudes and the physical cause of the effect lies with another induced property of the atmosphere, e.g., a reduced density or a greater mean free path of the atmospheric molecules. However, the cause and the simulated or observed pressure are intimately connected, so the effects are repeated here as a "pressure effect" with a notation of the physical causes.

5-4.1 SINGLE ENVIRONMENTAL FACTOR

5-4.1.1 COMBUSTION

As atmospheric pressure decreases with altitude, there is a proportional decrease of the partial pressure due to oxygen and conse-

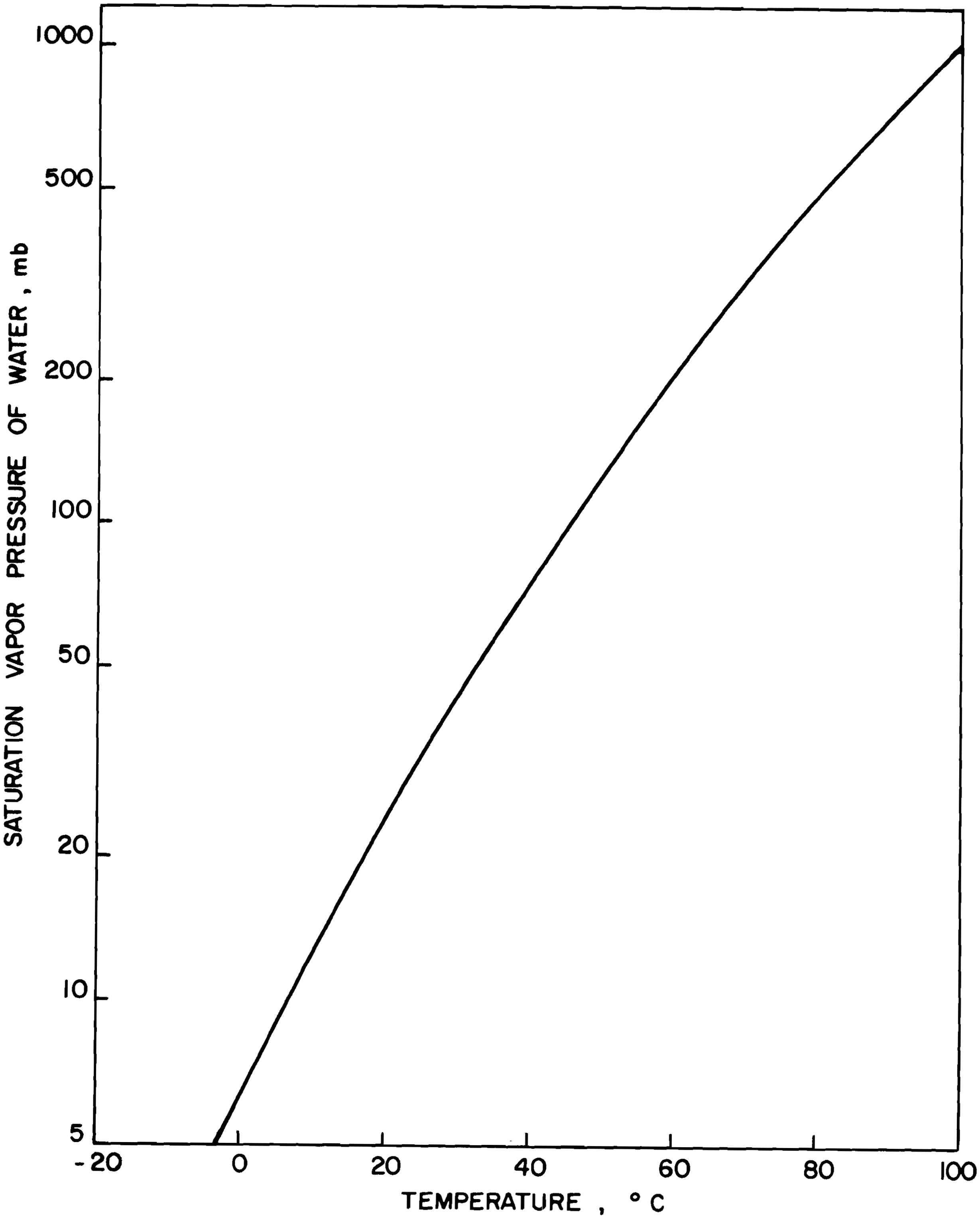

Figure 5-8. Equilibrium (Saturation) Water Vapor Pressure as a Function of Temperature (Ref. 10)

TABLE 5-6

ILLUMINATION CHARACTERISTICS OF YELLOW FLARES (Ref. 17)

Simulated altitude,* ft	Temperature, °F	Lot Y-1			Lot Y-2		
		Relative luminous intensity	Burning time, s	Yellow color value	Relative luminous intensity	Burning time, s	Yellow color value
0	70	1.000	19.0	0.038	2.325	9.8	0.052
10,000	70	0.735	21.0	0.047	2.120	11.0	0.062
20,000	70	0.360	24.0	0.058	1.706	9.5	0.062
40,000	70	0.125	49.0	0.064	1.031	12.0	0.072
0	-65	0.835	16.5	0.055	1.462	9.5	0.074

*Pressure reduced to simulate conditions at altitudes shown quently a decrease of the oxygen density. Materiel that is dependent upon combustion is affected since less oxygen is available. Vehicles, pyrotechnics, portable generators, etc., work at reduced efficiency and capability. Furthermore, ignition becomes more difficult and the characteristics of fires are affected.

Resnick (Ref. 17) reports (see Table 5-6) that flares are more difficult to ignite, and burn for a longer time with reduced illumination as the pressure is reduced to simulate high altitudes. However, the color values increase. The dimensions of the flame depend upon the composition of the flare, rather than the pressure.

TABLE 5-7

TYPICAL DRAWBAR PULL AND DRAWBAR HORSEPOWER LOSSES AT DIFFERENTIAL ALTITUDES (CONDENSED FROM Ref. 18)

Vehicle	Speed mi hr^{-1}	Yuma, 100 m		Percent loss	
		Drawbar pull, lb	Drawbar horsepower	Ft. Carson 1,720 m	Camp Hale 2,781 m
T113E1 Personnel Carrier	3.1	10,000	84	30	45
	6.0	7,750	124	30	42
	11.6	3,700	111	43	48
XM476 Carrier	4.7	5,100	64	20	33
	6.9	4,400	81	23	39
	11.0	2,600	76	33	45
M29C Cargo Carrier	3.9	3,600	37	-	28
	5.1	2,950	39	-	33
	9.2	1,500	37	-	39

TABLE 5-8

POWER LOSS DUE TO ALTITUDE (NO DERATING) (Ref. 19)

	Percent change in going from 500 to 12,000 ft		
	DF-2*	CIE*	
	2,800 rpm	2,800 rpm	1,500 rpm
Ambient air density	-35	-35	-35
Power	- 7	- 9	-69
Turbo speed	+26	+17	-46
Manifold absolute pressure	-24	-25	-49

*DF-2 and CIE are fuels.

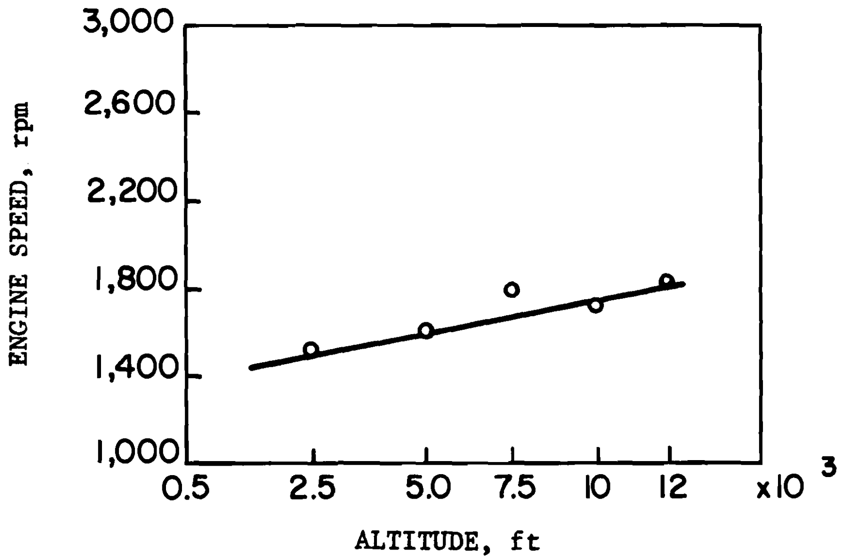

Figure 5-9. Critical Engine Speed for Turbocharger Operation (At speeds under the line with full-load operation, the turbocharger will not function to its full capacity with full-load capacity) (Ref. 19)

As the air pressure is reduced, air-fuel mixtures become enriched for the same amount of fuel ingested into the air. In some instances, the possibility of creating an explosive atmosphere is enhanced. For internal combustion engines, the greater fuel-air ratio may inhibit ignition, reduce acceleration, and/or cause increased fuel consumption unless carburetion and timing adjustments are made.

Performance tests made on cargo carriers at Yuma, Ariz., at an elevation of 100 m, and at Ft. Carson and Camp Hale, Colo., at elevations of 1,720 and 2,781 m, respectively, indicate the extent of power losses due to increased altitude (Ref. 18). The loss in drawbar pull and drawbar horsepower with an increase in altitude, as shown in Table 5-7, occurred for all, but varied for different vehicles tested. The drawbar pull of a vehicle (the net positive force developed by the vehicle) and drawbar horsepower (a measure of the ability of a vehicle to climb slopes) are lost as available oxygen is reduced. One of the vehicles that successfully climbed a 60-percent slope at Yuma stalled on a 42-precent slope at Camp Hale. Tests were made for fuel consumption, acceleration rates, and maximum road speeds at the three elevations and all decreased with altitude.

Similar power losses and excessive smoke occurred in tests of diesel engines using different fuels at altitudes of up to 4,000 m (see Table 5-8) (Ref. 19). Turbochargers force air into the engine, creating a higher pressure (move available oxygen); below a critical engine speed, which increases with altitude, they were unable to function at full capacity (Fig. 5-9). Differences in the efficiency of the motor fuels were found since the efficiency varies with combustion rates. Generally, the liquid fuel blends that produce optimal engine performance at sea level are not those that are most effective at higher altitudes where fuels with less octane units do better.

The combustion characteristics of various materials and vapor mixtures have been extensively studied in connection with fire and explosion prevention. As pressure decreases, the energy required for ignition increases (Ref. 20), as does the minimum ignition temperature (Table 5-9). Decreased pressure also affects explosion pressures, which increase up to approximately 20,000 ft, then decrease above that level. Ignition delay—the

TABLE 5-9

COMPARISON OF IGNITION TEMPERATURES OF AIRCRAFT FLUIDS (Ref. 20)

Chamber condition	Ignition temperature, °F						
	A	B	C	Fluid* D	E	F	G
850-ft alt	910	970	-	895	-	-	-
5,000-ft alt	950	1,010	1,015	935	965	1,095	990
10,000-ft alt	1,010	1,065	1,025	985	975	1,115	1,050
15,000-ft alt	1,100	1,100	1,045	1,040	1,000	1,130	1,090
20,000-ft alt	1,200	1,120	1,090	1,090	1,025	1,145	1,125
25,000-ft alt	-	-	-	1,140	1,045	-	1,145
10 in. O_2	1,060	820	725	575	940	935	505
8 in. O_2	-	920	955	790	980	975	560
6 in. O_2	-	1,010	1,090	980	1,005	1,040	675
4 in. O_2	-	1,080	1,185	1,125	1,030	1,135	1,020

*A	Hydraulic fluid, petroleum base, MIL-C-5606
B	Aviation fuel, JP-4
C	Lubricating oil, MIL-O-7808
D	Hydraulic fluid, Oronite (MLO-8200) (93.3% Disiloxane, 4.6% Silicone)
E	Hydraulic fluid, methyltetrachlorophenyl (G.E. #81644)
F	Hydraulic fluid, Disiloxane, Ester Blend, MIL-H-8446 (78.68% Disiloxane, 4.3% Silicone, 15% Di (2-ethylhexyl) Sebacate
G	Naphthenic mineral oil, MLO-7117

time interval from the contact of an oxidant and a combustible to ignition–increases with decreased pressure as shown in Fig. 5-10.

The combustion rates of solids also depend upon the material and the amount of available oxygen. The propagation of flames through a closed capsule is dependent upon the available oxygen, and the types and amount of material that are being burned. The preferred gas mixture for fire retardation in an encapsulated environment is the minimum amount of oxygen needed for life support systems with an incombustible gas providing the remaining required pressure.

5-4.1.2 LUBRICITY

As the partial pressures of water vapor and oxygen in the air decrease, the lubricity of carbon-graphite materials also decreases (Ref. 21). Fig. 5-11 shows the increase in graphite wear-rate with the decrease in the partial pressure of water vapor. Brushes of these

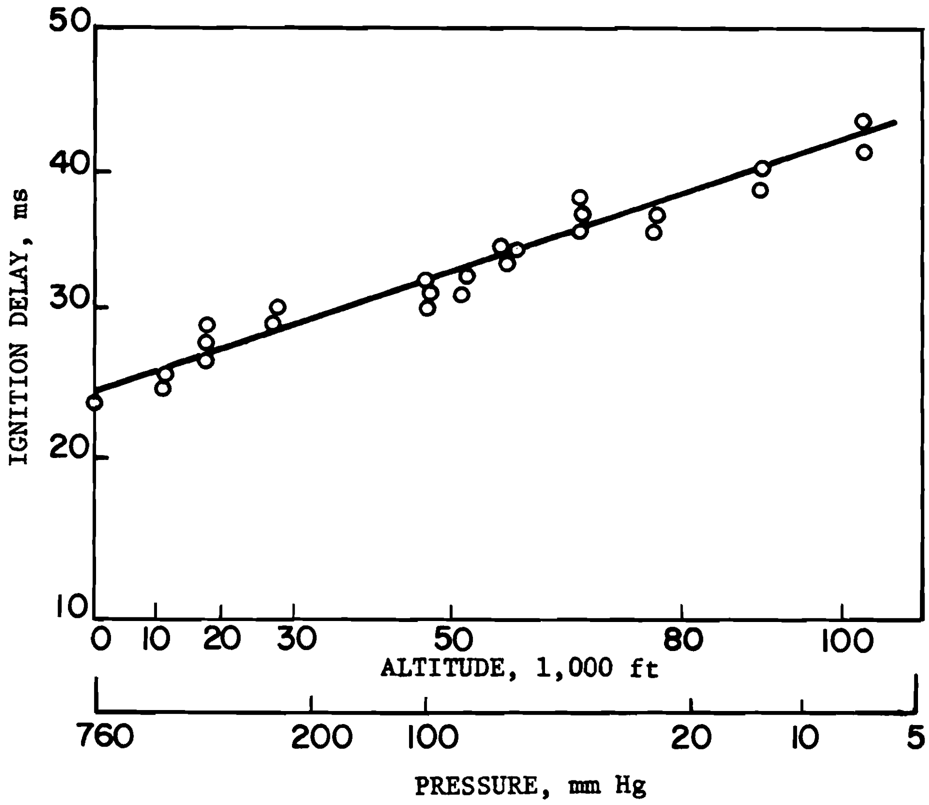

Figure 5-10. Ignition Delay at Reduced Pressures (Ref. 20)

materials are used in motors and generators as sliding electrical contacts. The lubricating properties of the carbon-graphite, which prevent friction of the sliding surfaces, depend on a thin adsorbed film of water vapor and/or oxygen from the air. As this film is broken down by rubbing, by increased temperature, and by electric current, it must be replenished to avoid brush wearout. Above 3 km, where there is less water vapor and oxygen available to replenish the film, difficulties can occur, being more likely under conditions of low humidity.

5-4.1.3 DIELECTRIC BREAKDOWN PROPERTIES OF AIR

When an electric charge is placed upon a surface, some of the air molecules that come in contact with the surface become ionized and, as a result of the molecular motion, may be able to transfer the charge to a surface of opposite charge, thereby establishing a current flow between the two surfaces. At sea-level pressures, for a given voltage differential and geometry of the surfaces, the amount of current flow is usually quite small. As the pressure (density) decreases, the mean free path of a charged molecule increases. With fewer collisions with molecules of opposite charge, more charge is transferred, hence, greater current. As a consequence, components depending upon the dielectric properties of air (e.g., transmitters, vibrator or relay contacts, resistors, capacitors, and transformers) may malfunction at reduced pressure (high altitude) unless precautions are taken. Three types of discharges are commonly described as arc, glow, and corona.

(1) *Arc discharge.* Commonly called arc-over, these discharges are luminous and maintain paths between the two surfaces, normally following the path of maximum potential difference. Electrons are also emitted from the cathode because of its heat. Once a path has been established between the electrodes, the air becomes ionized and remains so as

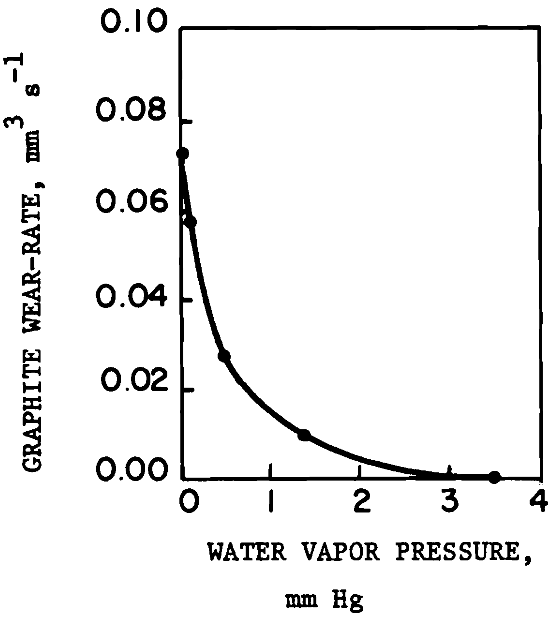

Figure 5-11. Graphite Wear-rate Dependence Upon Water Vapor Pressure (Ref. 23)

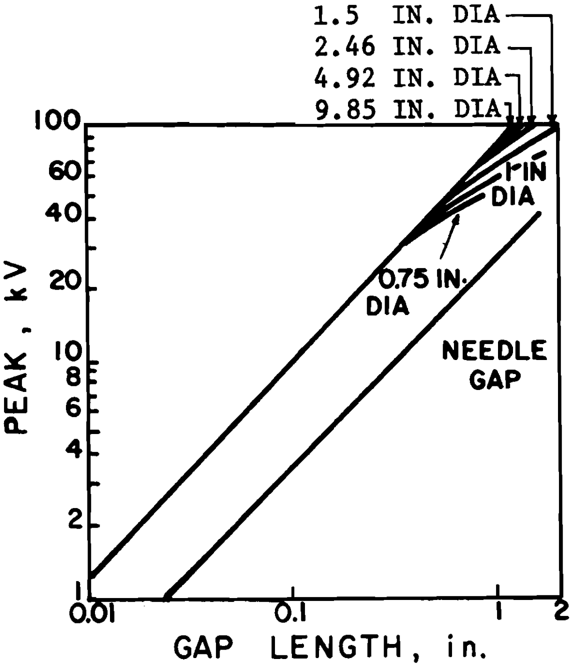

Figure 5-12. Spark-gap Breakdown Voltages (Ref. 24)

long as the voltage is maintained. Fig. 5-12 shows the peak voltage for breakdown as a function of gap length between needle points and polished hemispheric surfaces of various diameters at standard sea-level conditions. With the aid of the multipliers given in Table 5-10, the breakdown voltages (for those geometries) can be determined from Fig. 5-12 for other temperatures and pressures. For example, 1-in.-diameter spheres, separated by a gap of 0.1 in., arc at approximately 10 kV at standard conditions. At a pressure of 20 in. Hg, the same gap will arc at a voltage of 7.2 kV if the temperature is 20°C.

An approximate rule for uniform electric fields at all frequencies up to at least 300 MHz is that the breakdown voltage gradient of air is 30 kV cm^{-1} (peak) (75 kV in.$^{-1}$) at sea-level pressure and 25°C. The breakdown voltage is approximately proportional to the pressure and inversely proportional to the absolute temperature (Ref. 24).

The arc-over produces a malfunction or complete loss of the equipment system. Arc-over in a control circuit can damage other portions of a system by overloading them. Ozone and nitrogen oxides are produced by the ionizing currents and may damage natural rubber, contaminate other insulators, or corrode metals.

(2) *Glow discharge.* The effects of a glow discharge are similar to the arc discharge; however, the current is smaller, generally less than 25 mA. The voltage difference is larger, but, since the temperature of the cathode is cooler, cathode electrons are not emitted (Ref. 25).

(3) *Corona discharge.* Prior to the development of breakdown—e.g., when the voltage has not reached its peak for breakdown, or the air pressure is still high enough to prevent breakdown—a corona discharge of very small arcs at high voltage points occurs. These discharges are not as destructive as the others, but cause unnecessary loss of energy and interfere with communication.

In addition to depending on air pressure, the dielectric properties of air also depend upon the amount of water vapor and dust

TABLE 5-10

PRESSURE-TEMPERATURE CORRECTION FACTORS FOR SPARK-GAP BREAKDOWN VOLTAGES (Ref. 24)

Pressure		Temperature, °C					
in. Hg	mm Hg	-40	-20	0	20	40	60
5	127	0.26	0.24	0.23	0.21	0.20	0.19
10	254	0.47	0.44	0.42	0.39	0.37	0.34
15	381	0.68	0.64	0.60	0.56	0.53	0.50
20	508	0.87	0.82	0.77	0.72	0.68	0.64
25	635	1.07	0.99	0.93	0.87	0.82	0.77
30	762	1.25	1.17	1.10	1.03	0.97	0.91
35	889	1.43	1.34	1.26	1.19	1.12	1.05
40	1016	1.61	1.51	1.42	1.33	1.25	1.17
45	1143	1.79	1.68	1.58	1.49	1.40	1.31
50	1270	1.96	1.84	1.73	1.63	1.53	1.44
55	1397	2.13	2.01	1.89	1.78	1.67	1.57
60	1524	2.30	2.17	2.04	1.92	1.80	1.69

TABLE 5-11

HEAT-ABSORBING CAPACITY OF AIR (Ref. 22)

Altitude, ft	Percent heat-absorbing capacity of given volume of air compared to that at sea level
0	100
20,000	50
40,000	25
60,000	10
80,000	3
100,000	1

present, the type of current (alternating or direct), and the geometry and composition of the electrodes.

5-4.1.4 HEAT TRANSFER

The specific heat at constant pressure of the atmosphere is 0.24 cal g^{-1} K^{-1} and is independent of pressure and temperature provided that the atmospheric composition remains constant. As the atmospheric density is reduced (e.g., pressure decreases), the mass of air available to absorb heat is proportionally reduced (Table 5-11). Temperature sensitive instruments or components may be adversely affected by the buildup of heat. Artificial ventilation of equipment may be required to remove the heat.

5-4.1.5 VAPORIZATION PROCESSES

The reduction of pressure lowers the boiling temperature of water (par. 5-3.3) and other liquids. For those liquids that have a high saturation vapor pressure at normal sea level conditions, evaporation losses or even boiling at lower pressure may occur. Boiling of the liquid generally requires that the temperature of the liquid be increased above ambient conditions (to increase the saturation vapor pressure) and that the pressure be decreased. Oils or other lubricants that are heated by friction but are exposed to reduced pressures during the lubrication cycle are susceptible to these vaporization losses. When sufficient lubricant is lost, friction and abrasion of the lubricated surfaces are increased, possibly resulting in cold welding of the surfaces (Ref. 22).

5-4.1.6 EFFECTS OF PRESSURE DIFFERENTIALS

Pressure differentials create a restoring force, acting from high pressure toward low pressure, which attempts to equalize the pressure by transfer of mass. When the mass transfer is inhibited by a seal or a solid object, forces proportional to the pressure gradient may rupture the seal, distort a sealed container, or move the object. The largest pressure gradient and the greatest hazard to materiel are experienced with explosive decompression of an aircraft, with rapid vertical displacement through the atmosphere, and with tornadoes. Less dramatic but nonetheless important effects are produced with smaller but frequent changes of pressure gradients.

In a tornado, the excess pressure inside a building may cause explosion of the building, especially those with large, poorly supported roofs. The opening of windows and doors offers some protection by giving the air some opportunity to escape and equalize the pressure.

Explosive decompression results from a sudden loss of pressure from sealed, pressurized containers and aircraft. The pressure change is quite rapid but its magnitude depends upon the differences between the internal pressure and the ambient, external pressure, e.g., the altitude. In pressure changes involving aircraft, emergency supplies of oxygen may be required for the aircrew and multiple physiological effects experienced. With materiel, the sudden loss of pressure may severely strain equipment seals by exposing them to pressures that they were not designed to encounter. Unprotected pressure-sensitive equipment may be damaged or may malfunction.

Seal failure occurs when the load on a seal exceeds the breaking tension of the sealant. At an equilibrium condition, the pressure differential ΔP across an interface (e.g., canister wall) is related to the tension on the sealant σ by

$$\Delta P = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{5-8}$$

where R_1 and R_2 are the principal radii of curvature of the surface at the point in question (Ref. 26). Thus, the likelihood of seal failure depends upon the pressure differential, the breaking tension of the sealant, and the geometry of the package. Seals at sharp corners or edges are more susceptible to failure.

Differences between inside and outside pressure can cause leakage of fluids from hydraulic lines, hermetically sealed enclosures, and gasketed connections. Leakage occurs when seals fail or are not securely applied; less frequently, air or liquid may permeate the container. A tendency for a material to leak can cause numerous difficulties; air will leak out when the outside pressure drops. Then should the outside pressure increase rapidly and the pressure differential be sufficient, the container will collapse. Should the outside pressure increase less rapidly, air will leak back into the container, possibly carrying water vapor, which can damage moisture-sensitive items either immediately or slowly as water accumulates from condensation during repetitions of the cycle. Such items as ammunition, electrical equipment, and food are susceptible to damage by this process. Liquids leaking out of containers, when the outside pressures are lower, can evaporate or cause damage to their surroundings, particularly if they are flammable, corrosive, or toxic. If combustible vapors are formed, explosive conditions or fire hazards are created. Repeated exposure to large pressure changes may also weaken some seals resulting in eventual failure.

5-4.2 COMBINED ENVIRONMENTAL EFFECTS

In the natural environment, atmospheric pressure occurs in conjunction with other environmental factors, which vary with time and place and have differing effects on materiel. In some cases, the effects caused by these other factors, especially temperature and humidity, will intensify or reduce those caused by pressure. Various combinations are discussed, namely:

(1) *Low pressure and low temperature* comprise the most usual combination at high elevations; this combination intensifies physiological discomfort and constitutes a danger to human beings. Some low pressure effects, e.g., leakage through seals, are aggravated due to fluid congealing from low temperature and

the contraction and embrittlement of materials. Rates of combustion fall with both decreasing temperature and pressure. Low pressure effects associated with vaporization—e.g., the drop in the boiling point of liquids, the tendency of liquids to evaporate, and the flammability of air-vapor mixtures—tend to be counteracted by low temperature. Low temperature tends to compensate for the reduction in heat transfer by convection and conduction under low pressure conditions, and decreases the tendency of electrical and electronic components to overheat. Another compensating low-temperature effect on electric equipment is to increase the dielectric breakdown voltage.

(2) *Low pressure and high temperature* occur jointly as a result of aerodynamic heating at higher altitudes. This combination tends to intensify certain harmful effects; e.g., overheating caused by high temperatures is aggravated by the decreased heat transfer capacity of the air at low pressures.

(3) *High pressure and low temperature* normally occur near the surface of the earth during winter. Aircraft altimeters are calibrated to indicate the altitude in the standard atmosphere corresponding to the ambient pressure, e.g., pressure altitude. With a constant altimeter setting, the flight path is along a constant pressure surface and the aircraft descends, relative to mean sea level, when flying from warm toward cold air and ascends when flying from cold toward warm air. While flying towards a high pressure area, where the air between the surface and the flight altitude is significantly colder than standard, the difference between true altitude and constant pressure altitude increases. This combination of high pressure and low temperature may endanger low-altitude aircraft operations in mountainous regions (Ref. 27).

(4) *Low pressure and low humidity* occur at high altitudes. Low humidity reinforces the vaporization effects attributable to low pressures, e.g., lower boiling points and increased evaporation of liquids. Increased evaporation of lubricants due to low pressure and low humidity causes abrasion and increased wear on surfaces and moving parts, which are further intensified by low temperature.

Among the conditions that can be damaging to the operation of brushes used in electric motors and generators on aircraft are low atmospheric humidity of less than 15 percent and altitudes of 25,000 ft or more. The limits given are approximate, varying with the composition of the contacting materials. These conditions, in conjunction with high rubbing speeds, high electric current densities, and operating bulk surface temperatures of 150°C or more, would render the operation of ordinary brushes "virtually impossible" (Ref. 21).

(5) *Low pressure and high humidity* occur together mostly during storms, both at sea level and aloft, and tend to decrease insulation resistance and the dielectric strength of the air. Under these conditions, breakdown voltage and corona-starting levels of electrical and electronic equipment are reduced.

(6) *Low pressure and ozone* occur increasingly with height up to 50,000 ft in the zone under consideration. Both factors contribute to insulation breakdown and arc-over. Ionization of the air in connection with corona discharge due to low pressure, increases the ozone content of the ambient air.

(7) *Low pressure and wind* occur together during severe storms—especially tornadoes and hurricanes—and combine to cause collapse or distortion of structure.

(8) *Low pressure and explosive atmosphere* effects are varied. Pressure directly affects explosions and fires through its effects on combustion and on the air-vapor mixture required for ignition. Generally, low pressure tends to reduce both the possibility and the strength of fires and explosions especially at altitudes above 40,000 ft, where the low pressures and decreased concentration of oxygen combine to deter combustion. On the other hand, low pressure increases the possibility of fires and explosions set off by

sparks from corona or arc-over. Pressure differentials can cause seepage of flammable or explosive gases or liquids from containers.

(9) *Pressure changes and high humidity* may affect materiel through a process known as breathing. When air is forced into enclosed spaces as a result of pressure differentials and contains more water vapor than the air that leaks out, damage to moisture-sensitive items such as meteorological instruments, electronic tubes, and cartridges can occur through the accumulation of condensation.

(10) *Low pressure, low temperature, low humidity, high solar radiation, and ozone* is a common combination at high altitudes. All of these elements work to induce alteration of electrical properties, and all except solar radiation cause loss of mechanical strength.

5-5 GUIDANCE FOR DESIGN

5-5.1 LOW-PRESSURE REGIONS

Since pressure drops with altitude, the lowest pressures in the zone considered in this chapter occur near 16 km. Pressures aloft are also lower at high latitudes and during cold seasons. The range between maximum and minimum pressures varies with both altitude and latitude.

On the surface of the earth, the lowest station pressures normally occur in high mountain areas. Extensive areas of high elevation occur in Central Asia, western South America, Greenland, Antarctica, New Guinea, and the western United States. In high-latitude mountains, where temperatures are lower, pressures will also be lower than at similar elevations in low latitudes.

At sea level, the lowest pressures occur during tornadoes, hurricanes, and other tropical storms. The largest and most rapid declines in pressure occur during tornadoes; despite their destructiveness, however, it is not practical to design equipment to withstand them. Maximum and minimum pressure criteria that military equipment should be designed to meet at sea level and at other altitudes are given in MIL-STD-210 (Ref. 28) and AR 70-38 (Ref. 29).

Tables 5-12, 5-13, and 5-14 present extreme values of high and low atmospheric pressure as a function of altitude, latitude, and probability of being exceeded 10 percent, 5 percent, and 1 percent of the time, respectively.

5-5.2 PROTECTION AND CONTROL

Various methods are used to prevent or minimize the adverse effects of pressure. These practices include the selection of materials, proper design, and utilization of sealing and pressurization techniques. A brief discussion follows:

(1) *Selection of materials.* The proper selection of materials within cost and design limitations is an important means of preventing undesirable pressure effects. Materials differ widely in their ability to withstand pressure-induced stresses of the type applied to containers and seals by pressure differentials resulting from rapid changes in pressure. When seeping gases or liquids are a potential problem, the permeability of materials in contact with them should be carefully evaluated. Lubricants and fuels differ in their susceptibility to evaporation, and some fluids are less subject to diffusion and seepage than others. Materials for use as brushes in motors and generators vary in their resistance to failure under low-pressure conditions. The destructive effects of corona and arcing can be minimized by the proper choice of insulating materials. Much useful design information on the characteristics of materials under low-pressure conditions has been generated by space program necessities and is available in such compendiums as the *Space Materials Handbook* (Ref. 31).

(2) *Design.* Many adverse pressure effects can be minimized or prevented by modification of design configuration to compensate for potential problems. This is particularly true of electrical and electronic equipment,

TABLE 5-12

EXTREME PRESSURE VALUES (mb) WITH 10 PERCENT PROBABILITY OF EXCEEDANCE (Ref. 30)

Altitude, km	Low Latitude		Midlatitude		High Latitude		Hemispherical	
	Min	Max	Min	Max	Min	Max	Min	Max
0	1006.9	1020.7	1005.3	1025.9	995.1	1025.3	995.1	1025.3
1	898.7	909.5	889.1	910.9	871.8	904.7	871.8	910.9
2	799.6	808.1	784.2	808.9	760.0	798.5	760.0	808.9
3	709.5	717.4	688.8	717.7	661.6	704.4	661.6	717.7
4	627.5	636.3	602.7	636.0	583.5	619.0	583.5	636.3
5	552.4	561.2	525.3	561.5	494.3	543.8	494.3	561.5
6	486.4	495.9	456.7	495.1	424.6	474.7	424.6	495.9
7	425.4	436.2	394.9	435.0	364.5	413.7	364.5	436.2
8	370.4	382.2	339.9	380.3	311.5	358.7	311.5	382.2
9	321.4	334.2	292.2	332.3	265.8	309.7	265.8	334.2
10	279.1	291.2	249.6	288.9	227.5	266.3	227.5	291.2
11	239.7	251.7	214.0	249.8	194.5	228.4	194.5	251.7
12	205.1	217.0	183.1	214.6	166.4	196.0	166.4	217.0
13	175.8	186.3	156.4	184.1	141.7	168.1	141.7	186.3
14	149.3	158.3	134.0	156.6	120.9	144.3	120.9	158.3
15	126.7	134.4	114.8	132.9	103.3	123.9	103.3	134.4
16	107.3	113.6	98.1	112.6	88.4	106.1	88.4	113.6

TABLE 5-13

EXTREME PRESSURE VALUES (mb) WITH 5 PERCENT PROBABILITY OF EXCEEDANCE (Ref. 30)

Altitude, km	Low Latitude		Midlatitude		High Latitude		Hemispherical	
	Min	Max	Min	Max	Min	Max	Min	Max
0	1005.6	1021.4	1000.9	1028.9	991.0	1030.9	991.0	1030.9
1	897.4	910.1	884.7	912.0	867.9	908.0	867.9	912.0
2	798.3	808.4	779.8	910.0	756.1	801.4	756.1	910.0
3	708.2	718.0	684.0	718.8	658.4	707.3	658.4	718.8
4	626.2	636.9	598.4	637.0	581.5	621.9	581.5	637.0
5	551.1	561.9	520.9	562.5	490.3	547.0	490.3	562.5
6	485.1	496.5	452.3	496.2	420.7	478.7	420.7	496.2
7	424.1	436.8	390.5	435.7	361.2	417.3	361.2	436.8
8	369.1	382.8	335.6	381.4	308.3	362.4	308.3	382.8
9	320.1	334.8	288.2	333.4	262.8	313.3	262.8	334.8
10	277.4	291.8	246.3	289.6	224.6	269.5	224.6	291.8
11	238.3	252.3	211.1	250.7	191.9	231.5	191.9	252.3
12	204.0	217.5	180.7	215.7	164.1	198.3	164.1	217.5
13	174.8	187.0	154.4	185.0	139.3	169.9	139.3	187.0
14	148.4	159.0	132.1	157.5	118.8	145.7	118.8	159.0
15	126.1	135.0	113.0	133.8	101.2	125.0	101.2	135.0
16	106.6	114.5	96.8	113.7	86.1	107.0	86.1	114.5

TABLE 5-14

EXTREME PRESSURE VALUES (mb) WITH 1 PERCENT PROBABILITY OF EXCEEDANCE (Ref. 30)

Altitude, km	Low Latitude		Midlatitude		High Latitude		Hemispherical	
	Min	Max	Min	Max	Min	Max	Min	Max
0	1001.8	1023.5	992.8	1033.2	984.2	1039.1	984.2	1039.1
1	894.1	911.8	877.3	914.6	858.6	913.0	858.6	914.6
2	795.0	809.7	772.4	811.6	747.3	805.8	747.3	811.6
3	704.4	719.6	676.7	720.8	652.6	711.6	652.6	720.8
4	621.9	638.1	591.7	639.7	579.0	626.6	579.0	639.7
5	546.9	563.5	513.9	564.9	483.0	552.1	483.0	564.9
6	480.3	498.4	445.3	497.5	413.4	484.4	413.4	498.4
7	419.8	438.5	383.5	437.4	355.0	422.7	355.0	438.5
8	365.3	384.5	328.9	383.1	301.6	368.1	301.6	384.5
9	316.3	336.4	281.8	334.7	256.4	319.0	256.4	336.4
10	272.8	293.5	241.6	290.9	218.2	275.2	218.2	293.5
11	234.4	254.2	206.9	250.7	186.1	236.3	186.1	254.2
12	200.9	219.2	177.2	217.4	160.6	202.3	160.6	219.2
13	172.1	188.6	151.4	186.3	134.6	173.1	134.6	188.6
14	146.1	160.8	129.5	159.2	114.7	148.1	114.7	160.8
15	124.4	136.7	110.5	135.7	97.3	126.8	97.3	136.7
16	105.5	116.3	94.6	115.4	82.4	108.5	82.4	116.3

where voltage breakdown at low pressures is a constant potential hazard. The shape and spacing of contacts on such equipment can affect breakdown resistance at differing voltages and altitudes.

Shape is often an important factor in the control of pressure effects. The shape and degree of rounding of electrodes affects voltage gradients. The shape of containers can affect their ability to withstand pressure differentials, with spherical and cylindrical types providing the most strength for a given weight. Modification of nozzles on jet engines permits matching the exhaust pressure from the engine with outside air pressure, thereby achieving effective engine thrust.

(3) *Hermetic sealing and pressurization.* Pressure levels can be maintained by sealing enclosures or containers at sea level or by blowing or pumping air into them to obtain the desired pressure. Hermetic sealing of items that have moving electrical contacts is a means of preventing explosions touched off by sparks from corona or arc-over. The superchargers used to maintain power in internal combustion engines of motor vehicles and helicopters are air pumps or blowers, which increase the pressure of the intake air charge. Aircraft cabins are pressurized to protect both occupants and some types of cargo. A pressure of approximately 750 mb, which is equivalent to that occurring near 10,000-ft altitude, is used.

Pressurization of equipment can cause, as well as solve, problems. Equipment that is pressurized tends to be larger, heavier, and more difficult to maintain. Explosive decompression—sudden loss of pressure—can be a major hazard; it can result from mechanical failure of the pressurizing apparatus and/or seals, or from combat damage. Safeguards include the provision of a secondary pressurization system and use of pressure suits.

5-6 TESTING AND SIMULATION

5-6.1 TEST OBJECTIVES

The environmental testing of pressure effects is oriented to equipment and components, since the effects on materials of construction are relatively insignificant in the zone considered in this chapter. As altitudes increase and pressures approach the low values of outer space, the effects on materials become of greater concern. Considerable work in testing pressure effects under space conditions has been performed in connection with the space program. In general, however, the application of ultra-high vacuum testing techniques is not applicable to the development and testing of most Army materiel. Environmental pressure tests of Army materiel are used largely to determine the suitability of equipment and components for shipment and operation of equipment at reduced pressures, to ascertain the performance characteristics of electronic equipment installed in aircraft, and to establish equipment performance in an explosive atmosphere. Tests are employed in the development, production, and acceptance phases of the procurement cycle. Tests have as their immediate objectives the optimization of design and material selection; determination of test criteria and specifications; maintaining of quality control during production; and evaluation of operational factors such as reliability, operability, and maintainability.

5-6.2 FIELD vs LABORATORY TESTING

Environmental testing can be conducted either in laboratories or under natural conditions. Laboratory simulation has the advantages offered by a scientifically controlled environment. Disadvantages of simulation techniques result from the tentative nature of the results; i.e., any test chamber is only an approximation of the natural environment, and often lacks the complex set of environmental factors found in nature. In the case of pressure, however, the nature of the stresses and effects that must be considered—e.g., rapid changes in pressure (often accompanied by similar changes in temperature and humidity) and high elevation—are such that simulation is the most practical method of testing. When large items of equipment, or components for such equipment, are being considered, the limitations of chamber size and the limited elevations at which they normally operate make natural environmental testing at high elevations in mountainous areas the most practical approach.

5-6.3 TEST PROCEDURES

MIL-STD-810 (Ref. 32) provides a number of tests (Methods 500, 504, and 518) for investigating low-pressure effects, both as a single environmental factor and in combination with other factors, i.e., temperature and humidity. Tests (Methods 511 and 512) are also provided for explosive atmospheres and permeability, the latter having specific application to hermetically sealed units.

Procedure I of the altitude test (Method 500) is a single environmental factor test designed to determine the effects of reduced pressure on equipment. This method tests the ability of equipment and components to withstand the reduced air pressure encountered during air shipment, and to operate satisfactorily under high-elevation pressure conditions. Procedure II determines the ability of equipment to operate satisfactorily both during and after exposure to reduced pressure and temperature conditions during flight.

The temperature-altitude test (Method 504) is designed primarily for investigating the characteristics of electronic components installed in aircraft capable of flight up to an altitude of 100,000 ft. As such, the test has a broader range of environmental stresses than those applicable to equipment in the zone up to 50,000 ft. Test procedures require simultaneously varying conditions of low pressure and high-low temperatures, and permit the analysis of the combined environmental stresses that result in such phenomena as leakage of gases or fluids from sealed containers, rupture of pressurized containers, congealing of lubricants, cracking and/or rupturing of materials, and harmful electrical effects.

The temperature-humidity-altitude test (Method 518) is basically a cycling test, designed to determine the effects of alternating low temperature/low pressure and of high temperature/high humidity. Although such effects result primarily from flying equipment between extreme environments, the test provides a means of investigating the harmful effects of pressure/humidity cycling characteristics of "breathing".

Ignitions under this test can originate with electrical, thermal, and chemical sources of energy. Equipment tested by this method includes ground equipment, containers, and nonhermetically sealed units.

The leakage test (Method 512), although not specifically a pressure test, is relevant to pressure effects since it is conducted to determine the integrity of hermetic seals.

5-6.4 TEST RANGES

The primary requirements for testing pressure effects in natural locations are elevation and accessibility. In general, such tests involve larger items of equipment such as vehicles and generators. The overall dependence of pressure on elevation, however, is such that many of the pressure effects requiring design consideration imply considerable height above the surface of the earth, necessitating either aerial flight or chamber simulation. Vehicular tests on larger components and items of equipment require natural locations, and military installations located in the western United States are the most practical choice. Tests on vehicles and carriers have been conducted, for example, at Ft. Carson and Camp Hale, Colo. These tests require elevation and access to the test grounds.

5-6.5 SIMULATION EQUIPMENT

The basic pressure test methods (altitude, temperature-altitude, and temperature-humidity-altitude) detailed in MIL-STD-810 can be performed in a wide variety of chambers now available. Many of these chambers can simulate pressure altitudes considerably above 50,000 ft and temperatures well in excess of (both above and below) those specified in the MIL-STD-810 tests. These tests are generally limited to altitudes up to 50,000 ft (Method 504 is applicable to an upper limit of 100,000 ft); the tests have maximum and minimum temperature requirements of 260°C and -62°C.

Several types of explosion chambers are now commercially available. They range in size from several cubic feet to approximately 300 ft^3, and provide simulated altitudes from ground level up to 500,000 ft.

A comprehensive treatment of environmental test chambers is provided by the *Index of Environmental Test Equipment in Government Establishments* (Ref. 33). This work contains detailed data on the operating characteristics of chambers, the types of chambers available, their location, and their associated Government activity. Chambers currently in use in industry are enumerated in *Facility Survey* (Ref. 34). Specifications applicable to individual items of equipment, materials, and specialized test procedures and test equipment are listed in the *Index of Specifications and Standards* (Ref. 35).

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CHAPTER 6

SOLAR RADIATION

6-1 DEFINITION AND INTRODUCTION

Solar radiation includes anything that emanates (i.e., radiates out) from the sun. The discussion in this chapter is confined to the electromagnetic portion of that radiation that impinges on the atmosphere of the earth because it comprises the bulk of the radiation energy that interacts with man's environment. Corpuscular (i.e., nonzero rest mass) radiation is similar in its effects to nuclear radiation, which is discussed in Chap. 9, "Nuclear Radiation", of Part Three, as well as in other sources (Ref. 1). Primary emphasis will be on that portion of the electromagnetic spectrum between 100 nm and 100 μm in wavelength (12.4 eV and 12.4 meV in energy, 3000 THz* and 3.0 THz in frequency). The shorter wavelengths are discussed with nuclear radiation and the longer wavelengths in Chap. 8, "Electromagnetic Radiation", of Part Three.

The 100-nm to 100-μm region of the solar electromagnetic spectrum contains all but 0.001 percent of the power that impinges on the earth from the sun (Chap. 18 in Ref. 2) and all but about 0.024 percent of the power involved in the heat balance of the earth—about two-thirds of the remainder consists of heat from the interior of the earth (Chap. 3 in Ref. 3).

It is necessary to distinguish between the solar spectrum, the energy of which is largely in the wavelength range between 0.1 and 2.2 μm, and terrestrial and atmospheric radiation between 6.8 and 100 μm. The two ranges are referred to as the short- and long-wavelength regions.

Insolation is generally defined as that solar radiation received at the surface of the earth but the term is also used to denote the rate at which direct solar radiation is received on a plane horizontal surface on or above the surface of the earth (Ref. 4). Insolation is thus affected by earth-sun geometry as well as by attenuation or reflection of the radiation before it reaches the surface. Because of the ambiguity—total versus direct solar radiation—the term insolation is infrequently employed in this chapter.

In addition to the direct effects of solar radiation, some of the secondary effects that result from terrestrial radiation are discussed in this chapter. This discussion is closely related to that of temperature in Chap. 3.

From the earth, if atmospheric effects are ignored, the sun appears as a spherical blackbody with the diameter of its photosphere (Ref. 2) and at a temperature in the range 5,000 to 6,000 K (Ref. 5). The exact temperature that is measured depends on the wavelength of the radiation being employed for the measurement and on the criteria used in analyzing the data. The exact temperature of the sun is not important in considering materiel effects provided that the radiation power density spectrum is accurately determined.

The electromagnetic spectrum has been divided into contiguous regions based on similarity of the effects of radiation within a defined wavelength span. The dividing lines, names, and subdivisions of the regions have not been standardized because of the diverse uses and properties of the radiation upon which division is based. The entire spectrum is extremely broad, ranging from wavelengths of

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*THz is the symbol for terahertz or 10^{12} Hz. See par. 6-2.

3×10^{7} m (frequency of 10 Hz) in the infrasonic limit to 3×10^{-17} m (frequency of 10^{25} Hz) in the high energy cosmic ray region. As would be expected, this 24-orders-of-magnitude range in wavelength corresponds to tremendous differences in effects and properties. A portion of the spectrum is shown in Fig. 6-1 in units of wavelength, photon energy, and frequency. The shorter wavelengths are usually referred to in units of photon energy, the longer wavelengths by frequency, and those in the midranges (visible, infrared, and microwave) by wavelength. The solar radiation region is shown in the figure to indicate that portion of the spectrum dealt with in this chapter. It includes the visible region and portions of the ultraviolet and infrared regions.

The radiation incident on the earth interacts with the atmosphere, especially in its upper regions. About 30 percent is reflected back into space. Most of the solar energy that is not reflected by the atmosphere is absorbed by the surface of the earth and, by reradiation at longer wavelengths, subsequently heats the atmosphere. The atmosphere reradiates energy into space, thereby maintaining the thermal balance of the planet.

The amount of energy incident on a surface in the outer atmosphere depends on the angle that a perpendicular to the surface makes with the solar rays (zenith angle) and on the distance to the sun. The variation in the distance to the sun (ellipticity of the orbit of the earth) is never more than ± 3.5 percent from the mean and is, therefore, negligible for engineering calculations. (This variation does result in the paradox that, in the Northern Hemisphere, the earth is closer to the sun in the winter than in the summer.) The variation in the zenith angle of the surface of the earth is important—it produces diurnal as well as seasonal variations in solar radiation levels.

The axis of the rotation of the earth is not perpendicular to the plane of the orbit of the earth but is tilted at 23.45 deg from the perpendicular. This angle is constant with respect to the fixed stars but appears to oscillate between ± 23.45 deg with respect to the sun. It is called the solar declination and sets the four seasons as defined in Table 6-1. In the Southern Hemisphere, the seasons are phase shifted by 180 deg. The geographic regions of the earth as noted in Table 6-2 are also defined by the solar declination. In the Arctic or Antarctic, daylight or night can be 24 hr in duration; in the tropics, the sun can be directly overhead at solar noon; in the temperature zones, neither can occur. The solar zenith angle Z of a point on the surface of the earth is directly related to the solar declination angle D, the latitude angle L, and the hour angle H (angle through which the earth must turn to bring the meridian of the point directly under the sun) by the equation

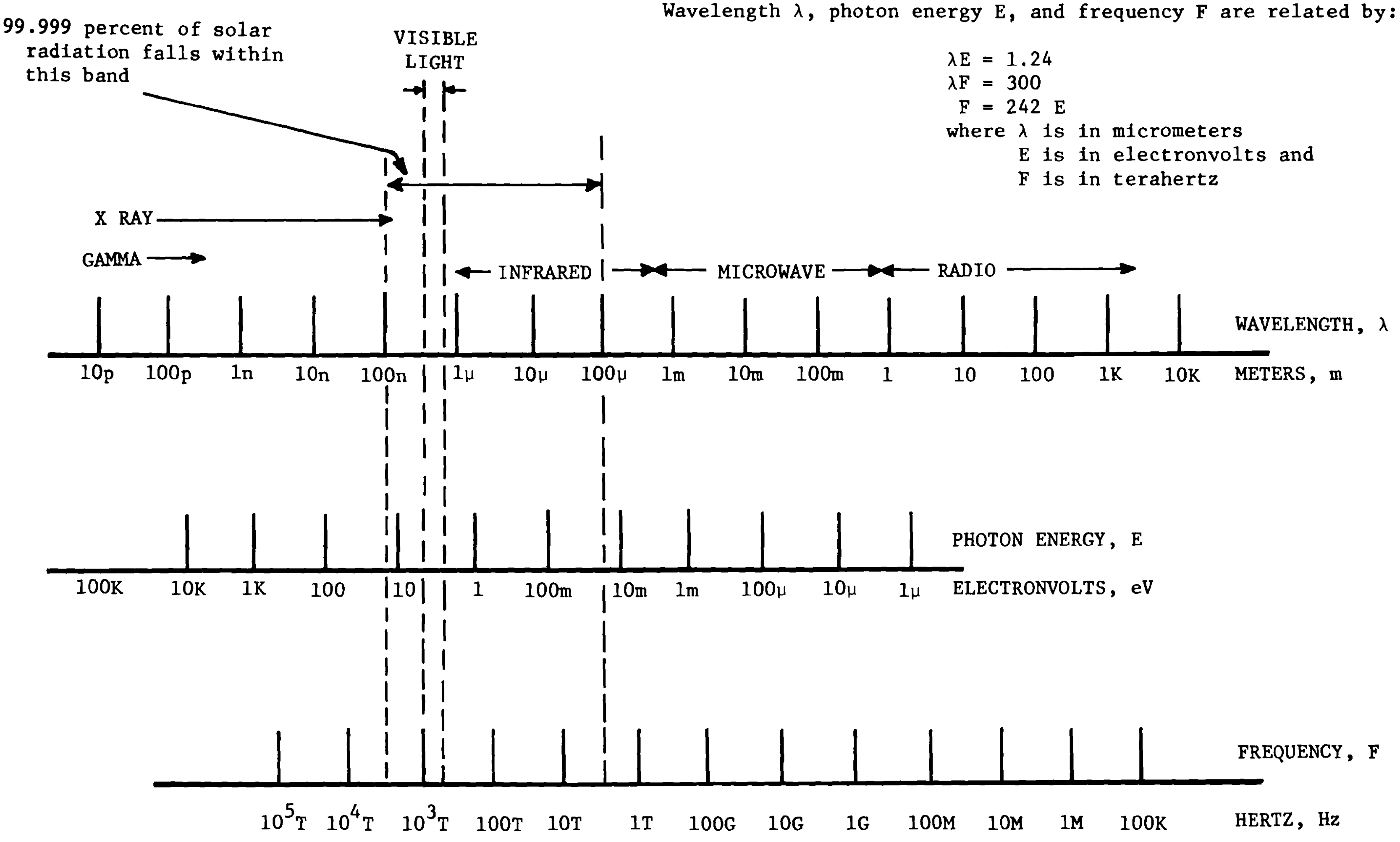
$$\cos Z = \sin L \sin D + \cos L \cos D \cos H \quad (6\text{-}1)$$

The declination angle is determined by the position of the earth in its orbit, i.e., the day of the year, while the hour angle is zero at solar noon and increases by 15 deg every hour. The solar radiation flux at a point is proportional to $\cos Z$. More detailed discussion of the zenith angle is given by Sellers (Ref. 3).

This variable flux of solar radiation has two important effects on materiel—the long wavelengths cause heating and the short wavelengths can initiate photochemical reactions. In par. 6-4, the various processes that affect the solar radiation flux after it enters the atmosphere of the earth are discussed and its distribution is described in par. 6-5. In par. 6-6, the measurement of solar radiation is discussed, followed in subsequent paragraphs by descriptions of the effects and methods for minimizing detrimental effects.

6-2 UNITS OF MEASUREMENT

Of primary interest in the measurement of solar radiation is the irradiance or the power per unit area per wavelength interval. In the International System of Units, the unit for energy is the joule J; for length, the meter m; and for time, the second s. The watt W, equal to 1 J s^{-1}, is the corresponding unit of power.



Wavelength λ, photon energy E, and frequency F are related by:

$\lambda E = 1.24$
$\lambda F = 300$
$F = 242\ E$
where λ is in micrometers
E is in electronvolts and
F is in terahertz

Figure 6-1. Electromagnetic Spectrum

TABLE 6-1

SOLAR DECLINATION AND THE SEASONS (NORTHERN HEMISPHERE)

Solar declination	Name*	Month**	Season
-23.45°	Winter solstice	December	
			Winter
0°	Vernal equinox	March	
			Spring
+23.45°	Summer solstice	June	
			Summer
0°	Autumnal equinox	September	
			Fall
-23.45°	Winter solstice	December	

*Solstice means "sun stands still", i.e., the time derivative of the solar declination is zero; equinox means equal day and night.

**Because the year does not have an integral number of days, the calendar time of the solstices and equinoxes varies from year to year.

TABLE 6-2

GEOGRAPHIC REGIONS OF THE EARTH

Latitude	Name	Zone
		Arctic
66.55° North	Arctic Circle	
		North Temperate
23.45° North	Tropic of Cancer	
		Tropics
23.45° South	Tropic of Capricorn	
		South Temperate
66.55° South	Antarctic Circle	
		Antarctic

Thus, for irradiance, the unit of measurement is watts per square centimeter per micrometer (W $cm^{-2}\mu m^{-1}$) and, for solar radiation, the unit is W cm^{-2}. However, a variety of other units have been employed in the study of solar radiation and in terms of which various data are available. In Table 6-3 conversion factors are given for the various units that have been employed in the measurement of radiation. The langley (ly), which is equivalent to 1 gram-calorie* per square centimeter, is the metric unit of radiation now superseded by W m^{-2} in SI† (Refs. 6,7).

In SI, a system of names and symbols has been adopted to form decimal multiples and submultiples of units. Since these have limited familiarity and are extensively used in this chapter, they are given in Table 6-4.

Frequency in SI has the unit hertz (Hz) with the dimensions of inverse time (s^{-1}) replacing the older nomenclature, cycles per second (cps). Wavelength is measured in meters; for solar radiation this is nanometers (nm) and micrometers (μm). Much data are recorded in terms of microns (equal to micrometers) or in angstroms (1 nm = 10 Å). The latter unit is approved for use with SI units (Ref. 7). In SI, degrees are not employed as a unit of temperature but rather kelvins (K), which are equivalent to the formerly used "degrees kelvin" and are equal in magnitude to centigrade degrees.

In considering the energy associated with solar radiation, the energy per photon (quantum) of the radiation is important. Photon energies are normally expressed in electron volts (eV), i.e., the energy of an electron accelerated by a potential difference of 1 V. One electron volt is equal to 1.6×10^{-19} J since the charge on an electron is 1.6×10^{-19} coulombs (C) and 1 CV = 1 J.

Another energy unit commonly employed in photochemistry is the einstein. The einstein is the energy absorbed when each molecule of a gram-molecule of a substance absorbs one photon. The einstein is, therefore, a function of the wavelength of the radiation and is obtained by multiplying the photon energy by Avogadro's number, 6.06×10^{23}, the number of molecules in a gram-molecule. Thus, at a wavelength of 1.24 μm where the photon energy is 1 eV, the einstein has a value of 6.06×10^{23} eV or 9.70×10^{4} J (2.32×10^{4} calories); whereas, in the blue region (0.5 μm), the einstein has a value almost 2.5 times greater.

6-3 RADIATION PHYSICS

In the consideration of solar radiation, knowledge of the principles of radiation physics is essential. Such basic knowledge can be derived from any of a large variety of physics and engineering texts, e.g., King (Ref. 8). Only a brief outline will be given in this paragraph.

All matter radiates electromagnetic energy, some or all of which is directly dependent on temperature and is, therefore, thermal energy. In the absence of other mechanisms of heat transfer (conduction and convection), a system will have a surplus or deficit of radiation over absorption of energy until it is in thermal equilibrium with its surroundings. This thermal equilibrium is dynamic. Thermal energy is constantly radiated and absorbed; the net flow is zero.

In the earth-sun system, thermal equilibrium will never be attained (for all practical considerations) since the temperature of the sun (6,000 K) is considerably in excess of that of the earth (287 K) plus the fact that the source of solar energy is virtually inexhaustible. The earth is, however, in thermal equilibrium with its total surroundings, as attested by the fact that the mean temperature of the earth is constant for practical considerations.

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*The thermochemical calorie, 4.184 J, differs from the gram-calorie, 4.190 J, and is more commonly employed. The thermochemical calorie is used in Table 6-3.

†SI is the designation for the International System of Units in all languages, after the French, Systême International d'Unités.

TABLE 6-3

CONVERSION OF UNITS OF RADIATION

	mW cm^{-2}	W cm^{-2}	W m^{-2}	erg cm^{-2} s^{-1}	W ft^{-2}	cal cm^{-2} min^{-1}	cal cm^{-2} s^{-1}	Btu ft^{-2} hr^{-1}	Btu ft^{-2} s^{-1}	ly min^{-1}
mW cm^{-2}	1	10^{-3}	10	10^{4}	9.29×10^{-1}	1.43×10^{-2}	2.39×10^{-4}	3.17	8.81×10^{-4}	1.43×10^{-2}
W cm^{-2}	10^{3}	1	10^{4}	10^{7}	9.29×10^{2}	1.43×10	2.39×10^{-1}	3.17×10^{3}	8.81×10^{-1}	1.43×10
W m^{-2}	10^{-1}	10^{-4}	1	10^{3}	9.29×10^{-2}	1.43×10^{-3}	2.39×10^{-5}	3.17×10^{-1}	8.81×10^{-5}	1.43×10^{-3}
erg cm^{-2} s^{-1}	10^{-4}	10^{-7}	10^{-3}	1	9.29×10^{-5}	1.43×10^{-6}	2.39×10^{-8}	3.17×10^{-4}	8.81×10^{-8}	1.43×10^{-6}
W ft^{-2}	1.08	1.08×10^{-3}	1.08×10	1.08×10^{4}	1	1.54×10^{-2}	2.57×10^{-4}	3.42	9.49×10^{-4}	1.54×10^{-2}
cal cm^{-2} min^{-1}	6.97×10	6.97×10^{-2}	6.97×10^{2}	6.97×10^{5}	6.48×10	1	1.67×10^{-2}	2.22×10^{2}	6.15×10^{-2}	9.99×10^{-1}
cal cm^{-2} s^{-1}	4.18×10^{3}	4.18	4.18×10^{4}	4.18×10^{7}	3.89×10^{3}	60	1	1.33×10^{4}	3.69	5.99×10
Btu ft^{-2} hr^{-1}	3.15×10^{-1}	3.15×10^{-4}	3.15	3.15×10^{3}	2.92×10^{-1}	4.51×10^{-3}	7.52×10^{-5}	1	2.78×10^{-4}	4.51×10^{-3}
Btu ft^{-2} s^{-1}	1.13×10^{3}	1.13	1.13×10^{4}	1.13×10^{7}	1.05×10^{3}	1.63×10	2.71×10^{-1}	3.60×10^{3}	1	1.62×10
ly min^{-1}	6.97×10	6.97×10^{-2}	6.97×10^{2}	6.97×10^{5}	6.49×10	1.00	1.67×10^{-2}	2.22×10^{2}	6.15×10^{-2}	1

TABLE 6-4

SI PREFIXES

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{12}	tera	T	10^{-1}	deci	d
10^{9}	giga	G	10^{-2}	centi	c
10^{6}	mega	M	10^{-3}	milli	m
10^{3}	kilo	k	10^{-6}	micro	μ
10^{2}	hecto	h	10^{-9}	nano	n
10^{1}	deka	da	10^{-12}	pico	p
			10^{-15}	femto	f
			10^{-18}	atto	a

The intensity of radiation incident on a surface is its irradiancy; that leaving a surface is its radiancy, which consists of the sum of the reflected energy and the energy actually emitted by the system. The reflectivity r of a surface is the fraction of incident energy that is reflected. The emissivity e of a surface equals $1 - r$ when the system is in thermal equilibrium. A body for which r equals zero and e equals 1 is a blackbody. The absorptivity a of a body is the fraction of incident energy that is absorbed. Therefore, for a blackbody,

$$a = 1 - r = e = 1 \tag{6-2}$$

and a blackbody is a perfect absorber of radiant energy.

In calculating the temperature of the sun from its radiancy, it is assumed that the sun is a blackbody.

The Stefan-Boltzmann fourth-power law of radiation states that the true radiancy of a body R_s is given by

$$R_s = e\sigma T^4, \text{ nW m}^{-2} \tag{6-3}$$

where T is temperature in kelvins, and σ is the Stefan-Boltzmann constant

$$\sigma = 56.70 \text{ nW m}^{-2}\text{ K}^{-4} \tag{6-4}$$

To calculate the temperature of the sun, first the solar constant, 1353 W m^{-2} (see par. 6-4.1), is multiplied by the square of the ratio of the average earth-sun distance (149.6 Gm) to the radius of the sun (0.6970 Gm) to obtain the radiancy of the sun,

$$\begin{aligned} R_s &= 1353\,(149.6/0.6970)^2 \text{ W m}^{-2} \\ &= 62.33 \text{ MW m}^{-2} \end{aligned} \tag{6-5}$$

Substituting this value in Eq. 6-3 gives

$$\begin{aligned} T &= (R_s/e\sigma)^{1/4} \\ &= [6.233 \times 10^7/(5.670 \times 10^{-8})]^{1/4} \\ &= 5758 \text{ K} \end{aligned} \tag{6-6}$$

where the emissivity e is set equal to 1 under the assumption that the sun is a blackbody (Refs. 5,8).

The radiation emitted by a body is distributed over the spectrum in a form such as is shown in Fig. 6-2. This distribution is best described by Planck's law:

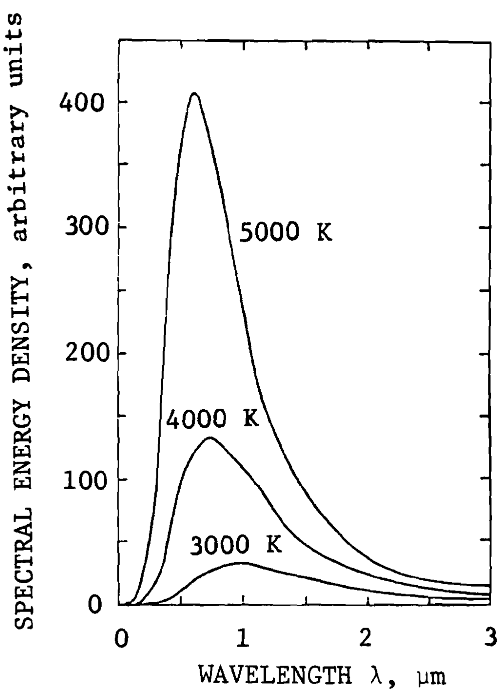

Figure 6-2. Spectral Energy Distribution in the Radiation From a Blackbody at Three Different Temperatures

$$U_\lambda = \frac{8\pi hc\lambda^{-5}}{\exp\,[hc/(k\lambda T)] - 1} \qquad (6\text{-}7)$$

where

U_λ = monochromatic energy density, J m^{-4}

c = speed of light, 2.998×10^8 m s^{-1}

λ = wavelength, m

k = Boltzmann's constant, 1.381×10^{-23} J K^{-1}

h = Planck's constant, 6.626×10^{-34} J s

As is illustrated in Fig. 6-2, the maximum energy density appears at a peak wavelength λ_m that depends on temperature, the relation between these being described by Wien's displacement law,

$$\lambda_m T = C \qquad (6\text{-}8)$$

where C, the Wien constant, equals 2.898 mm K.

From the peak wavelength, 0.47 μm, of the solar spectrum, the temperature of the sun can be calculated again,

$$T = C/\lambda_m = 2.898 \times 10^{-3}/(0.47 \times 10^{-6})$$

$$= 6166\,\text{K}. \qquad (6\text{-}9)$$

The difference between this value and that calculated in Eq. 6-6 for the temperature of the sun lies in the assumptions and in the difficulty in determining λ_m.

6-4 CHARACTERISTICS OF SOLAR RADIATION

The important characteristics of solar radiation are its intensity and spectral distribution as determined by solar radiation flux, geometry, atmospheric absorption, cloud cover, surface albedo, and transmission within materials. In the paragraphs that follow, these factors that affect the actual amount of solar radiation received by materiel on the surface of the earth are discussed.

6-4.1 SOLAR CONSTANT AND SPECTRUM*

In order to ascertain the effects of various environmental factors on solar radiation, it is necessary to know what the radiation would be at the position of the earth if the earth were not there to change it. The average irradiancy under these conditions is known as the solar constant S. The value of the solar constant is 135.3 mW cm^{-2} or 1.940 cal cm^{-2} min^{-1}. It is taken for a mean earth-sun distance of 1 AU (astronomical unit) equal to 1.496×10^{11} m and in the absence of the atmosphere of the earth. The estimated error is ± 2.1 mW cm^{-2} or ± 0.03 cal cm^{-2} min^{-1}. (The calorie is the thermochemical calorie and the milliwatt is 10^{-3} absolute joules per second). In Table 6-5, the solar constant is

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*A general reference for this paragraph is Ref. 5.

TABLE 6-5

VALUE OF THE SOLAR CONSTANT *S* IN VARIOUS UNITS

135.3 mW cm^{-2}
0.1353 W cm^{-2}
1353 W m^{-2}
1.353×10^{6} erg cm^{-2} s^{-1}
125.7 W ft^{-2}
1.940 cal cm^{-2} min^{-1}
0.0323 cal cm^{-2} s^{-1}
429.2 Btu ft^{-2} hr^{-1}
0.119 Btu ft^{-2} s^{-1}
1.937 ly min^{-1}

given in various units used either formerly or presently for irradiancy.

On the basis of the foregoing value of the solar constant, the values in Table 6-6 were derived to give the variation in total solar radiation† with changes in earth-sun distance during the year. Such variation can be determined with greater accuracy than can the absolute value of the solar constant.

In addition to the solar constant, the spectral irradiance of the sun is important since many effects depend on the wavelength or frequency of the incident energy. The spectral irradiance of the sun at a distance of 1 AU in the absence of the atmosphere of the earth is given in Table 6-7 and in Fig. 6-3. The estimated error in these values is ± 5 percent in the wavelength range of 0.3 to 3.0 μm. Outside these wavelength limits, the uncertainties are greater.

As can be seen in Table 6-7, the peak of the solar irradiancy is at 0.460 μm with an average value of 0.2066 W cm^{-2} μm^{-1}. In the table, the average irradiancy is given as P_λ. The total irradiancy, i.e., incident power, for all the wavelengths up to the wavelength A_λ in Table 6-7 is given, as is D_λ, the percent portion of the solar constant with wavelengths less than that listed.

The solar electromagnetic spectrum over the wavelength range 10^{-9} to 10 m is shown in Fig. 6-4. The *x*-axis shows the wavelength and associated frequency. The *y*-axis gives the solar spectral irradiance at a distance of 1 AU in the absence of the atmosphere of the earth. Both *x*- and *y*-axes are in log scale. For the wavelength range above 40 μm, the range of values on the *y*-axis changes three times, each time by six decades.

The spectral irradiance in the wavelength range 0.14 to 20 μm is based on the values given in Table 6-7. Other sources are used for $\lambda < 0.14$ μm and $\lambda > 20$ μm.

The spectral irradiance from a blackbody of the same radius as the sun at the distance of 1 AU is shown by the dashed curve in Fig. 6-4. Over most of the spectral range, the temperature chosen for the blackbody curve is 5,762 K. This is the temperature derived from the Stefan-Boltzmann equation corresponding to a solar constant value of 135.3 mW cm^{-2}. At the two extreme ends of the spectrum, other values of temperature more closely related to the brightness temperature have been used.

The spectral irradiance values in the range $\lambda < 0.14$ μm are based on Hinteregger's data (Ref. 10). In this range the solar spectrum consists of a large number of narrow emission lines superposed on a relatively weak continuum. Because this detailed structure cannot be shown adequately on the highly reduced wavelength scale of Fig. 6-4, the

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†The term total solar irradiance refers to total radiant energy received at a given distance, whereas the term solar constant describes the same parameter at 1 AU.

TABLE 6-6

ANNUAL VARIATION IN SOLAR CONSTANT

Date	Solar irradiance*, mW cm^{-2}
January 3 (perihelion)	139.9
February 1	139.3
March 1	137.8
April 1	135.5
May 1	133.2
June 1	131.6
July 1 (aphelion)	130.9
August 1	131.3
September 1	132.9
October 1	135.0
November 1	137.4
December 1	139.2

*The changes in earth-sun distance for the same date from year to year are such that values may vary ±0.1 mW cm^{-2}. For precise comparison, the table of radius vectors given in Ref. 9 should be consulted.

energy has been integrated over narrow bands of 5-mm width each. The irradiance values seem to change considerably during the solar cycle. Those given here are for medium solar activity.

In the range of 20 μm to 0.6 cm, the spectral curve has been computed from the values of brightness temperature quoted by Shimabukoro and Stacey (Ref. 11). An average wavelength-dependent brightness temperature has been derived from the best available information, and at each wavelength the corresponding irradiance has been computed.

For the microwave and radio range of $\lambda >$ 0.6 cm, the values listed by Allen (Ref. 12) have been used and curves have been drawn for four different types of solar energy emission.

As noted in par. 6-1, only the range from 100 nm (1000 Å) to 100 μm is of concern in this chapter.

6-4.2 GEOMETRIC FACTORS*

Two of the factors that determine the incident solar radiation on a terrestrial surface are primarily dependent on geometry. The first is the relative orientation and the distance between the sun and the earth. This factor determines the solar radiation on a plane surface at the top of the atmosphere. The second geometrical factor is the orientation and slope of surfaces. This enables the calculation of the radiation on any surface, given that on a horizontal surface.

Since the area of the surface of the earth (presumed a sphere) is four times the area of a flat circular disc that would intercept the same amount of solar radiation, the average radiation incident on the earth is 0.25 of the solar constant. This is for a horizontal surface at the top of the atmosphere and is an annual average over the entire surface.

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*Much of this paragraph is derived from *Physical Climatology* by W.D. Sellers (Ref. 3).

TABLE 6-7

SOLAR IRRADIANCE AT 1 AU (Ref. 4) (SOLAR CONSTANT OF 135.30 mW cm^{-2}) (SHEET 1 OF 2)

Wavelength λ, μm	Average Irradiance* P_λ, W cm^{-2} μm^{-1}	Area under curve, 0 to λ A_λ, mW cm^{-2}	Portion of solar constant with wavelength $< \lambda$ D_λ, %
0.120	0.000010	0.00059993	0.00044
0.140	0.000003	0.00073000	0.00054
0.150	0.000007	0.00072000	0.00058
0.160	0.000023	0.00093000	0.00069
0.170	0.000063	0.00135000	0.00101
0.180	0.000125	0.00230000	0.00170
0.190	0.000271	0.00428000	0.00316
0.200	0.00107	0.010985	0.0081
0.210	0.00229	0.027785	0.0205
0.220	0.00575	0.067985	0.0502
0.225	0.00649	0.098585	0.0729
0.230	0.00667	0.131485	0.0972
0.235	0.00593	0.162985	0.1205
0.240	0.00630	0.193560	0.1430
0.245	0.00723	0.227385	0.1681
0.250	0.00704	0.263060	0.1944
0.255	0.0104	0.306660	0.2267
0.260	0.0130	0.365160	0.270
0.265	0.0185	0.443910	0.328
0.270	0.0232	0.548160	0.405
0.275	0.0204	0.657160	0.486
0.280	0.0222	0.763660	0.564
0.285	0.0315	0.897910	0.644
0.290	0.0482	0.09716	0.811
0.295	0.0584	1.36366	1.008
0.300	0.0514	1.63816	1.211
0.305	0.0603	1.91741	1.417
0.310	0.0689	2.24041	1.656
0.315	0.0764	2.60366	1.924
0.320	0.0330	3.00216	2.219
0.325	0.0975	3.45341	2.552
0.330	0.1059	3.96191	2.928
0.335	0.1061	4.49691	3.324
0.340	0.1074	5.03566	3.722
0.345	0.1069	5.57141	4.118
0.350	0.1093	6.11191	4.517
0.355	0.1083	6.65591	4.919
0.360	0.1068	7.19366	5.317
0.365	0.1132	7.74366	5.723
0.370	0.1181	8.32191	6.151
0.375	0.1157	8.90641	6.583
0.380	0.1120	9.47566	7.003
0.385	0.1098	10.0302	7.413
0.390	0.1098	10.5792	7.819
0.395	0.1189	11.1509	8.242
0.400	0.1429	11.8054	8.725
0.405	0.1644	12.5737	9.293
0.410	0.1751	13.4224	9.920
0.415	0.1774	14.3037	10.572
0.420	0.1747	15.1839	11.222
0.425	0.1693	16.0439	11.858
0.430	0.1639	16.8769	12.474
0.435	0.1663	17.7024	13.084
0.440	0.1810	18.5707	13.726
0.445	0.1922	19.5037	14.415
0.450	0.2006	20.4857	15.141
0.455	0.2057	21.5014	15.892
0.460	0.2066	22.5322	16.653
0.465	0.2048	23.5607	17.414
0.470	0.2033	24.5809	18.168
0.475	0.2044	25.6002	18.921
0.480	0.2074	26.6297	19.682
0.485	0.1976	27.6422	20.430
0.490	0.1950	28.6237	21.156
0.495	0.1960	29.6012	21.878
0.500	0.1942	30.5767	22.599
0.505	0.1920	31.5422	23.313
0.510	0.1882	32.4927	24.015
0.515	0.1833	33.4214	24.702
0.520	0.1833	34.3379	25.379
0.525	0.1852	35.2592	26.060
0.530	0.1842	36.1827	26.743
0.535	0.1818	37.0977	27.419
0.540	0.1783	37.9979	28.084
0.545	0.1754	38.8822	28.738
0.550	0.1725	39.7519	29.381
0.555	0.1720	40.6132	30.017
0.560	0.1695	41.4669	30.648
0.565	0.1705	42.3169	31.276
0.570	0.1712	43.1712	31.908
0.575	0.1719	44.0289	32.542
0.580	0.1715	44.8874	33.176
0.585	0.1712	45.7442	33.809
0.590	0.1700	46.5972	34.440
0.595	0.1682	47.4427	35.065
0.600	0.1666	48.2797	35.683
0.605	0.1647	49.1079	36.296
0.610	0.1635	49.9284	36.902
0.620	0.1602	51.5469	38.098
0.630	0.1570	53.1329	39.270
0.640	0.1544	54.6899	40.421
0.650	0.1511	56.2174	41.550
0.660	0.1486	57.7159	42.658
0.670	0.1456	59.1869	43.745
0.680	0.1427	60.6284	44.810
0.690	0.1402	62.0429	45.856
0.700	0.1369	63.4284	46.880
0.710	0.1344	64.7849	47.882
0.720	0.1314	66.1139	48.865
0.730	0.1290	67.4159	49.827

*Spectral irradiance averaged over small bandwidth centered at λ:

0.3 to 0.75 μm (bandwidth, 100 Å)

0.75 to 1.0 μm (bandwidth, 500 Å)

1.0 to 5.0 μm (bandwidth, 1000 Å)

Because of the annual variation in solar declination, the actual incident radiation varies over the year as is shown in Fig. 6-5. This figure is from the *Smithsonian Meteorological Tables* (Ref. 13) and employs cal cm^{-2} as the units of solar energy density. In these units the solar constant is 1.940 cal cm^{-2} min^{-1} as given in Table 6-5; the daily solar constant is 2,793.6 cal cm^{-2} day^{-1}. One-fourth of this, the worldwide annual average, is, therefore, 698.4 cal cm^{-2} day^{-1}. As seen in Fig. 6-5, the actual top-of-the-atmosphere value exceeds 1,100 cal cm^{-2} day^{-1} for over 1 mo in the Antarctic at the time of the winter solstice and the average is exceeded at the equator throughout the year.

The geometrical considerations relative to the calculations for Fig. 6-5 are illustrated in Fig. 6-6. The following definitions are necessary:

TABLE 6-7 (Continued)

SOLAR IRRADIANCE AT 1 AU (Ref. 4) (SOLAR CONSTANT OF 135.30 mW cm^{-2}) (SHEET 2 OF 2)

Wavelength λ, μm	Average Irradiance* P_λ, W $cm^{-2} \mu m^{-1}$	Area under curve, 0 to λ A_λ, mW cm^{-2}	Portion of solar constant with wavelength < λ D_λ, %
0.740	0.1260	68.6909	50.769
0.750	0.1235	69.9384	51.691
0.800	0.1107	75.7934	56.019
0.850	0.0988	81.0309	59.890
0.900	0.0889	85.7234	63.358
0.950	0.0835	90.0334	66.544
1.000	0.0746	93.9859	69.465
1.100	0.0592	100.676	74.409
1.200	0.0484	106.056	78.386
1.300	0.0396	110.456	81.638
1.400	0.0336	114.116	84.343
1.500	0.0287	117.231	86.645
1.600	0.0244	119.886	88.607
1.700	0.0202	122.116	90.256
1.800	0.0159	123.921	91.590
1.900	0.0126	125.346	92.643
2.000	0.0103	126.491	93.489
2.100	0.0090	127.456	94.202
2.200	0.0079	128.301	94.827
2.300	0.0068	129.036	95.370
2.400	0.0064	129.696	95.858
2.500	0.0054	130.286	96.294
2.600	0.0048	130.796	96.671
2.700	0.0043	131.251	97.007
2.800	0.00390	131.661	97.3104
2.900	0.00350	132.031	97.5838
3.000	0.00310	132.361	97.8277
3.100	0.00260	132.646	98.0384
3.200	0.00226	132.889	98.2180
3.300	0.00192	133.098	98.3724
3.400	0.00166	133.277	98.5047
3.500	0.00146	133.433	98.6200
3.600	0.00135	133.573	98.7239
3.700	0.00123	133.702	98.8192
3.800	0.00111	133.819	98.9057
3.900	0.00103	133.926	98.9848
4.000	0.00095	134.025	99.0580
4.100	0.00087	134.116	99.1252
4.200	0.00078	134.199	99.1862
4.300	0.00071	134.273	99.2412
4.400	0.00065	134.341	99.2915
4.500	0.00059	134.403	99.3373
4.600	0.00053	134.459	99.3787
4.700	0.00048	134.510	99.4160
4.800	0.00045	134.556	99.4504
4.900	0.00041	134.599	99.482195
5.000	0.0003830	134.63906	99.511500
6.000	0.0001750	134.91806	99.717709
7.000	0.0000990	135.05506	99.818965
8.000	0.0000600	135.13456	99.877724
9.000	0.0000380	135.18356	99.913939
10.000	0.0000250	135.21506	99.937221
11.000	0.0000170	135.23606	99.952742
12.000	0.0000120	135.25056	99.963459
13.000	0.0000087	135.26091	99.971109
14.000	0.0000055	135.26801	99.976356
15.000	0.0000049	135.27321	99.980200
16.000	0.0000038	135.27756	99.983415
17.000	0.0000031	135.28101	99.985965
18.000	0.0000024	135.28376	99.987997
19.000	0.0000020	135.28596	99.989623
20.000	0.0000016	135.28776	99.990953
25.000	0.000000610	135.29328	99.995037
30.000	0.000000300	135.29556	99.996718
35.000	0.000000160	135.29671	99.997568
40.000	0.000000094	135.29735	99.998038
50.000	0.000000038	135.29801	99.998525
60.000	0.000000019	135.29829	99.998736
80.000	0.000000007	135.29855	99.998928
100.000	0.000000003	135.29865	99.999002
1000.000	0.000000000	135.30000	100.000000

*Spectral irradiance averaged over small bandwidth centered at λ:

0.3 to 0.75 μm (bandwidth, 100 Å)

0.75 to 1.0 μm (bandwidth, 500 Å)

1.0 to 5.0 μm (bandwidth, 1000 Å)

(1) *Zenith angle Z.* Angular distance of the sun from the local vertical of a point.

(2) *Hour angle H.* Angle through which the sun must turn to bring the meridian of the point directly under the sun.

(3) *Solar declination angle D.* Angle between axis of rotation of the earth and normal to plane of orbit about sun; also the angle between rays of the sun and plane of equator.

(4) *Latitude L.* Angular distance north or south of the equator of the earth.

(5) *Azimuth A.* A horizontal direction expressed as the angular distance between the direction of a fixed point and the direction of an object; in this case, the angle between south and the horizontal direction of the sun.

As given in Eq. 6-1, the zenith angle Z is

$$\cos Z = \sin L \sin D + \cos L \cos D \cos H.$$

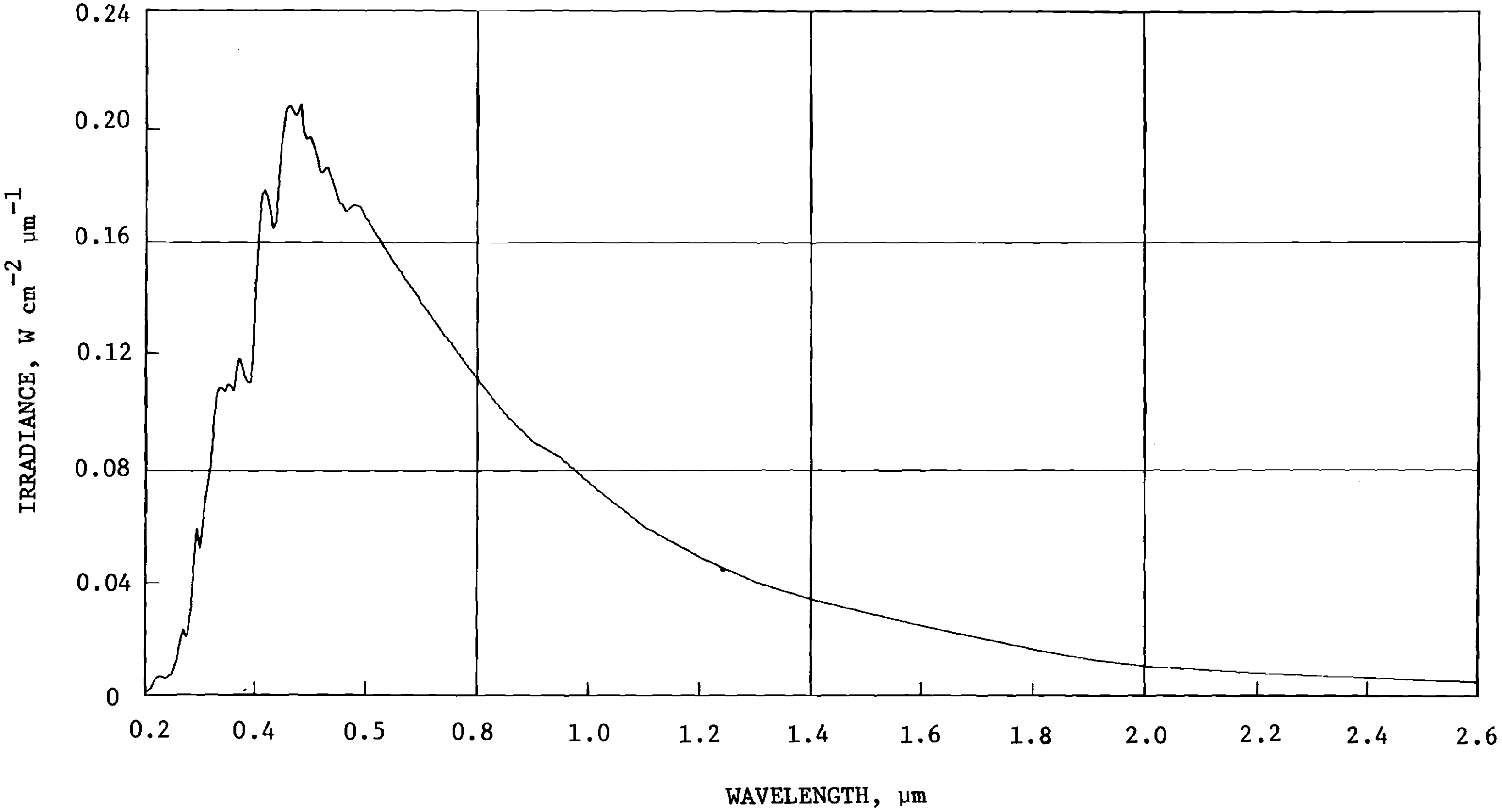


Figure 6-3. Solar Spectral Irradiance (Ref. 5)

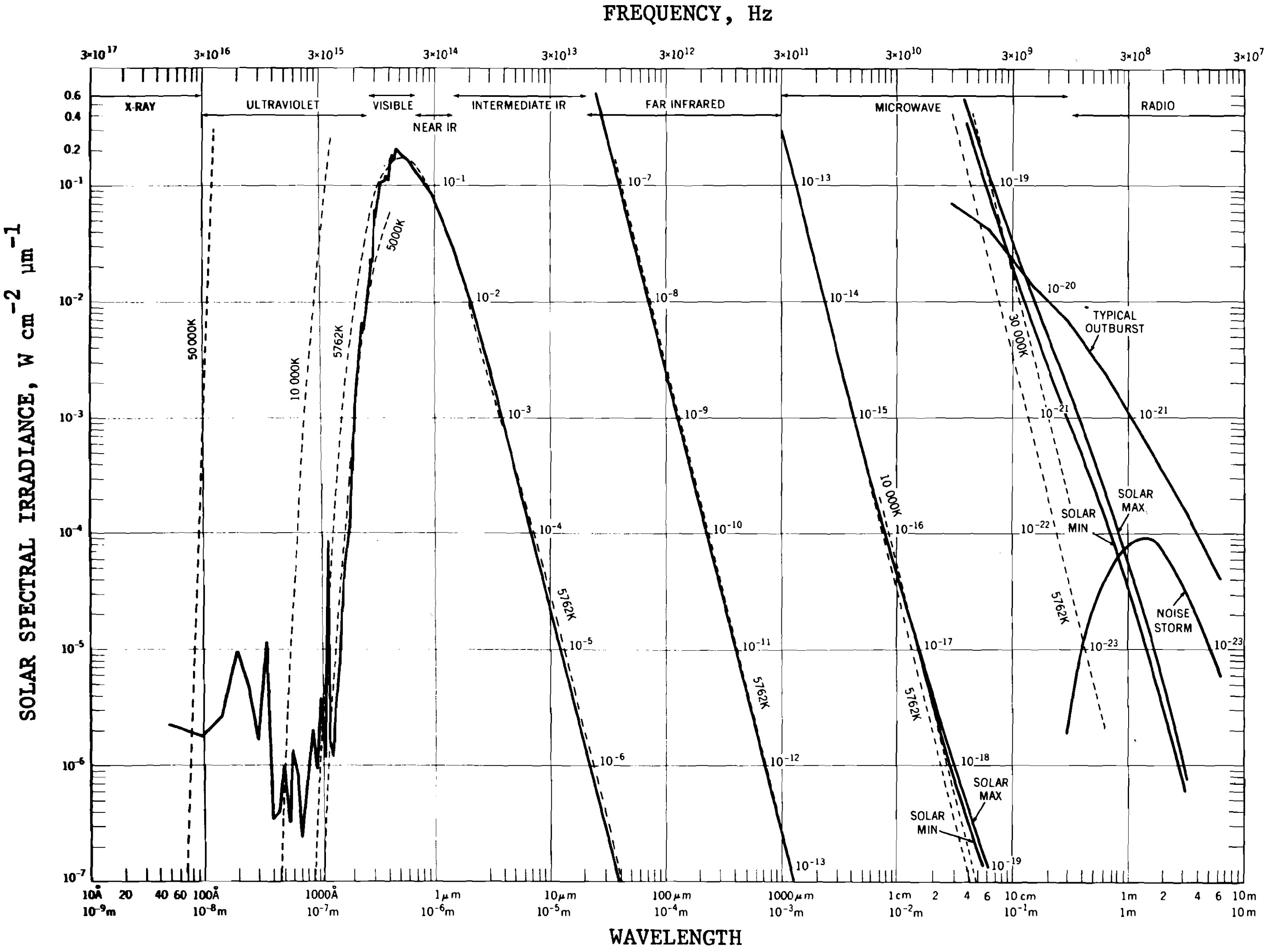


Figure 6-4. The Solar Electromagnetic Spectrum (Ref. 5)

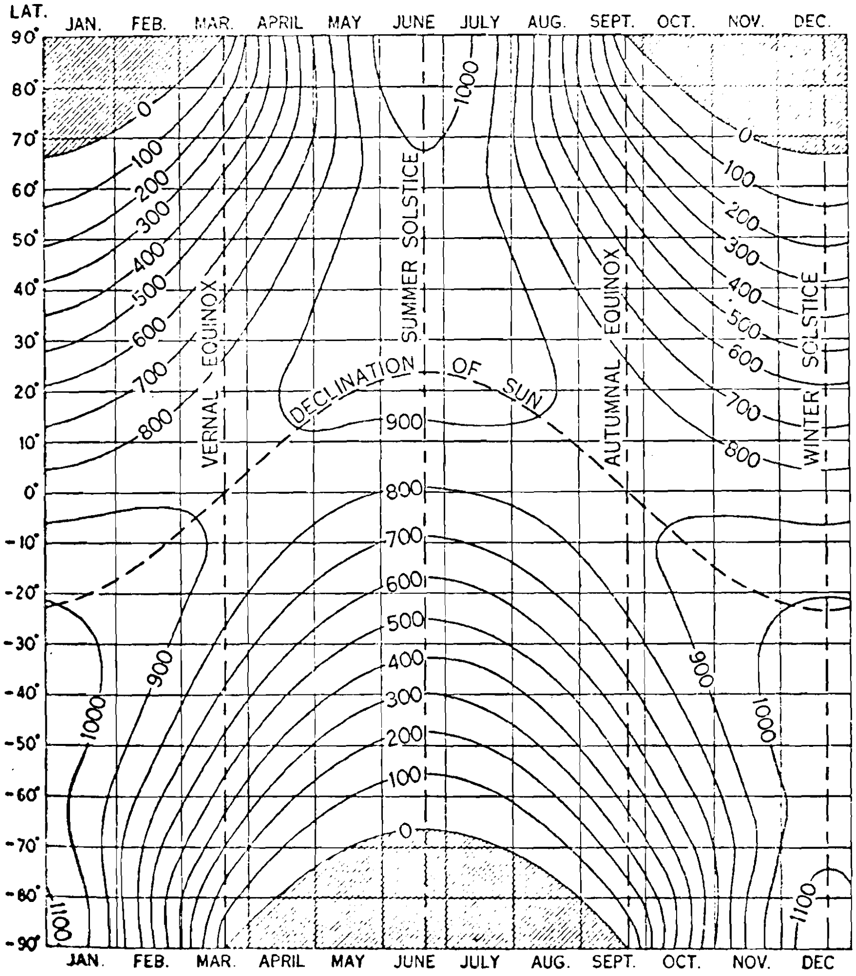


Figure 6-5. Daily Solar Radiation at the Top of the Atmosphere (Solid curves are in units of cal cm^{-2} day^{-1}; shaded areas represent continuous darkness.) (Ref. 13)

From this, it can be seen that at the poles where $L = \pi/2$ rad, $\cos L = 0$ and $\sin L = 1$, so that $\cos Z = \sin D$. Thus, at the poles, the elevation angle of the sun (complement of the zenith angle) is always equal to the solar declination angle.

At the solar noon, $H = 0$, $\cos H = 1$, and the zenith angle is the difference between the latitude and declination angles.

At sunrise and sunset, at any latitude except the poles, $Z = \pi$, $\cos Z = 0$, and $\cos H_{1/2} = -\operatorname{Tan} L \tan D$ where $H_{1/2}$ is now the half-day angle. For $H_{1/2} = \pi/2$ rad (half-day length of 6 hr), either $\tan L$ or $\tan D$ must equal zero. The latitude angle L is zero at the equator so the half-day length is always 6 hr there. The declination angle D is equal to zero at the time of the equinoxes.

The azimuth angle A of the sun with respect to south is given by either

$$\sin A = \frac{\cos D \sin H}{\sin Z} \tag{6-10}$$

or

$$\cos A = \frac{\sin L \cos Z - \sin D}{\cos L \sin Z} \tag{6-11}$$

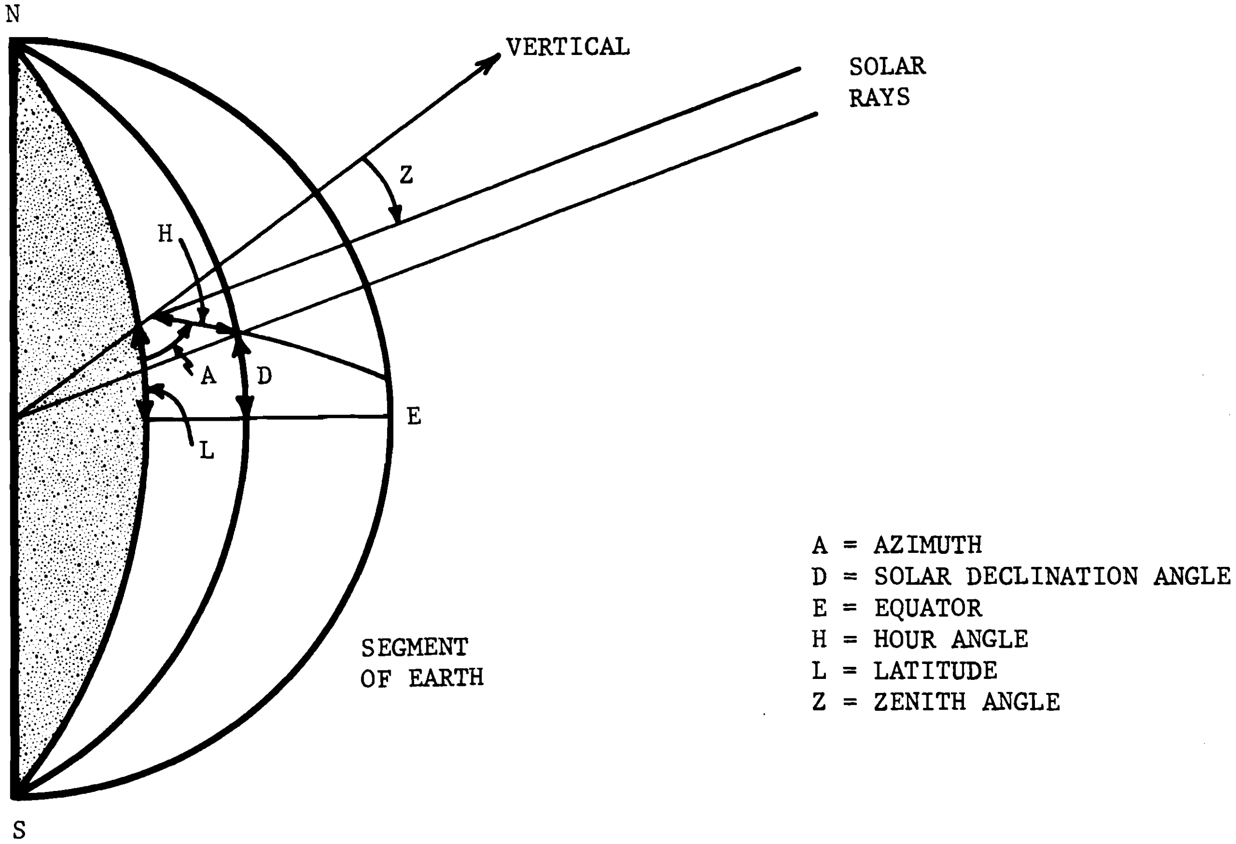


Figure 6-6. Geometrical Model for Calculation of Solar Radiation Distribution on Earth

At sunrise and sunset, the zenith angle is $\pi/2$ rad, $\cos Z = 0$, $\sin Z = 1$, and $H = H_{1/2}$.

Also

$$\sin A_{1/2} = \cos D \sin H_{1/2} \qquad (6\text{-}12)$$

and

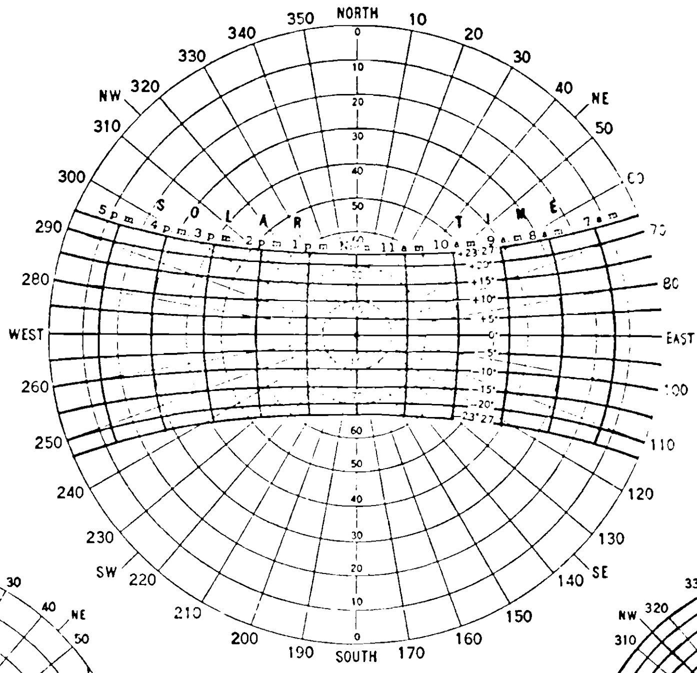
$$\cos A_{1/2} = -\frac{\sin D}{\cos L} \qquad (6\text{-}13)$$

give the azimuth angles. Convenient charts of solar azimuth are given in the *Smithsonian Meteorological Tables* (Ref. 13), examples of which are given in Fig. 6-7. In these, the azimuth of the sun is given as a function of solar time, solar declination, and latitude.

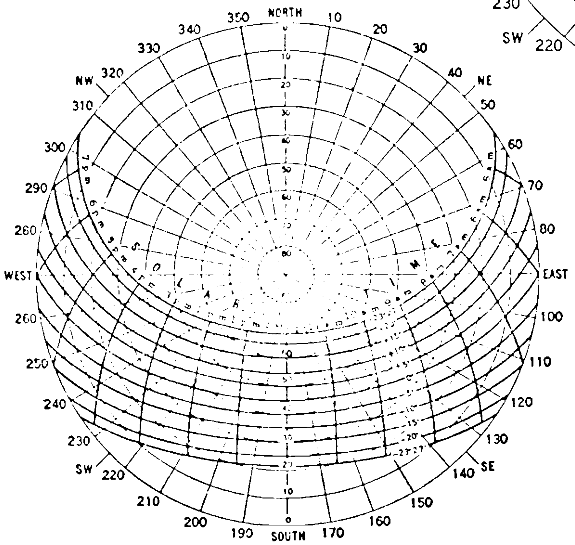
Solar time is related to local mean time in a complicated but cyclic manner. Corrections to be applied to local mean time to obtain true solar time are tabulated in the ephemeris (Ref. 9). A sample of data from the ephemeris is given in Table 6-8 to illustrate its form, the magnitude of the equation of time, and other parameters of the earth-sun relative motion. Local civil time is the mean time for a standard meridian, usually one which is a multiple of 15 deg east or west of Greenwich. Local mean time is obtained by noting the longitude, the longitude of the standard meridian, and applying a correction factor of 4 min for every degree to the local civil time.

To calculate the amount of solar radiation on a plane surface at the top of the atmosphere, the equation is

$$Q_a = S\left(\frac{\bar{d}}{d}\right)^2 \cos Z \qquad (6\text{-}14)$$

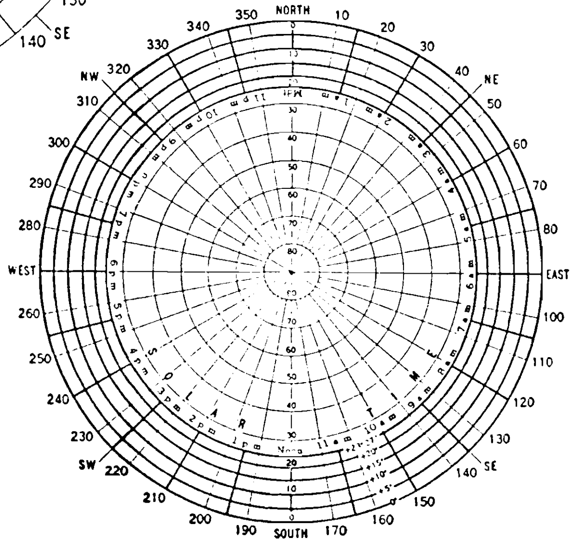


(B) 0°



(A) 45° N

Declination	Approx. dates
+23° 27′	June 22
+20°	May 21, July 24
+15°	May 1, Aug. 12
+10°	Apr. 16, Aug. 28
+ 5°	Apr. 3, Sept. 10
0°	Mar. 21, Sept. 23
− 5°	Mar. 8, Oct. 6
−10°	Feb. 23, Oct. 20
−15°	Feb. 9, Nov. 3
−20°	Jan. 21, Nov. 22
−23° 27′	Dec. 22



(C) 90° N

Figure 6-7. Examples of Solar Azimuth Charts (Ref. 13)

TABLE 6-8

1950 EPHEMERIS OF THE SUN (Ref. 13)

Date	Declination		Longitude		Equation of time		Radius vector
	deg	min	deg	min	min	s	
Jan. 1	-23	4	280	1	- 3	14	0.98324
Jan. 17	-20	54	296	19	- 9	54	0.98378
Feb. 1	-17	19	311	34	-13	34	0.98533
Feb. 17	-12	15	327	46	-14	10	0.98819
Mar. 1	- 7	53	339	51	-12	38	0.99084
Mar. 17	- 1	39	355	50	- 8	42	0.99508
April 1	+ 4	14	10	42	- 4	12	0.99928
April 17	+10	12	26	25	+ 0	13	1.00390
May 1	+14	50	40	4	+ 2	50	1.00739
May 17	+19	9	55	32	+ 3	44	1.01138
June 1	+21	57	69	56	+ 2	27	1.01405
June 17	+23	22	85	15	- 0	33	1.01602
July 1	+23	10	98	36	- 3	31	1.01667
July 17	+21	21	113	51	- 5	57	1.01639
Aug. 1	+18	14	128	11	- 6	17	1.01494
Aug. 17	+13	41	143	31	- 4	12	1.01244
Sept. 1	+ 8	35	157	59	- 0	15	1.00917
Sept. 17	+ 2	34	173	32	+ 5	10	1.00510
Oct. 1	- 2	53	187	14	+10	1	1.00114
Oct. 17	- 8	58	203	3	+14	25	0.99659
Nov. 1	-14	11	217	59	+16	21	0.99249
Nov. 17	-18	48	234	4	+15	10	0.98869
Dec. 1	-21	41	248	13	+11	16	0.98604
Dec. 17	-23	20	264	28	+ 4	17	0.98405

Notes: All data are for 0000 hr Greenwich Civil Time in the year 1950. For meteorological purposes, variations from year to year are negligible but larger variations occur in a 4-yr cycle (leap-year). The declination of the sun is the angular distance north (+) or south (-) of the celestial equator. The longitude of the sun is the angular distance of the meridian of the sun from the vernal equinox measured eastward along the elliptic. The equation of time (apparent-mean) is the correction to be applied to mean solar time in order to obtain apparent (true) solar time. The radius vector of the earth is the distance from the center of the earth to the center of the sun expressed in terms of the length of the semimajor axis of the orbit of the earth.

where

Q_a = instantaneous solar radiation per unit area

S = solar constant

d and $\bar{d}$ = instantaneous and mean distance of the earth from the sun, respectively (Table 6-8)

In order to obtain the average daily radiation, it is necessary to integrate this equation over the time of sunlight. The result is as given in Fig. 6-5.

In calculating the solar radiation on an arbitrary surface, it is assumed that solar radiation Q_e on a horizontal surface is known. Q_e is Q_a decreased by atmospheric attenuation and reflection as discussed in par. 6-4.3. Using the geometry of Fig. 6-8, a vertical surface will have direct beam solar radiation Q_v given by

$$Q_v = Q_e \tan Z \cos (A - A') \qquad (6\text{-}15)$$

The instantaneous solar radiation Q on a sloping surface with angle θ as shown in Fig. 6-9 is given by

$$Q = Q_e [\cos \theta + \tan Z \sin \theta \cos (A - A')] \qquad (6\text{-}16)$$

The variation of this instantaneous rate with slope, azimuth, time of year, and time of day has been graphically plotted by Sellers (Ref. 3) and Geiger (Ref. 14).

6-4.3 ATMOSPHERIC ABSORPTION AND REFLECTION

Of the solar energy incident on the earth at the top of the atmosphere, only a portion reaches the surface of the earth. The disposition of solar radiation is discussed by Sellers (Ref. 3), Geiger (Ref. 14), and Gates (Ref. 15). Table 6-9 lists the major flow paths for solar energy on its way to the surface of the earth.

Atmospheric reflection and absorption as given in Table 6-9 are global averages. At any one point, the solar radiation reaching the surface of the earth is dependent on:

(1) Cloud cover

(2) Air mass through which the radiation passes

(3) Atmospheric aerosol concentration

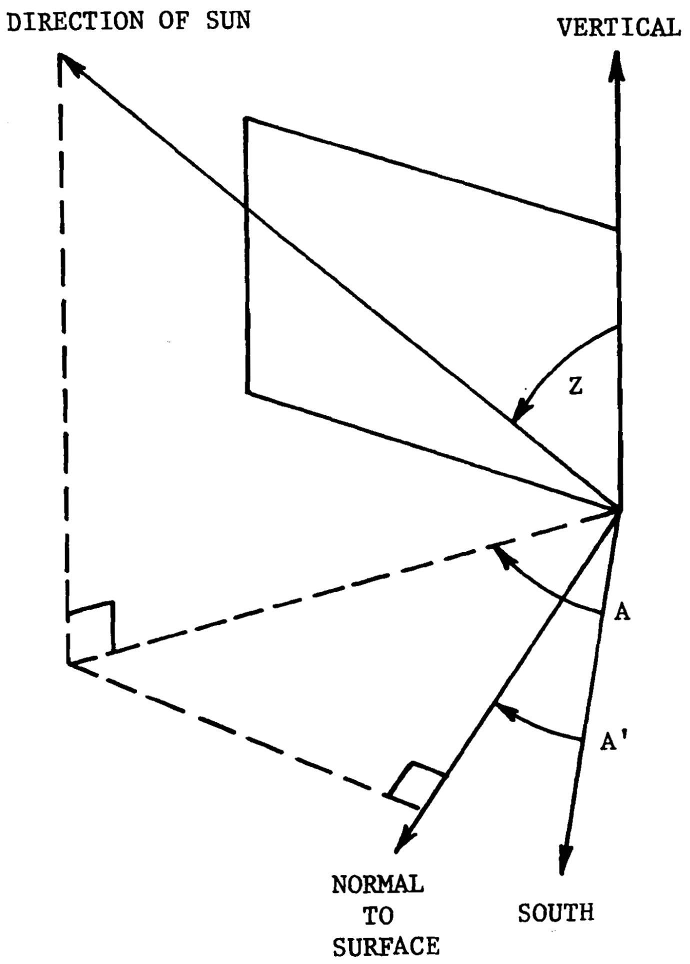
(4) Precipitable water content of the atmosphere

(5) Elevation of the surface above mean sea level.

As is evident in satellite photography, the clouds reflect a considerable amount of the incident energy back into space. Clouds may reflect between 50 and 90 percent of the radiation incident on them. The cumulative global average of 24 percent of incident solar energy that is reflected by clouds is determined by the average extent and the nature of the cloud cover. Individual clouds do not absorb as much radiation as they scatter and reflect. The average absorption is close to 10 percent (Ref. 15) but the global average for solar energy absorption by clouds is on the order of 3 percent of the total solar radiation incident on the earth.

Air molecules and atmospheric aerosols scatter about 6 percent of the radiation back into space. Absorption by these atmospheric constituents is more important. At wavelengths below 0.3 μm, virtually all of the incident radiation is absorbed by oxygen and ozone—none of this radiation reaches the surface. At wavelengths greater than 0.7 μm, the water vapor and carbon dioxide in the air are strong absorbers.

Scattering is most effective for the shortest wavelengths. During cloudless and dustfree periods when the sun is at its zenith, more than 50 percent of blue radiation is scattered, while almost all red radiation is transmitted.



Z = SOLAR ZENITH ANGLE

A = AZIMUTH ANGLE OF SUN FROM SOUTH

A' = AZIMUTH ANGLE OF SURFACE NORMAL FROM SOUTH

Figure 6-8. Solar Radiation on a Vertical Surface

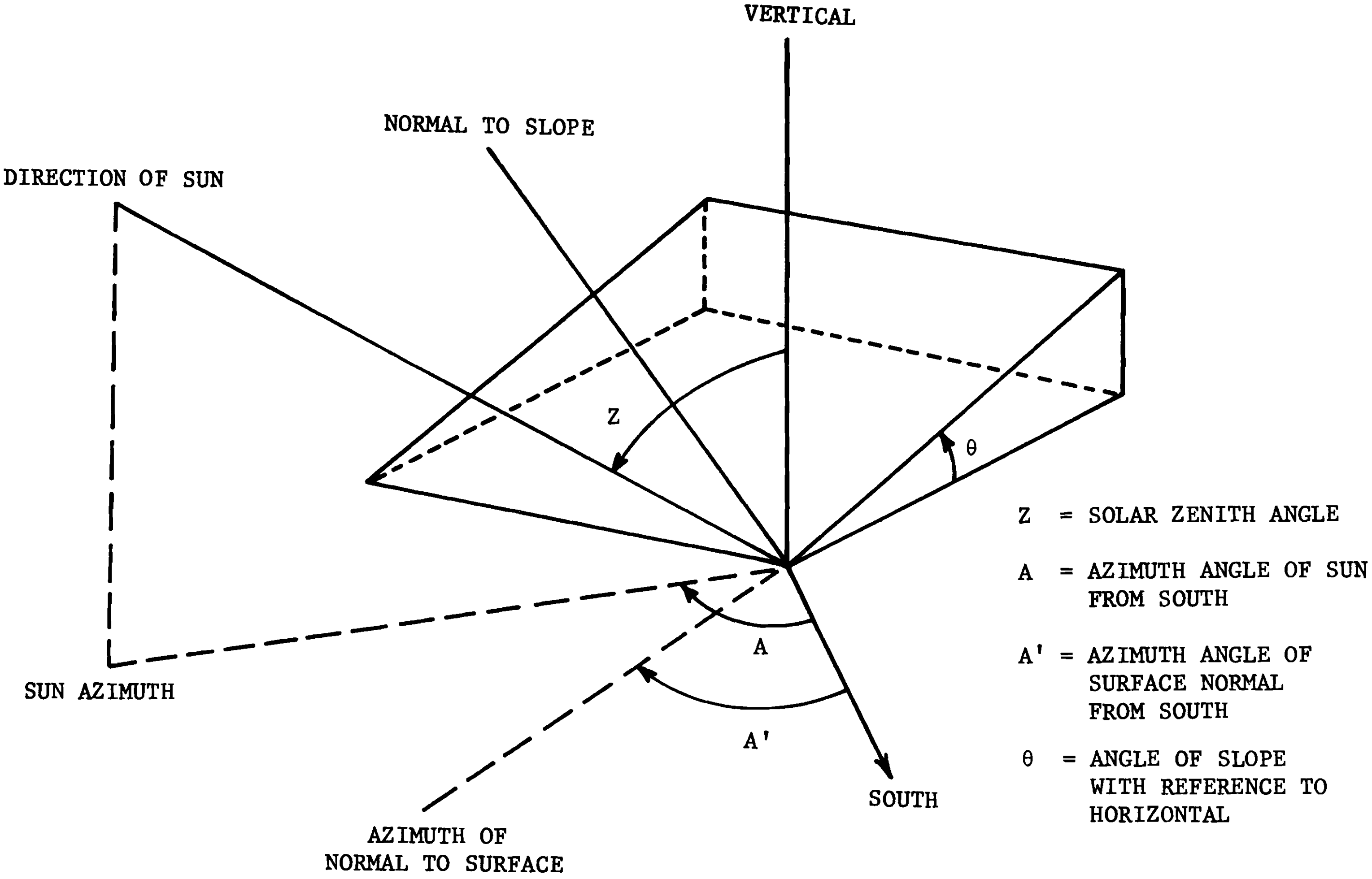


Figure 6-9. Solar Radiation on a Slope

TABLE 6-9

DISPOSITION OF SOLAR ENERGY (Ref. 14)

	Fraction of total
Reflected or scattered back into space	
By clouds	0.24
By air molecules, dust, water vapor	0.06
Absorbed	
By clouds	0.03
By air molecules, dust, water vapor	0.14
Reaches earth	
As diffuse sky radiation	0.22
As direct beam radiation	0.31
Total solar energy available at top of atmosphere	1.00

This accounts for the predominantly blue color of the sky. When the sun is low on the horizon in the morning and evening, the number of air molecules in the path of the incoming solar rays is highest. The smaller number of air molecules in the path of solar rays similarly accounts for the more brilliant tropical noonday sun as compared to the noonday sun at high latitudes. Very fine dust, smoke, and other types of atmospheric pollution cause the sun to appear as a red ball even at noon, and consequently decrease the net radiation reaching the surface of the earth (Ref. 16).

Reflection of solar radiation is caused by particles in the atmosphere, such as water droplets, ice crystals, dust, and various products of combustion. In contrast to scattering, no discrimination exists between different wavelengths of the incident light. Nearly all of the solar ray is reflected and only a small portion is absorbed by the particles. Therefore, reflection affects the total light intensity, not the color of the sky. Clouds account for most of the reflection.

The actual solar radiation reaching the surface of the earth depends on a variety of factors. The transparency of the atmosphere for solar radiation exists only because of a distinct frequency separation of the absorption processes of nature. The short-wavelength, high-frequency absorption bands are associated with electronic transitions, and the long-wavelength, low-frequency absorption bands are associated with transitions in vibrational and rotational states of atoms within molecules. These different transitions seldom overlap in energy and, for the relatively simple gases comprising the atmosphere of the earth, a convenient frequency gap in the visible region exists through which sunlight streams to warm and illuminate the surface of the earth. Through gaps in the absorption band associated with vibrational and rotational transitions in atmospheric gases at infrared wavelengths, the surface radiates energy to space (Ref. 15).

With the sun at a zenith angle of zero degrees, solar radiation passes through a minimum of the atmosphere to reach the surface. At other angles, the transmission path is longer and attenuation is greater. The airmass is defined as the ratio of the length of a slant path to the length of a vertical path; for zenith angles of less than 72 deg, the airmass is equal to the secant of the zenith angle. For larger angles, correction must be made for atmospheric refraction of the solar rays.

Gates has adopted as reference values for 1 airmass: 10.0 mm of precipitable water as the total in the zenith air column, a surface aerosol concentration of 200 particles per cubic centimeter, and the total amount of ozone as 0.35 cm expressed as the height of ozone in the air column as if it were all concentrated in the base at atmospheric pressure (Ref. 15). For a zenith angle of 60 deg, the airmass is 2 and reaches 8 at an angle of 83 deg 12 min.

The elevation also affects the equivalent path of radiation passing through the atmosphere. In calculations, this is most conveniently compensated for by multiplying the airmass as determined from the zenith angle by the ratio of actual atmospheric pressure to standard atmospheric pressure.

Atmospheric aerosols consist of condensed water droplets as found in clouds and solid particles originating in natural processes that inject dust and salt particles into the atmosphere and in air pollution. In urbanized regions, the aerosols originating in air pollution sources can double the solar attenuation in the layer of the atmosphere closest to the earth (Ref. 17).

In the longer, near infrared, wavelengths, absorption by water vapor and carbon dioxide dominates the attenuation of solar radiation. These absorptions, which collectively form absorption bands, are the result of quantum transitions in vibrational and rotational states of the molecules. Each absorption band is comprised of hundreds of narrow individual absorption lines, which merge to form the band. Even in the windows between the bands, the wings of these numerous lines contribute a definite amount to the continuum extinction. The extinction coefficients for the infrared absorption bands and for the windows between the bands have been derived from direct observation of the solar spectrum. These values are expressed as a function of the total amount of water vapor, in the zenith direction, between the surface of the earth and space, known as the "precipitable water". The amount of precipitable water, in centimeters, is the thickness of liquid water that would be formed if all the water in the zenith direction were condensed at the surface. An extremely dry atmosphere may contain as little as 0.1 cm of precipitable water, and a very humid atmosphere, as much as 3.0 cm. A very frequently occurring amount is 1.0 cm at sea level locations. The amount of water vapor in the sky is one of the most variable of all the atmospheric constituents; therefore, the infrared solar radiation at the surface varies considerably. The infrared extinction is comprised of two parts: (1) a continuum extinction at all frequencies, caused by scattering and the wings of water vapor and carbon dioxide absorption lines, and (2) a selective absorption within each individual line contributing to the total absorption band (Ref. 15).

6-4.4 RADIATIVE PROCESSES AT THE SURFACE

Solar radiation that reaches the surface of the earth can be either absorbed or reflected. Absorption provides energy to the terrestrial environment and produces various other effects that are described in par. 6-7. Reflection causes radiation to reenter the atmosphere to be scattered, absorbed, or returned to space. In addition, the absorbed energy that is reradiated to the atmosphere and the atmospheric radiation play important roles in the radiation balance at the surface.

The ratio of the amount of electromagnetic energy reflected by a body to the amount incident upon it is known as the albedo of the surface. Reflectivity of a surface is properly employed to describe the albedo at a specific wavelength. Albedos vary widely with differences in surfaces, generally being lower for wet or dark surfaces. Albedos depend on other factors in addition to the color of the surface. These factors include the angle of incidence of the radiation, the texture of the

TABLE 6-10

TYPICAL ALBEDOS (Ref. 3)

Water surfaces	0.06-0.21
Fresh snow	0.75-0.95
Old snow	0.40-0.70
Sea ice	0.30-0.40
Dry sand	0.35-0.45
Wet sand	0.20-0.30
Soil	0.10-0.45
Dry concrete	0.17-0.27
Blacktop road	0.05-0.10
Savanna, dry season	0.25-0.30
Savanna, wet season	0.15-0.20
Chaparral	0.15-0.20
Green meadow	0.10-0.20
Decidious forest	0.10-0.20
Coniferous forest	0.05-0.15
Tundra	0.15-0.20
Cropland	0.15-0.25
Human skin, blonde	0.43-0.45
Human skin, brunette	0.35
Human skin, dark	0.16-0.22

surface, and the spectral nature of the radiation. Typical values are given in Table 6-10.

For direct solar radiation, the albedo of a plane surface as a function of angle is calculable from optical principles employing the laws of Snell and Fresnel (Ref. 18). The values obtained are poor approximations to naturally occurring values, examples of which are shown in Fig. 6-10. The dependence of albedo on angle of incidence is evident in its latitudinal dependence. The average albedo of water surfaces can vary from 0.06 to 0.21 with an increase from 0 to 60 deg in latitude.

The albedo of surfaces for the diffuse portion of the solar radiation is important since, of the total incident radiation, 22 percent reaches the surface as diffuse radiation as compared to 31 percent as direct solar rays. Unless otherwise specified, albedos include both the direct and diffuse components. Anderson (Ref. 19) calculated the total diffuse solar radiation albedo to be 0.17. Measurements are generally lower because of the difficulty in separating the direct solar rays.

The dependence of albedo on angle of incidence is important in calculating the heat budget of snow-covered polar regions and the energy budget of slopes and irregular land features. It is not important for vegetation or for forested regions.

The texture of the surface affects the albedo for much the same reasons as the angle of incidence does. A plowed field has a much lower albedo than does an unplowed field because, even though the average angle of incidence may be near normal, the effective average may deviate considerably from normal due to a random orientation of microscopic surfaces.

The albedo varies with wavelength. Examples of this variation are shown in Fig. 6-11. This dependence arises from the dispersive properties of materials; i.e., the optical properties such as index of refraction are wavelength-dependent. Most natural surfaces have low albedos at the shorter wavelengths.

The absorption and reflection of radiation do not necessarily occur at the surface. A surface may have a significant transmission so that absorption or reflection as well as effects of the radiation are distributed within the material. In clear water almost three-fourths of the radiation in the 0.2- to 0.6-μm band (ultraviolet to orange) penetrates to the 10-m depth, 6 percent reaches 100 m. At longer wavelengths penetration is less, water being as opaque as coarse grained sand at wavelengths above 1 μm. Fig. 6-12 shows this spectral dependence.

Another way of describing the penetration of radiation in water is in terms of transmissivity. Transmissivity is a measure of the portion of incident light that is transmitted through a medium, given in units of percent per unit length. Pure water has a

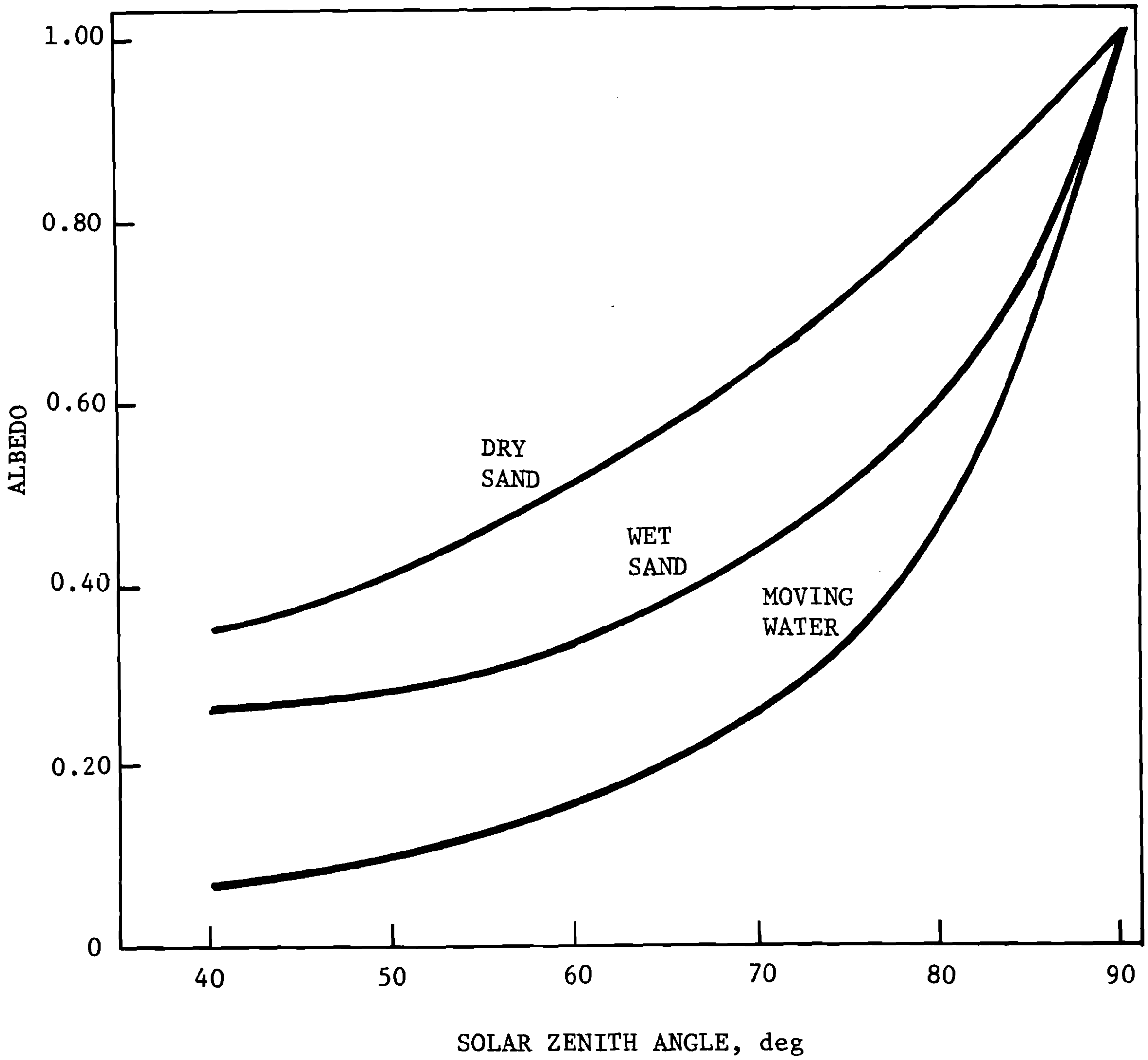


Figure 6-10. Albedo Dependence on Zenith Angle (Ref. 3)

transmissivity exceeding 80% m^{-1} in the wavelength range from 370 to 600 nm, but it decreases rapidly with increasing wavelength. At 1 μm transmissivity is virtually zero (Ref. 14).

In natural water bodies, transmissivity is typically 20 to 30 percent below that of pure water due to dissolved and suspended substances.

In sand, the light penetration depends largely on the average grain size as shown in Fig. 6-13 but is nevertheless three orders of magnitude less than that of water.

The penetration of electromagnetic radiation, including light, into snow is usually treated as following an exponential law of the form

$$I_z = I_o e^{-\lambda z} \qquad (6\text{-}17)$$

where

I_z = intensity of radiation at a normal distance z below the surface, Wm^{-2}

z = normal distance below surface of snow, cm

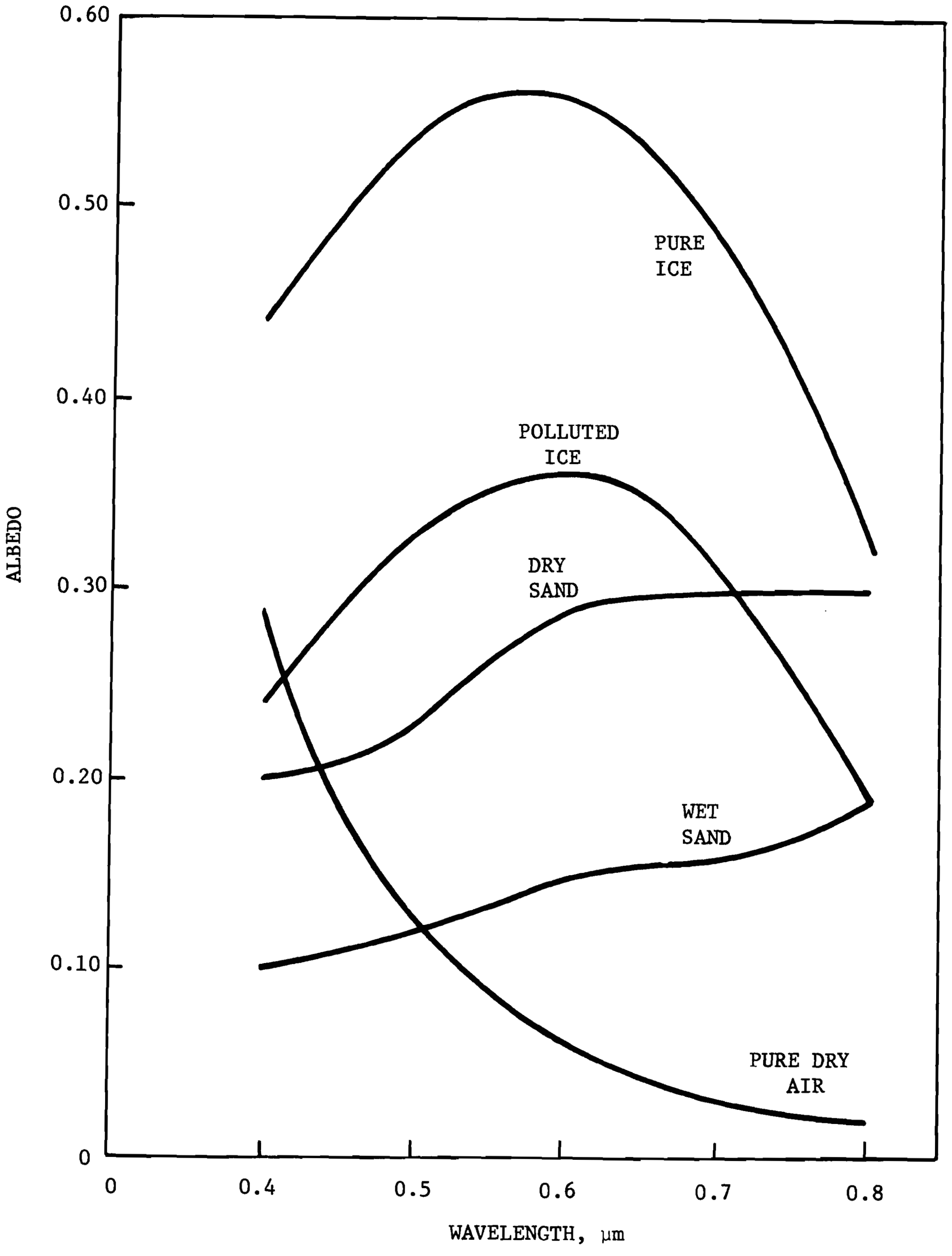


Figure 6-11. Spectral Dependence of Albedo (Ref. 3)

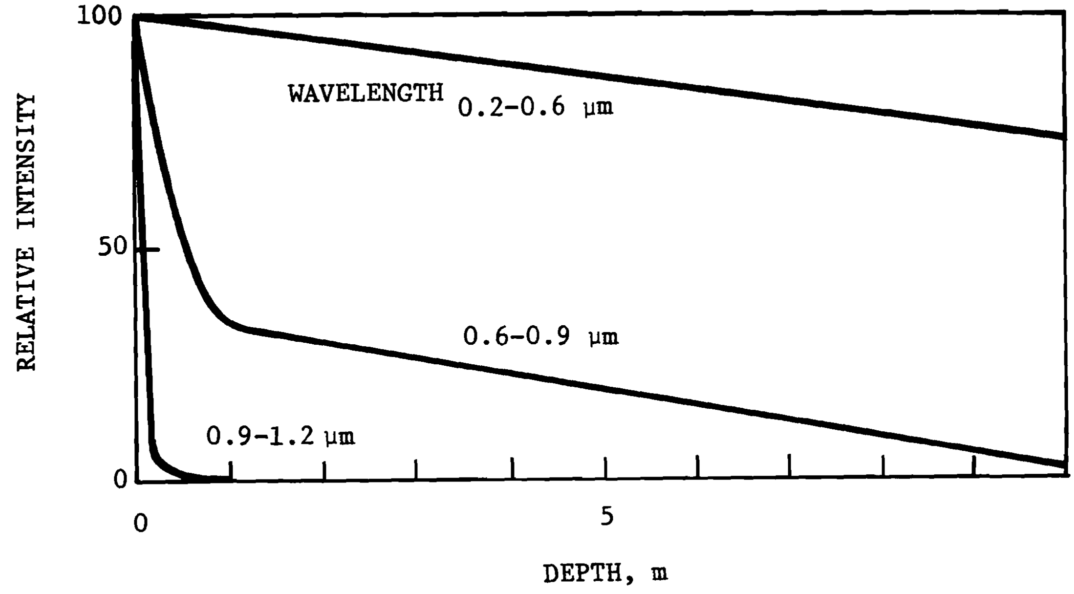


Figure 6-12. Light Attenuation With Depth in Water (Ref. 14)

λ = attenuation constant that describes the decreasing intensity (more usually referred to as the extinction coefficient), cm^{-1}

I_o = intensity of radiation at surface, Wm^{-2}

The transmissivity D is related to the extinction coefficient by

$$D = 100e^{-\lambda}, \% \, cm^{-1} \tag{6-18}$$

where λ is in units of cm^{-1}. This relation is plotted in Fig. 6-14.

Extinction coefficients for snow occur in the range of 0.07 to 0.23 cm^{-1} corresponding to transmissivities of 93 to 79.5% cm^{-1}. Higher values ranging up to 0.7 and higher have been observed (Ref. 14). In Fig. 6-15,

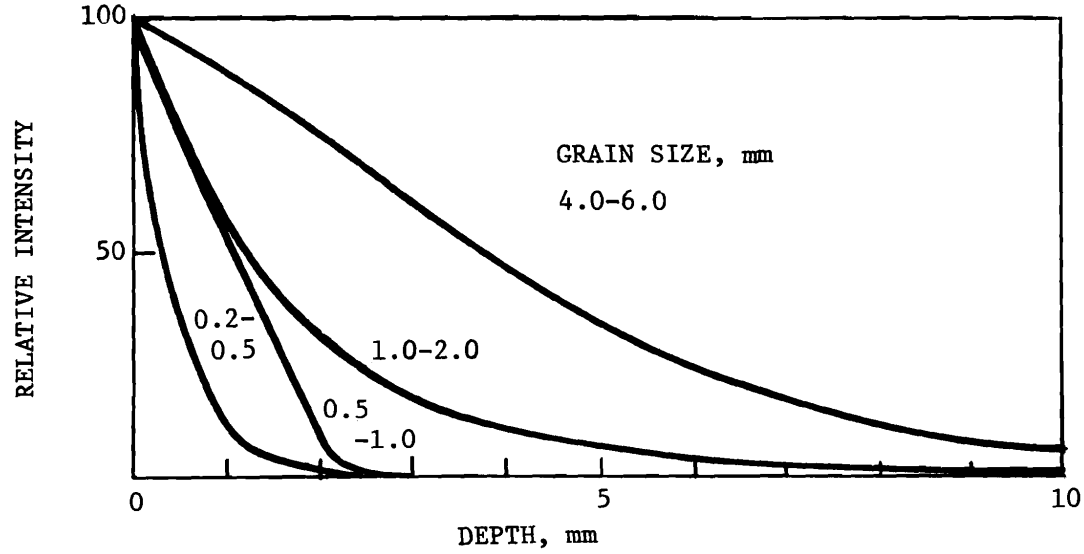


Figure 6-13. Light Attenuation With Depth in Quartz Sand (Ref. 14)

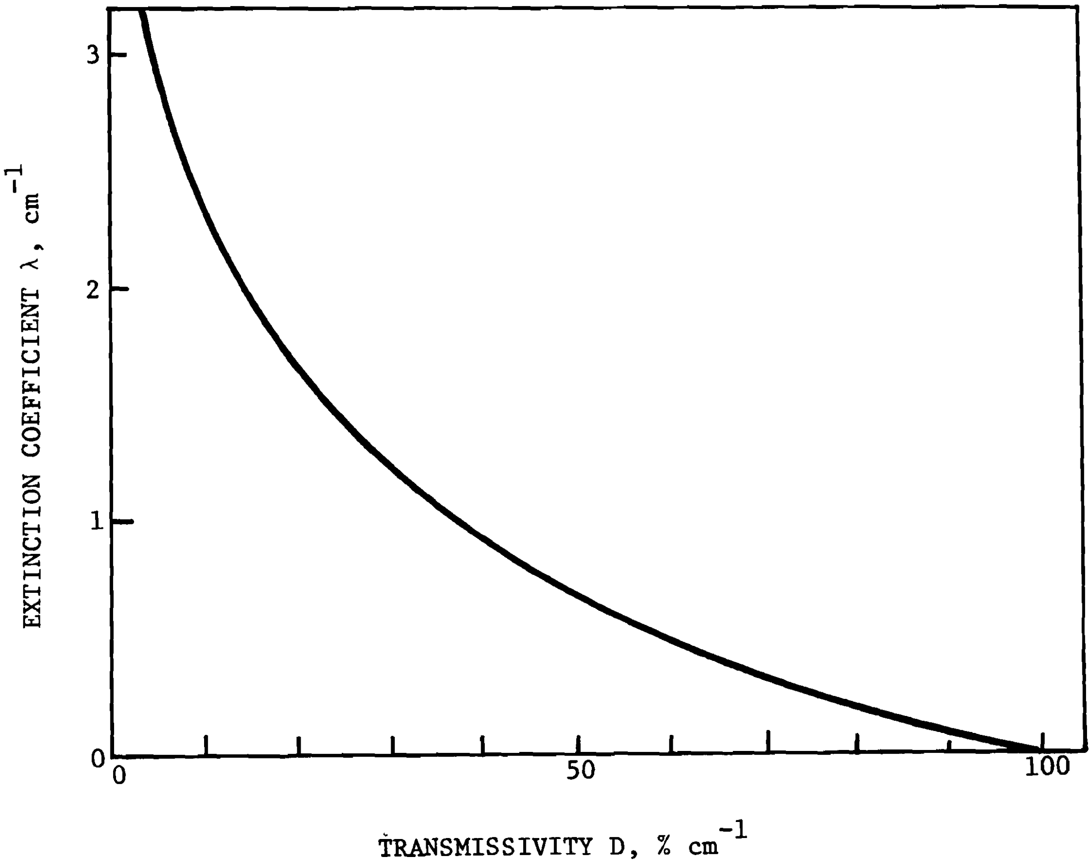


Figure 6-14. Relation of Extinction Coefficient and Transmissivity

light-penetration curves for snow and ice (and lake water for comparison) are shown. The extinction coefficient in snow has a spectral dependence increasing with wavelength and decreases in magnitude with increasing snow density (Ref. 20).

Ice transmits short-wavelength radiation better than snow but it depends on the purity and structure of the ice. Relatively clear ice can exhibit an extinction coefficient of 0.05 or lower; impure ice, 2.0 or higher; and at longer wavelengths (> 700 nm), 10.0 and higher.

The radiation balance equation that is applied to the surface of the earth may be expressed as (Ref. 14)

$$S = I + H + G - \sigma T^4 - R \qquad (6\text{-}19)$$

with the terms identified in Table 6-11. Geiger (Ref. 14) reports the results of a study in Hamburg that derived the estimates for the various factors given in the table.

The direct, diffuse, and reflection components have been discussed. The terrestrial radiation σT^4 is that thermal energy reradiated by the earth as a consequence of its being heated by solar radiation. It consists of long wavelengths as determined by the temperature (see Eq. 6-8) and is largely absorbed by atmospheric water vapor and carbon dioxide. These constituents of the atmosphere also radiate energy that returns to the earth and is almost completely absorbed since, at long wavelengths, the earth is essentially a blackbody—reflection is nil. While these two factors of the radiation equation are of no consequence either to the

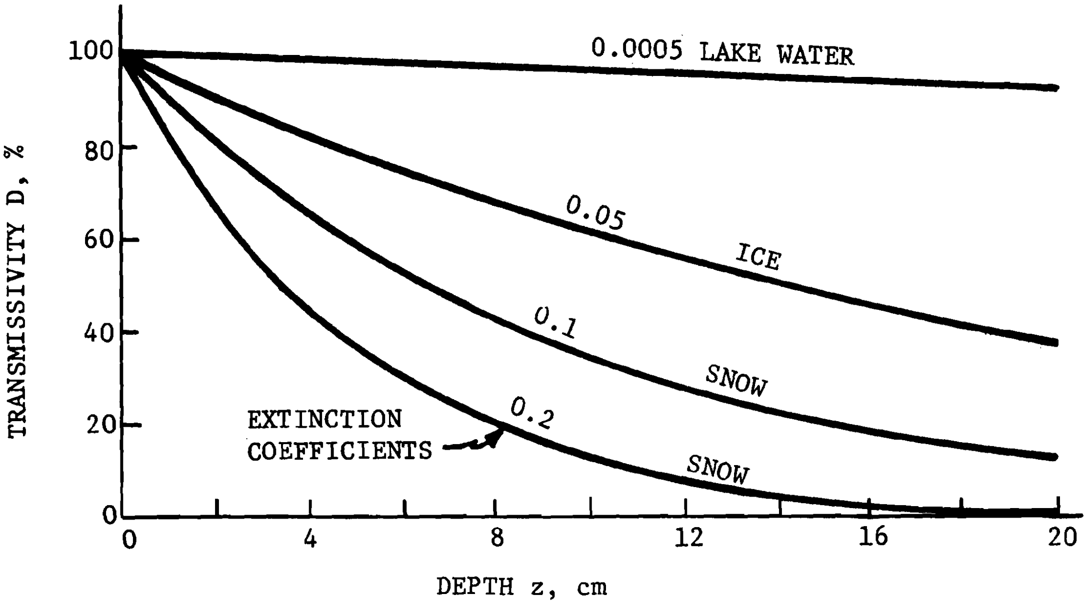


Figure 6-15. Penetration of Light Into Snow, Glacier Ice, and Lake Water (Ref. 14)

radiative heat balance of the earth as a planet or to the effects of solar radiation on materiel, they are of extreme importance in the radiative balance at the surface of the earth.

6-5 DISTRIBUTION OF SOLAR RADIATION

The various processes that cause insolation to differ in integrated intensity and in spectral distribution from its top-of-the-atmosphere characteristics vary with location on the surface of the earth. Instantaneous measures of solar radiation, e.g., observations of extreme high values, are not available nor would they be of much utility since effects are dependent on accumulated exposure levels over periods of time measured in days or months while instantaneous solar radiation levels are subject to a variety of localized variables.

In this discussion it is necessary to distinguish direct solar radiation, indirect (atmospheric shortwave) radiation, and their sum, called global radiation.

6-5.1 GEOGRAPHIC AND TEMPORAL DISTRIBUTION

The amount of solar radiation received at a point is governed primarily by latitude, altitude, season, cloudiness, and atmospheric turbidity. Location with respect to major water bodies and mountains is of local importance, as are fogs, which may have a profound seasonal influence on both radiation intensities and sunshine durations.

Worldwide observations of solar radiation were obtained during the third IGY* (1957-1958) and included global, diffuse, normal incidence, and net radiation (Ref. 21). The data included for the first time information from Antarctic stations. The WMO† World Data Center in Geneva collected these data from which the maps in Figs. 6-16 and 6-17 were constructed.

The yearly means of the daily solar radiation rates are shown in Fig. 6-16. The highest annual totals are on the order of 180

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*International Geophysical Year
†World Meteorological Organization

TABLE 6-11

ANNUAL MAGNITUDE OF RADIATIVE ENERGY FLOW (Ref. 14)

Factor	Wavelength range	cal cm^{-2} yr^{-1}	W m^{-2}
Direct solar radiation I	Short	+ 34,153	54.29
Diffuse sky radiation H	Short	+ 43,444	57.61
Atmospheric counterradiation G	Long	+240,533	318.95
Terrestrial radiation σT^4	Long	-268,837	-356.48
Reflected radiation R	Short	- 14,367	- 19.05
Net radiation S	Short	+ 34,926	46.05

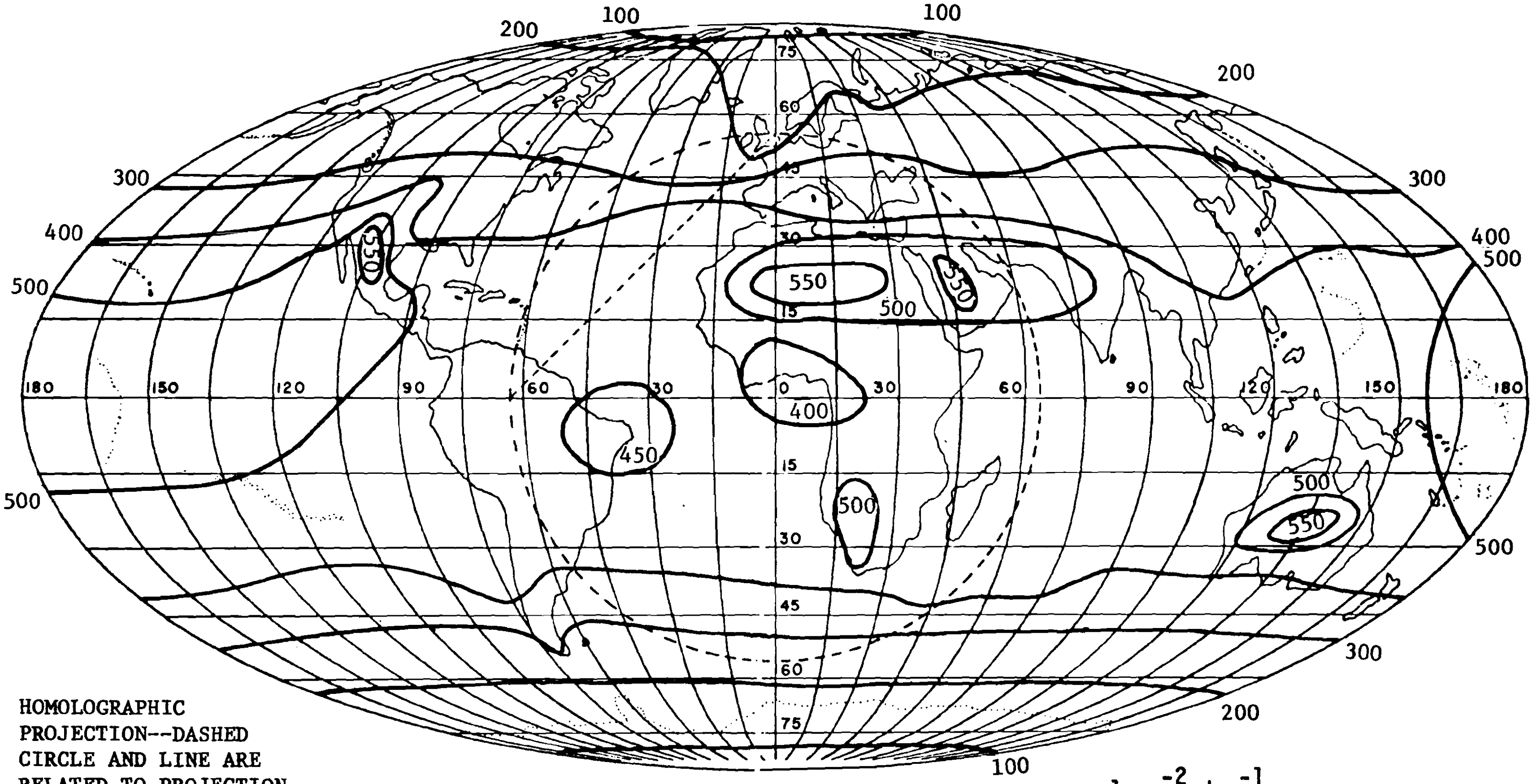
to 200 kcal cm^{-2} (240 to 260 W m^{-2}) and are found in the northern and southern subtropics. The northern subtropics receive greater radiation amounts than do the southern subtropics, probably because of the uneven distribution of landmasses in the two hemispheres. An annual total of no more than 150 kcal cm^{-2} ($\approx$ 200 W m^{-2}) of solar radiation is received in the equatorial zone. It is interesting to note that both the Arctic and Antarctic receive during their respective summers a total amount of radiation that is not much smaller than that recorded on either side of the English channel in a year.

At the solstices, solar radiation is a maximum not in the subtropics but in the Arctic and the Antarctic where the radiation flux incident on unit area of slopes in the ice-bound regions is greater than that at any other part of the surface of the earth.

In Fig. 6-17 the June and December mean monthly global solar radiation is presented. The December isolines show daily rates that indicate a southward decrease of radiation from the equator to the 60th parallel, after which the daily irradiation increases steadily because of the increasing length of the day. Extremal values for the entire earth were obtained in the Antarctic where the observing station was 9,186 ft above sea level. At the North Pole solar radiation values in June are higher than anywhere in the temperate zones but they are lower than at the South Pole in December. Next to the polar regions the subtropics are the most radiation-rich regions in summer. Since diffuse radiation in the cloudless subtropical summer comprises no more than 10 to 15 percent of the global radiation, it is evident that the subtropics, which include most of the surface area of the earth, are the greatest radiation reservoirs of all the land and sea surfaces.

At the time of the winter solstice, the polar regions are shrouded in darkness that lasts for several months, dependent on the latitude (see Fig. 6-5), causing global radiation values to decrease steadily as one moves toward the pole. While 500 cal cm^{-2} day^{-1} (240 W m^{-2}) is found at latitude 10 deg N., this decreases to 50 (24 W m^{-2}) in Western and Central Europe and along the United States-Canadian border and drops to 10 cal cm^{-2} day^{-1} (4.8 W m^{-2}) at latitude 60 deg N.

At the time of the equinoxes, the 100 cal

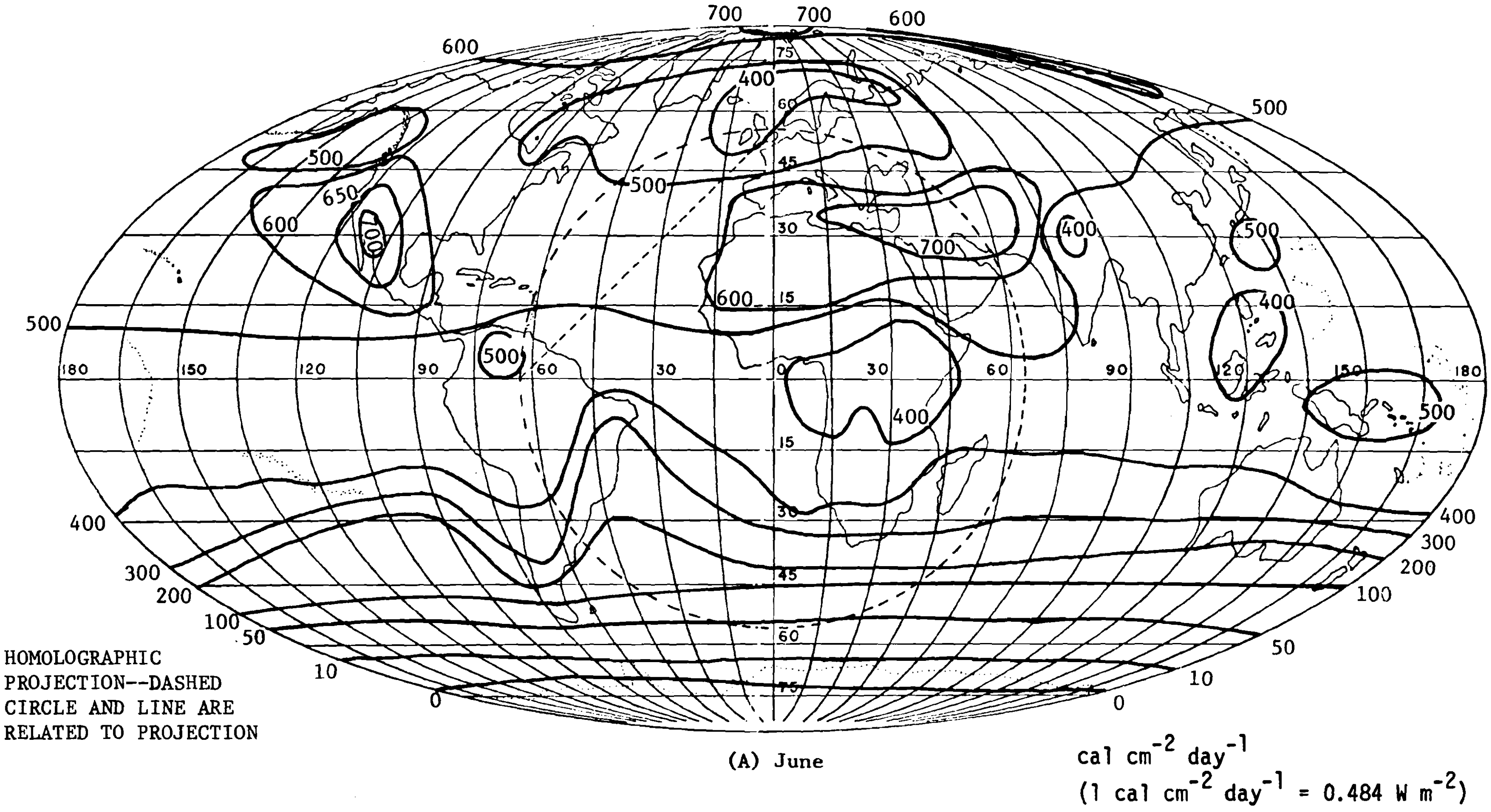


HOMOLOGRAPHIC PROJECTION--DASHED CIRCLE AND LINE ARE RELATED TO PROJECTION

cal cm^{-2} day^{-1}

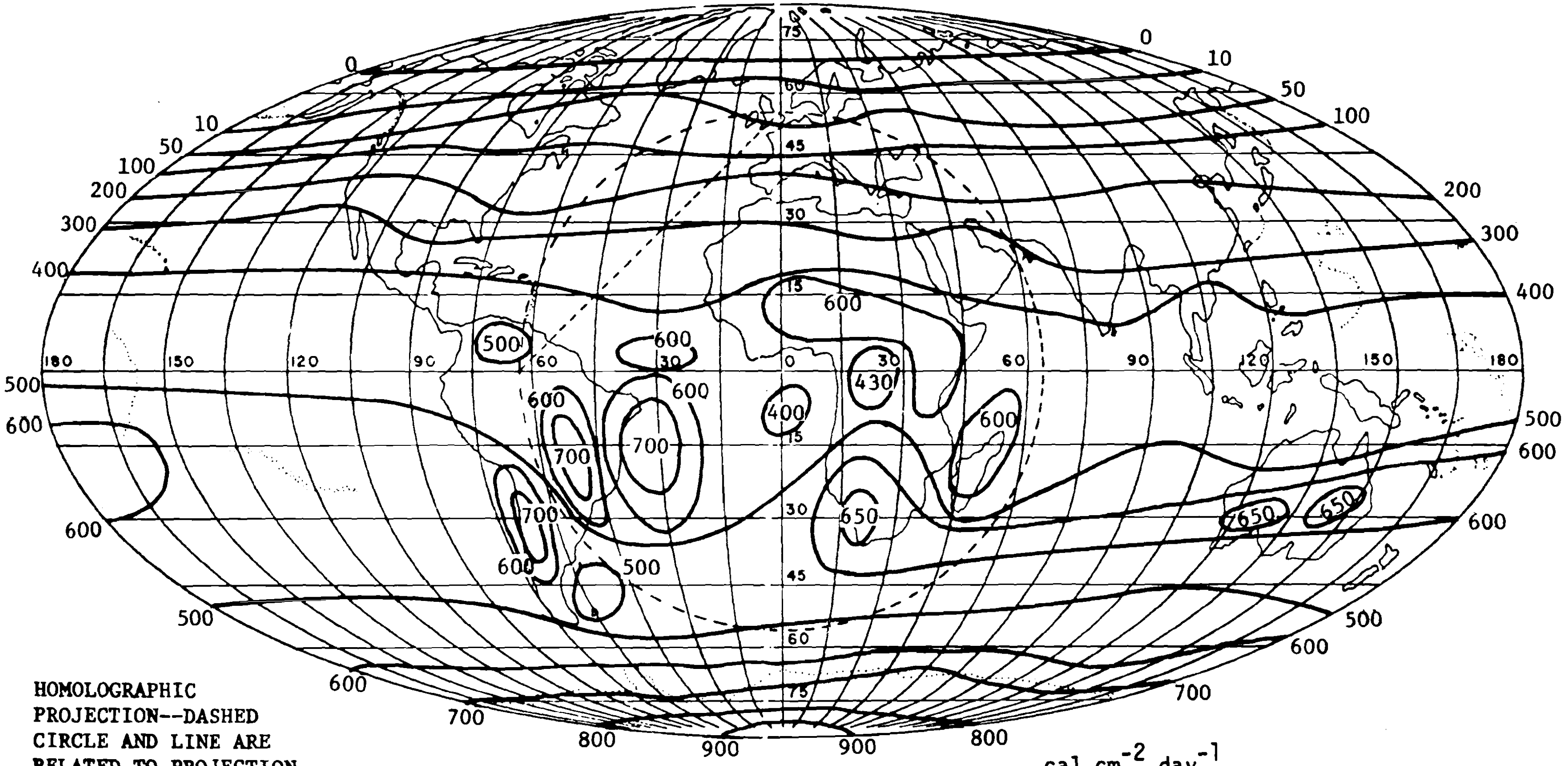
(1 cal cm^{-2} day^{-1} = 0.484 W m^{-2})

Figure 6-16. Mean Monthly Global Solar Radiation (Annual) (Ref. 21)



(A) June

Figure 6-17. Mean Monthly Global Solar Radiation (Ref. 21)



HOMOLOGRAPHIC
PROJECTION--DASHED
CIRCLE AND LINE ARE
RELATED TO PROJECTION

cal cm^{-2} day^{-1}
(1 cal cm^{-2} day^{-1} = 0.484 W m^{-2})

(B) December

Figure 6-17 (Continued). Mean Monthly Global Solar Radiation (Ref. 21)

cm^{-1} day^{-1} (48 W m^{-2}) radiation isopleth is around latitude 80 deg N. and S., while the tropics receive about 500 cal cm^{-2} day^{-1} (240 W m^{-2}); the temperate zones receive 100 to 200 cal cm^{-2} day^{-1} (March) in the Northern Hemisphere and 300 in the Southern Hemisphere.

In 1966, the distribution of average daily solar radiation throughout the world was compiled in the form of 12 monthly maps (Ref. 22). It is noted in this study that the wide dispersion of data in many areas of the world necessarily limited the accuracy of the results. Also, in assembling world plots, it is difficult to indicate microclimatic variability in regions where high mountains or other local geographic conditions cause substantial variation in cloud cover or atmospheric clarity between points a few miles or even a few hundred miles apart. The variations in solar radiation due to major geographic factors such as mountains, ocean currents, large deserts, and islands are clearly seen and are of major significance. Although it is not shown on the maps that were prepared, the maximum average monthly value of solar radiation anywhere in the world was at the South Pole: the December average is about 900 cal cm^{-2} day^{-1} (435 W m^{-2}). Four maps for the solstice and equinox months are given in Fig. 6-18. The isolines that are formed by broken lines on the maps indicate estimates based upon relatively little data as well as extrapolations from the other radiation contours. Since little data are available for most of the ocean areas, only a few isolines are given in these maps for the ocean regions.

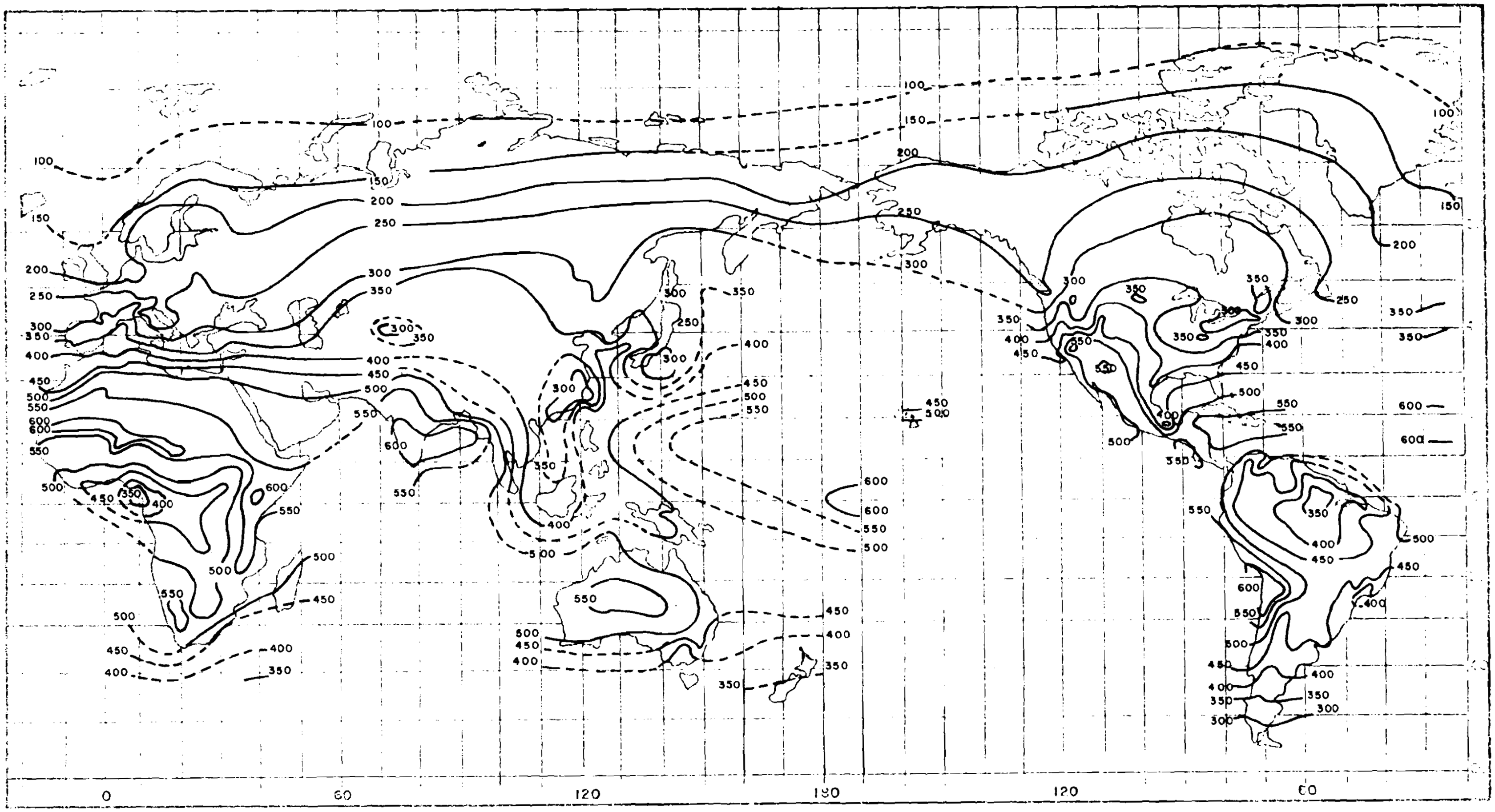
The authors of the report containing these maps point out several interesting applications of them. In their first example, they consider application of the map to a problem of solar energy utilization using as an example the northeast coast of Brazil. The objective is an estimate of the amount of energy that can be recovered by a horizontal solar collector in a typical year. Using the 12 monthly maps, an annual total radiation of 171.8 kcal cm^{-2} (corresponding to about 634,000 Btu ft^{-2}) was determined. If the average efficiency of the solar device is about 50 percent, then around 86 kcal cm^{-2} will be recovered in a typical year. The maximum energy input of about 570 cal cm^{-2} occurs in November; the minimum of 350 cal cm^{-2} occurs in June; useful energy of about 10^4 and 4×10^3 cal cm^{-2} $month^{-1}$, respectively, would be attained, representing about a threefold difference in the energy output when the dependence of the solar collector efficiency is considered.

In temperate and high latitudes, the distribution of solar radiation is basically zonal, approximating the parallels of latitude. In low latitudes, distinct regions of high global radiation values coincide with areas of low cloud coverage, which are primarily desert areas. Monsoon regions, which have a high degree of cloudiness, have lower values of global radiation, as do equatorial areas, where there is heavy cloud cover much of the time (Ref. 23).

The highest average annual radiation levels—more than 2.93×10^{-2} W cm^{-2}—are observed in northeastern Africa where minimum cloudiness is experienced throughout the year. Levels of 2.66×10^{-2} W cm^{-2} (200 kcal cm^{-2} yr^{-1}) or more are observed in three desert areas of the world: the Sahara, the Arabian, and the Thar in India (Ref. 23).

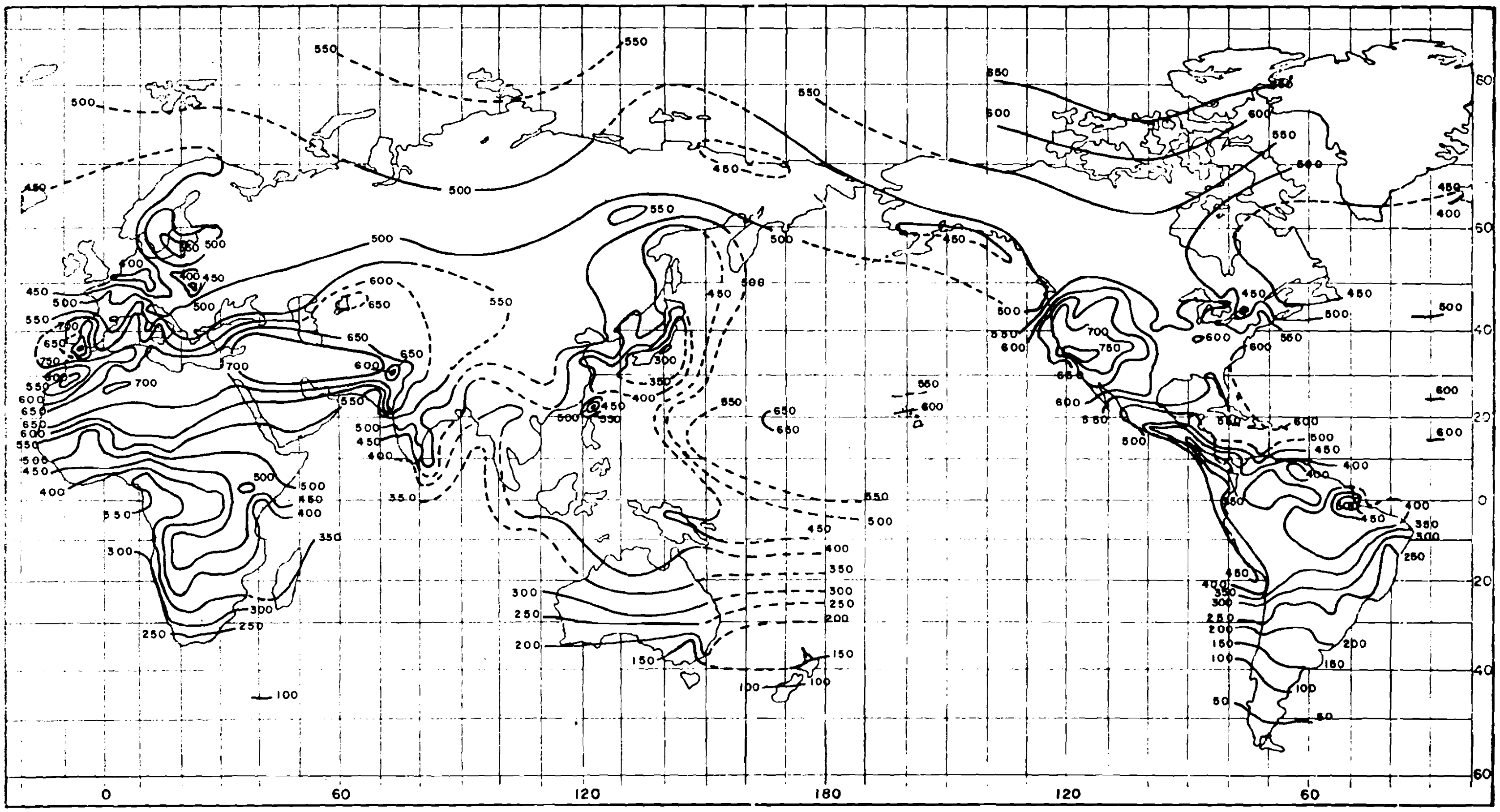
During the winter season, in both the Northern and Southern Hemispheres, there is a rapid decrease in solar radiation in the middle and high latitudes with increasing latitude. The zero isoline is on the latitude where the sun does not rise above the horizon throughout a given month.

The largest level of solar radiation is received in the Southern Hemisphere where, during the month of December, the average rate is over 2.87×10^{-2} W cm^{-2} (18 kcal cm^{-2} mo^{-1}) in South Africa and in Australia (see Fig. 6-17). In the summer season, in both the Northern and Southern Hemispheres, the values of global radiation change comparative-



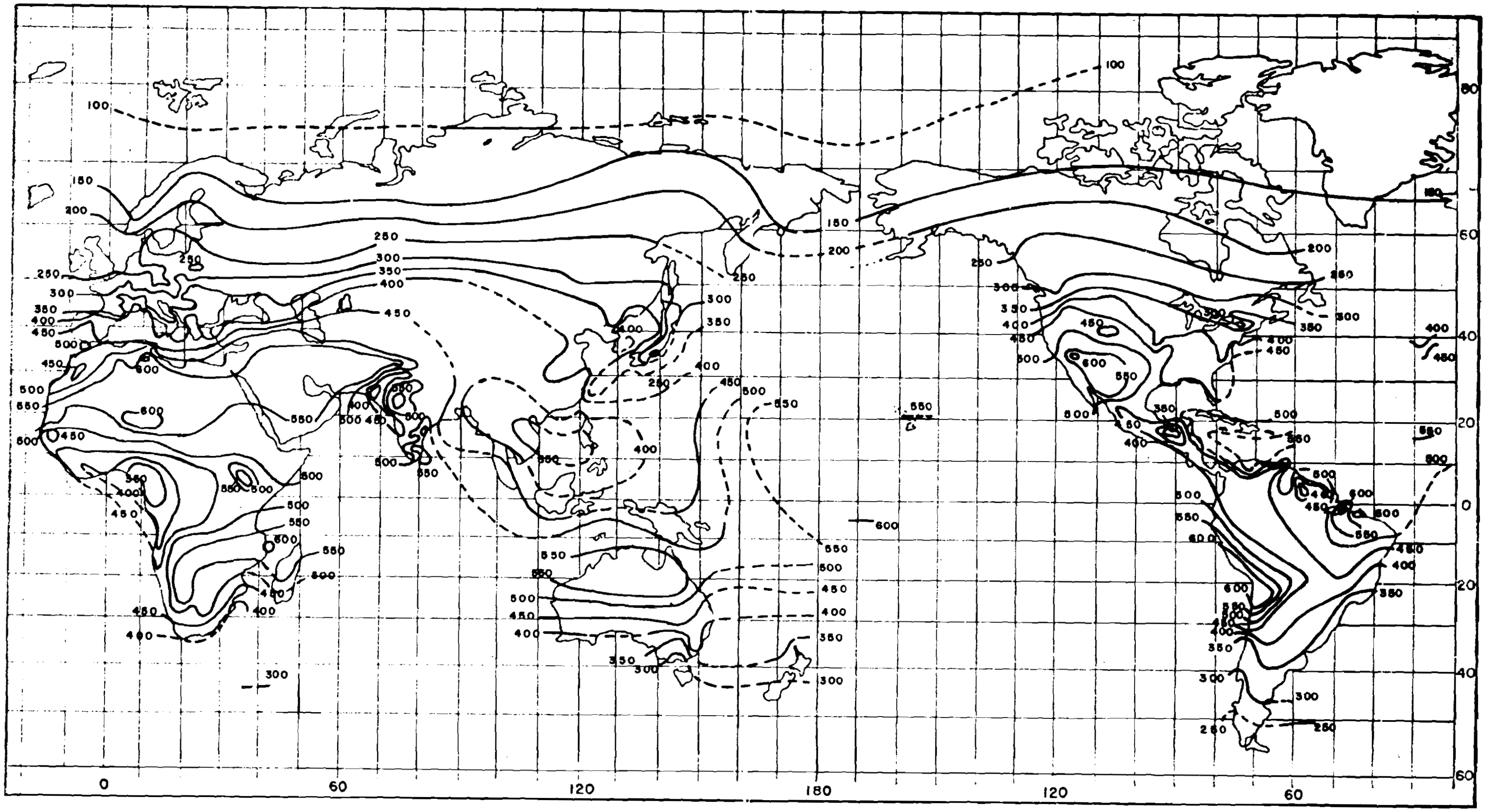
(A) March

Figure 6-18. Daily Means of Total Solar Radiation (Direct Plus Diffuse) Incident on a Horizontal Surface (cal cm^{-2} day^{-1}) (Ref. 22)



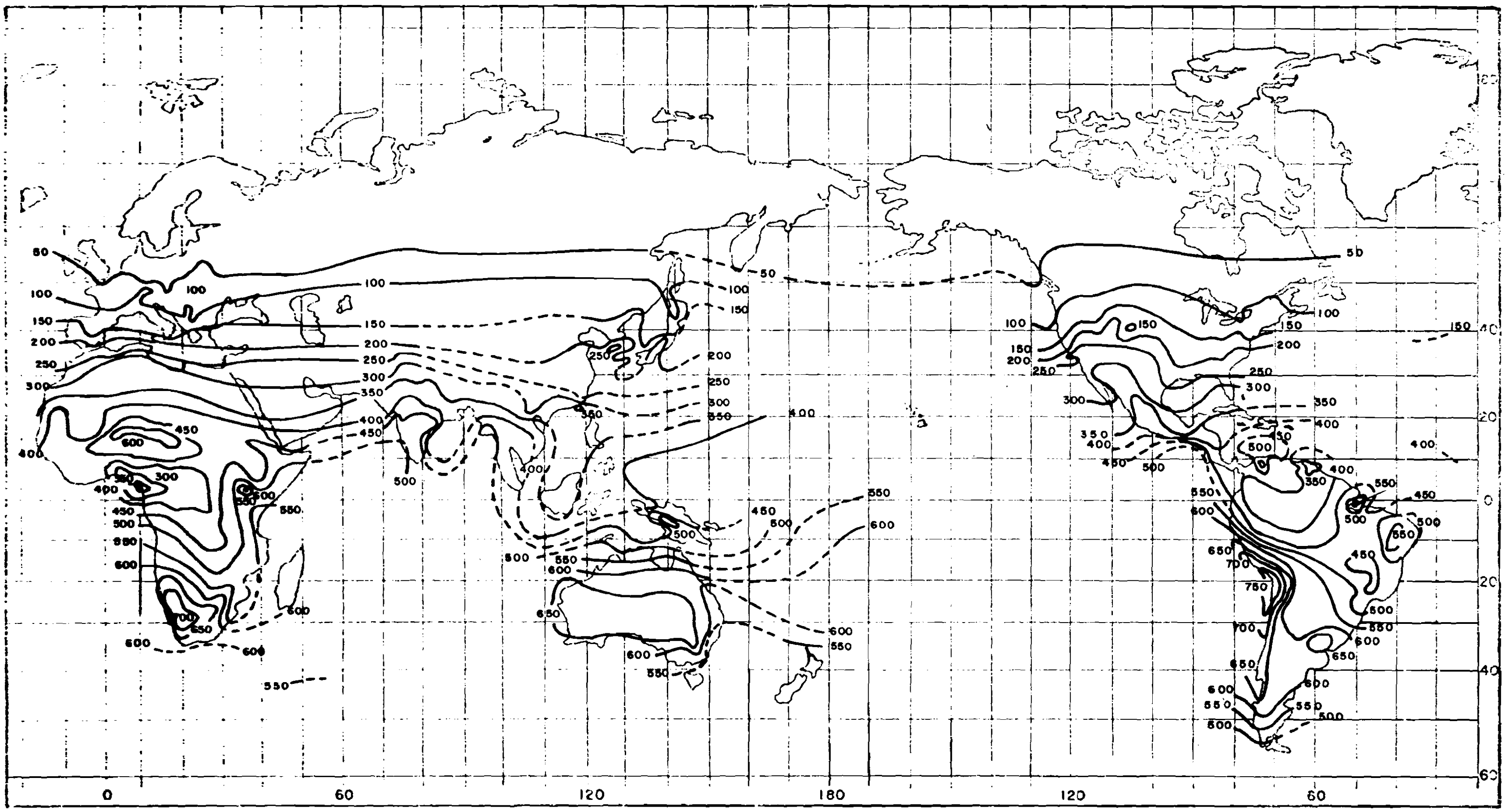
(B) June

Figure 6-18 (Continued). Daily Means of Total Solar Radiation (Direct Plus Diffuse) Incident on a Horizontal Surface (cal cm^{-2} day^{-1}) (Ref. 22)



(C) September

Figure 6-18 (Continued). Daily Means of Total Solar Radiation (Direct Plus Diffuse) Incident on a Horizontal Surface (cal cm^{-2} day^{-1}) (Ref. 22)



(D) December

Figure 6-18 (Continued). Daily Means of Total Solar Radiation (Direct Plus Diffuse) Incident on a Horizontal Surface (cal cm^{-2} day^{-1}) (Ref. 22)

ly little with latitude. The form that isolines take is determined, to a considerable degree, by cloud conditions. The highest monthly mean rates during the month of June (in excess of 3.51 X 10^{-2} W cm^{-2}) are in the Sahara, the Arabian and Iranian deserts, and the Colorado desert of the United States and Mexico (Fig. 6-18).

The amount of absorbed solar radiation is smaller than that of incident radiation but its distributional patterns are similar except that the isolines of the absorbed radiation are not continuous from landmass to ocean area owing to the contrasting albedos of the surfaces. A relatively small difference between total and absorbed radiation (about 5 to 20 percent) is observed on the major portions of the landmass and oceans. This difference increases somewhat in deserts and in regions covered with snow and ice. Loss of heat by longwave terrestrial radiation is generally less variable than is incident radiation. This partially is due to the fact that changes in temperature and in absolute humidity are associated with each other (an increase in temperature usually is followed by an increase in absolute humidity). The largest mean annual terrestrial radiation rates are observed in tropical deserts, where they reach 1.06 X 10^{-2} W cm^{-2}. This results from a tremendous warming of the surface in deserts relative to the air temperature. Near the equator the effective mean average radiation rate is lowered to about 0.40 X 10^{-2} W m^{-2} (30 kcal cm^{-2} yr^{-1}) and there is very little difference between land and ocean. Effective radiation rates over the ocean at high latitudes increase to about 0.53 X 10^{-2} W m^{-2} (40 kcal cm^{-2} yr^{-1}) at the 60 deg parallel. Over land in the extratropical latitudes, effective radiation is somewhat higher than over the oceans in the same latitudes, particularly in the arid regions.

Records for the United States include mean sky cover, which attenuates direct solar radiation (Figs. 6-19 and 6-20), as well as mean daily insolation or solar radiation (Fig. 6-21 and 6-22), both on an annual and monthly record basis. The monthly means for June and December as given in Fig. 6-22 show the large differences between summer and winter solar radiation levels. It is useful to compare these with the top-of-the-atmosphere values given in Fig. 6-5. Between latitude 20 and 60 deg N., the range, at the top of the atmosphere, in the month of June is 900 to 1,000 ly day^{-1}. In Fig. 6-22, the range of the daily average is 500 to 800 ly day^{-1} at the surface of the earth, including both direct and atmospheric radiation.

6-5.2 SPECTRAL DISTRIBUTION

In Figs. 6-3 and 6-4, the solar spectrum irradiance is shown before it is affected by the atmosphere. In Fig. 6-23, this spectrum, as well as a 5,900 K blackbody spectrum, are shown along with the spectrum of solar radiation at sea level. Gates (Ref. 15) has investigated the effects on the sea level direct solar spectrum of slant-path, expressed in terms of airmass (Fig. 6-24) and of altitude (Fig. 6-25). For slant-path dependence, he has also constructed a curve for global radiation (Fig. 6-26).

6-6 MEASUREMENT AND INSTRUMENTATION

Since World War II, the state-of-the-art of radiation measurement has probably advanced more than that of any other basic environmental factor. As a result, a whole family of radiation-measuring instruments is now available to the sophisticated investigator for measurement of the various components of the radiation balance.

Discussion of this instrumentation will be treated in three paragraphs: (1) measurement of the duration of sunshine; (2) measurement of the intensity of shortwave solar radiation—both direct and diffuse, including measurement of spectral components and measurement of ultraviolet radiation; and (3) measurement of terrestrial and sky longwave radiation.

In the past, considerable confusion has existed concerning the proper terms for instruments used in measuring the various

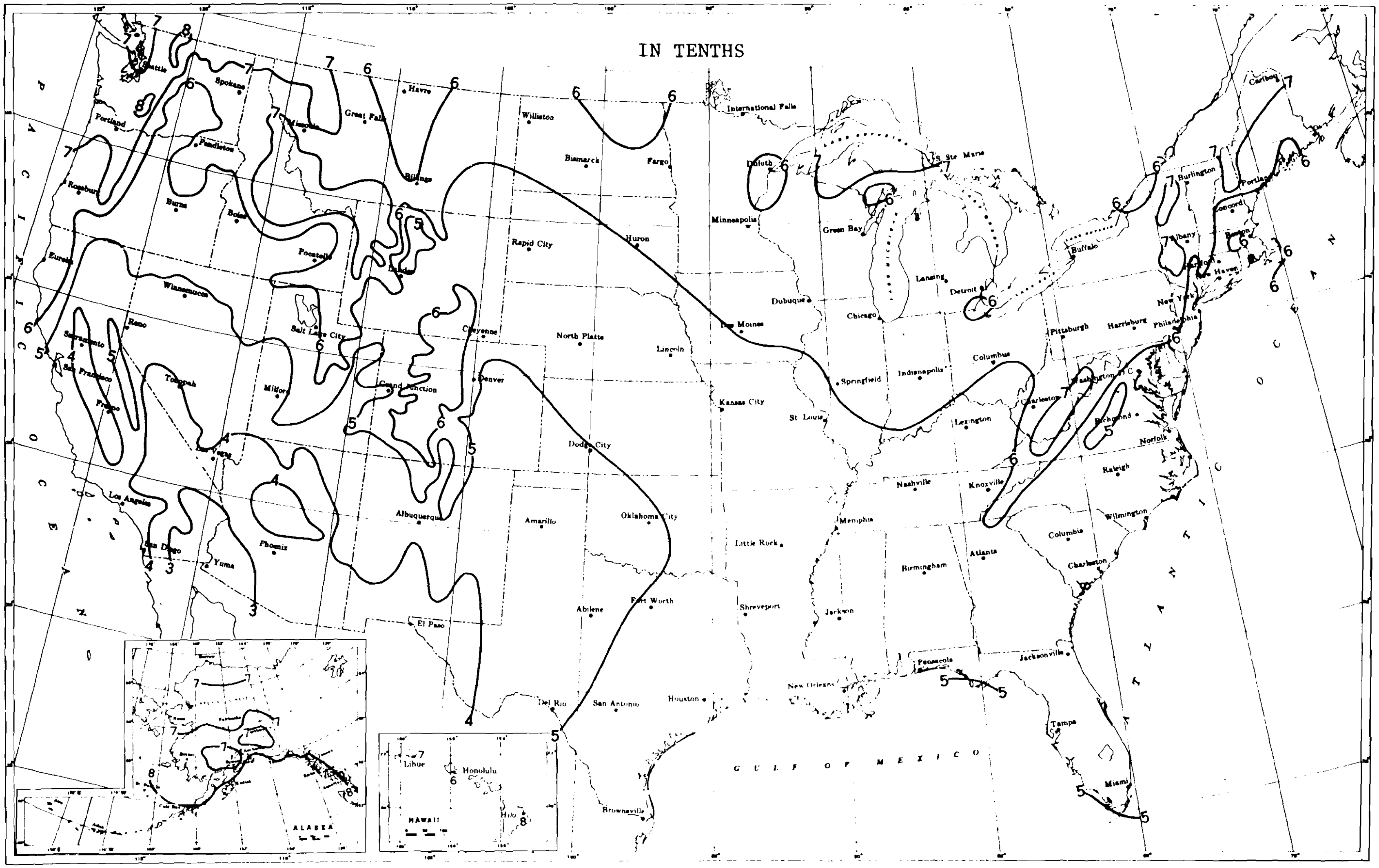
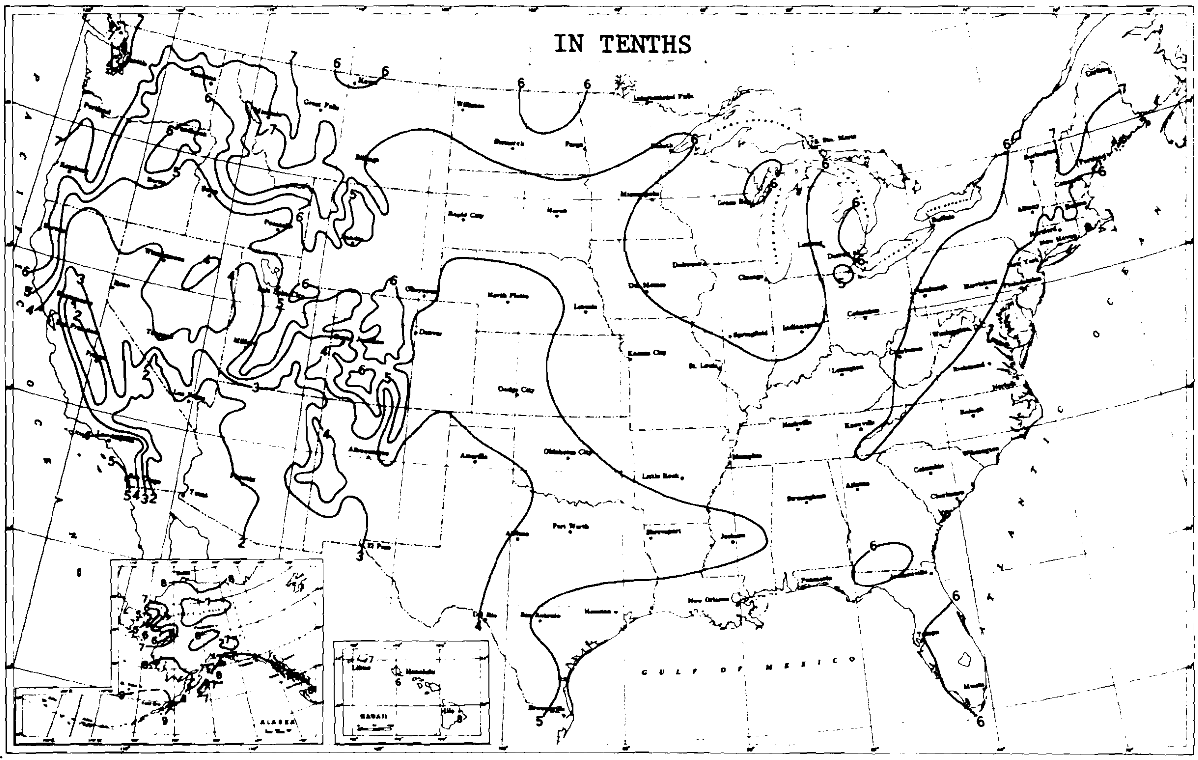
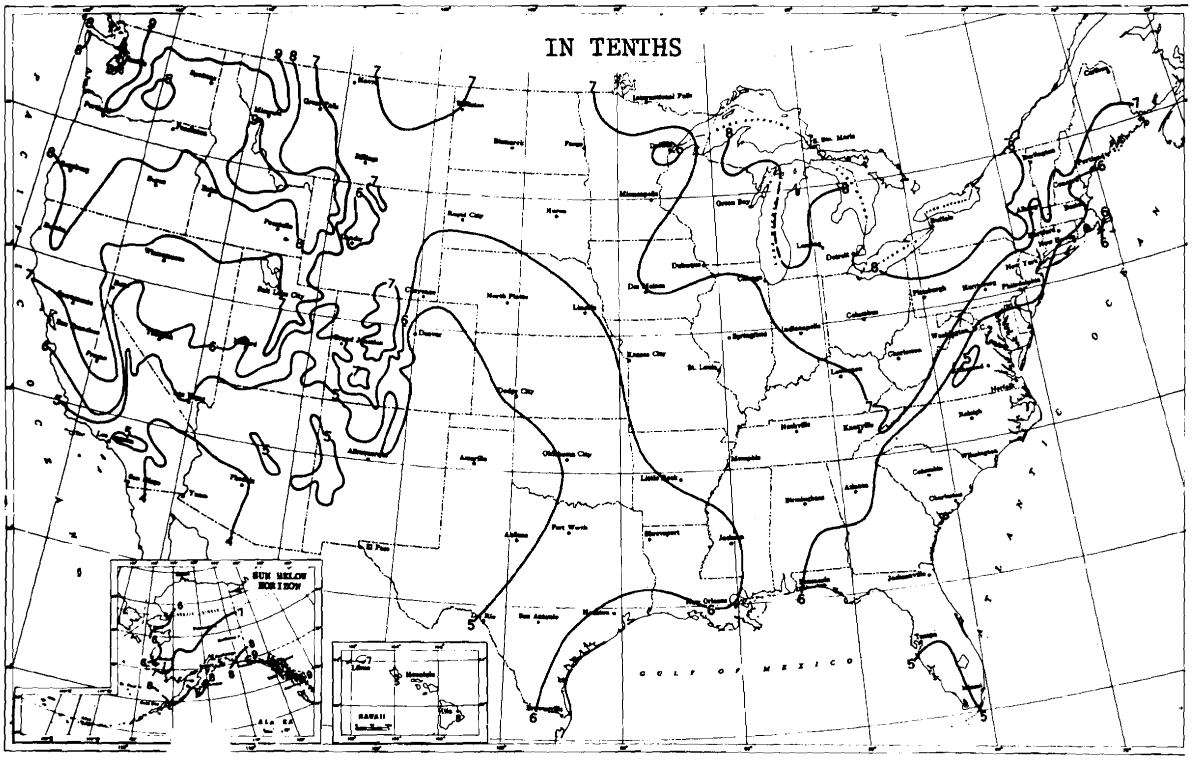


Figure 6-19. Annual Mean Sky Cover, Sunrise to Sunset in the United States (Ref. 24)



(A) June



(B) December

Figure 6-20. Monthly Mean Sky Cover, Sunrise to Sunset in the United States (Ref. 24)

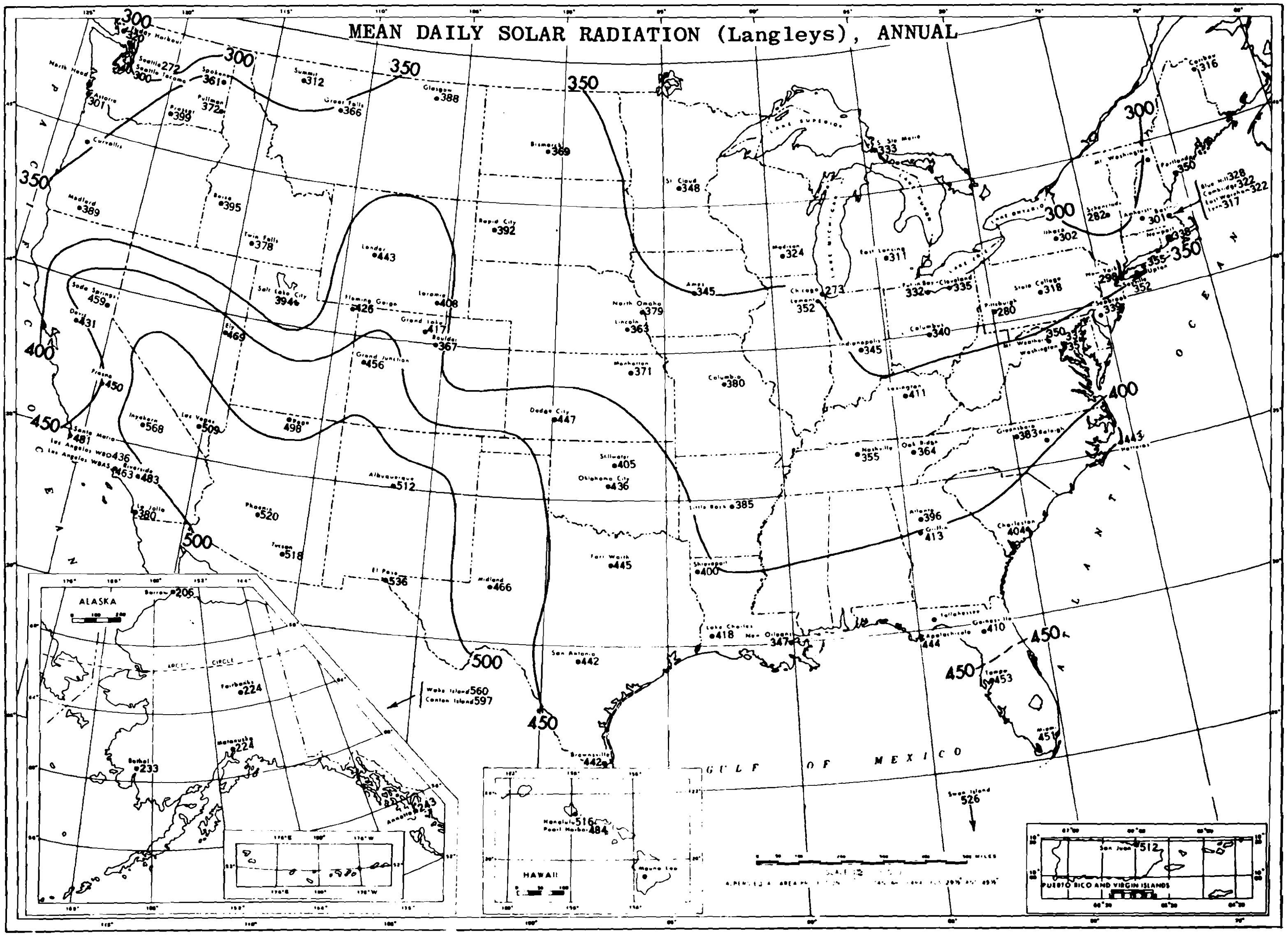
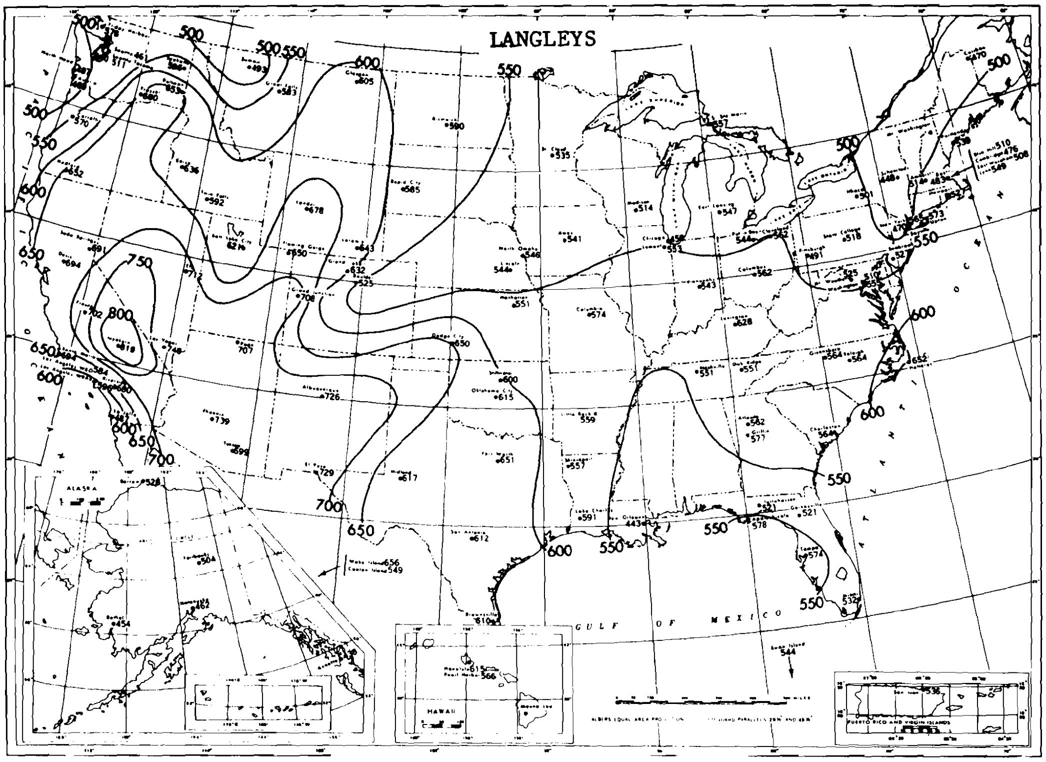
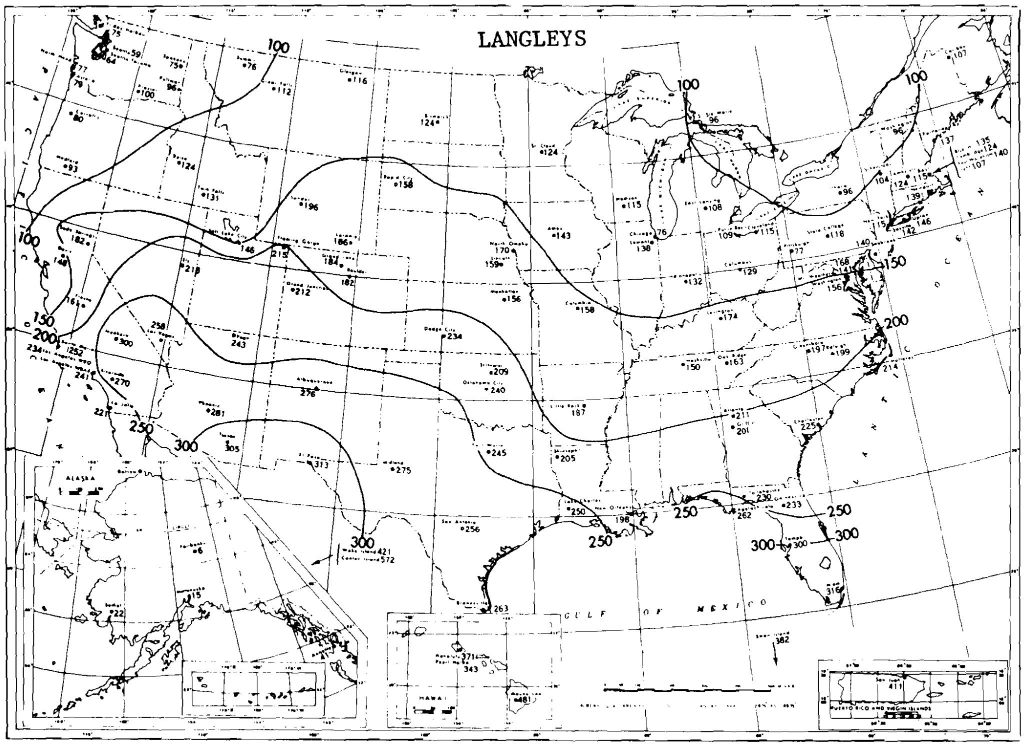


Figure 6-21. Mean Daily Solar Radiation in the United States (Annual) (Ref. 24)



(A) June



(B) December

Figure 6-22. Mean Daily Solar Radiation in the United States (Monthly) (Ref. 24)

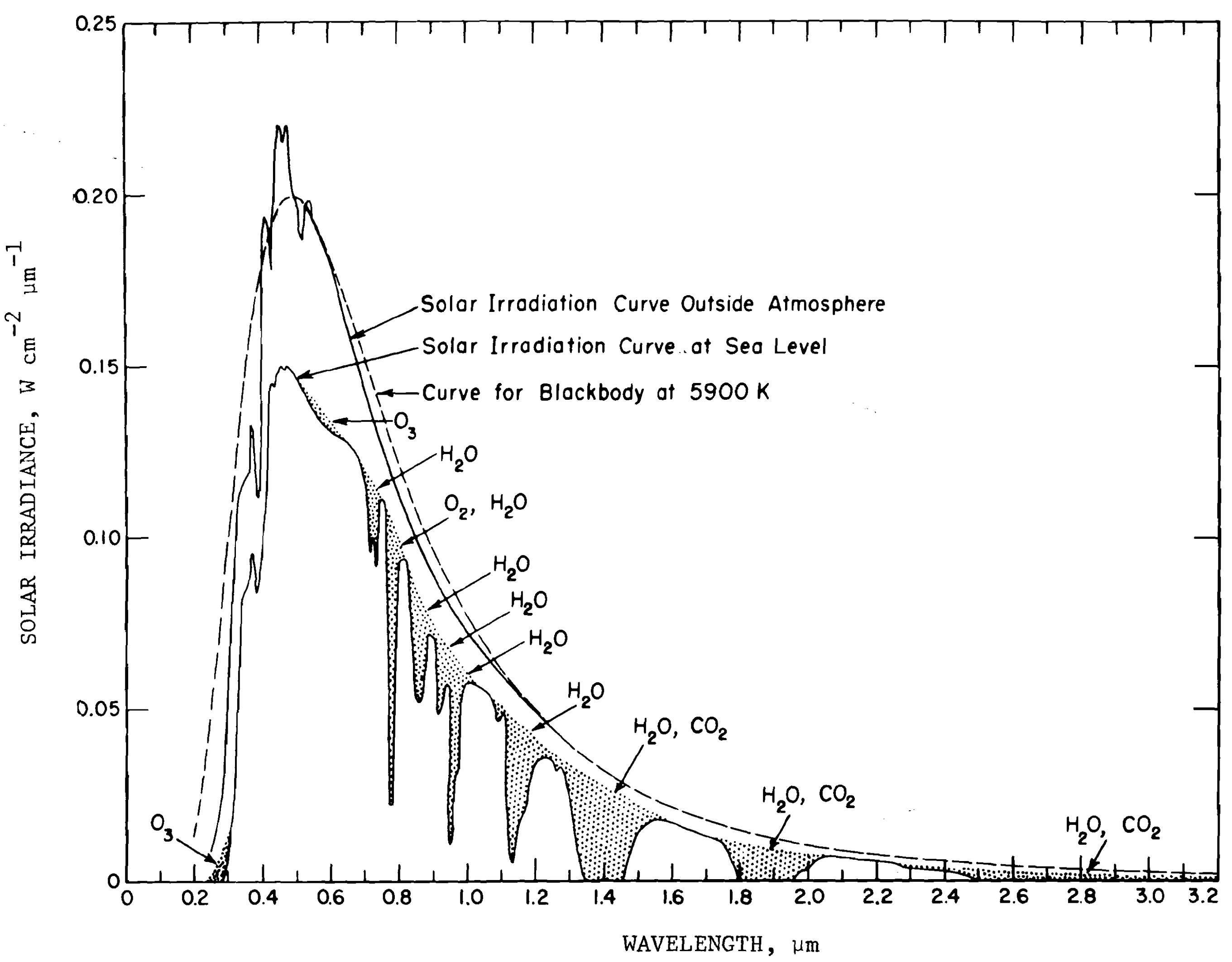
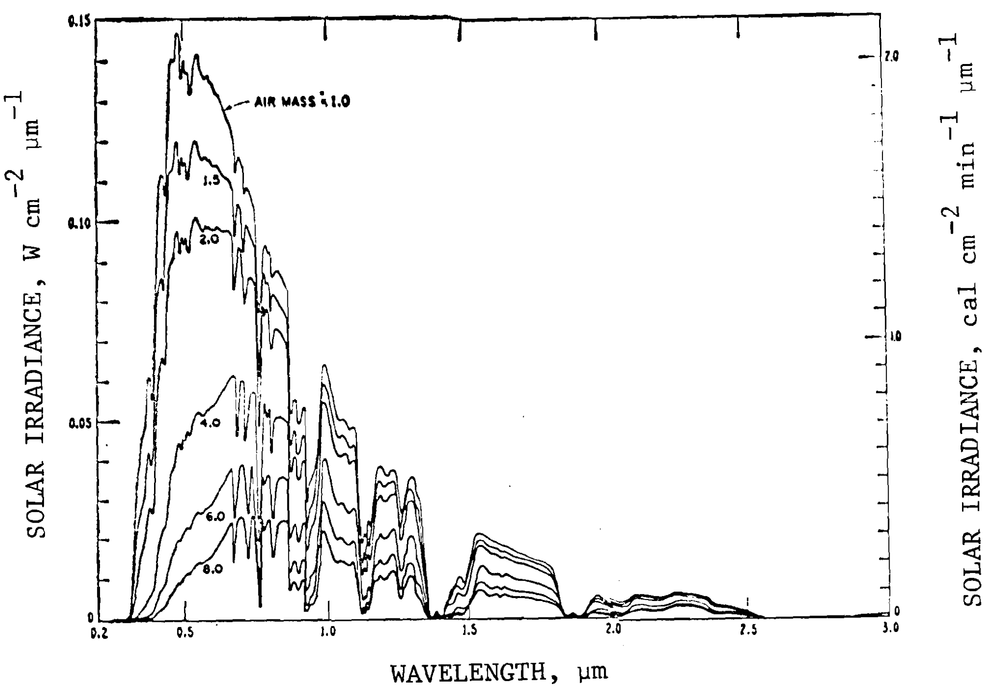


Figure 6-23. Spectral Distribution Curves Related to the Sun (Shaded areas indicate absorption, at sea level, due to the atmospheric constituents shown.) (Ref. 2)



TOTAL ENERGY

AIRMASS	W cm^{-2}	cal cm^{-2} min^{-1}
1.0	0.0865	1.24
1.5	0.0750	1.08
2.0	0.0640	0.917
4.0	0.0372	0.533
6.0	0.0240	0.344
8.0	0.0152	0.218

Normally incident radiation at sea level

Precipitable water 10 mm

Aerosol 200 cm^{-3}

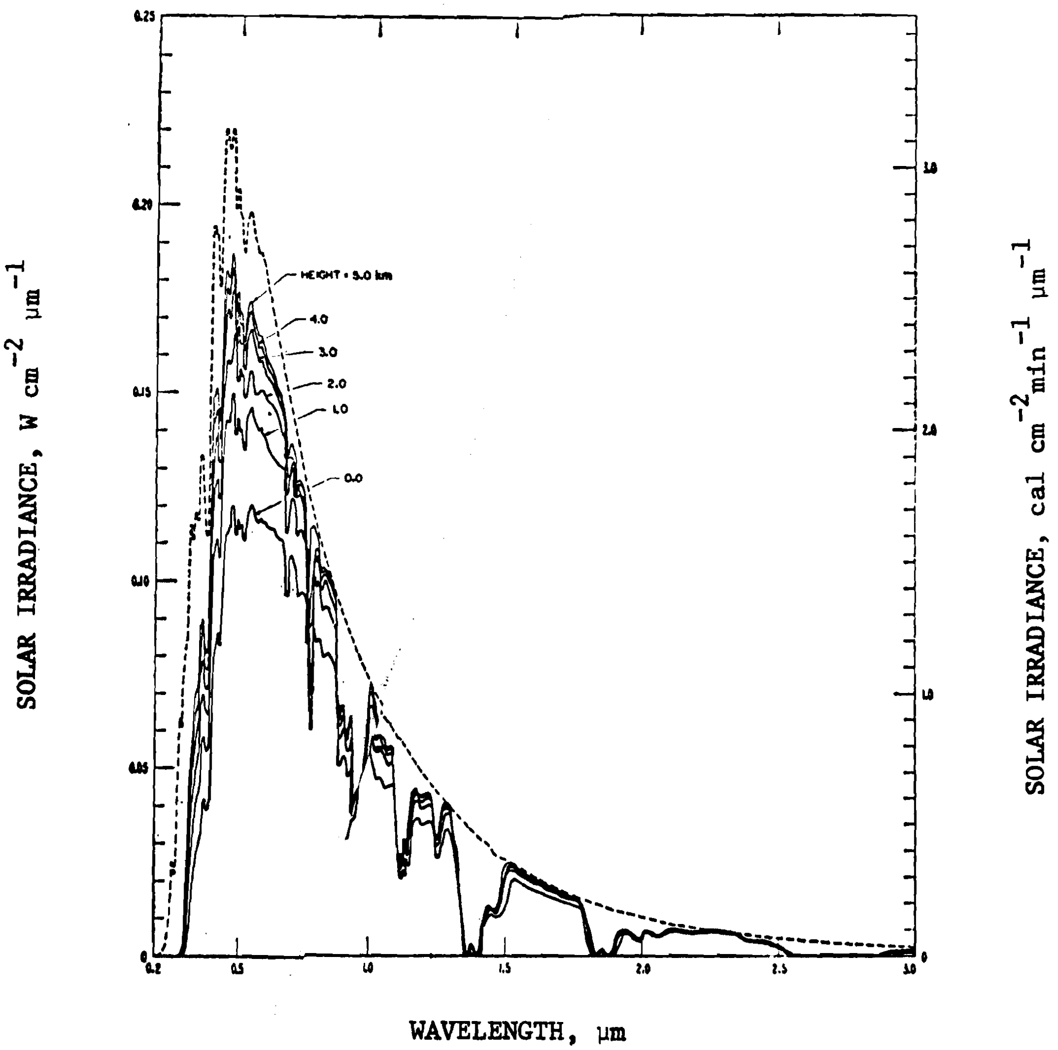
Ozone 0.35 cm

Figure 6-24. Spectral Distribution as a Function of Wavelength of Direct Solar Radiation for Various Slant-paths (Ref. 15)

types of radiation (radiometers). To avoid ambiguity, the terminology recommended at the Daves International Radiation Conference of 1956 will be used (Ref. 25). Because many of the terms are new, the names by which some instruments have been known for years will be indicated in the instrument identification.

Because of the continuing rapid improvement in radiation instrumentation, it should be noted that where individual items are identified in the following text, new and improved instruments undoubtedly will have been developed within a few years. In view of this, efforts should be made to obtain the most recent information before making decisions concerning instrumentation required for a specific problem.

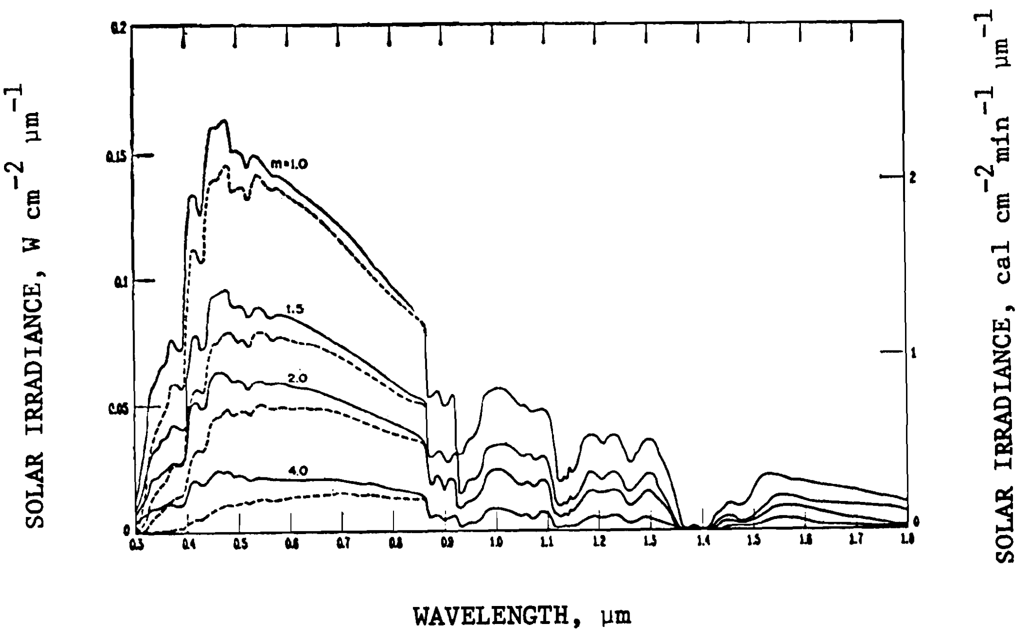
Caution must be exercised in measuring radiation phenomena, since fluctuations often



---EXTRATERRESTRIAL SOLAR ENERGY

	TOTAL ENERGY	
HEIGHT, km	W cm^{-2}	cal cm^{-2} min^{-1}
0	0.0747	1.07
1	0.0894	1.28
2	0.0961	1.38
3	0.101	1.45
4	0.103	1.48
5	0.105	1.51
EXTRATERR.	0.139	2.00

Figure 6-25. Variation With Altitude of Spectral Intensity vs Wavelength (For direct solar radiation perpendicular to solar rays for an air mass of 1.5) (Ref. 15)



TOTAL ENERGY ON HORIZONTAL SURFACE

	W cm^{-2}		cal cm^{-2} min^{-1}	
AIRMASS	DIRECT SOLAR	GLOBAL	DIRECT SOLAR	GLOBAL
1.0	0.0838	0.0898	1.20	1.29
1.5	0.0475	0.0530	0.687	0.759
2.0	0.0302	0.0322	0.432	0.462
4.0	0.0089	0.0130	0.127	0.186

——— GLOBAL RADIATION

- - - DIRECT SOLAR

Figure 6-26. Spectral Distribution as a Function of Wavelength (of the global and direct solar radiation incident at sea level on a horizontal surface, for various slant paths corresponding to indicated air masses) (Ref. 15)

produce unrepresentative data—e.g., instantaneous values of global (sun and sky) radiation are often unreliable, in contrast to intensity measurements of the direct solar beam. It is, therefore, necessary to arrange for continuous records and subsequent integration of values where this is called for.

Sunshine recording instruments have, as their principal purpose, the detection and recording of sunshine occurrence and duration. Since magnitudes are not involved, results are expressed in units of time, i.e., time of day and duration.

Information on radiation instrumentation is available in a number of sources (Refs. 26-29) that comprise the general references for the information that follows.

6-6.1 SUNSHINE DURATION RECORDERS

The occurrence and duration of sunshine is measured at many stations around the world. Instruments for this purpose depend on concentration of energy from the sun, or actinic effects of shortwave radiation on sensitized paper, as indicators of the occur-

Figure 6-27. Campbell-Stokes Sunshine Recorder

rence of sunshine. Threshold values of occurrence of sunshine (e.g., morning and twilight), however, are not well defined and published records of sunshine duration are, to some extent, dependent on the type of instrument and evaluation techniques used. To overcome this, the Campbell-Stokes recorder, probably the most commonly used instrument, has been designated as a reference standard by the World Meteorological Organization (Ref. 26). Other instruments, therefore, should be calibrated against the Campbell-Stokes recorder described. A discussion of specific recorders follows:

(1) *Campbell-Stokes sunshine recorder.* The Campbell-Stokes instrument consists of a small clear glass sphere mounted on an adjustable support and base within a section of a larger spherical bowl. The diameter of the bowl is arranged so that solar rays are focused by the glass sphere on a specially prepared chart card. The card is placed in one of several slots in the bowl segment depending on the latitude of the station and the season of the year. When the Campbell-Stokes sunshine recorder is used, its installation and use should comply with detailed specifications prepared by the British Meteorological Office (Ref. 30).

The solar rays, concentrated by the spherical glass lens, burn a narrow track on the graph corresponding to the path of the sun in the sky. The width and depth of the track depend on the intensity of the rays and the path of the track on the chart gives the time duration of the sunshine. A Campbell-Stokes sunshine duration recorder is shown in Fig. 6-27.

(2) *Jordan sunshine recorder.* The Jordan sunshine recorder is another sundial type of instrument and requires no power other than that of the sun. The instrument consists of two semicylinders so oriented that the sun shines through a slit of one cylinder in the morning and the other cylinder in the afternoon. The solar rays strike sensitized paper (blueprint paper) to indicate the occurrence of sunshine. The accuracy of the instrument is dependent on uniformity of sensitivity of the photographic paper. Like the Campbell-Stokes, the instrument must be adjusted for latitude.

(3) *Pers sunshine recorder.* The Pers sunshine recorder uses a lens-hemispherical mirror system to reflect the solar rays on blueprint paper. The movement of the sun is traced in a circular path that is relatively easy to calibrate into duration of sunshine. The instrument needs no adjustment for latitude. Like the Jordan recorder, the accuracy of the trace is limited by variable sensitivity of the recording paper, but, unlike the Campbell-Stokes and Jordan instruments, it can be used at any latitude.

(4) *Foster sunshine switch.* The Foster sunshine switch senses radiation by the measurement of the heat differential between shaded and unshaded photovoltaic cells. The differential during periods of sunshine activates a relay that initiates the recording mechanism, thus recording the occurrence of sunshine each minute.

(5) *Marvin sunshine recorder.* The Marvin sunshine recorder, used for years by the U S Weather Bureau, is another example of a differential recorder. It consists of a clear

bulb and a black bulb joined by a narrow tube and operating as a differential air thermometer. When the sun is shining, the black bulb is heated, expanding the gas it contains and forcing a mercury column through the connecting tube. The mercury closes an electrical circuit, activating a relay on a recorder pen mechanism, thus providing a trace on the recorder chart paper during periods of sunshine. This instrument is subject to calibration error, responds to diffuse as well as direct radiation, and is fragile.

6-6.2 SUNSHINE INTENSITY MEASUREMENT

The measurement of solar radiation intensity is not a standard function at most meteorological stations geared to the requirements of the weather forecaster. From the researcher's point of view, this is unfortunate, for undoubtedly an understanding of the heat budget and transformation of solar energy impinging on the atmosphere and the surface of the earth is of fundamental climatic importance. Only a few hundred of the many thousands of weather stations around the world measure radiation intensity, and records at many of these stations cover only short periods of time.

The situation in the last 40 yr, however, shows considerable improvement. In 1928, Kimball presented mean values of solar radiation for 32 stations around the world (Ref. 31). In 1968, Berlyand reported that approximately 1,000 stations measure either components of or the total amount of radiation balance (Ref. 32).

Not only has the number of stations where solar radiation intensity measurements are made increased, but the quality of measurement has also improved. In the first three decades of this century, a number of instruments for the measurement of solar radiation were developed without proper identification of what was actually being measured. Since World War II, however, much attention has been devoted to improvements in measuring techniques and evaluation of records. There also has been more international concern with standardization of observation methods and presentation of data.

The instruments for measurement of solar radiation are divided into two categories. First are those instruments (known as pyrheliometers) for the measurement of the intensity of the direct solar beam. Second are those instruments (known as pyranometers) used for measurement of global radiation, including the direct beam from the sun and the diffuse sky radiation.

6-6.2.1 PYRHELIOMETERS

Pyrheliometers are the most accurate instruments for measuring direct solar radiation and are used as primary and secondary standards for other instruments, such as pyranometers. They are essentially receiving systems with the uppermost surface blackened, in some manner, to absorb a high proportion of the solar beam. Pyrheliometers are mounted so that the receiver is maintained normal to the beam. The receivers are mounted in a tube or surrounded by spaced diaphragms arranged so that only radiation from the sun and a narrow annulus of sky is permitted to fall on the receiving surface. For practical reasons, it is not possible to occult the disk of the sun only. A small circumsolar sky contribution defined by the instrument aperture of a few degrees is also accepted by the instrument. Pyrheliometers are equipped with a sighting device to insure that the surface of the instrument is exactly normal to the solar beam. The construction of the mount carrying the pyrheliometer permits rapid adjustment of the azimuth and elevation. Often a provision is made for use of filters to segregate a portion of the solar spectrum.

Observations of solar intensity should not be made when clouds are near to or obscuring the disk of the sun. Preferably, periods of low atmospheric turbidity (i.e., absence of thick haze or fog) should be selected to obtain more uniform observing conditions.

A discussion of specific pyrheliometers follows:

(1) *Angstrom electrical compensation pyrheliometer.* The electrical compensation pyrheliometer introduced by K. Angstrom in 1899 is one of the best known and most reliable instruments for measuring the intensity of solar radiation. It is used as a standard for the calibration of other pyrheliometers. In the United States, several modifications in the design of the original instrument have been made. The Smithsonian Institution encased it in wood to minimize temperature changes and effects of wind gusts, and made other changes to decrease the effects of reflected radiation. The Eppley Laboratory of Newport, R.I., has developed another model of the Angstrom pyrheliometer.

Essentially, the sensing element of the Angstrom pyrheliometer is comprised of two very thin, almost identical thermocouples attached on the under surfaces. In operation, the solar beam is allowed to impinge on one strip, while electric energy is applied to the other strip to obtain identical temperatures. Solar intensity is measured as a function of the balancing energy applied. The Eppley version of the Angstrom pyrheliometer differs from earlier models mainly in that the solar beam measured includes less diffuse radiation from the area around the solar disk. This is accomplished through the use of a cylindrical metal tube and precision controls for sighting the sun.

(2) *Silver disk pyrheliometer.* The silver disk pyrheliometer, developed at the Smithsonian Institution, possesses high reliability and has served as a standard in this country since its development in 1913 by Abbott. The instrument consists basically of a mercury thermometer in good thermal contact with a silver disk positioned at the lower end of a tube with a small aperture to allow entrance of the solar beam but very little diffuse radiation.

The operational procedure involves alternately shading and exposing the disk and reading the temperature of the disk. Precise timing of this procedure is mandatory. Corrections must be made to the rough readings for air, stem, and bulb temperature.

In 1934, the Smithsonian Institution determined through comparison with other instruments that silver disk pyrheliometer values were higher by about 2 percent than other standards (particularly, the Angstrom compensation pyrheliometer). Due to the reliability of the instrument and its general acceptance, secondary pyrheliometers in the United States have been calibrated against the silver disk pyrheliometer until as recently as 1956, when an International Pyrheliometric Scale (IPS) was adopted. Radiation intensity measurements in the United States prior to 1956, therefore, should be reduced by 2 percent (Ref. 29).

(3) *Thermopile pyrheliometers.* Since the Smithsonian silver disk pyrheliometer is not suitable for taking continuous measurements, substitute instruments with similar aperture exposure to the sun and capable of continuous measurement have been developed. These instruments employ a blackened thermopile as a sensor. In the United States, the Eppley Laboratory has manufactured normal incidence pyrheliometers for more than 40 yr. In this period, three different types of thermopile detectors have been used. Instruments with similar sensors have been manufactured in Europe, the U.S.S.R., and Australia, but are not commonly used in the United States.

The state-of-the-art in the development of these instruments is advancing rapidly, and instruments available now will certainly be improved to meet requirements for increased sensitivity, stability, reliability, and response time. An example of a thermopile pyrheliometer is shown in Fig. 6-28.

(4) *Bimetallic pyrheliometers.* The operating principle of a bimetallic pyrheliometer, like that of a bimetallic thermometer, is dependent on the differential expansion of two metals when heated. In the case of the

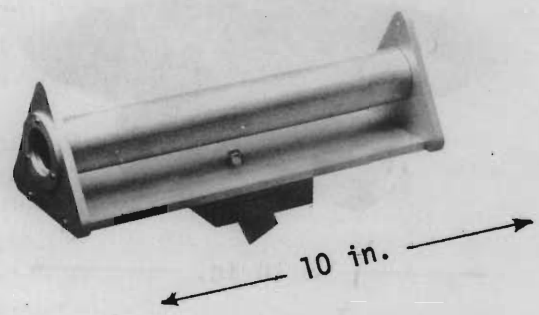


Figure 6-28. Thermopile Pyrheliometer

bimetallic pyrheliometer, a microscope is used to observe the deflection of the strip caused by differential expansion of the metals.

The first bimetallic pyrheliometer constructed by Michelson in Moscow in 1908 is a secondary instrument that must be calibrated from another standard. The instrument must be handled very carefully, but is reliable and has satisfactory response. It is portable and suitable for use on a daily routine basis and as a secondary standard in a radiation network. It is seldom used in the United States.

6-6.2.2 PYRANOMETERS

Instruments used for measurement of the total incoming shortwave radiation from the sun, both direct and diffuse, are designated as pyranometers. Radiation is usually reported in terms of total energy impinging on a unit area integrated over a given period of time. Instantaneous values of incoming global radiation are often unrepresentative–sometimes exceeding the solar constant–and it is necessary to have continuous records for proper evaluation.

Because pyranometers are normally exposed continuously and in all weather conditions, they must be designed to operate in conditions that are not applicable to pyrheliometers. It is necessary, for example, to pay particular attention to the glass or quartz envelope(s), which obviously must be clean and free from condensation, snow, and ice.

Site requirements for pyranometers are also more stringent than those for pyrheliometers; these instruments must be exposed to the full dome of the sky, and be free from obstructions and radiation reflected from light-colored walls or other objects.

The discussion that follows is divided into treatment of the simpler mechanical pyranometers or pyranographs, and the more sophisticated and more accurate electrical pyranometers. These two classes of instruments have one thing in common–the sensing elements depend on differential heating of blackened and whitened surfaces.

(1) *Mechanical pyranometers.* The most commonly used pyranometer throughout the world is the bimetallic pyranometer (more commonly known as an actinograph) developed by Robitzsch in 1932 and extensively modified since then. The design is attractive, but various drawbacks have been found. Despite improvements in recent years, the instrument is not recommended where accuracy of daily total radiation closer than 5 to 10 percent is required. Instantaneous values are even less reliable because of the inherent lag of the instrument. As an indicator of the occurrence of sunshine, the Robitzsch-type actinometer is superior to the sunshine recorders. It has a place in radiation networks in which the output is frequently checked against a more accurate instrument. It has the virtues of being simple and inexpensive, but its limitations must be recognized.

The Robitzsch-type mechanical pyranograph consists of an approximately horizontal receiving platform of three bimetallic strips arranged side by side. The upper surface of the middle strip is blackened while the outer strips are white. The strips are mechanically linked so that the temperature difference of the strips is indicated on a chart by the deflection of a pen. An example of a mechanical pyranograph that is self-contained and mechanically operated is shown in Fig. 6-29. The range of this instrument is about 3 cal cm^{-2} min^{-1} over a 3-in. chart span.

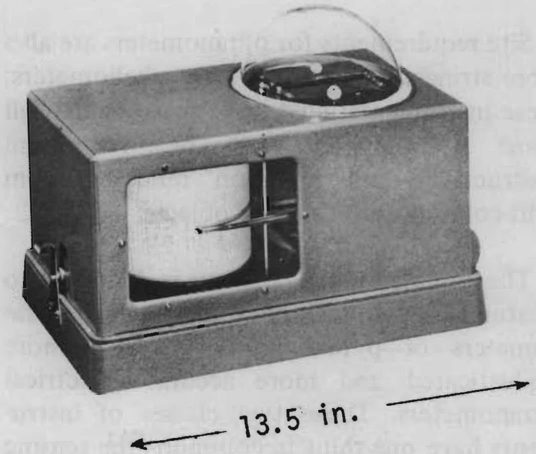


Figure 6-29. Mechanical Pyranograph

(2) *Electrical pyranometers:*

(a) The Moll-Gorczynski solarimeter. One of the better known pyranometers used outside the United States is the Moll-Gorczynski solarimeter. This instrument consists of a rectangular, blackened thermopile covered by two concentric ground and polished hemispherical domes. The outer dome can be replaced by a filter for measurement of selected portions of the spectrum. The Moll-Gorczynski thermopile has been used in several pyranometers and is accepted for its sensitivity and reliability in Europe, but these instruments have not been used for routine measurements in the United States. One difficulty with the current instrument is that the rectangular Moll-Gorczynski thermopile needs careful orientation–a factor of less importance with circular sensors. This instrument as shown in Fig. 6-30 has a sensitivity of about 7.9 mV per 1 cal cm^{-2} min^{-1} with the thermopile consisting of 14 constantan-manganin thermocouples.

(b) Eppley pyranometers. Two classes of Eppley pyranometers are manufactured in the United States. The first, the general purpose pyranometer (Fig. 6-31) is the general field instrument developed by Kimball and Hobbs in 1923 for the U S Weather Bureau, and now considerably improved. The second is a precision spectral pyranometer developed

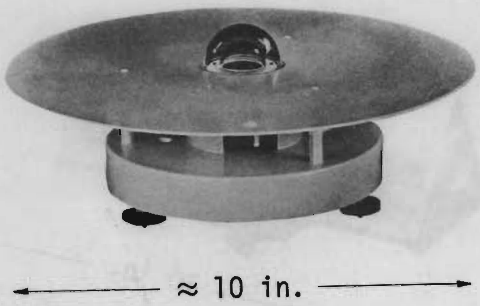


Figure 6-30. Moll-Gorczynski Solarimeter

under a U.S. Army contract. The two types of Eppley pyranometers (formerly known as 180-deg pyrheliometers) differ in the number of thermojunctions employed in the construction of the thermopile unit. The thermopile sensors consist of a concentric copper on constantan junctions. The hot and cold junction receivers are coated with Parson's black and barium sulfate, respectively; the whole unit is hermetically sealed in a specially blown lamp bulb, almost spherical and approximately 3 in. in diameter, made of thin soda lime glass. The unit is secured to a tripod that has two leveling screws and a hole in each leg for mounting to a support.

The precision spectral pyranometer (Fig. 6-32) has been developed in order to achieve the highest accuracy possible in the measurement of global and diffuse sky radiation. The original precision pyranometer was an improvement over the older, general-purpose pyranometer; optical compensation for elimination of reflection losses (the so called cosine error) was introduced, and an electrical circuit for temperature compensation of the instrument was incorporated. The most recent version of the precision pyranometer is more compact, is more rugged, and contains an improved thermopile.

Both versions of the precision pyranometer have inner and outer hemispheres that allow the use of a wide range of filters for separation of solar radiation into well-defined wavelength intervals. Filters recommended for use internationally and available at this time

Figure 6-31. Kimball-Hobbs Pyranometer

include broad bandpass filters that eliminate the transmission radiation at wavelengths below 500, 530, 630, or 700 nm. These shortwave cutoff points show a small shift to longer wavelengths with higher temperatures.

In addition to the broad bandpass filters described, narrow bandpass filters are also available that isolate relatively small wavelength intervals of the order of about 50 nm in the ultraviolet, 100 nm in the visible, and several hundred nm in the infrared. All filters require careful calibration and many are susceptible to damage from rough usage.

(c) Photovoltaic solarimeters. A more recently developed lower cost solarimeter utilizes the silicon photovoltaic cell such as is employed in solar cell power generation arrays. One such unit uses nine cells and provides instantaneous readings as well as integrated values on an ampere-hour meter with no external power required. The photovoltaic solarimeter has a high response speed compared to the thermal units and a different spectral response, peaking at 850 nm. One such instrument is shown in Fig. 6-33. The U S Weather Bureau has evaluated and used silicon-cell pyranometers to obtain continuous recording of total solar radiation intensities. This evaluation indicated that the average silicon cell response was 0.74 percent higher than the working standard pyranometer under clear skies and 4.12 percent lower under cloudy skies (Ref. 33).

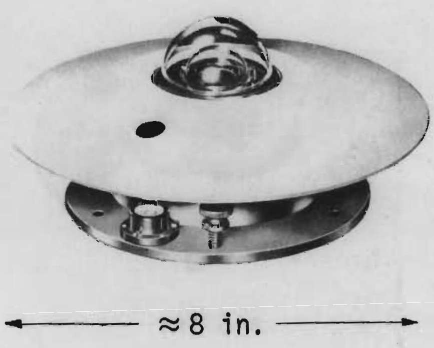


Figure 6-32. Precision Spectral Pyranometer

6-6.3 LONGWAVE (TERRESTRIAL) RADIATION MEASUREMENT

The importance of longwave radiation in consideration of energy balances in the atmosphere and at the surface of the earth has been long appreciated. The thermal state of any item is dependent upon the balance between the incoming and outgoing exchange of longwave (terrestrial) radiation. The term "terrestrial" is used here to include all radiation originating at the surface of the earth or in the atmosphere.

Despite the importance of longwave radiation balances, they have not been measured in a systematic manner comparable to the measurement of solar radiation. Both interest in, and instruments for, measurement of terrestrial radiation have long been lacking. This is not the case now, although it will require time for most of the recently developed radiometers to become available for other than research use at a few locations.

Longwave (terrestrial) radiation in the spectral region between 5 and 100 μm plays an important role in the heat balance of the atmosphere up to an altitude of 80 km. Below this altitude, water vapor, carbon dioxide, and ozone all absorb and emit radiation in this spectral band, so that the longwave radiation fluxes between ground, clouds, and atmosphere are quite complicated. Discussion of these fluxes is beyond the scope of solar

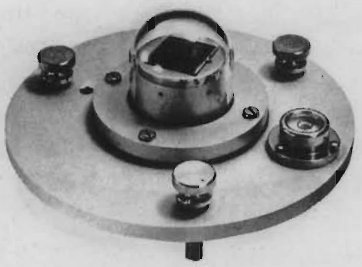


Figure 6-33. Photovoltaic Solarimeter Utilizing Silicon Cells

radiation but the measurement is closely related to it.

The terms "longwave pyranometer" and "effective pyranometer" are often employed to denote longwave sensing instruments. Confusion is avoided, however, if all longwave sensors are referred to as radiometers—distinct from pyrheliometers and pyranometers that sense shortwave solar radiation.

All radiometers measure the exchange of energy between a receiving surface and the target at which it is pointed. In the case of the shortwave sensing pyranometer, the longwave exchange between the glass hemisphere and the sensor is effectively zero since they are at approximately the same temperature. A radiometer that is to measure the total terrestrial radiation upward or downward must exchange radiation freely with all parts of the appropriate hemisphere. A completely uncovered matt-black receiver will do this, but unfortunately, it is subject to other avenues of heat exchange (in addition to radiation), particularly, convective heat loss that will falsify readings.

One solution to the problem of convective heat loss is provision of a cover transparent to total radiation. This principle is used in both the Schulze radiometer and, more recently, in the Australian-made Funk radiometer. Both of these instruments have hemispherical shields of polyethylene that are transparent to longwave radiation, thereby eliminating the convective heat loss from the sensor. (Some doubt remains, however, about the effectiveness of polyethylene as a transmitter of longwave radiation.)

Only partial information is available on two instruments that are thought to advance the state-of-the-art in radiation measurement. The first of these was developed at Davos, Switzerland, and is intended for complete measurement of radiation fluxes, longwave and shortwave. It consists of two double hemispherical shortwave sensors and two single hemispherical polyethylene hemispheres for longwave sensing. It has been used in U S. Army investigation of the radiation climatology of a site in the Antarctic*.

The other state-of-the-art instrument is designed for measurement of longwave radiation. It employs a special glass hemisphere made of a substance known as KRS-5, which, reportedly, is a better longwave window than polyethylene. The inner side of the hemisphere is coated with a special material that isolates energy in the wavelengths between 3,000 and 50,000 nm. This instrument, developed by the Eppley Laboratory, employs thermoelectric temperature regulation of the radiation sensor (Ref. 33).

A Fritschen net radiometer is shown in Fig. 6-34. This instrument is used to measure net radiation, i.e., the difference between total downward and total upward radiation flux. Its small size will not appreciably alter the radiation balance by overly shading the surface, and it is sensitive from 0.3 to 60 μm. A 22-junction manganin-constantan thermopile is used for the sensor giving a response time of 12 s and a sensitivity of 3.5 mV per cal cm^{-2} min^{-1}. Absorbing surfaces are exposed through polyethylene windows in both the upward and downward directions such that the thermopile indicates the temperature difference and thus the net flux of radiation.

***Additional information about this instrument can be obtained from the Earth Sciences Laboratory, U.S. Army Topological Command, Ft. Belvoir, Va.**

Figure 6-34. Fritschen Net Radiometer

6-7 EFFECTS OF SOLAR RADIATION

Solar radiation produces a variety of effects that influence requirements for and performance of materiel. To obtain perspective on these effects, they may be listed as follows:

(1) *Photochemical degradation of materials.* This is a widespread and important effect and is the primary subject of the paragraphs that follow.

(2) *Heating of materiel and the environment.* This is the most important effect of solar radiation, sufficiently so as to merit separate consideration as an environmental factor in Chap. 3 of this handbook.

(3) *Personnel performance degradation.* Solar radiation causes stress on human beings either by direct burning, by restricting vision, by thermal stress, or by acting in combination with other environmental factors to produce synergistic reactions. This requires protective measures–clothing, shelter, eye protection, air conditioning, tinted windows–to maintain acceptable performance capabilities.

(4) *Optical sensor degradation.* Sensors employed for guidance, detection, surveillance, and reconnaissance may be degraded in performance either temporarily or permanently by exposure to direct or reflected solar radiation.

(5) *Decreased covertness.* In operational environments, reflected solar radiation often serves to reveal operations that otherwise would remain undetected. It is necessary to provide operational materiel with a minimum of highly reflective surfaces.

While all of these are important, the discussion that follows is restricted to the effects of solar radiation on materials. The processes of degradation are primarily photochemical in nature and are controlled by the amount and spectral distribution of the radiation. Thus, blue and ultraviolet wavelengths, which are characterized by photon energies greater than 2.5 eV*, are sufficient to cause chemical changes. The changes produced depend on the chemical composition of the material, its period and degree of exposure, and the presence or absence of other factors such as high temperature, water, oxygen, ozone, sulfur dioxide, or other chemical reactants.

This discussion of the effects of solar radiation on materials pertains to a terrestrial environment in which adequate oxygen is always present. In such an environment, irradiation of materials by wavelengths shorter than about 290 nm is, for all practical purposes, nonexistent, since ozone absorbs the far ultraviolet before it penetrates the atmosphere to the surface of the earth. The exact values at the short-wavelength end of the range vary slightly with the time of day, season of year, elevation, etc.

Because many organic polymers are used extensively in space technology, such applications subject them to irradiation by the complete solar spectrum unless protective measures are taken. Solar radiation that has not been modified by passage through the atmosphere of the earth includes relatively high energy photons, i.e., it has a high ultraviolet content. Thus, these conditions can significantly affect materials with high absorption coefficients and the strikingly different exposure conditions in space can adversely affect the severity and rate of actinic (photochemical) degradation compared to terrestrial environments.

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*A convenient conversion formula from wavelength to energy is given by $\lambda E = 1.24$ where λ is in micrometers and E in electronvolts.

When light of sufficient energy is incident on matter, it can disassociate molecules into atoms, simpler molecules, or free radicals, or it can excite molecules or atoms producing fluorescence or phosphorescence. Alternatively, the absorbed energy may excite the molecule but the excitation energy is converted to thermal energy by intermolecular collisions and vibrations. In order for chemical reactions to occur, molecules must absorb energy sufficient to rupture chemical bonds. This process can occur only if the energy is not dissipated in other ways and depends not so much upon the total energy but more on the amount of energy per photon at the wavelength of that energy. Most chemical reactions require energies of between 25 and 100 kcal mol^{-1} for activation—this corresponds to photons, with energies from 1 to 4 eV (wavelengths from 1.24 to 0.31 mm), interacting with a molecular bond. Texts on photochemistry should be consulted for a more complete discussion (Ref. 34).

A basic knowledge of activation energies of chemical reactions is useful in evaluating the possibility of photochemical degradation. The degradation can assume many forms, usually the breakdown of a chemical into less complex constituents, for example, the breakdown of nitrogen dioxide to nitrous oxide and oxygen. In other materials such as polymers, the reactions are more complex. The two main types of chemical reactions occurring in polymeric materials exposed to energetic radiation are cross-linking and chain-scission. Both processes are induced by free radical formation and interaction, and cause structural changes within and between adjacent polymer chains. Chain-scission causes weight loss and induced porosity or formation of internal stresses. When cross-linking becomes excessive, elastomers, for example, show a loss in flexibility. In rigid plastics, however, cross-linking produces cracking and crazing, which is a result of internal stress.

Although all wavelengths of the electromagnetic spectrum can cause heating and, in many cases, other effects on terrestrial bodies, the effects on different materials are not the same but vary with the ability of a body to absorb, reflect, and transmit incident energy. In this paragraph, concern is focused on the solar radiation reaching any part of the surface of the earth where the Army may need to operate. This radiation includes only the near and some of the middle shortwave ultraviolet (between about 290 and 380 nm), all the visible range (between 380 and 760 nm), and the near and middle longwave infrared (between about 760 and 4,000 nm).

Ultraviolet radiation is the most destructive solar radiation. Visible radiation can also be destructive, but to a lesser extent. Infrared radiation is normally less harmful.

The ultraviolet content of sunshine causes photochemical degradation of most organic materials. Because of the deleterious effect on the relatively weak bonds of their molecular structure, the elasticity and plasticity of certain rubber compounds and plastic materials are likely to be adversely affected. The degradation is also manifested by the fading of fabric colors, and checking of paints, natural rubber, and plastics. These minute checkered patterns are exaggerated by the presence of ozone. Optical glass exposed to ultraviolet, including that used as transmitting media, becomes increasingly opaque with radiant intensity and time. By contrast, ultraviolet radiation has little effect on the stronger chemical bonds of metals, ceramics, and inorganic compounds. The effect of ultraviolet on structural metals is negligible.

The visible portion of the solar spectrum also bleaches out colors in paints, textiles, leather, and paper. In some instances, visible light may make illegible the important color coding of components. Both the near infrared and visible radiation penetrate some materials and the human body. The absorption of radiation near the surface of the skin or surface of an inanimate object raises the temperature in essentially the same way as thermal radiation. Skin tanning occurs in a narrow band around 297 nm, and skin burning occurs at about 313 nm. Germicidal radiations range from 200 to 330 nm. Photographic reactions occur between 380 and 760 nm.

An excellent review of the effects of solar radiation on materials is given by Greathouse and Wessel (Ref. 35), which forms the basic reference for the discussion that follows.

6-7.1 TEXTILES

Solar radiation is the most active climatic or nonbiological factor causing deterioration of exposed textiles. The deterioration is generally manifested by a loss in tensile strength, by a loss in elasticity, and by discoloration of fibers. The presence or absence of oxygen is of major importance in determining the effect of sunlight on textiles. In the absence of light, however, oxygen has no effect on textiles (Ref. 36).

The characteristics of a fiber have an important bearing on its resistance to the harmful effects of sunlight. Delustered (dull) nylon, for example, contains titanium dioxide (TiO_2, anatase), which catalyzes the degradation of nylon. The rate of photochemical degradation is also affected by some dyestuffs, sizing, weighting, various other finishing materials, fungicides, acids, alkalis, salts, soaps, and oils.

In general, those factors influencing the ultraviolet decomposition of cellulose are complex and difficult, often impossible, to isolate in exposure tests. The numerous interrelated factors vary daily at any given place, and differ in occurrence and intensity throughout the world. Scientific evidence from many investigations over a long period of time makes it reasonably safe to conclude that the more auxiliary factors are present—moisture, oxygen, ozone, heat, chemicals, etc.—the faster and more severe the effect of radiation on a cellulosic fiber is likely to be for wavelengths of any given intensity.

The great variation in individual fiber strength, the difficulty of setting up and monitoring single-fiber tests, and the lower variability in strength of apparently comparable yarns and fabrics have encouraged investigators to prefer multifiber to single-fiber specimens in their comparative studies of different textiles.

6-7.1.1 NATURAL FIBERS

Natural textile fibers are of plant (e.g., cotton, linen, and jute) and animal (e.g., wool and silk) origin. The action of sunlight on natural fibers varies with the kind of fibers. Authorities on the subject believe that sunlight breaks or weakens the glycosidic linkages within the cellulosic molecules. Once these are damaged, oxygen greatly accentuates the degrading action on cellulose. Thus, cotton and linen continue to deteriorate for as long as 8 months in storage following exposure to sunlight. Actinic degradation of cellulose is relatively rapid during the first few months, with a gradual logarithmic decrease in the decomposition rate. In general, textile yarns and cordage are more resistant to photochemical action than smaller threads, since the outer fibers protect the inner ones. Ultraviolet wavelengths below 364 nm are the most harmful to cellulose.

Compared with vegetable fibers, wool is relatively resistant to the effects of sunlight because the greater stability of protein molecules (keratins) makes them less readily hydrolyzed than cellulose molecules (Ref. 37). One type of degradation occurs when light activates the disulfide groups in wool into hydrogen sulfide, which then oxidizes to sulfuric acid. The acid causes decomposition of wool irradiated in air (Ref. 36). Nevertheless, wool is superior to vegetable fibers such as cotton.

Silk is highly sensitive to solar radiation. The extent of damage is closely related to the acidity of the environment in which the fabric is exposed (Ref. 35).

Natural fibers listed in order of decreasing resistance to photochemical deterioration are wool, cotton and linen, jute, and silk. Deterioration is most commonly indicated by a loss in tensile strength and, secondarily, by a tendency for white cellulosic fibers to yellow (Ref. 35).

6-7.1.2 SYNTHETIC FIBERS

Semisynthetic fibers include those derived from complex molecules such as cellulose, protein, or glass. Sunlight generally causes a loss of tensile strength but little discoloration in semisynthetics such as cellulose acetate and rayon fibers. The surface luster of the fiber is important; bright rayon retains its strength twice as long as delustered rayon. Regenerated protein fiber is similar to wool in its characteristics, and glass fiber is relatively unaffected by solar radiation.

Synthetics include those fibers built up from basic chemical elements. Those made of unplasticized polyvinyl chloride fibers, polyvinyl alcohol fibers, and polyacrylonitrile fibers are extremely resistant to sunlight.

Prolonged exposure of polyamides to sunlight causes discoloration and loss of strength. The resistance of nylon to actinic deterioration depends upon its type and degree of luster. The resistance of dull nylon is a little better than silk, but bright nylon is almost equal to cotton. The better known nylon fabrics are generally more resistant to sunlight than corresponding silk fabrics (Ref. 38).

The prolonged exposure of polyester fiber to sunlight produces slow photochemical weakening at a gradually decreasing rate, but with no darkening or loss of color (Ref. 39).

The copolymers, vinyl chloride-acrylonitrile and vinyl chloride-vinyl acetate, become somewhat darker after long exposure. Polyvinylidene chloride also becomes slightly darker and loses slight tensile strength after prolonged exposure to sunlight.

Table 6-12 compares the general resistance of 10 synthetic and regenerated fibers to general outdoor environment in which solar radiation is the most destructive environmental factor. Table 6-13 contains a summary comparison of sunlight-resistance information of representative synthetic and natural fibers

TABLE 6-12

RESISTANCE OF FIBERS TO OUTDOOR EXPOSURE (Ref. 35)

Fiber	Resistance to outdoor exposure
Viscose rayon	Yellows slightly
Cuprammonium rayon	Good
Acetate	Loses strength somewhat
Nylon	Excellent
Vinyl chloride - acrylonitrile	Excellent
Polyvinylidene chloride	Excellent
Polyacrylonitrile	Excellent
Polyesters	Excellent
Glass	Excellent

TABLE 6-13

EFFECT OF SUNLIGHT ON FIBERS (Ref. 35)

Fiber	Type of chemical	Reported effect
Cotton	Cellulosic	Loss of strength, tendency to yellowing
Silk	Protein	Loss of tensile strength, affected more than cotton
Wool	Protein	Loss of tensile strength, dyeing affected, less affected than cotton
Viscose rayon	Regenerated cellulose	Loses tensile strength on prolonged exposure, very light discoloration, superior to acetate
Cuprammonium rayon	Regenerated cellulose	Loses strength on prolonged exposure
Acetate	Cellulose acetate	Slight loss of tensile strength, no discoloration
Nylon	Adipic acid and hexamethylene diamine	Loses strength on prolonged exposure. No discoloration. Bright yarn more resistant than semidull
	Caprolactam	Similar to nylon
	Vinyl chloride and vinyl-acetate	None
	Vinyl chloride and vinylidene chloride	Darkens slightly
	Vinyl chloride and acrylonitrile	Darkens somewhat after prolonged exposure, some loss of tensile strength
	Terephthalic acid and ethylene glycol	Some loss in strength, no discoloration, much more resistant behind glass than in direct sunlight
	Polyethylene	Some loss of tensile strength for clear, much less for pigmented. No darkening
	Protein	Very slow deterioration and loss of strength
Glass	Inorganic	None
Asbestos, chrysotile	Inorganic	None

compiled from the literature (Ref. 34).

The harmful effects of sunlight on synthetic fibers can be minimized by adding certain benzophenone derivatives and manganese salts (Refs. 39,40). Such treatments are particularly effective in the polyamides, acrylics, and polyesters.

Other protective agents have been reported by a number of investigators. The use of urea-formaldehyde resin, especially in combination with such pigments as lead chromate and chromium oxide, protects fabrics against weather. A number of workers have furnished favorable reports on the protective properties of trivalent chromium against actinic deterioration. Aside from the excellent sunlight protection provided by chromium oxide treatments, the addition of copper naphthenate protects fabric from soil deterioration with no loss in resistance to sunlight (Ref. 35).

6-7.2 PAPER

All papers are susceptible to damage from light in varying degrees. Like cotton and linen, paper consists mainly of cellulose, the use of which in either textiles or paper poses similar problems with regard to actinic degradation.

The effect of sunlight on paper is indicated by progressive discoloration (yellowing, bleaching, and whitening), embrittlement, and loss of tensile strength. The resistance of paper to sunlight depends on the kind and source of materials used in its manufacture.

In order of decreasing resistance, the common basic materials are new rag, refined sulfite, old rag, soda sulfite, and newsprint. The presence of rosin, glue, alum, iron, lignin, and other substances has a major influence on photochemical degradation. Sunlight and artifical light high in ultraviolet accelerate the degrading process. Relatively cheap papers are subject to more rapid deterioration by sunlight than are high grade papers, other conditions and ingredients being comparable. Contrary to general belief, bleaching and yellowing of paper may occur concurrently. Sulfuric acid and free rosin increase the effect of light on high quality papers much more than on cheap papers. An environmental factor that may either accelerate or retard degradation is water vapor. Experiments indicate that water vapor decreases the effect of light on paper made from wood pulp, but increases the effect of light on paper made from cotton.

Compared to textiles, relatively little is known about techniques for protecting paper from the effects of light, especially sunlight, although a few simple measures can be taken. Paper can be kept out of sunlight, or at least exposure can be minimized by storing in covered containers or in rooms in which sunlight is excluded. Avoidance of intense direct sunlight is especially important before usage. In some situations, the use of low-wattage lamps will be appropriate where paper is kept. The limited spectral transmission of glass protects papers made from purified wood pulp and provides some protection to sulfite papers, but none to unused newsprint containing 85 percent ground wood. Colored window glass provides some protection to paper, depending upon the type of glass, its color, and the degree of coloration. Ordinary window glass provides a minimum of protection against light.

6-7.3 PLASTICS

Plastics may be conveniently grouped as thermoplastics and thermosets. The thermoplastics are characterized by a predominantly chainlike molecular structure that can soften as a result of heat absorbed from solar radiation. By contrast, the thermosets have a highly cross-linked structure that hardens when exposed to solar radiation.

The general effect of solar radiation on most unprotected plastics is to produce a photochemical reaction*. In the presence of air, irradiation causes plastics to oxidize with the result that modifications in their molecular structures weaken them. Common evidences of photochemical damage are a loss of strength, embrittlement, cracking, crazing, discoloration, and a loss in electrical properties.

Since the absorbed radiant energy affects only an extremely shallow outer portion of the more massive forms of plastics, their structural strengths are not seriously impaired. However, thin sheets or coatings of plastic exposed to sunlight may suffer a relatively rapid change in properties (Ref. 41).

Table 6-14 shows some effects of sunlight on a number of thermoplastics. Crazing and embrittlement occur in unprotected polypropylene, polyethylene, and the cellulosic esters; exposure of unprotected polyvinylchloride causes hardening and discoloration. The mechanical properties of thermoplastics are appreciably altered.

As shown in Table 6-15, the thermoplastics are similar to other materials in that maximum effects are found in the ultraviolet wavelength range.

The most obvious effects of sunlight on thermosets are surface changes, for their well interconnected molecular structures are seldom affected by photochemical reactions. Since the structure of thermosets remains essentially unchanged by sunlight, their mechanical properties are generally also unaffected. Common effects of sunlight on thermosets are presented in Table 6-16, reflecting mainly the extent of changes in coloration and resistance of surface insulation or moisture absorption properties.

As with thermoplastics, the high energy ultraviolet band is the most harmful to thermosets. The most sensitive wavelength for various polyesters is reported to be 325 nm (Ref. 35).

Since the laminated plastics include the resin used in thermosets, the effects of sunlight, if any, on this group of plastics are also limited to slight surface degradation.

Since the value of many plastics lies in their flexible, moldable, colorless-transparent, or translucent qualities, considerable effort has been made to eliminate, or at least retard, the degrading effects of sunlight. The inclusion of small amounts of certain additive compounds, such as benzotriazole or benzophenone, in the manufacture of plastics provides good protection against the loss of the usually desired properties. An absorber, preferably colorless, with an absorption capacity many times greater than that of the most destructive ultraviolet wavelength, should be well distributed throughout a plastic material for maximum protection (Ref. 43).

6-7.4 RUBBER

Rubbers are polymeric materials in which molecules are long, flexible, and connected by few cross-links. Unlike the thermoplastics, however, their molecules are randomly coiled and only when the rubber is under stress do they tend to align themselves in rows parallel to the direction of stress. However, the deleterious effect of sunlight on natural rubber and some synthetic rubbers is generally similar to that on the thermoplastics. Rubber deterioration is caused primarily by oxygen and ozone. Other factors influence oxidation, including heat, light, moisture, and certain metallic ions in descending order of importance.

Photo-oxidation of vulcanized natural rubber by sunlight may cause simultaneous cross-linking and chain-scission of its molecular structure. The cross-linking effect is manifested by the gradual formation of an irregular pattern of very fine cracks on the surface of rubber or a random pattern similar to an aged outdoor paint film.

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*Reference should be made to American Society for Testing and Materials Committee 7-20 (Plastics) and Sub-group V (Permanent Properties) for results of radiation testing on a wide variety of plastics.

TABLE 6-14

EFFECT ON SUNLIGHT ON THERMOPLASTICS (Ref. 42)

Thermoplastics	Effect of Sunlight
ABS (acrylonitrile-butadiene-styrene)	None to slight yellowing and embrittlement
Acetals	Chalks slightly
Methyl methacrylate	None
MMA styrene copolymer	None
Acrylics	Slight strength loss
MMA/Alpha methylstyrene copolymer	None
Ethyl cellulose molding compounds and sheets	Slight when properly stabilized
Cellulose acetate	Slight
Cellulose propionate molding compound	Slight
Cellulose acetate butyrate	Slight
Cellulose nitrate	Discolors, becomes brittle
Chlorinated polyether	Slight loss in surface ductility
Fluoroplastics	None
Nylon	Embrittled by prolonged exposure but stabilized grades are available
Polyethylene	Unprotected material crazes rapidly. Requires carbon black for complete protection but other resistant grades are available.
Ethylene copolymers	Very slight yellowing
Polypropylenes	Unprotected material crazes, protected grades are available
Polystyrenes	Yellows slightly, some strength loss
Polycarbonate	Slight color change and embrittlement
Phenoxy	Slight discoloration and embrittlement
Polysulfone	Strength loss, slight yellowing
Vinyl butyral molding compounds	Slight
Vinyl polymers and copolymers	Slight
Polyvinylidene fluoride	Slight bleaching on long exposure
Urethane elastomers	Yellows slightly

TABLE 6-15

WAVELENGTHS OF MAXIMUM SENSITIVITY ON THERMOPLASTICS (Ref. 35)

Thermoplastic	Wavelengths of maximum sensitivity, nm
Polystyrene	318
Polyethylene	300
Polypropylene (nonheat-stabilized)	310
Polyvinylchloride (P.V.C.)	310
Polyvinylchloride (copolymer with vinyl acetate)	322 and 364

Chain-scission of rubber reduces the elongation and tensile strength. Like most other elastomers, rubbers are more profoundly affected by sunlight, oxygen, or ozone when under tensile or other internal physical stress—such as when sharply bent—than when in a relaxed state.

Visual inspection of vulcanized rubber is seldom an accurate means of determining the extent of damage caused by sunlight. When rubber specimens have been under tension, as is the case in most exposure tests, determining the degree of deterioration by observation is even less reliable.

Synthetic rubbers differ from natural rubbers in chemical composition but possess similar elastic qualities because of their molecular structure. The relative resistance of representative natural and synthetic rubbers to sunlight is given in Table 6-17.

The advantages of synthetic rubbers include superior resistance to sunlight and heat, and a lesser tendency in many cases to swell in oil. However, the resistance of a number of synthetic compounds depends largely upon the nature of the compounding. The effect of sunlight on polychloroprene, butadienestyrene, and nitrile rubbers is mainly photo-oxidation. This involves the formation of many random cracks on the surface, with a resultant loss in extensibility and an increased hardness; the tensile strength is little affected.

Deterioration of natural rubber can be lessened by the inclusion of compounding ingredients resistant to light. For example, the addition of carbon black to rubber acts as a light screen, thereby prolonging its life. The compounding ingredients giving the most effective protection against sunlight are certain paraffins or blended waxes. In a series of natural weathering tests, natural rubbers containing no wax lost as much as 60 percent of their original tensile strength within 120 days (Refs. 38,45).

Although plastics and rubbers are basically different substances, they possess many common, highly versatile, and useful properties. Neither of the materials, however, has all the properties that withstand the deleterious effects of sunlight and other agents. While differing in some respects, both plastics and rubbers have two major characteristics distinguishing them from other common construc-

TABLE 6-16

EFFECT OF SUNLIGHT ON THERMOSETS (Ref. 42)

Thermosets	Effect of sunlight
Casein	Colors may fade
Diallyl phthalate	None
Furan	None
Melamine-formaldehyde molding compounds	Slight color change
Phenol-formaldehyde and phenofurfural molding compounds	General darkening
Polyacrylic ester	None
Silicones	None to slight
Urea-formaldehyde	Pastel colors turn to gray
Epoxy resins	Slight to none
Allyl resins	Yellows very slightly
Phenolic resins (no filler)	Colors may fade
Phenolic resins (mineral filler)	Darkens
Phenolic resins (asbestos filler)	Darkens slightly
Polyester resins	Yellows slightly
Polyurethanes	Slight yellowing

tion materials like metal or wood. First, plastics and rubbers are mostly synthetics, and, second, they are high polymers compounded with a wide variety of substances, including fillers, plasticizers, dyes, pigments, vulcanizers, stabilizers, antioxidants, etc. Unlike other construction materials, plastics and rubbers cannot readily be protected from the agents of deterioration by applying coatings or treatments after fabrication. Plastics and rubbers also differ from most other materials in the nature of these effects, usually cracking, crazing or checking, discoloring, hardening (sometimes by softening first), and loss of pliability and elasticity. Fortunately, the chemical nature and almost infinite variations in the manufacture of plastics and rubbers provide a great range of possibilities for improving military items.

6-7.5 SURFACE COATINGS*

Organic surface coatings such as paint, varnish, enamel, and lacquer are subject to actinic degradation, which may be manifested by discoloration, darkening, cracking, or a loss of adhesion to the substrate. Short-wavelength radiation is most damaging.

Surface coatings consist of two components, the vehicle or binder, which is usually organic, and the pigment, which may be either organic or inorganic. Both of these are subject to actinic degradation. The organic constituents, particularly the vehicles that are based on vegetable oils, deteriorate more rapidly. Pigments such as magnesium carbon-

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*A general reference for this paragraph is Ref. 35.

TABLE 6-17

COMPARATIVE RESISTANCE OF NATURAL AND SYNTHETIC RUBBERS TO PHOTO-OXIDATION (Ref. 44)

Rubber	Comparative resistance
Natural	Low
Butadiene-Styrene (SBR)	Low
Butyl	High
Polychloroprene (neoprene)	High
Nitrile	Medium
Polysulphide	Medium
Silicones	High
Chlorosulphonated Polyethylene	High
Acrylate	High
Polyesters	High
Fluorinated	High

ate and zirconium oxide are good ultraviolet reflectors and serve to protect the vehicle. Paints employing inorganic vehicles, developed for space applications, are inherently more stable than the common paints (Ref. 41).

6-8 DESIGN

The consideration of solar radiation in design begins with the solar radiation intensities obtained from par. 6-5 when average values are required or from par. 6-4 if instantaneous or extreme values are required. Instantaneous values of solar radiation are important in design only when thermal loads on materiel are being considered (this subject is considered in Chap. 3 of this handbook) or when application of optical devices or human vision are being considered.

The design of optical devices is too highly specialized to warrant discussion in this chapter. Antireflection coatings on lenses, wavelength selective mirror surfaces, optical filters, and other techniques are applied so as to minimize interference with the equipment performance by solar radiation.

Human effects of solar radiation also constitute a highly specialized area but one for which protective devices must be provided. Snowblindness, sunburn, sunglare interference with vision, and sun-glint detection are factors requiring attention in certain geographic regions if operational capabilities are to be maintained. Protective goggles, nonreflecting surface coatings, sunburn medication, and other measures are required.

The primary design problem relating to solar radiation, however, is that of deterioration of materials by solar radiation. For this, integrated values of solar radiation must be considered over the operating life of the exposed material. In some cases, actinic degradation may limit the storage life of items of materiel; in other cases it may define the useful operational life. This is illustrated by some examples as follows:

(1) Clear acrylic sheets are employed as a nonshattering substitute for glass windows in instruments and shelters. After prolonged exposure to solar radiation, the acrylic gradually increases in opacity until it transmits a much reduced level of light and restricts or greatly limits the ability to observe objects through it.

(2) Paper exposed to sunlight becomes yellow and brittle. If the paper contains information, it is more susceptible to destruction and loss. If the paper is unused, it becomes waste. If the paper is used as a packaging material, it provides less protection.

(3) Paint on exposed structures and equipment gradually deteriorates thereby exposing the surface to other degradation mechanisms. This creates expensive logistic and maintenance problems.

(4) Plastic parts exposed to sunlight lose their strength and color. Typical examples are plastic handgrips, insulation, coatings, containers, and construction materials.

The avoidance of such actinic deterioration is primarily accomplished by giving attention to it at the design stage. Materials can be selected that are more resistant to degradation and provisions can be made for replacements where degradable materials are required. In logistical and operational activities, practices can be accomplished wherein exposure and thus degradation is avoided. Given such attention, the effects of solar radiation can be minimized to where they become an unimportant factor in Army materiel considerations.

6-9 TESTING FOR SOLAR RADIATION EFFECTS

Testing for the effects of solar radiation is accomplished either by outdoor exposure to sunlight or by use of solar radiation simulation facilities. Outdoor testing is often preferred since it more accurately produces the actual conditions of usage of the materiel being tested. At the same time, outdoor testing is subject to the vagaries of the weather, the difficulty of ascertaining exposure levels over extended test periods, and difficulties in interpreting the results. Thus, if a material is exposed for 6 mo in a tropical test site and deterioration is observed, it may be possible to ascribe the deterioration to solar radiation, high temperature, excessive humidity, microbiological organisms, salt, or to some combination of these factors. It is important to identify the most significant factor or factors before remedial steps can be taken.

Simulation offers the advantage of control of the environmental factors so as to allow identification of the degradation mechanism and of accelerated testing; in simulation chambers, one may obtain 24 hr of "sunshine" at noontime intensities or even higher every day. In simulation chambers, it has been found possible to accurately reproduce solar radiation thermal loads on materiel; this constitutes the main emphasis of solar simulation. The actinic and optical effects are more difficult to simulate because of the limitation on radiation sources. Specifically, in the very important short wavelength ultraviolet end of the spectrum, it is not possible to reproduce the energy-wavelength spectrum of solar radiation, only to approximate it to varying degrees.

Solar simulators are widely employed. A bibliography (Ref. 46) and survey (Ref. 47) of solar radiation simulation have been prepared but these are primarily concerned with the thermal effects. Standards are available for both outdoor and simulation testing of various materials*, each of which

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*ASTM Recommended Practices include D 795-65T Exposure of Plastics to S-1 Mercury Arc Lamp, D1501-65T Exposure of Plastics to Fluorescent Sunlamp, E 187-63T Conducting Natural Light (Sunlight and Daylight Exposures Under Glass), E. 188-63T Operating Enclosed Carbon-Arc Type Apparatus for Artificial Light Exposure Tests, and others. These are found in the *1967 Book of ASTM Standards* (Ref. 48). A new edition of the Book of Standards is issued annually and consists of a number of parts (32 in 1967) including two on plastics, two on textiles, one on rubber, and one on electrical insulation among its comprehensive coverage of materials and methods.

points out the inherent difficulties of the test.

6-9.1 TEST RANGES

Tests of the resistance of military materials to solar radiation under field conditions are normally accomplished in conjunction with other test programs. For the most part, solar radiation field tests consist of exposing the test material to the direct rays of the sun for specified periods of time and observing and measuring these effects during and at the end of the test period. Although testing of this type may be done at almost any field installation, the best results are obtained under conditions of intense sunshine associated with desert areas. Therefore, most solar radiation testing by military agencies is done in the western deserts of the United States. The Army uses the Yuma Proving Ground and its facility in the Death Valley Desert for such tests. The Navy uses a test facility in the desert area at China Lake, Calif., and the Air Force conducts tests at Edwards Air Force Base, Calif., and in the Death Valley area.

Commercial facilities also exist for solar radiation testing. The three best-known are Phoenix Desert Sunshine Exposure Tests in Phoenix, Ariz.; South Florida Test Service, Miami, Fla.; and Subtropical Testing Service, Miami, Fla. As indicated by their locations, the first facility is used primarily for testing materials under desert sunlight conditions; the remaining two test sites are characterized by subtropical, humid conditions.

6-9.2 SIMULATION TESTING

When simulating solar radiation, the total radiant energy per unit area as well as the distribution of the energy throughout the spectrum must be controlled. The concentration of radiation on the test item will depend upon the wattage and spacing of the lamps used, the efficiency of the lamp reflector unit, and the distance between lamps and surfaces of the test specimen. Radiation sources should be located at least 30 in. from any outer surface of a test item. Before conducting a radiation test, the actual intensity of radiation should be measured at the site where the test item is to be positioned.

Method 505, MIL-STD-810 (Ref. 49), specifies criteria and procedures to be used in conducting solar radiation tests that simulate the terrestrial portion of the solar spectrum. This method covers that part of the spectrum existing as an environmental factor at the surface of the earth and in the lower atmosphere. It does not include radiation absorbed at high altitudes, e.g., the ultraviolet below 290 nm as well as most of the far infrared. In general, the distribution of the sea level spectrum that simulation methods should try to approximate consists of 4 to 6 percent ultraviolet, 40 to 70 percent of infrared, and the balance in the visible range.

A space simulation method is also defined in MIL-STD-810 that provides for a different spectrum as well as giving attention to the pecularities of the space environment.

The most widely used solar radiation simulation equipment is the solar radiation test chamber. A number of military establishments have test chambers, some of which are located at Frankford Arsenal, Philadelphia, Pa.; Redstone Arsenal, Ala.; and the Aberdeen Proving Ground, Md. Test chambers are also operated by Air Force and Navy activities, as well as by a number of commercial firms.

There are two types of test chambers used for solar radiation testing. The type used for testing Army materials simulates solar radiation as experienced on the earth. A second type is designed to simulate solar radiation in space and is widely used in the aerospace industry and in NASA and Air Force laboratories. This type of test chamber—which requires high intensity light sources, a wider spectral composition, and light collimation—is not used for testing Army equipment. The discussion that follows is restricted to test chambers used for Army material testing.

For accelerated steady-state testing, MIL-STD-810 specifies radiant energy at the rate of 100 to 120 W ft^{-2}, with an acceptable distribution of 4 to 7 W ft^{-2} of ultraviolet (below 380 mm), 50 to 72 W ft^{-2} of infrared (above 780 mm), and the balance in the visible range (380 to 780 mm). Test duration should be at least 48 hr, during which the chamber temperature should be maintained at 45°C ± 3°C (113°F ± 5.4 °F).

Simulated cycling temperature and solar radiation testing requires an item to be exposed to five continuous 24-hr cycles of controlled simulated solar radiation and dry-bulb temperature levels. Tolerance limits for control of total radiation are established at ± 10 W ft^{-2}, and for air temperature control at ± 3 deg C (± 5.4 deg F).

Standard ambient conditions should be maintained within the test chamber at the beginning and end of each test cycle except that chamber relative humidity (uncontrolled) should be a maximum of 40 percent (equivalent to 50 grains moisture per pound of dry air) at ambient temperature. Air velocity within the chamber should be maintained at 3 to 6 kt (300 to 600 ft min^{-1}). For further specifics on procedures, MIL-STD-810 should be consulted.

In addition to a test chamber, which is clearly a fundamental requirement, radiation sources must be provided that closely approximate the spectral distribution at the surface of the earth. The following radiation sources are deemed acceptable in MIL-STD-810 for simulation of the terrestrial solar spectrum:

(1) Mercury-vapor lamps (internal-reflector-type only)

(2) Combination of incandescent spot lamps (including infrared filters) with tubular-type mercury-vapor lamps with external reflector

(3) Combination of incandescent spot lamps (including infrared filters) together with mercury-vapor lamps with internal reflectors (with filters as required)

(4) Carbon-arc lamps with suitable reflectors

(5) Mercury-xenon arc lamps with suitable reflectors (with filters as required).

Mercury-vapor lamps give the approximate distribution specified when used alone, although the ultraviolet energy is slightly more than desired. At the Frankford Arsenal in its Sunroom for "Earth" Solar Radiation Simulation, a mix of 400-W internal-reflector-type mercury-arc lamps with 300-W internal reflector incandescent flood lamps was employed to achieve a close approximation to the specified spectral distribution. However, as stated, "the output was somewhat low in the oranges and reds in the visible range and too high in the far infrared. One method used for improving the spectral output was by filtering some of the far infrared by using special glass filters mounted under the incandescent flood lamps. In this manner, we have been able to at least come close to the proper percentages in the ultraviolet, visible, and infrared for simulation of sunlight at sea level." (Ref. 50)

Measurement within the test chamber of radiant flux density and spectral distribution is difficult to obtain. A thermoelectric-type pyrheliometer is commonly used for measuring total direct and diffuse radiation. This instrument measures radiation by determining the rate of increase in temperature of a receiving surface contained within the instrument. Spectral distribution is measured by means of conventional photospectrometers, or by means of several filters and a pyrheliometer.

There is no assurance that the "successful" exposure of equipment in a test chamber for a certain period of time will guarantee adequate field performance under all environmental conditions; nor does it mean that exposure in a test chamber a certain number of hours is comparable to a certain number of hours under operational or open dump storage conditions. The real-life environment in general will be more complex than that attained under simulated conditions, and will contain combinations of environmental factors that are difficult if not impossible either to foresee or duplicate. As a result, all synergistic effects on materials and materiel exposed under natural conditions may not be revealed by chamber testing. Normally, solar radiation testing in chambers is rarely performed in combination with other environmental tests. It is conceivable, however, that humidity, temperature, sand and dust, and vibration and shock tests could be conducted simultaneously.

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CHAPTER 7

RAIN*

7-1 INTRODUCTION AND DESCRIPTION

Rain, which affects many military activities and items of equipment, is a complex environmental factor because it has many different aspects. Amount, intensity, raindrop size and impact, and chemical content of rainwater are some examples that vary in time and space, and in relation to each other and to other environmental factors such as wind and topography.

Different rain characteristics, or combinations of them, cause different kinds of problems for different kinds of equipment. Intense rain interferes with transmission of radar signals. Large raindrops can erode the surfaces of fast-moving aircraft and missiles. Too much rain can cause floods or heavy mud, and too little can cause dust or shortage of water supplies. Rainwater can penetrate the interiors and destroy the contents of structures and containers.

This chapter is concerned with liquid precipitation in the form of rain and drizzle. Characteristics and geographic distributions pertinent to design of military equipment are described; various methods of measuring and testing critical values and of providing protection against rain are indicated and references to more detailed data are given. Freezing rain, snow, and other hydrometeors such as glaze and fog are considered in other chapters.

Definitions that follow are based on the *Glossary of Meteorology* of the American Meteorological Society (Ref. 1).

(1) *Rain* is precipitation in the form of liquid waterdrops. Both the amount that falls and the actual falling action of the waterdrops are often designated as rainfall. *Drizzle* is precipitation in the form of very small, numerous, and uniformly dispersed waterdrops that may appear to float while following air currents. A *raindrop* is a drop of water of diameter greater than 0.5 mm* falling through the atmosphere. Drops of 0.2 to 0.5 mm diameter are called drizzle drops.

(2) *Rainfall* or *drizzle intensity* is the amount that falls per unit of time. For weather observing purposes, rainfall intensity may be classified as:

(a) Very light. Scattered drops that do not completely wet an exposed surface, regardless of duration.

(b) Light. The rate of fall between very light and 0.10 in. hr^{-1} (2.54 mm hr^{-1}); the maximum rate is no more than 0.01 in. (0.25 mm) in 6 min.

(c) Moderate. A rate of 0.11 to 0.30 in. hr^{-1} (2.8 to 7.6 mm hr^{-1}); maximum rate of no more than 0.03 in. (0.76 mm) in 6 min.

(d) Heavy. Over 0.30 in. hr^{-1} (7.6 mm hr^{-1}) or more than 0.03 in. (0.76 mm) in 6 min.

Conditions necessary for rain to occur are moist air, a lifting mechanism for adiabatic cooling of the moist air, the condensation of water vapor, and a suitable opportunity for

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*Acknowledgment is made to Pauline E. Riordan and Ruth L. Wexler, Earth Sciences Laboratory, U.S. Army Natick Laboratories, Natick, MA., who prepared the manuscript on which this chapter is based.

*Most meteorological measurements of rain microstructure (raindrop size, liquid water content, etc.) have been made in metric units. Until recently, measurements of rainfall intensity, amount, etc., were made in English units. This chapter contains both.

the growth of condensation products to precipitation size.

Moisture, evaporated into the air from oceans or other water sources, is subsequently lifted by various mechanisms. As the moist air rises, it expands and thus cools as the pressure decreases with height. When the dewpoint is reached, the air becomes saturated and, in the presence of condensation nuclei, the water vapor condenses to water droplets.

The lifting, cooling, and condensing continue, sometimes to great heights, until the temperature of the rising air becomes as low as that of its surroundings. The particles formed by condensation grow until they become too heavy to be supported by the air, then fall as rain or drizzle. Drop growth results from several actions, probably in combination: principally increased condensation, collisions between droplets, and coalescence of droplets.

Condensation, the most important process in precipitation, does not necessarily result from saturation. In relatively pure water vapor, for example, condensation takes place only after considerable supersaturation. However, the presence of nuclei such as sea salt and smoke particles greatly facilitates the process and, in the case of hygroscopic nuclei (e.g., sea salt), condensation occurs below the saturation point. Sea-salt and smoke particles are examples of effective condensation nuclei commonly found in the atmosphere.

Rain varies in the way it falls—slowly or quickly, in a few large drops or in many small ones, continuously or intermittently, and long or short duration. Various classifications have been devised to designate types of rain; a common one is based on three types of air-lifting mechanisms that produce rain, namely:

(1) *Convective uplift* is caused by a disruption in the density stratification of an air column due to changing temperature relationships between the horizontal layers. This disruption can be caused by increased warming of the lower layers or by cooling of the upper ones. When a parcel of air becomes warmer and lighter than the air above it, it naturally tends to rise. The rising air, or updraft, called a convective cell, is generally about 10 mi (16 km) or less in horizontal extent (Ref. 2); it is lifted relatively rapidly (generally within 1 hr or less) (Ref. 3), sometimes to heights of more than 50,000 ft (15,240 m) (Ref. 4).

Convective rain takes the form of heavy, localized showers with the heaviest of all rains usually occurring in thunderstorms produced by the fastest, highest convective uplifts. A thunderstorm, consisting of one or more (usually several) convective cells goes through three stages of development: (a) the cumulous or growing stage, in which updrafts occur; (b) the mature stage, in which downdrafts are added by the falling rain; and (c) the dissipation stage, containing only diminishing downdrafts. Thunderstorms may be randomly scattered over an area or grouped in clusters or lines. They are the most common type of storm. An estimated 44,000 occur over the earth in an average day (Ref. 2). Either they are associated with thermal instabilities, such as when cool air passes over hot land or warm ocean surfaces or when land surface is heated by solar radiation, or they are triggered by cyclonic or orographic uplift.

(2) *Cyclonic uplift* results from convergence and frontal lift associated with low pressure systems. The convergence is caused by horizontal flow of air into low pressure centers (cyclones) with subsequent rising of the air as it accumulates within a limited region. Frontal lift is the forced ascent of a warmer, less dense airmass over a colder airmass at or near the transition zone (front) between the two airmasses. Cyclonic lifting can take place over a period of several days (Ref. 3) and is effective over a larger area than is convective lifting (i.e., > 10 mi). These can be concurrent. Cyclonic rain ranges from light to very heavy, is generally continuous, steady, and is often prolonged.

Characteristic differences occur between

TABLE 7-1

RAINDROP DIAMETERS TYPICAL OF DIFFERENT TYPES OF RAIN (Ref. 6)

Type	Largest drops, mm	Median drops, mm
Generic:		
Thundershowers	8	1.4
Showers	5	1.7
Steady rain	4.7	1.6
Climatic:		
Temperate	4.6	1.0
Tropical	7	1.8
Composite	7	1.7

rains associated with warm and cold fronts. The fast-moving cold fronts push the air up more rapidly and tend to create instability, triggering convective showers and thunderstorms. Along slow-moving warm fronts, the rain generally extends over a wider area and the rainy period tends to last longer; however, moist unstable air along warm fronts can also trigger convective showers that sometimes interrupt the periods of more steady cyclonic rain.

(3) *Orographic uplift* is caused by the upward deflection of horizontally moving air as it encounters sloping terrain. This mechanism generally accentuates convective and cyclonic airlifting; consequently, orographic rain may be either showery or steady. It is difficult to separate these three rain-producing mechanisms because more than one usually occur simultaneously.

A pragmatic classification of rainfall as thundershowers, showers, and continuous rain is used by some observers (see Refs. 5 and 6). These three can easily be differentiated by observers.

Another useful, pertinent classification relates to the temperature and condition of the clouds in which raindrops form; Ohtake (Ref. 7) defines three such categories:

(1) *Cold rain*, formed on ice crystals.

(2) *Supercooled warm rain*, caused by growth of water droplets cooled to at least −5°C (23°F).

(3) *Warm rain*, formed in clouds whose temperature at the top is above 0°C (32°F).

7-2 PROPERTIES OF RAIN

The properties of rain that are important to design engineers are given in this paragraph.

7-2.1 RAINDROP SHAPE

The shape of a raindrop is determined by surface tension, hydrostatic pressure gradients, and external aerodynamic pressure (Ref. 8). Small raindrops are spherical because the rate of fall is insufficient to cause significant aerodynamic pressure. But, if the equivalent spherical diameter is greater than 1.0 mm, the drops are flattened on the bottom and spread laterally and, if the diameter is above 2.0 mm, oscillations in this oblate shape begin to occur (Ref. 9). All large raindrops oscillate about a preferred shape; observed eccentricities vary linearly from 0.99 for 2-mm drops to 0.71 for 6-mm drops. When windspeed is high compared to the fall velocity of the drops (see par. 7-2.8), distortion of shape is increased further.

7-2.2 RAINDROP SIZE (Ref. 6)

The extreme range of raindrop diameter is 0.2 to 8.0 mm but less than 1 percent of observed diameters exceed 4.0 mm. Although there may be many drops below 0.5 mm, these contribute relatively little to the intensity or the effects of rain. Variation in the diameters, which is characteristic of different types of rain or climatic conditions, is shown in Table 7-1. A composite median diameter for all types of rain is 1.7 mm.

The median and maximum raindrop sizes characteristic of rainstorms are plotted in Figs. 7-1 through 7-4 as cumulative frequency of occurrence distributions for various climatic conditions; these distributions are not to be confused with raindrop size distributions in a given storm, as discussed in par. 7-2.4. In Fig. 7-1 it can be noted that median diameters vary little with type of rainstorm but maximum diameters vary greatly. Greater differences are seen with climate, as shown in Fig. 7-2, but only 3 percent of the observed rains have maximum raindrop diameters greater than 6.7 mm in the tropics and 4.5 mm in the temperate zones. Fig. 7-3 gives a composite size distribution for all types of precipitation and for all climates. The data presented in Fig. 7-4 shows that observed characteristic drop sizes are related to rainfall intensity.

7-2.3 MASS

Since the density of pure water is 1 g cm^{-3} or 62.4 lb ft^{-3}, the mass or weight is obtained directly from the diameter of the drop. Representative drop masses and weights are given in Table 7-2.

7-2.4 RAINDROP SIZE DISTRIBUTION

The median and maximum diameters of raindrops previously given characterize rainfall for many purposes but, for some applications, it is necessary to know the size distribution. In Figs. 7-5 through 7-8, average size distributions are given (Ref. 10); in these, the number of raindrops with diameters in each 0.1-mm increment per cubic meter of volume is given. For example, the top curve in Fig. 7-5 is for a rainfall rate of 95.6 mm hr^{-1}, which occurs 0.01 percent of the time. In such a rainfall, eight drops with diameters $\geqslant$ 5.0 mm but $<$ 5.1 mm are found in each cubic meter of the atmosphere. The curves in Fig. 7-5, compiled from all data available from nine locations around the world, represent a large number of observed distributions, but the curves for the several climatic classifications are less representative because the temperate zone data were obtained from three locations, the tropical from two, and the arctic data from Alaska only.

Raindrop size spectra are highly variable in time and space and partially with storm type because small sampling volumes are often used. An accepted representation of the size spectra is the Marshall-Palmer equation (Ref. 11):

$$N_D = N_o \exp(-\Lambda D),\ \text{cm}^{-4} \qquad (7\text{-}1)$$

where

N_D = number density of drops with diameters between D and $D + \Delta D$, cm^{-4}

N_o = value of N_D extrapolated to $D = 0$, cm^{-4}

and Λ is given by

$$\Lambda = 3.67/D_0 = 41\,R^{-0.21},\text{cm}^{-1} \qquad (7\text{-}2)$$

where

R = rainfall intensity, mm hr^{-1}

D_o = median volume diameter of raindrops, cm

To an acceptable approximation, N_o = 0.88 (Ref. 12).

7-2.5 CONCENTRATION

Drop concentrations ranging from 8 to more than 13,000 m^{-3} are possible (Ref. 5). Concentration of drops in a spectrum have been grouped by Diem (Ref. 13) according to

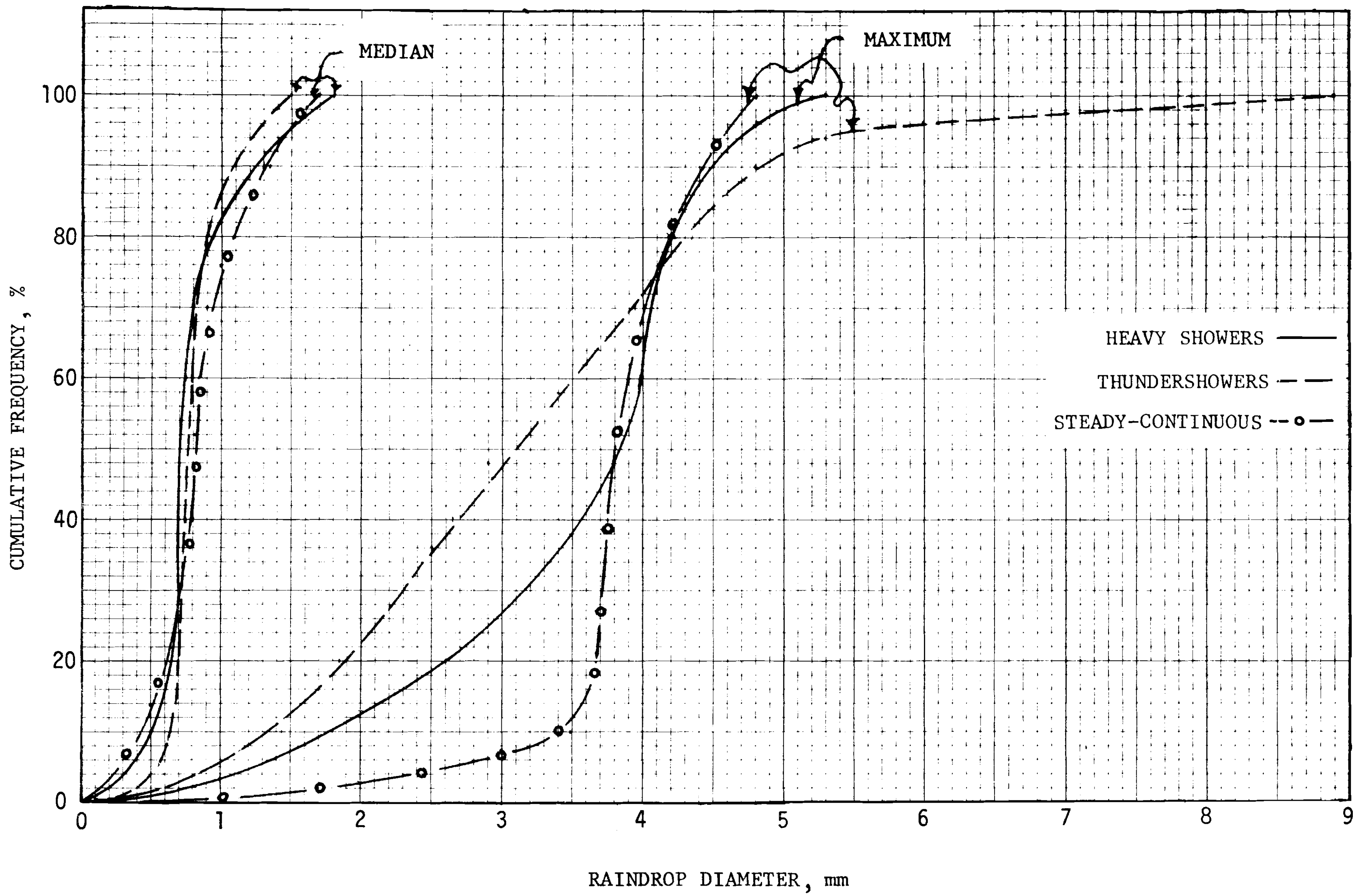

Figure 7-1. Cumulative Frequency of Occurrence of Raindrop Diameters in Heavy Showers, Thunderstorms, and Steady-continuous Rain (Ref. 6)

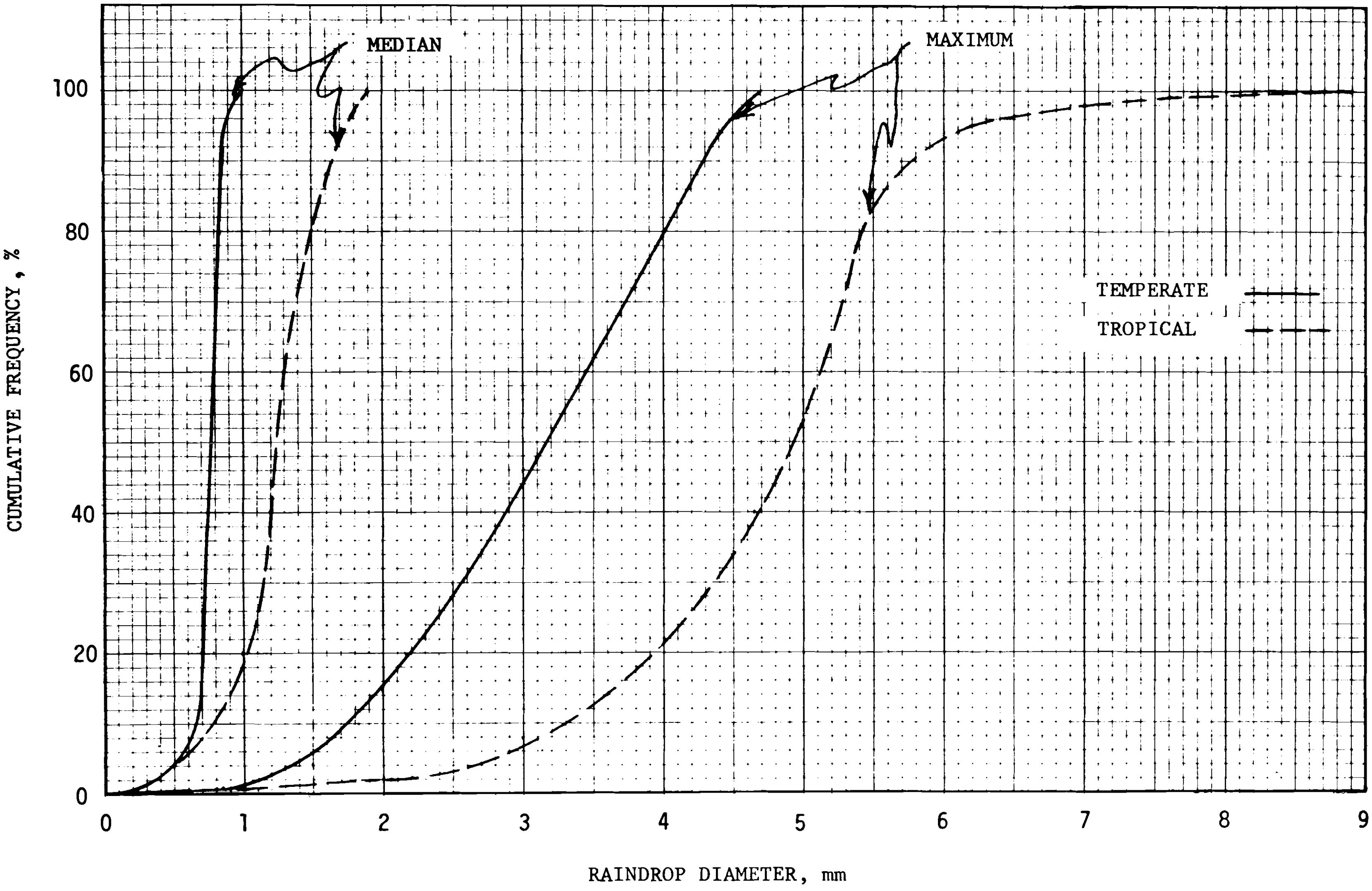

Figure 7-2. Cumulative Frequency of Occurrence of Raindrop Diameters in Temperate and Tropical Regions (Ref. 6)

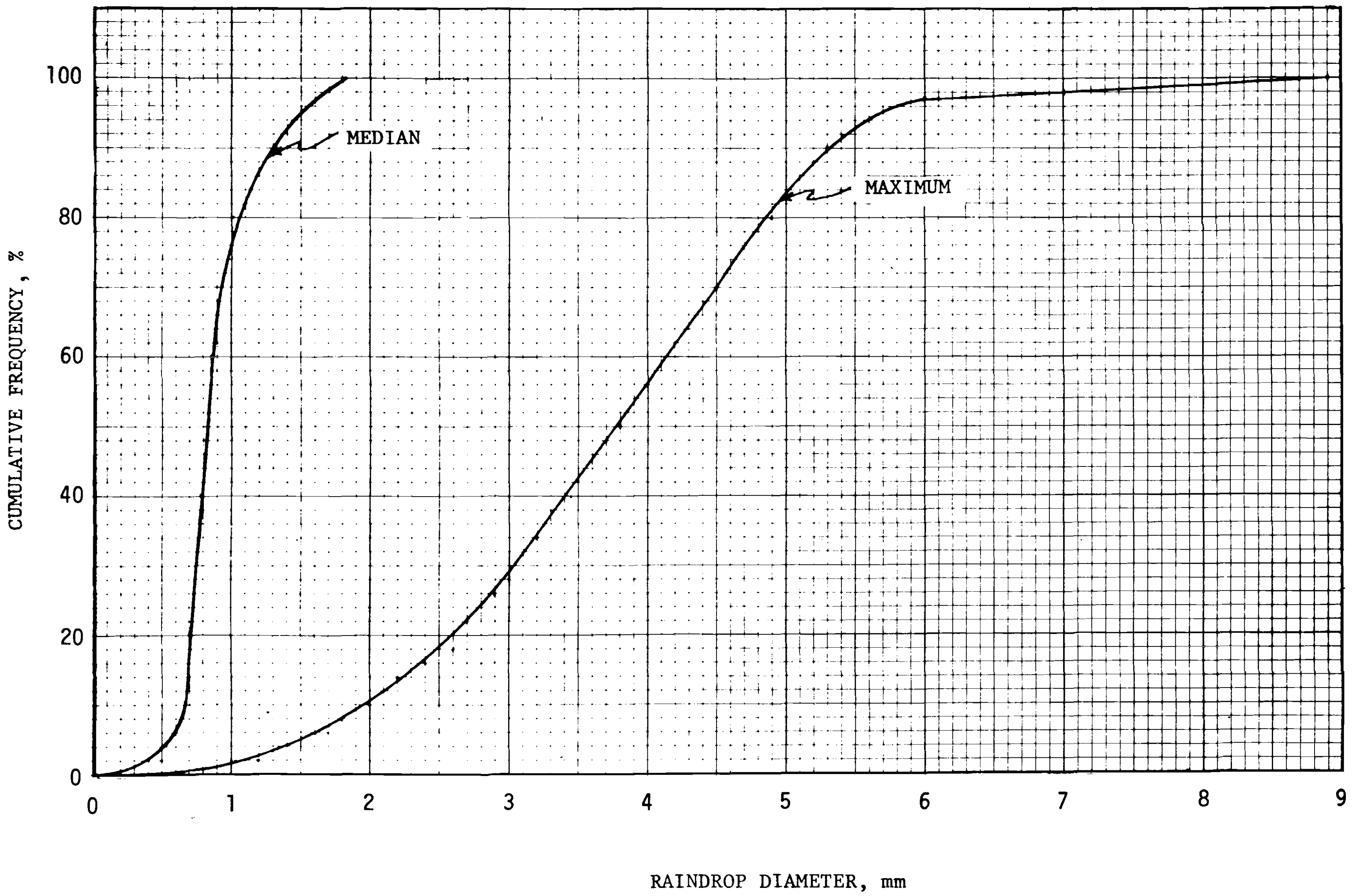

Figure 7-3. Composite Cumulative Frequency of Occurrence of Raindrop Diameters (Ref. 6)

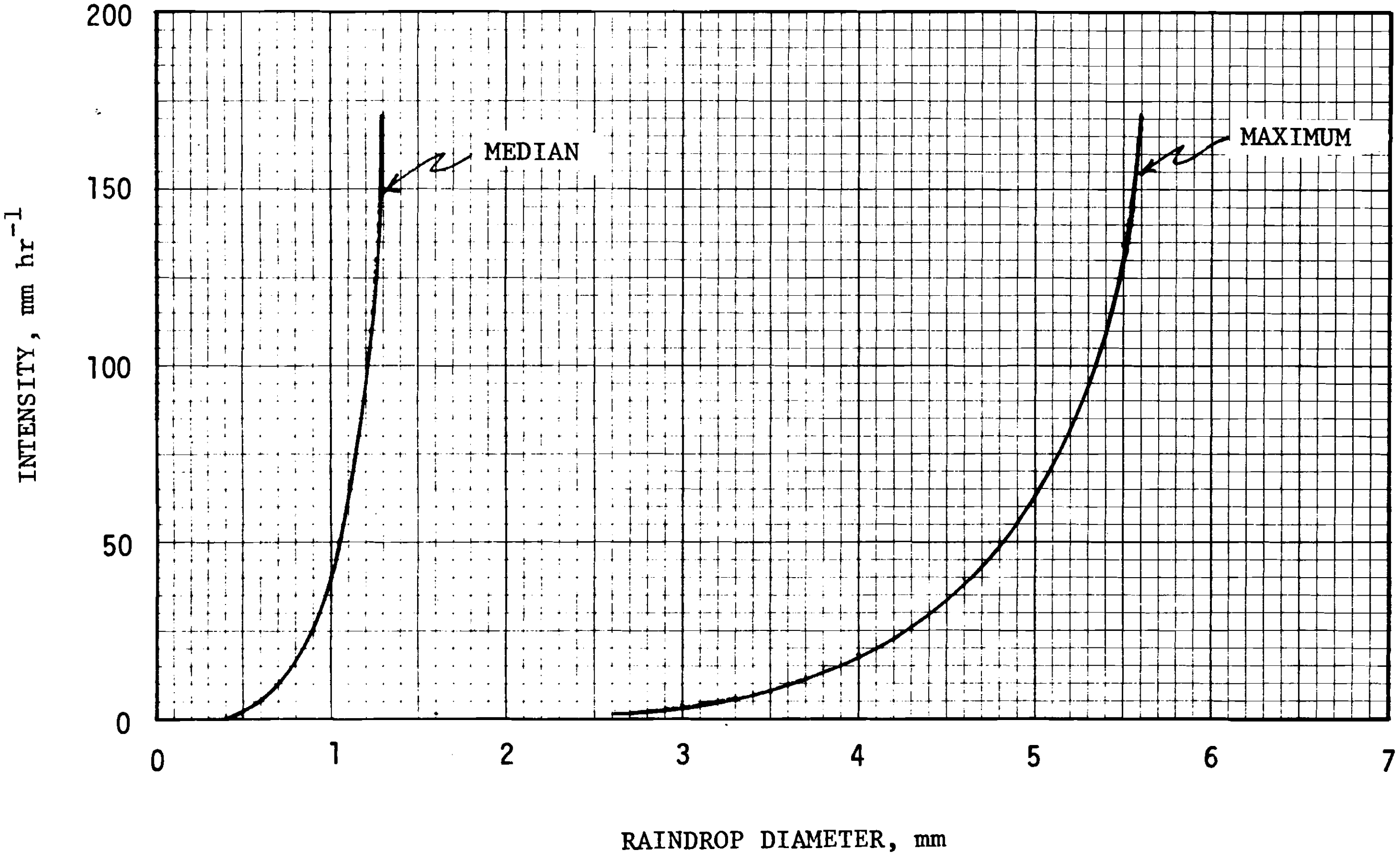

Figure 7-4. Variation of Raindrop Diameter With Intensity (Ref. 6)

TABLE 7-2

RAINDROP MASS

Diameter, mm	Mass, 10^{-3}g	Weight, 10^{-5}lb
0.5	0.065	0.0143
1.0	0.524	0.115
1.5	1.77	0.390
2.0	4.19	0.925
2.5	8.18	1.81
3.0	14.1	3.12
3.5	22.5	4.96
4.0	33.5	7.4
4.5	47.7	10.5
5.0	65.5	14.5
5.5	87.2	19.3
6.0	113.0	24.9

the number that fall per minute on a square meter of horizontal surface. He assigned values of < 500, 500 to 2,000, and > 2,000 for low, average, and high concentrations, respectively. Generally he found low concentrations in orographic rains, and low, average, and high concentrations in cyclonic uplift rains. In the low latitudes, about 20 percent of the rains had average and high concentrations.

Diem (Ref. 14), Grunow (Ref. 15), and Blanchard (Refs. 16 and 17) observed no correlation between drop concentration and rainfall intensity. Both Blanchard and Hardy (Ref. 18) explained that the lack of correlation and the inconsistencies were caused by complex factors of wind shear, breakup, evaporation, drop collision, coalescence, accretion, and vertical updraft.

7-2.6 LIQUID WATER CONTENT

In rain, the mass of water per unit volume of airspace (liquid water content) is determined by the number and sizes of the drops and can be calculated from the drop size spectrum. It ranges from about 0.01 to 30.0 g m^{-3}. Values greater than 30 g m^{-3} rarely occur, either at the surface or aloft in severe thunderstorms (Ref. 19).

Liquid water content varies with rainfall intensity, and thus with the types of rainfall. In areas where light continuous rains prevail, liquid water content is low; it is high in heavy showers and heavy tropical rains. Table 7-3 shows maximum and minimum values for liquid water content and rainfall intensity (rate) at several locations. In Oregon and Alaska, where light continuous rains are the rule, values are similar—both showing low intensity and low liquid water content. The Marshall Islands and Indonesia, both representative of tropical conditions, also have similar values. The very high values for Miami, Fla., result from a plentiful moisture supply combined with high instability due to cooler, drier air aloft (Ref. 5).

Data indicate that a linear relationship between liquid water content L (g m^{-3}) and rainfall rate R (mm hr^{-1}) is adequate for estimating purposes. This relationship is:

$$L = 0.042\,R, \text{ g m}^{-3} \qquad (7\text{-}3)$$

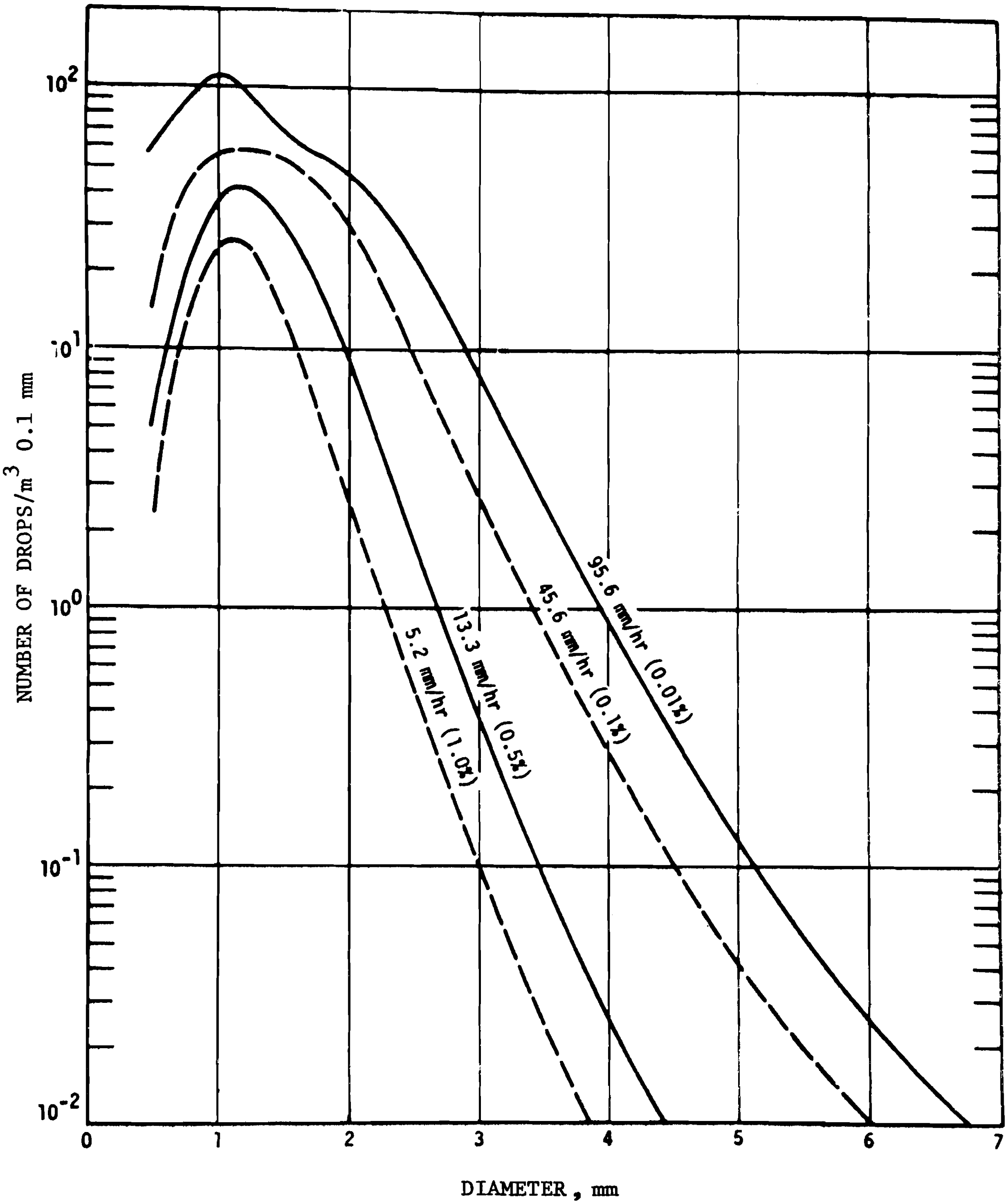

Figure 7-5. Average Drop-size Spectra in All Climates (Ref. 10)
(These curves are for natural rainfall rates occurring 0.01, 0.1, 0.5, and 1.0 percent of the time and include all available data from nine locations in all major climatic zones around the world.)

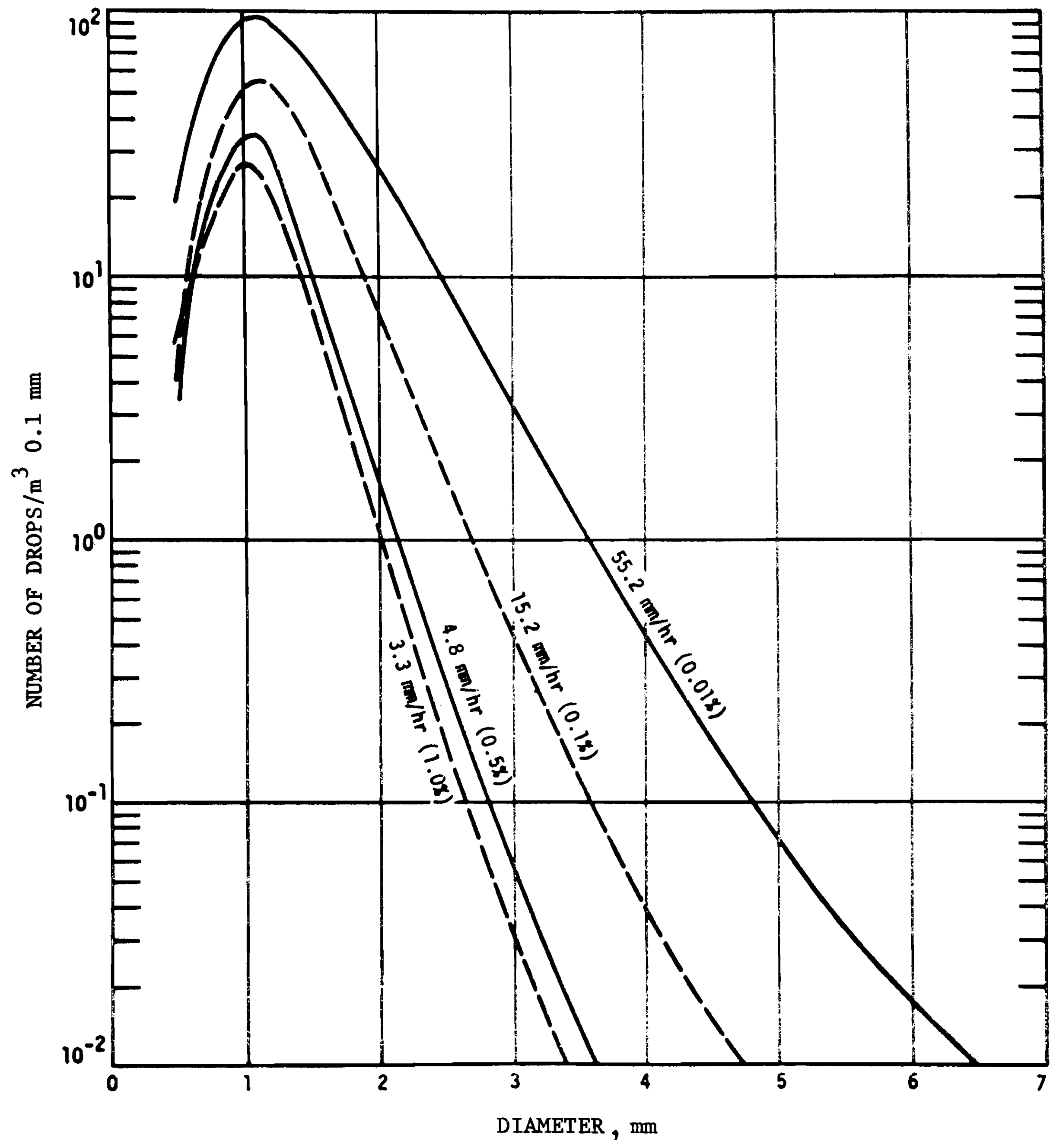

Figure 7-6. Average Drop-size Spectra in Temperate Climates (Ref. 10)
(These curves are for natural rainfall rates occurring 0.01, 0.1, 0.5, and 1.0 percent of the time.)

7-2.7 RAINFALL INTENSITY

The rate at which rain falls (i.e., the rainfall intensity) is directly related to the concentration and size distribution of the raindrops, which in turn are dependent on the amount of moisture available in the atmosphere and on the complex pattern of atmospheric motion. Rainfall intensity varies from zero to a world record of over 30 mm in 1 min (Ref. 20).

Rainfall intensity is usually expressed in inches or millimeters per hour. Precipitation is

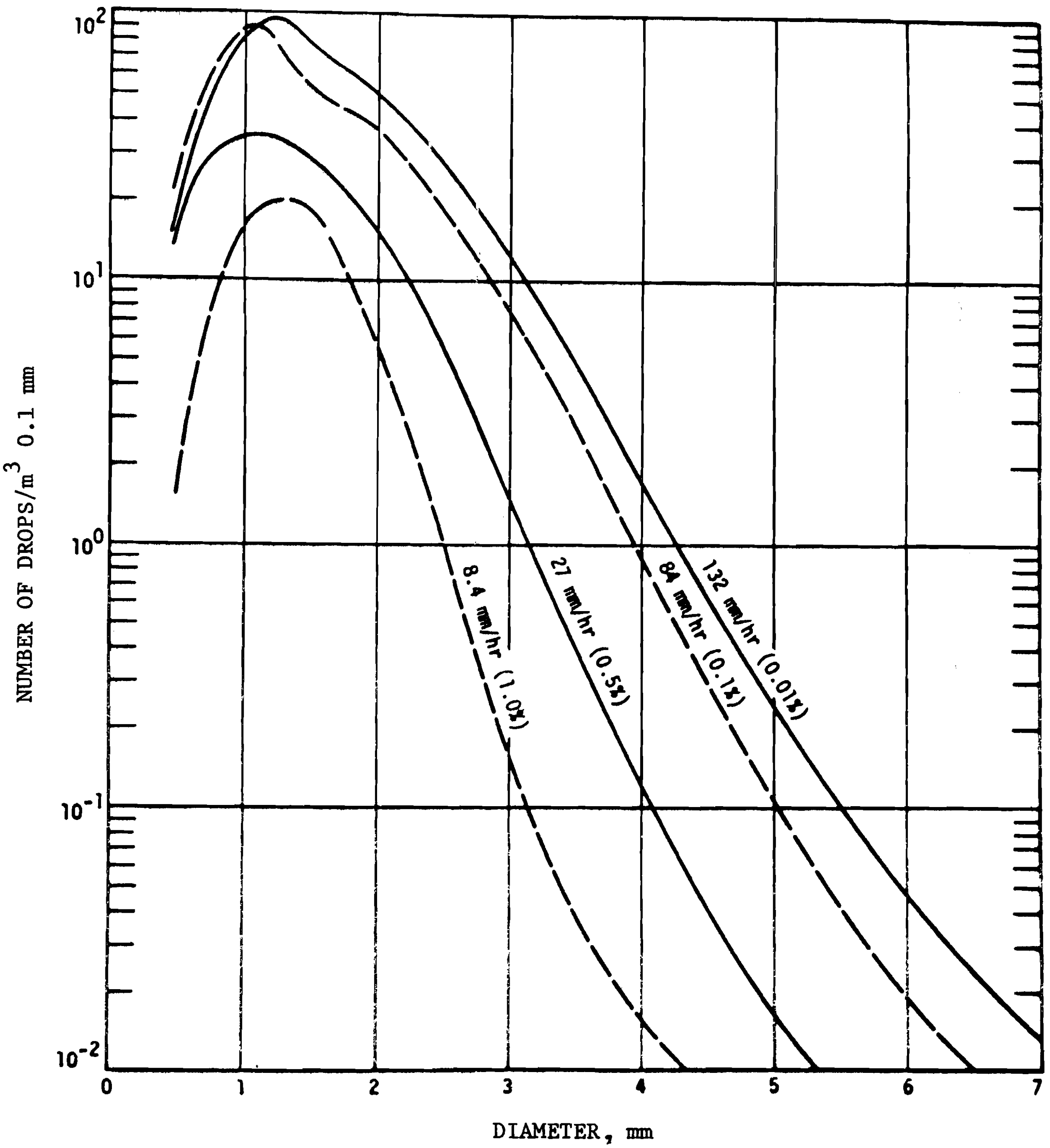

Figure 7-7. Average Drop-size Spectra in Tropical Climates (Ref. 10)
(These curves are for natural rainfall rates occurring 0.01, 0.1, 0.5, and 1.0 percent of the time.)

usually recorded on a monthly, seasonal, and annual basis in weather records. Clock hourly rates are recorded at a number of stations in the United States and Europe, while instantaneous rates have been obtained in only a few cases. Since the rainfall intensity, measured hourly (the clock hourly rate), and the rainfall intensity, measured at 1-min intervals (instantaneous rate), can differ significantly and since both are required for consideration of effects, it is desirable to provide a basis for estimation of these rainfall parameters from available data. Statistical analysis of the data for stations where complete records are avail-

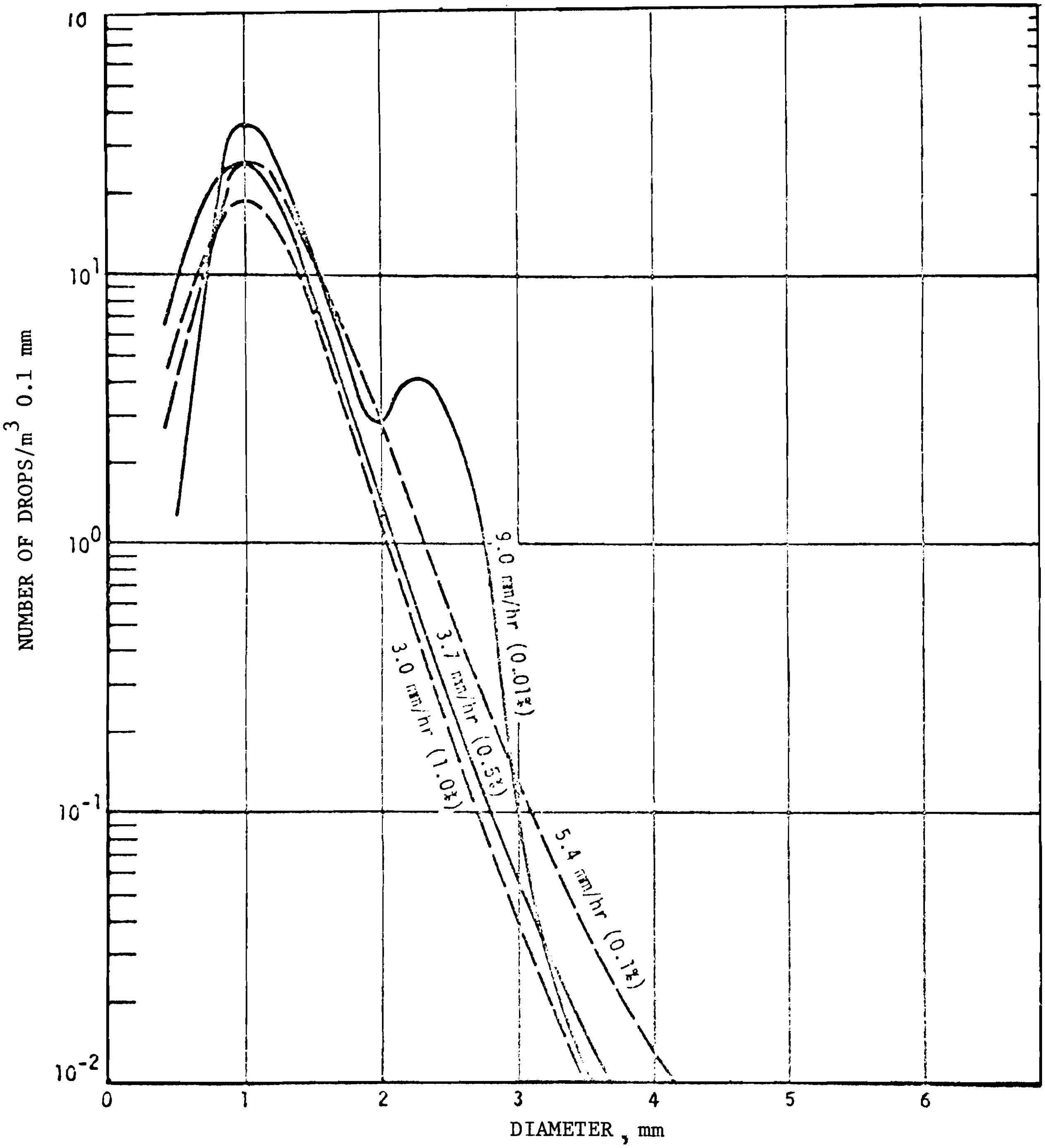

Figure 7-8. Average Drop-size Spectra in Arctic Climates (Ref. 10)
(These curves are for natural rainfall rates occurring 0.01, 0.1, 0.5, and 1.0 percent of the time.)

able provide these estimations.

In Fig. 7-9, the percentage of time in which clock hourly rates exceeded the indicated rate is compared with the ratio of annual precipitation to the number of days with measurable precipitation. The indicated points are those for 22 stations for which clock hourly rates are available; a linear regression equation was obtained in each case, and the standard error of estimates S_y and the correlation coefficient γ are given in each case. These relations apply to warm temperature and subpolar regions and should agree with rainfall inten-

TABLE 7-3

RAINFALL RATES AT VARIOUS LOCATIONS (Ref. 5) (10-s RATES)

Location	Days of sample	Samples	Liquid water content, g m^{-3}		Rainfall rate, mm hr^{-1}	
			Min	Max	Min *	Max
Woody Island, Alaska	74	2688	0.01	1.39	0.1	26
Miami, Fla.	79	2506	0.03	29.18	1.0	722
Majuro, Marshall Islands	93	2552	0.03	11.35	1.0	270
Corvallis, Oreg.	59	1706	0.01	1.24	0.1	26
Bogar, Indonesia	76	1879	0.01	13.47	0.1	282
Champaign, Ill.	36	1126	0.01	5.56	0.1	130
Island Beach, N.J.	78	2354	0.01	8.13	0.1	155
Coweeta, N.C.	85	3369	0.01	13.49	0.1	310

*Arbitrary lower limit of 0.1 or 1.0 mm hr^{-1} applied, depending on location.

sity data within 30, 10, and 8 hr/yr 68 percent of the time for rates ≥ 0.06, 0.12, and 0.18 in. hr^{-1}, respectively (Ref. 19).

The instantaneous rainfall rate can be estimated from the data in Fig. 7-10 (Ref. 21). The rainfall intensities, expressed as hourly rates but determined by averaging over different intervals, are compared. The climate of Washington, D.C., where these data were obtained, is sufficiently representative so that Fig. 7-10 can be used to convert clock hourly rate frequencies* to instantaneous rate frequencies in other areas of the world (Ref. 19). To do this, determine, for a given rainfall rate, the ratio of the hours/year for the instantaneous curve to the hours/year for the 1-hr curve. For the same rate in another area, multiply the clock hourly rate frequency by this ratio to obtain the instantaneous rate frequency.

Rainfall intensities vary considerably with latitude, climate, and season. Specific geographical distributions are discussed in par. 7-3. Generally, the highest rates occur in thunderstorms and in hurricane-type storms. In thundershowers, rain seldom lasts over 0.5 hr, but 0.5 to 1.5 in. of rain can fall in that time. In hurricanes, it is common to record 6 to 12 in. of rain in a 24-hr period. Typical rainfall intensities are given in Table 7-4; in all climates, rainfall intensities greater than 3.8 in. hr^{-1} are experienced only 90 hr yr^{-1}, but

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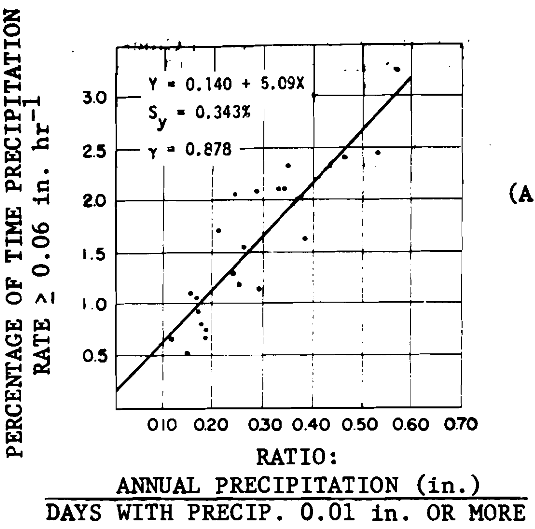
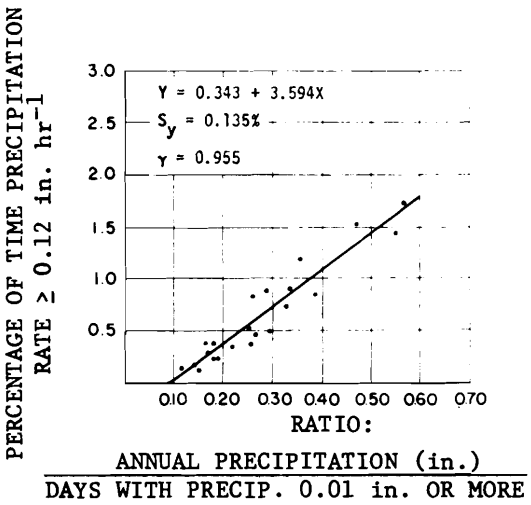
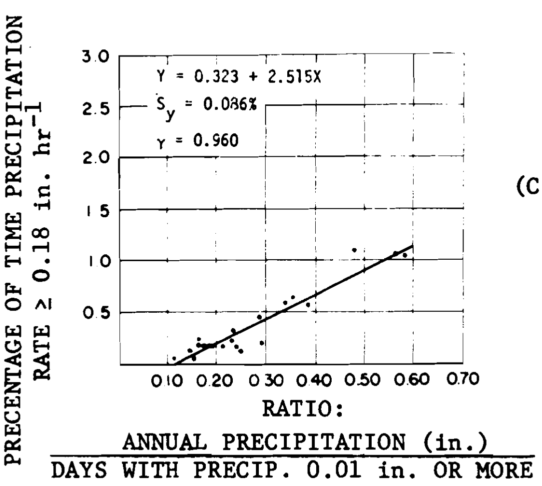
*Frequency in this connotation means number of hours or minutes per year and is directly convertible to percentage of time. A clock hourly rate frequency of 87.6 hr/yr is equivalent to 1 percent of time.



(A) Correlation Between Annual Probability of Clock Hourly Precipitation Equal to or Exceeding 0.06 in. hr^{-1} and Usually Available Precipitation Data



(B) Correlation Between Annual Probability of Clock Hourly Precipitation Equal to or Exceeding 0.12 in. hr^{-1} and Usually Available Precipitation Data



(C) Correlation Between Annual Probability of Clock Hourly Precipitation Equal to or Exceeding 0.18 in. hr^{-1} and Usually Available Precipitation Data

Figure 7-9. Clock-hourly Precipitation Rates Compared With Ratio of Annual Precipitation to Days Having Measurable Precipitation (Ref. 19)

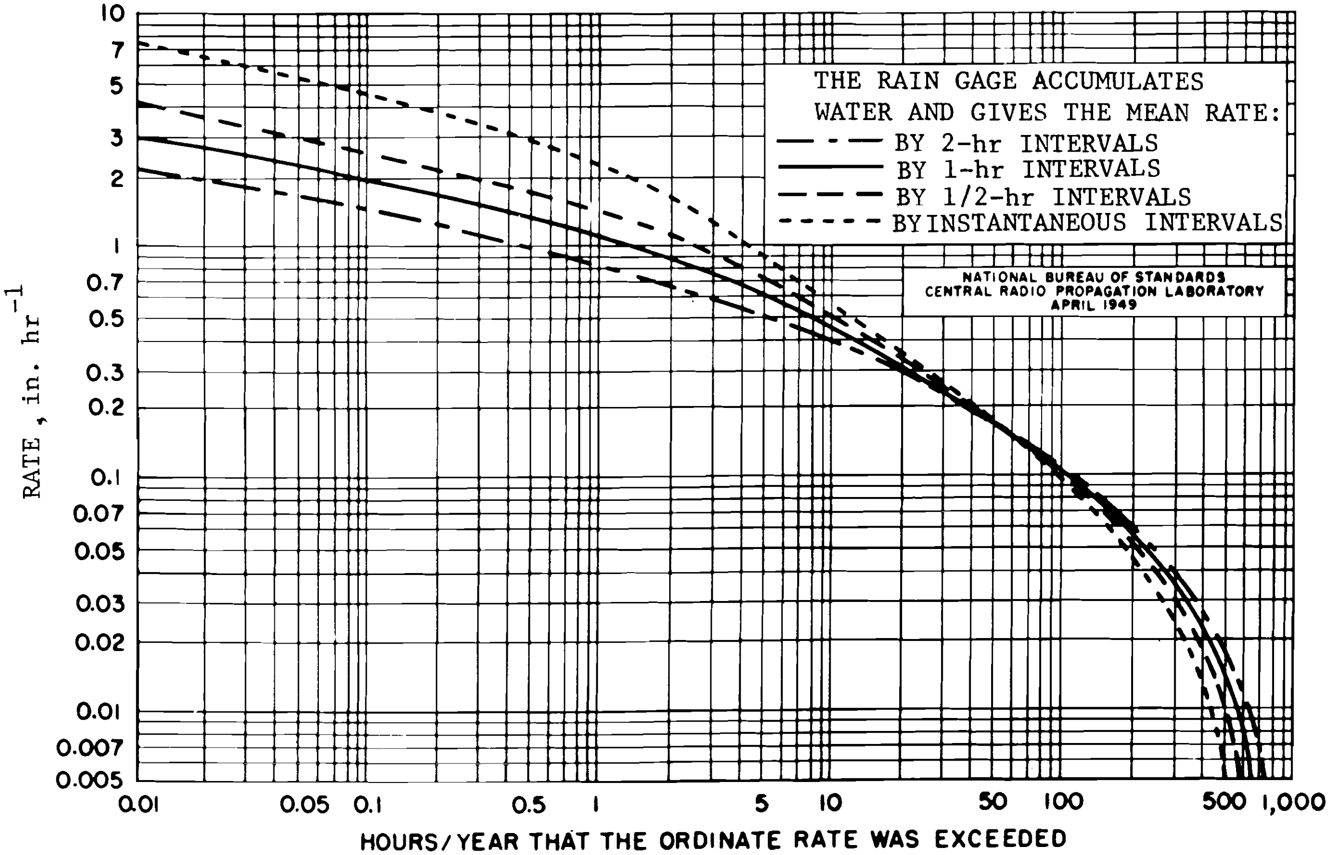


Figure 7-10. Cumulative Distribution of Rainfall Rates (Ref. 21) (These are all for one location, Washington, D.C. The 1-hr. curve is based upon observed long-time data; the other three curves are derived from the 1-hr curve.)

TABLE 7-4

TYPICAL RAINFALL INTENSITIES, in. hr^{-1}

Climate	Percent of time the rate is exceeded 0.1	1.0	10
Tropical (Indonesia)	6.5	3.2	1.0
Subtropical (Florida)	5.9	3.8	3.2
Temperate (Illinois)	3.3	1.8	0.6

about 900 hr yr^{-1} (37 days) at 0.6 in. hr^{-1} are experienced at these typical locations. On the other hand, minimum precipitation rates of 1 in. yr^{-1} are common in desert areas.

7-2.8 RAINDROP VELOCITY

The velocity of a raindrop is determined by its size and the windspeed. In still air, a constant vertical velocity is attained when the gravitational force on the drop is balanced by the drag of the air through which it is falling. This velocity is called terminal velocity; it increases with the size of the drops until the drops become so large that their spherical shapes begin to flatten out. For drops with diameters greater than 5 mm, the terminal velocity approaches a constant value of approximately 9.2 m s^{-1} (20.6 mph).

In Table 7-5 and Fig. 7-11, data on terminal velocities of waterdrops in still air are given. These data, for an atmospheric pressure of 1,013 mb and a temperature of 20°C, represent the most reliable measurements available (Ref. 22). The terminal velocities for drop diameters below 1.0 mm are based on measurements by Beard and Pruppacher (Ref. 23), and above 1.0 mm, by Gunn and Kinzer (Ref. 24). The terminal velocity is dependent on pressure and temperature: at 900 mb and 20°C, the constant terminal velocity for large drops is about 9.5 m s^{-1}, and it increases as pressure and temperature decrease (Ref. 25).

The distance a drop falls before attaining terminal velocity varies with its size, smaller drops requiring greater distance (Ref. 26).

Velocities of raindrops are dependent on windspeed, there being less than 1 percent difference between the horizontal component of velocity of raindrops and horizontal windspeeds (Ref. 27). Raindrops carried by the wind fall at an angle from the vertical, and their velocity is given by:

$$V_R = (V_W^2 + V_t^2)^{1/2} \tag{7-4}$$

where

V_R = velocity of drops in wind

V_W = windspeed

V_t = free-fall terminal velocity

The highest wind-rain combinations occur during hurricanes and other severe cyclonic storms. Light winds of under 20 mph (32 kph) generally have a negligible effect on terminal velocity. Strong updrafts of air can prevent drops from falling and will carry them upward, while strong downdrafts will accelerate the speed of fall.

7-2.9 IMPACT ENERGY AND PRESSURE

With no wind, a rainfall of 2.5 cm hr^{-1} delivers 0.025 m^3 hr^{-1} of water to each square meter of the surface of the earth. This is a mass deposition rate of 6.9 g s^{-1} m^{-2}, giving, for a terminal velocity of 4 m s^{-2}, an energy deposition rate of over 0.05 W m^{-2} where the only energy considered is the

TABLE 7-5

TERMINAL VELOCITIES OF RAINDROPS (Ref. 22)

Drop diameter, mm	Terminal velocity*	
	ms^{-1}	$ft\ s^{-1}$
0.02	0.012	0.039
0.04	0.047	0.15
0.06	0.103	0.34
0.08	0.175	0.57
0.10	0.256	0.84
0.20	0.71	2.3
0.40	1.60	5.25
0.60	2.46	8.07
0.80	3.25	10.7
1.00	4.03	13.2
1.20	4.64	15.2
1.40	5.17	17.0
1.60	5.65	18.5
1.80	6.09	20.0
2.00	6.49	21.3
2.2	6.90	22.6
2.4	7.27	23.9
2.6	7.57	24.8
2.8	7.82	25.7
3.0	8.06	26.4
4.0	8.83	29.0
5.0	9.09	29.8
5.8	9.17	30.1

*To obtain mph use 1 ms^{-1} = 2.24 mph

kinetic energy of the falling rain. This rate is equivalent to 0.068 ft-lb s^{-1} m^{-2}. The momentum of the water falling each second on a square meter of surface is 2.8×10^{-2} kg m s^{-1}, for these conditions.

The kinetic energy (KE) of individual raindrops, with no wind, is obtained directly from the terminal velocity V_t and mass m using the relation

$$KE = mV_t^2/2 \qquad (7\text{-}5)$$

being careful to convert weight W in pounds to mass in slugs when English units are employed, i.e.,

$$KE = WV_t^2(2g)^{-1} \qquad (7\text{-}6)$$

where g is the acceleration due to gravity in English units, 32 ft s^{-2}. Representative values are shown in Table 7-6.

The force exerted on a surface by falling rain is equal to the time rate of change of the momentum of the rain

$$F = d(mV)/dt \qquad (7\text{-}7)$$

Using the parameters given earlier in this subparagraph, i.e., a mass deposition rate of 6.9 g s^{-1} and a momentum of 2.8×10^{-2} kg m s^{-1} for the rain falling each second on a square

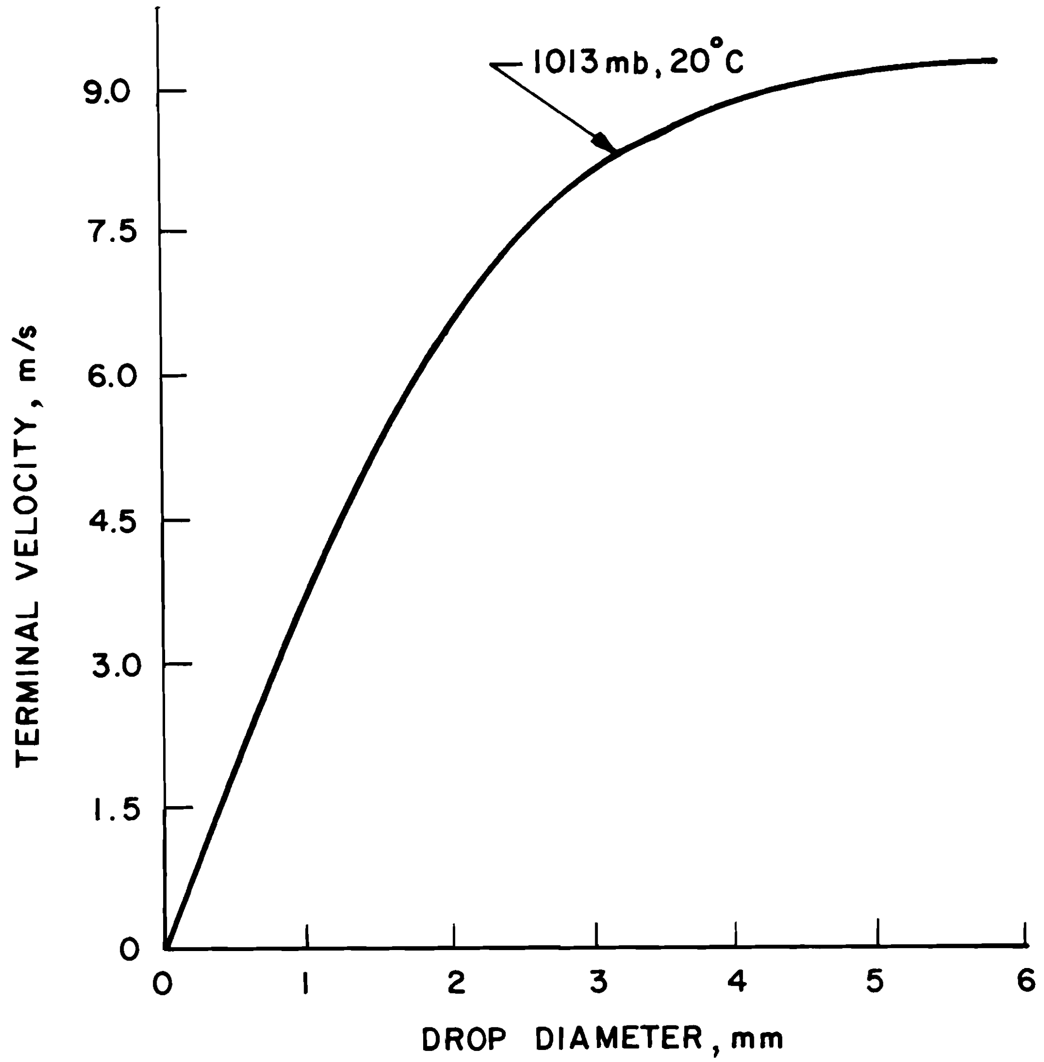


Figure 7-11. Terminal Velocity of Raindrops With No Wind (Ref. 22)

meter of area, gives a force of 2.8×10^{-2} N or a pressure of 2.8×10^{-2} N m^{-2} *.

More accurate calculation of pressure may be accomplished by summation over the size distribution characteristic of a given type of rain

$$P = \frac{\pi \rho N_o}{60} \Sigma D_n^3 V_n^2 \exp(-\Lambda D_n)\, \Delta D \qquad (7\text{-}8)$$

where

P = pressure, N m^{-2}

ρ = density of water, g cm^{-3}

N_o = constant from Eq. 7-1, ≈ 0.88 cm^{-4}

d_n = diameter of raindrops in diameter interval n, cm

V_n = velocity of raindrops in diameter interval n, cm s^{-1}

Λ = function of raindrop intensity, Eq. 7-2, cm^{-1}

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*In the International System of Units, the force is given in newtons (N). Conversion factors for English units are given in the "International System of Units" by E. A. Mechtly and other publications (Ref. 28). A selection of conversion factors is given in Appendix A.

TABLE 7-6

KINETIC ENERGY OF FALLING RAINDROPS (NO WIND)

Diameter, mm	1	2	3	4	5	6
KE, 10^{-6}J	4.25	88.2	458	1,310	2,710	4,780
KE, 10^{-5}ft-lb	0.316	6.55	33.9	97.1	200	355

The summation is over the diameter range encompassing the raindrop size distribution in intervals of ΔD as designated by n. It is necessary to carry out this solution using a computer unless an approximate expression for the terminal velocity in terms of diameter is derived.

The wind has a large effect on impact energy and pressure. Windspeed is normally given in miles per hour. Equivalent speeds in international units are given in Table 7-7. The impact energy is determined by the magnitude of the vector velocity (Eq. 7-4), but the force is determined by the component of the vector velocity that is normal to the surface on which the rain is impacting.

A vehicle moving through rain experiences a force due to its relative velocity with respect

TABLE 7-7

CONVERSION OF UNITS OF SPEED

Miles per hour, mph	Meters per second, m/s
10	4.47
20	8.94
30	13.4
40	17.9
50	22.4
60	26.8
70	31.3
80	35.8
90	40.2
100	44.7

to the rain. At 50 mph relative velocity or 22.4 m s^{-1}, for example, a vehicle is impacted on its front surface by 22.4 g m^{-2} s^{-1} of rain if the liquid water content of the rain* is 1 g m^{-3}. This gives a pressure of 0.5 N m^{-2}. For both moving and stationary surfaces, rain force can be calculated by using data given in this subparagraph.

7-2.10 PHYSICAL AND CHEMICAL PROPERTIES

Rain is formed by condensation of water vapor on condensation nuclei. During their fall, additional suspended aerosols and gases are entrained with the raindrops. Thus, rainwater, often considered pure, is actually a chemically and physically complex substance containing over 20 identifiable dissolved or suspended solid elements as well as dissolved atmospheric and pollutant gases. The properties of water are extensively documented; only those properties that are affected by its being a precipitant are discussed here.

The atomic constituents of water—hydrogen and oxygen—each have three stable isotopes that combine to form 18 different types of water molecules (Ref. 29). The isotopic combinations in rainwater vary with time and place. In regions with high temperature, low humidity, and small amounts of rainfall, the heavier isotopes are more prevalent. In high latitudes, the temperature effect is most important; in low latitudes, it is the amount of rainfall. A global survey of isotopic content of rainwater has been made (Ref. 30).

Pure water has a pH, or hydrogen-ion concentration value of 7 (values above 7 are basic, below 7 are acidic). Rainwater is usually slightly acidic (pH $\approx$ 6.8 to 6.9) because of dissolved gases, especially carbon dioxide (Ref. 31); however, the acidity can increase to a pH of about 3 (Ref. 32) as the accumulation of atmospheric substances increases. These substances include the various gases that make up the atmosphere of the earth as well as the atmospheric aerosols that originate from soil dust, sea spray, and various industrial, volcanic, cosmic, and organic sources.

Precipitation scavenging of the atmosphere has been an active research field for over a decade. It was stimulated originally by interest in radioactive fallout, but recently has been spurred by concern with pollution. Recent research is reviewed in *Precipitation Scavenging* (Ref. 33). The scavenging process has three steps: (1) delivery or transport of the material to the scavenging site, (2) in-cloud scavenging, usually called rainout, and (3) below-cloud scavenging by the precipitation, usually called washout. The processes involved are complex, particularly in washout. Solubility, chemical reactivity, electric charge, and atmospheric conditions have all been used to explain observations.

Gases are removed by absorption and fixation by cloud elements, and can be dissolved in the water or transformed by oxidation or other chemical reactions. Within the rain cloud, aerosols are accumulated by consumption as condensation nuclei during the formation of cloud elements, or by attachment to cloud elements that are already formed; below the cloud, they are accumulated through interception by falling raindrops. Generally, the rate of removal of the aerosols by rain is greater than that of the gases, and most of the removal takes place within the cloud. An exception is when concentrations of aerosols are much larger below the cloud, as in the case of sea-salt particles over seacoasts.

The amount and kind of substances removed from the atmosphere by rain vary not only with the amount and kind present in the atmosphere at the time and place the rain occurs but also with the drop size and amount and duration of rainfall. The concentration of dissolved gases (N_2O, NO, H_2S, Cl_2, I_2, CO, CH_4, and CH_2O) has been calculated as 10^{-4} to 10^{-6} mg $liter^{-1}$, which is negligible compared to the concentrations of other components in rainwater. The gases that undergo transformation when scavenged by rain in-

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*This is the terminology of the profession – the "liquid water content per unit volume of air" is more descriptive.

TABLE 7-8

CONCENTRATIONS OF MAJOR NUCLEOGENIC IMPURITIES IN RAIN (Refs. 22, 32, 34)

Impurity	Sources	Locale	Normal range, mg liter^{-1}
SO_4	Fossil fuels, forest fires, and volcanoes via oxidation of SO_2; sea salt	Country air Polluted air Marine air	≈ 1 ≈ 10 ≈ 1
NH_4	Fossil fuels forest fires, decay of organic matter	Marine air Inland air	0.04-0.29 0.10-0.76
NO_3	Industrial processes, internal combustion engines	Inland air Marine air	0.3-5 0.1-0.6
Cl, N_2	Sea salt, soil particles	Inland air Marine air	0.1-0.5 1-20

clude CO_2, O_3, SO_2, NH_3, and NO_2. Concentrations of CO_2 in rainwater at a pH value of 5.5 and 20°C (68°F) have been calculated to be 1.17 mg liter^{-1} (Ref. 32).

Some of the more important impurities and their concentrations in rainwater are given in Table 7-8. Both the individual and the relative concentrations vary with location and time. Total concentrations tend to be greatest near cities and industrial areas where the sources of atmospheric pollution are greatest. Concentration of chlorides and other salts are greatest near the seacoast, and concentrations of nitrogen compounds are greatest inland. Seasonal changes can be caused by such factors as increased use of fossil fuels in winter and changes in the prevailing wind direction at different times of the year.

Concentration ranges for a number of trace elements in rainwater are given in Table 7-9. These data, recorded for only one location, are only indicative of the concentration ranges to be expected elsewhere.

Concentrations of impurities in rain decrease with duration of the rain as the result of:

(1) Continuous dilution of the contaminated water contained in the cloud by pure water entering the cloud in the form of condensed vapor.

(2) Gradual exhaustion of impurities in clouds and in the subcloud layer due to rainout and washout by falling raindrops. Makhon'ko (Ref. 35) states that the washout coefficient of atmospheric aerosols in the subcloud layer is 10^{-5} to 10^{-4} s^{-1}, and that in clouds it is 10^{-4} to 10^{-3} s^{-1}; thus, removal of contaminants by precipitation occurs mainly in the clouds.

The concentration of aerosols in rain also varies with raindrop size, as shown in Table 7-10 (Ref. 37). Small drops are more efficient collectors of soluble material than are large drops; hence, lesser amounts of rainfall of small drop size are needed to reduce concentrations of soluble material in the atmosphere. The size of the aerosol particles also affects the efficiency with which they are washed out

TABLE 7-9

TRACE-ELEMENT CONCENTRATIONS IN RAINWATER (Ref. 36)

Element	Concentration range, μg $liter^{-1}$
Ag	< 0.01-1.1*
As	< 0.1-1.4
Au	< 0.02
Br	1.6-3.8
Cl	300-1400
Co	< 0.01-0.045
Cr	< 0.2-2
Cs	0.01-0.07
Cu	0.40-3.4
Fe	< 10-35
Hg	< 0.1-1
K	12-630
Mn	0.19-2.9
Na	120-760
Rb	< 0.5-2
Sb	< 0.01-0.18
Sc	< 0.0005-0.003
Se	< 0.01-0.07
Zn	3-20

*The notation "< 0.01-1.1" should be read "from less than 0.01 to 1.1", "< 0.02" should be read "less than 0.02".

of the air, the larger sizes being removed first. Finally, the distance that drops fall affects aerosol concentration in rain; drops falling longer distances collect more aerosols during their descent.

The chloride and sulfate content of rain is particularly important to the design engineer—both produce a marked acceleration in metal corrosion.

More detailed information on the properties of rain can be found in scientific encyclopedias (such as Ref. 29). An an-

TABLE 7-10

CONCENTRATION OF SOLUBLE MATERIAL VS RAINDROP SIZE (Ref. 37) (FALL FROM 1,000 m)

Diameter, mm	Concentration, mg liter^{-1}
0.2	71
0.4	45
0.8	29
1.6	15
3.2	7.5

notated bibliography on the chemistry of precipitation by Rigby and Sinha (Ref. 38) contains references to investigations up to 1960, and later references can be found in the *Meteorological and Geoastrophysical Abstracts* (Ref. 39).

7-3 RAINFALL DISTRIBUTION

The distribution of rainfall has general patterns associated with the climatic and geographic nature of the locale, which in turn determines the predominant rainfall mechanism. Although knowledge of these patterns allows for supposition about the likely rainfall characteristics of a specific location, more definitive information can be derived from the meteorological data that have been accumulated for many locations. Actual rainfall rates and frequencies often vary considerably in a given small region. This paragraph is divided into a discussion of the general patterns of rainfall followed by a synopsis of meteorological records.

7-3.1 GENERAL PATTERNS

Latitudinal distribution of rainfall is affected by the amount of moisture in the air (which declines from the equator poleward), and by the zones of ascending and descending air associated with global circulation. Generally, the heaviest rains are in the tropics; there are dry areas in the subtropics, rainbelts in the middle latitudes, and drier areas in the high latitudes.

This general pattern varies longitudinally, however, because of differences in topography and factors such as prevailing wind direction and location in regard to water bodies. Over land areas, rainfall is generally more abundant in highlands and near the coasts. However, some coasts are wetter than others, such as east coasts in the subtropics, where the trade winds blow onshore, and west coasts in the path of the middle latitude westerlies. Coasts adjacent to warm ocean currents are wetter than those near cold currents. Mountains parallel to wet coasts have especially large amounts of rain. In general, areas of low precipitation occur in the interiors of continents, on the lee sides of high mountains, on coasts adjoining cool currents, in the zones of high atmospheric pressure where the air is subsiding, and in high latitudes.

7-3.1.1 CONVECTIVE RAIN

Convection storms may be randomly scattered over an area or grouped in clusters or lines of clusters. They are the most common kind of storm, with an estimated worldwide total of 44,000 occurring on an average day (Ref. 2). They are caused by thermal instability, such as that resulting from the passage of cooler air over hot land or warm ocean masses, and can also be triggered by other airlifting mechanisms. They are most frequent in late spring and summer in warm regions.

TABLE 7-11

REPRESENTATIVE DISTRIBUTION OF RAINFALL RATES WITH HEIGHT (Ref. 42)

Height above surface, km	Percent of surface rate
Surface	100
1	90
2	75
3	57
4	34
5	15
6	7
7	2
8	1
9	0.1
10 and over	Less than 0.1

7-3.1.2 CYCLONIC RAIN

In the middle and higher latitudes much of the rainfall, especially in winter, is frontal and associated with cyclones that generally move from west to east at about 20 to 35 mph. In lower latitudes, where temperature differences between airmasses are less pronounced, frontal activity is less important. Storms in these areas tend to be associated with tropical depressions or easterly waves that occasionally give rise to hurricanes. Such storms, moving from the subtropics into the mid-latitudes, can bring very heavy and prolonged rain, with larger total amounts of rainfall than any other type of storm.

7-3.1.3 OROGRAPHIC RAIN

As would be expected, orographic rain is distributed in relation to topography. Highland areas in the path of moisture-carrying winds have abundant and frequent rainfall. Windward slopes that face a warm sea have the highest average annual rainfalls of any places on earth (Ref. 40). Conversely, leeward slopes and the inland areas adjacent to them often experience a rain-shadow effect in which rainfall is scarce because much of the moisture has already been lost on the windward slopes; the descending air, warmed adiabatically, is able to hold the remaining moisture.

7-3.1.4 COLD AND WARM RAINS

Cold rain is usually associated with thundershowers in all areas and with much of the convective and cyclonic rainfall in middle and high latitudes. Almost all rain falling over inland areas is of the cold type. Warm rain, often falling as drizzle, is most prevalent in maritime regions and during summer.

7-3.1.5 VERTICAL DISTRIBUTION

Ground elevation has an important effect on rain. As previously noted, the orographic influence produces high amounts of rainfall on windward slopes of mountains, while the leeward slopes may experience a scarcity of rainfall (Ref. 41).

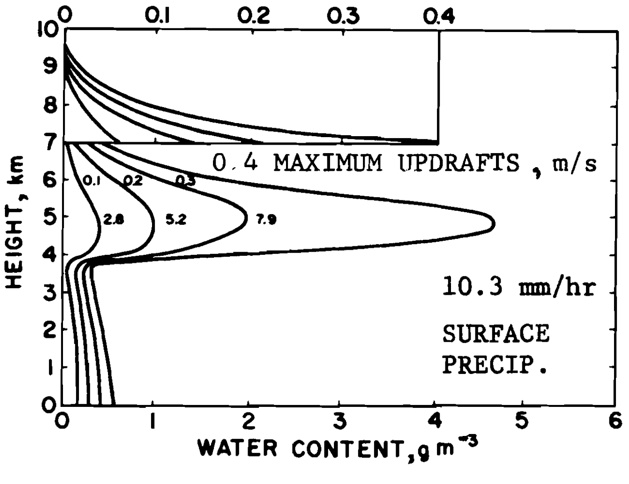
Vertical distribution of rain in the air affects many rain parameters. Drop-size distribution can change considerably between the cloud and the ground due to evaporation, gravity separation, and drop collision. Rainfall intensity, as shown in Table 7-11, decreases with altitude above the ground (Ref. 42). The liquid water content of rain is very low at cloud level, increases sharply as the rain falls as the result of updrafts, and then declines as the raindrops approach ground level. Fig. 7-12 illustrates this effect for two types of rainfall (Ref. 43).

An upper ceiling for rain encounter is fixed by the height of the −40°C (−40°F) isothermal (at which all water is frozen) or by the tropopause (at which cumulo-nimbus activity ceases).

7-3.1.6 FREQUENCY AND INTENSITY

Rainfall frequency is the number of times that precipitation of a certain magnitude or

(A) Vertical Profile of Water in Summer Rain in the Temperate Zone



(B) Vertical Profile of Water in Spring and Fall Rain in the Temperate Zone

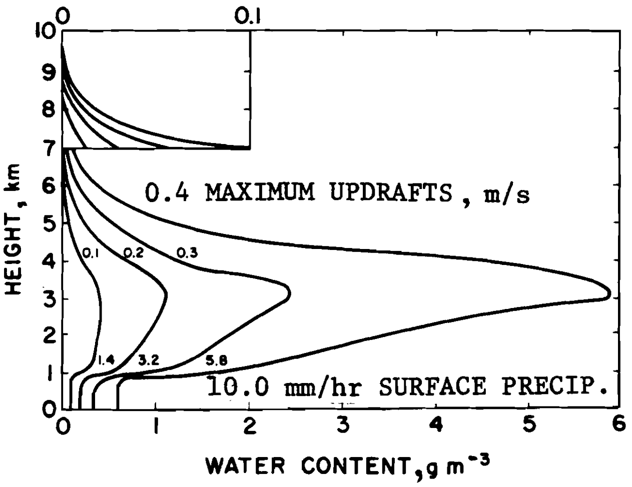


Figure 7-12. Vertical Distribution of Water in Rain (Ref. 43)

greater occurs or may be expected to occur at a station during a specified period of time. Rainfall occurrence frequency is the number of days per given calendar period (month, year, etc.) on which rain occurs (Ref. 1).

Frequency factors are normally presented in terms of the percentage of time during an average year when given rates of precipitation will be equaled or exceeded at a given location or area. Rates of precipitation may be instantaneous or clock-hourly. Table 7-12 is an example of frequencies related to clock-hourly rates and instantaneous rates at selected stations. See the discussion of rainfall intensity in par. 7-2.7 for further information on these parameters.

Frequency of occurrence (days/year) is an input to rainfall frequency calculations. The frequency of occurrence of rain for the capital cities of ten countries in Europe, Asia, and North America is shown in Table 7-12. Table 7-13 provides frequency of occurrence and rainfall frequency factors for other areas of interest to designers of military equipment (Ref. 44).

TABLE 7-12

PRECIPITATION DATA FOR SELECTED STATIONS (Ref. 19)

(Percentage of time during an average year in which clock hourly and instantaneous rates of precipitation equal or exceed 0.06, 0.12, and 0.18 in. hr^{-1})

Station		Average annual precip., in.	Number of days with measurable precip.	Clock-hourly rates			Instantaneous rates		
				0.06 %	0.12 %	0.18 %	0.06 %	0.12 %	0.18 %
Athens	37° 30' N 23° 43' E	15.70	98	0.94	0.24	0.08	0.85	0.23	0.08
Berlin	52° 30' N 13° 25' E	22.88	169	0.84	0.16	0.03	0.76	0.15	0.03
Dublin	53° 20' N 6° 15' W	27.37	218	0.78	0.13	0.01	0.70	0.12	0.01
London	51° 25' N 0° 20' E	24.47	167	0.89	0.20	0.06	0.80	0.19	0.06
Moscow	55° 45' N 37° 37' E	24.13	132	1.05	0.30	0.13	0.95	0.29	0.13
Paris	48° 52' N 2° 20' E	22.62	160	0.84	0.16	0.03	0.76	0.15	0.03
Rome	41° 45' N 12° 15' E	26.70	105	1.45	0.59	0.33	1.31	0.55	0.03
Tokyo	35° 41' N 139° 46' E	61.40	149	2.22	1.13	0.72	2.00	1.06	0.72
Warsaw	50° 14' N 21° 00 E	22.21	164	0.84	0.16	0.03	0.76	0.15	0.03
Washington	38° 55' N 77° 00 W	42.20	124	2.11	0.90	0.60	1.90	0.85	0.60

TABLE 7-13

RAINFALL FOR SELECTED LOCATIONS (Ref. 44)

Location	Frequency of occurrence, days/yr	Hours per year						
		Clock-hourly rates, in./hr, ≥						
		0.05	0.1	0.25	0.5	1.0	2.0	2.5
Sacramento, Calif.	53.2	118.0	35.0	5.2	0.2	-	-	-
Honolulu, Hawaii	86.2	92.0	52.0	20.4	9.2	3.0	0.2	0.2
Guam	269.0	515.0	265.0	77.0	22.5	3.3	0.5	0.2
Clark AFB, Philippines	122.2	286.0	175.0	77.4	28.8	6.8	0.4	-
Shemya, Aleutians	199.0	121.0	25.7	1.0	-	-	-	-
Clear, Alaska	100.0	60.2	13.0	0.5	-	-	-	-
North Platte, Nebr.	87.6	102.0	49.0	13.6	3.0	0.6	-	-
Laos-Burma	93.6	210.0	126.0	51.0	18.6	3.8	0.2	-
Midway Island	151.1	172.0	93.0	33.4	11.4	4.3	0.2	0.2
Torrejon, Spain	74.0	86.5	41.3	11.3	2.8	0.82	0.19	-
Fylingsdale, United Kingdom	167.5	117.0	29.0	2.24	-	-	-	-
Townsville, Australia	80.8	189.0	116.0	51.1	19.0	4.5	0.26	-
Adana, Turkey	73.9	123.0	49.1	7.3	0.28	-	-	-
Thule, Greenland	64.5	17.8	3.8	0.2	-	-	-	-
Fairbanks, Alaska	94.2	31.2	5.14	0.2	-	-	-	-

Frequency of occurrence is not necessarily related to the amount of rainfall in any given locality. Table 7-12, for example, shows that Berlin had more days of rain than the other nine cities listed except for Dublin, yet six cities had a greater amount of rainfall. A review of the data used in preparation of Table 7-13 shows that Laos-Burma averages 46.8 in./yr of rain based on 93.6 days/yr of rainfall. North Platte, Nebr., with nearly as many days of rain (87.6), had an average annual rainfall of 21.3 in.

The occurrence of warm, supercooled warm, and cold rain* for different forms of rainfall is shown in Table 7-14. These data are based on analysis of rain observations over a 1-yr period at 62 stations in the Northern Hemisphere. Cold rain is by far the most prevalent type, and "slight" rains and showers are the most frequent form of rainfall.

Some relationship between the frequency of thunderstorms and rainfall amounts was found by Portig and Gerhardt (Ref. 3). An increase of rainfall in the tropics is associated with an increase of thunderstorm activity up to a certain amount of rain, but beyond this point the thunderstorm activity drops with increasing amounts of rain. The ratio of thunderstorm frequency to the amount of rainfall varies geographically. It is large in continental and small in oceanic climates, with maxima in West Africa, the Rocky Mountains, and Tibet (Ref. 3).

7-3.2 RAINFALL DATA

Globally, on the average, the maximum yearly precipitation is received in the equatorial zone, and the minimum occurs in the high latitudes (Arctic and Antarctic) and in the subtropical desert zone. The most humid regions receive over 80 in. (2.0 m) of rain annually, with considerably higher amounts recorded in some of the Pacific islands and elevated coasts of continents. The highest average annual rainfall, over 460 in./yr (11.7 m/yr), occurs at Mt. Waialeale, Kanai, Hawaii; it results from the tropical easterlies (Ref. 45). Cherrapunju, India, receives an average annual rainfall of 450 in. (11.4 m/yr) as a result of the moist, tropical monsoon (Ref. 40).

Throughout the subtropical zone of high pressure and minimum cloudiness, the total precipitation is less than 1 in./yr (0.025 m/yr), with some desert areas (Chile, Peru, Sahara) receiving no precipitation at all for several years.

In the middle latitudes, Great Britain receives an annual average of about 42 in. (1.07 m) (Ref. 2), much of Europe ranges from 20 to 30 in./yr (0.51 to 0.76 m/yr), and the United States about 29 in. (0.74 m). The highest amount of rain in the United States falls in a relatively narrow region bordering on the Gulf of Mexico; e.g., the average annual rainfall in New Orleans is about 57 in. (1.45 m) (Ref. 4).

Recorded record rainfalls for various time durations are given in Table 7-15 (Ref. 46).

The average number of days with thunderstorms varies seasonally throughout the world as shown in Fig. 7-13 (Ref. 47). In Florida, the average for the December-February quarter is 5 to 10 days with thunderstorms while in the June-August quarter it is from 30 to over 50. In the arctic regions, thunderstorms are rare.

Normal monthly precipitation for the United States is shown in Fig. 7-14 (Ref. 48) and comprehensive worldwide precipitation data are given in Appendix B.

7-4 MEASUREMENTS AND INSTRUMENTATION

Table 7-16 shows, for each of the common parameters of rain, the unit of measurement, the range of values, and the instrument or method used. Some parameters are measured

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*Warm rain results from condensation and coalescence of liquid droplets; cold rain derives from ice crystals; and supercooled warm rain derives from liquid droplets but these form at subfreezing temperatures and therefore are supercooled.

TABLE 7-14

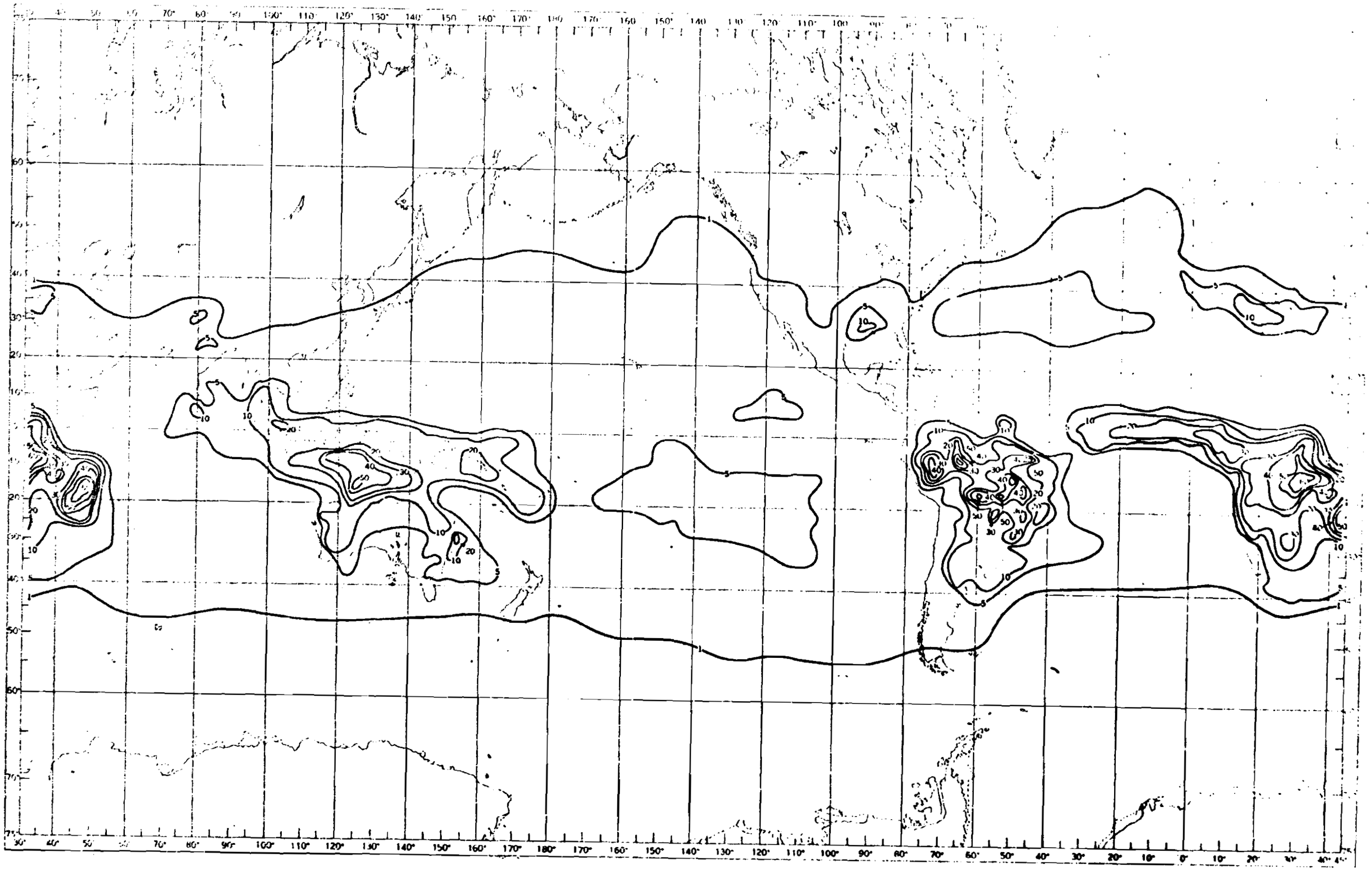
OCCURRENCE OF DIFFERENT RAINFALL FORMS IN THE TEMPERATE ZONE (Ref. 7)

Rainfall form	Frequency, days/yr		
	Warm	Supercooled warm	Cold
Drizzle, not freezing, intermittent, slight	48	15	46
Drizzle, not freezing, continuous, slight	136	77	139
Drizzle, not freezing, intermittent, moderate	2	2	2
Drizzle, not freezing, continuous, moderate	19	6	13
Drizzle, not freezing, intermittent, dense	1	0	0
Drizzle, not freezing, continuous, dense	1	1	4
Drizzle and rain, slight	9	8	38
Drizzle and rain, moderate or heavy (dense)	1	0	5
Rain, not freezing, intermittent, slight	38	33	333
Rain, not freezing, continuous, slight	119	93	1380
Rain, not freezing, intermittent, moderate	6	0	45
Rain, not freezing, continuous, moderate	11	11	197
Rain, not freezing, intermittent, heavy	0	0	3
Rain, not freezing, continuous heavy	0	1	1
Rain shower(s), slight	275	72	680
Rain shower(s), moderate, heavy	19	3	91
Rain showers, violent	0	0	3
Slight rain, thunderstorm during the preceding hour but not at time of observation	2	1	16
Moderate or heavy rain, thunderstorm during the preceding hour but not at time of observation	1	1	4
Thunderstorm, slight or moderate, rain or snow	7	3	60
Thunderstorm, heavy, without hail, rain or snow	0	0	3

TABLE 7-15

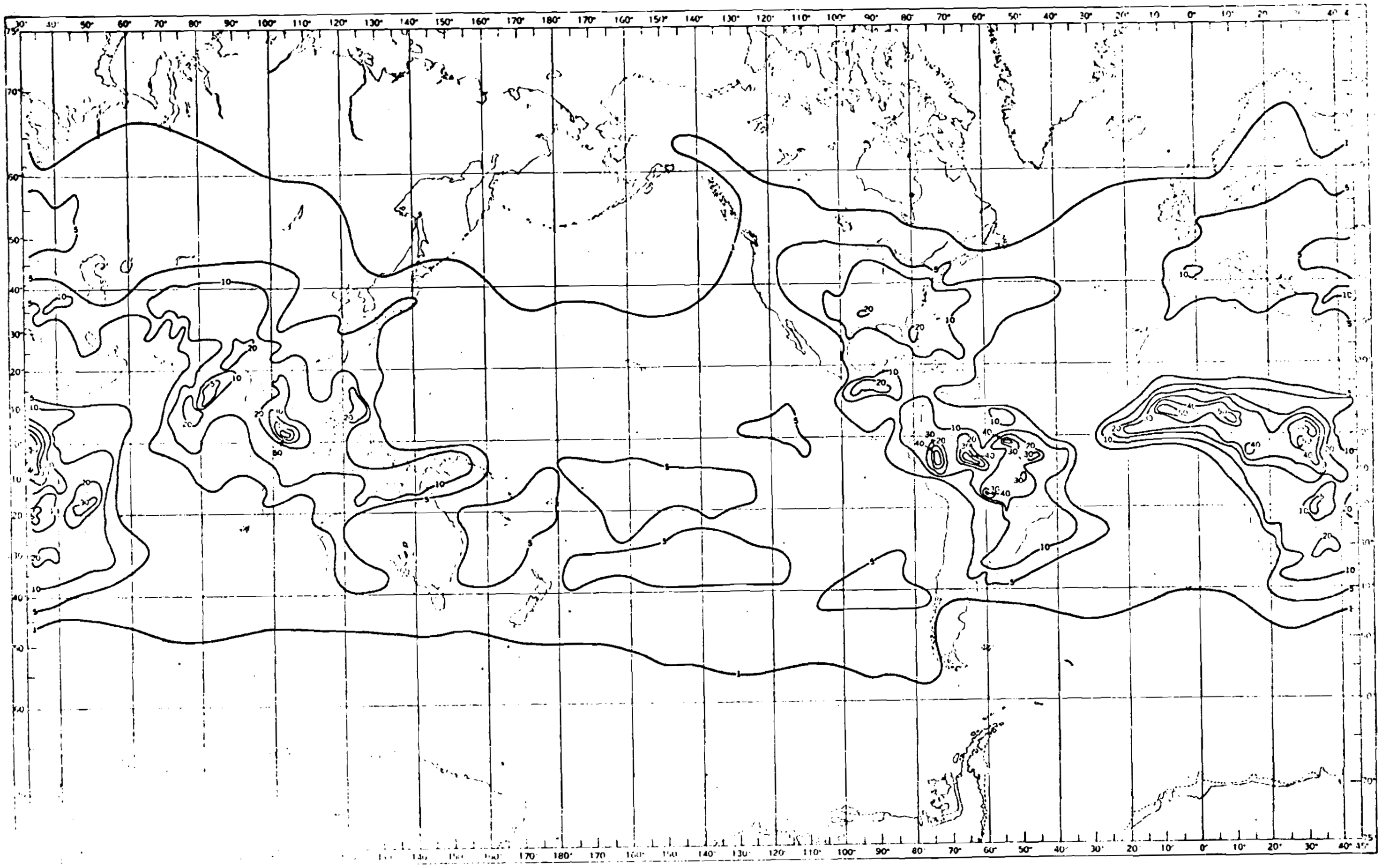
WORLD'S GREATEST OBSERVED RAINFALLS (Ref. 46)

Duration	Depth		Location	Date
	in.	mm		
1 min	1.23	31.2	Unionville, Md.	4 July 1956
20 min	8.10	206.0	Curtea-de Arges, Romania	7 July 1889
42 min	12.00	305.0	Holt, Mo.	22 July 1947
12 hr	53.00	1346.0	Belouvre, LaReunion Island	28-29 February 1964
24 hr	74.00	1880.0	Cilaos, LaReunion Island	15-16 March 1952
5 days	152.00	3861.0	Cilaos, LaReunion Island	13-18 March 1952
1 mo	366.00	9296.0	Cherrapunji, India	July 1861
12 mo	1042.00	26467.0	Cherrapunji, India	August 1860-July 1861



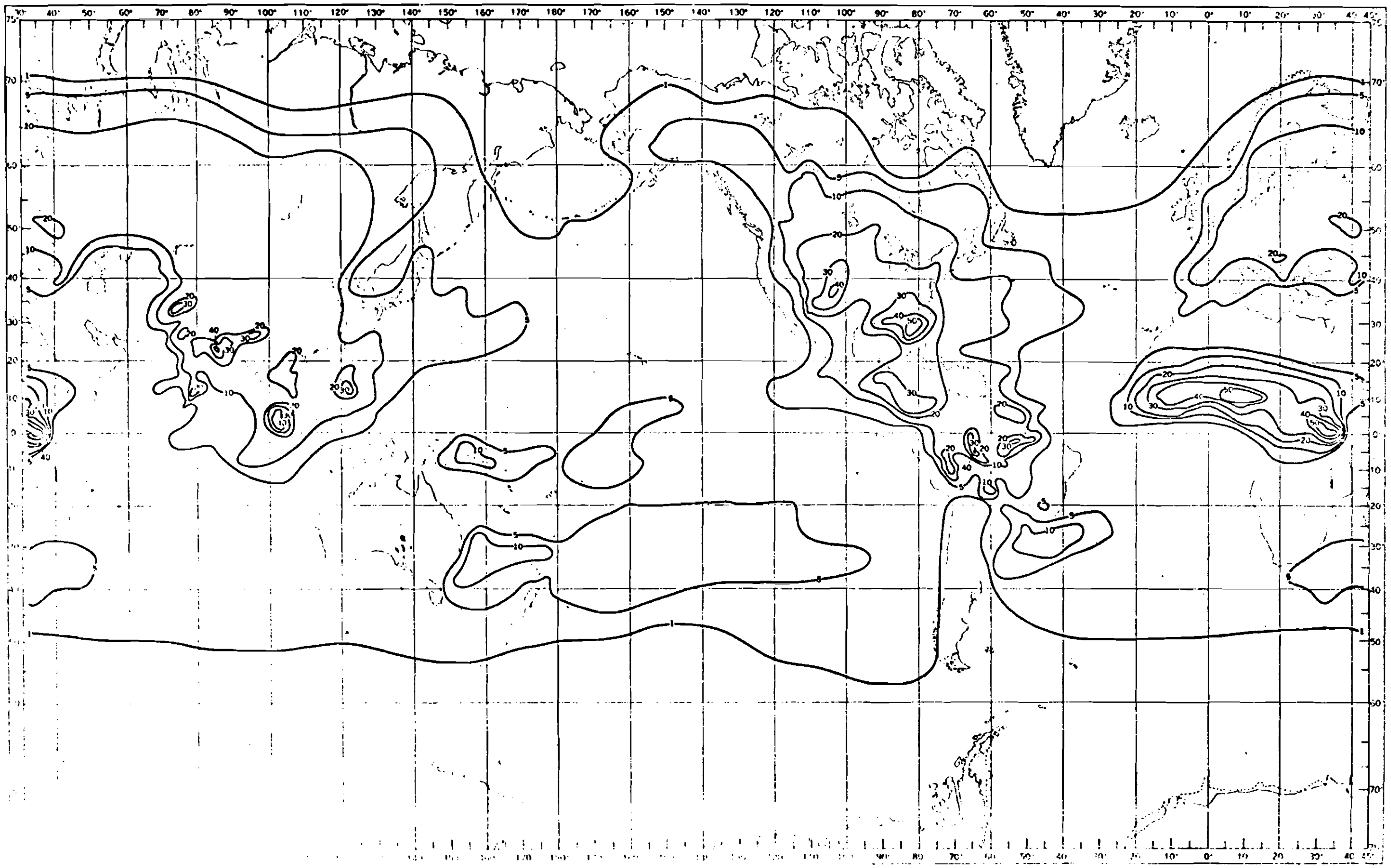
(A) December-January-February

Figure 7-13. Average Number of Days With Thunderstorms—Quarterly (Ref. 47)



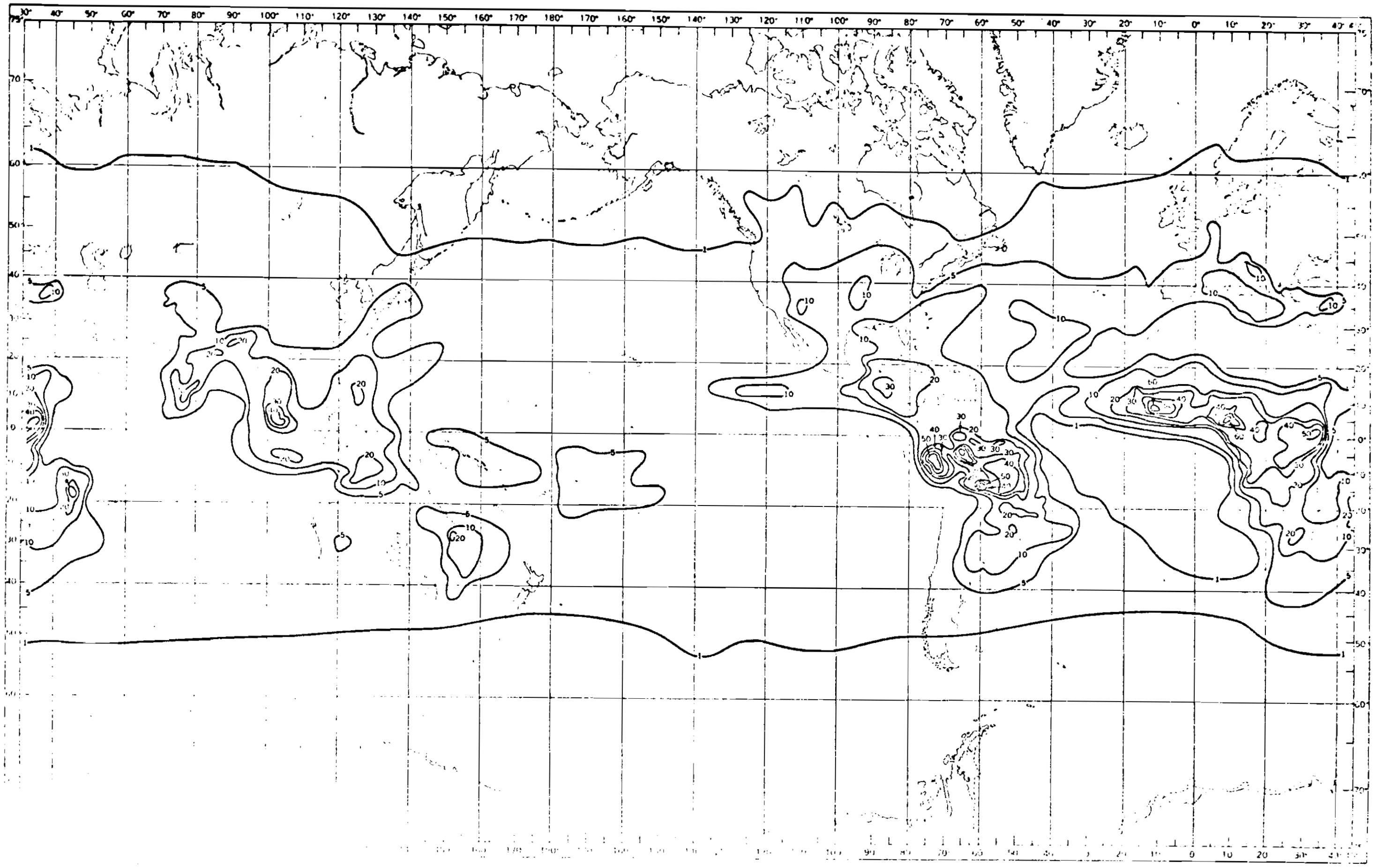
(B) March-April-May

Figure 7-13 (Continued). Average Number of Days With Thunderstorms—Quarterly (Ref. 47)



(C) June-July-August

Figure 7-13 (Continued). Average Number of Days With Thunderstorms—Quarterly (Ref. 47)



(D) September-October-November

Figure 7-13 (Continued). Average Number of Days With Thunderstorms—Quarterly (Ref. 47)

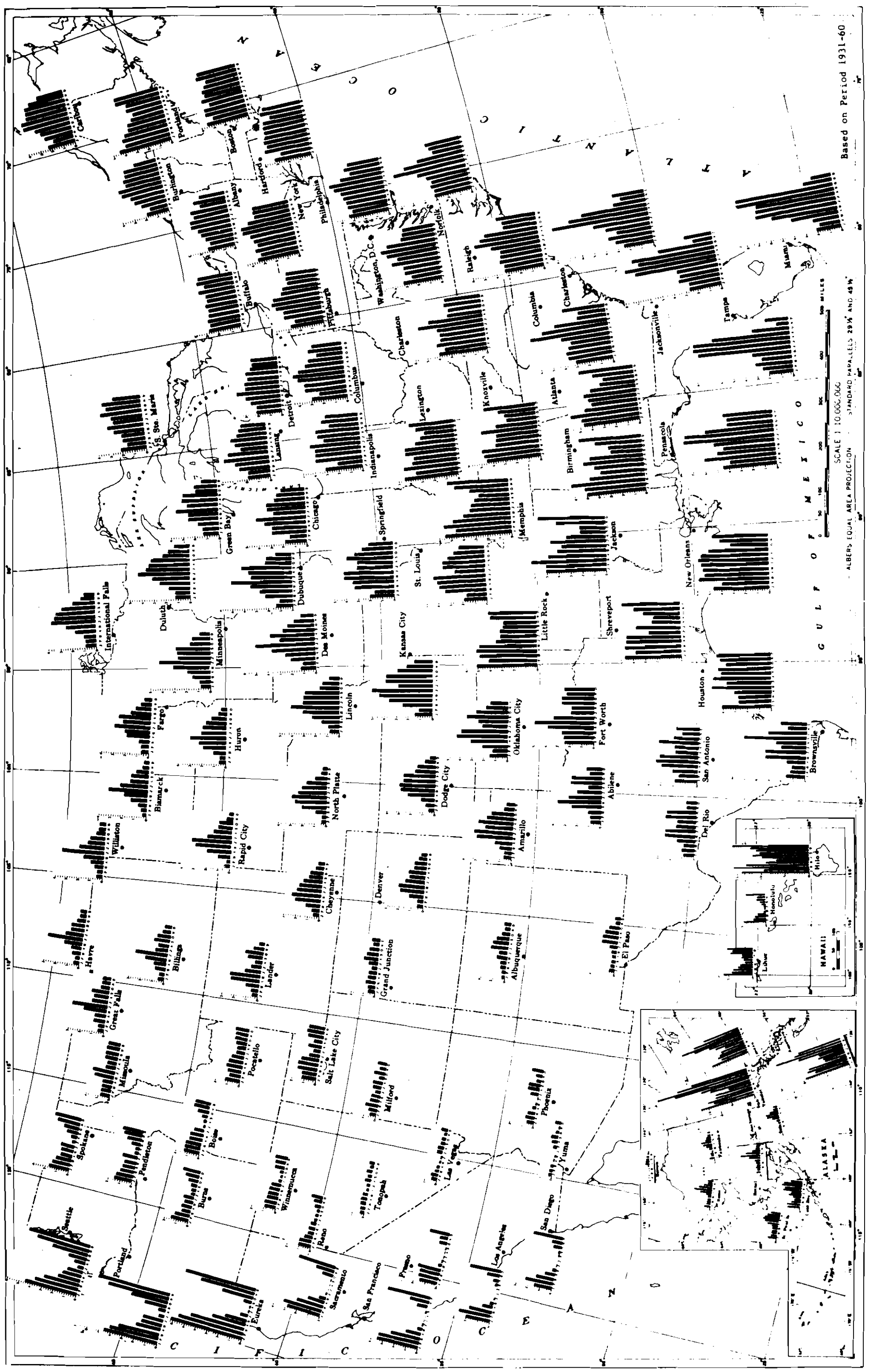


Figure 7-14. Normal Monthly Total Precipitation (Inches)

TABLE 7-16

RAIN PARAMETERS AND THEIR DETERMINATION

Parameter	Range of values	Measuring instrument or method of determination	References
Amount: depth during a given period of rainfall	0.1-40 in.	Ordinary and recording rain gages Meteorological radar	49, 50 51, 52
Duration: length of time of a given fall or rainy period	1.0 min-1.0 week	Recording rain gage Meteorological radar Chronometers	49, 50 51, 52
Intensity or rate (R)	0.1 mm/hr- 30 mm/min	Recording rain gage Rate-of-rainfall recorder Meteorological radar	49, 50 49 5, 43, 51, 52
Raindrop mass	0.005-268 g	Calculate from size or terminal velocity Weigh	24, 53
Raindrop concentration	8.0-1.3x10^{3} m^{-3}	Raindrop camera	5, 54
Raindrop size: diameter, and Raindrop size distribution: number frequency of drops per unit volume within stated range of diameters over entire range of diameters	0.2-8.0 mm (See Eq. 7-1)	Dye impregnated filter paper Flour pellet size Doppler radar Photographic film Impactor High voltage discharge Electrostatic charge Photoelectric detector Photography	5, 22, 55 5, 22, 56 22, 52, 57, 58, 59 55 60, 61 62 63 64, 65 5, 54
Median volume diameter: diameter at which total volume of drops with greater diameters equals total volume of drops with small diameters (D_0)	≈1-6 mm	Calculate from drop size distribution	22, 43
Raindrop velocity Raindrop terminal velocity	0.01-9.2 m/s 0.04-30 ft/s	Photography Doppler radar Electrostatic detector	53, 54 52, 58 24

TABLE 7-16 (Continued)

RAIN PARAMETERS AND THEIR DETERMINATION

Parameter	Range of values	Measuring instrument or method of determination	References
Liquid water content: Amount of	$0.1\text{-}30.0\ g/m^3$	Calculate from drop size distribution Calculate from radar reflectivity	5 43
Radar reflectivity	$10^{-12}\text{-}10^{-8}cm^{-1}$		5, 43, 52, 57, 59
Radar signal attenuation	$\approx 0.3\text{-}6.0$ dB/km	Calculate from scattering theory Measure with separated transmitter and receiver	5, 22, 43, 59, 66
Raindrop impact energy	$10^{-6}\text{-}10^{-2}j$ $10^{-6}10^{-2}$ ft lb	Calculate from mass and velocity	31
Raindrop impact pressure	$\approx 3.0\text{x}10^{-2}N/m^2$ or $1.4\ lb/ft^2$	Calculate: $\rho A = m\ dv/dt$ Piezoelectric pressure gage	67 67
Impurity content	$10^{-8}\text{-}10^{-2}$ g/l	Chemical analysis of collected rainwater using: polarography-chlorides, nitrates titration-chlorides, sulfates colorimetry - nitrates, nitrites, ammonia, acidity flame photometry - sodium, potassium, calcium potentiometric-acidity nuclear activation-trace elements	33, 68, 69
Electrical conductivity		Conductivity cell	70

directly, while others are calculated from their known relationship to other characteristics or properties.

A great many measuring devices have been used for studying rain and rainfall. No attempt is made to describe all of them.

A brief description of the instrumentation most frequently used follows:

7-4.1 TYPES OF INSTRUMENTS

(1) *Ordinary rain gage.* Descriptions of the ordinary rain gage, which consists basically of a collector above a funnel leading into a receiving container, are in the literature (Refs. 49, 50). The capacity of the receiver is related to the frequency of readings, with large receivers or totalizers provided for weekly or monthly samples.

The water collected in gages is measured using either graduated measuring cylinders or dip rods. The former method is more suitable for daily gages and the latter for weekly, monthly, or seasonal gages. For the required accuracy, the maximum error of the graduations should not exceed ± 0.02 mm below this mark. It is also possible to weigh the water (taking the weight of the receiver into account), which has the advantage of eliminating spillage and adhesion of water to the receiver, but the other methods are simpler and less expensive (Ref. 50).

Proper exposure of the gage is important in collecting a representative sample. The quantity of water collected depends on the wind velocity and on the nature and height of surrounding objects. Airflow by the gage can cause eddies that, if in the form of updrafts over the orifice, will reduce the catch. Downdrafts on the other hand will increase it. The site also affects the air paths near the instrument. The gage should be so situated that the airflow across its mouth is horizontal. Surrounding objects should not be closer to the gage than four times their height, but a site should be chosen that is sheltered from the full force of the wind. Criteria for site selection and exposure should be uniform for all gages in an area or country.

Major sources of measurement error can result from improper site selection. Smaller errors stem from the use of inaccurate measures, the spilling of water when transferring it to the measure, and the inability to transfer all the water from the receiver to the measuring cylinder. Additionally, losses by evaporation can occur but are not likely to be serious except in dry climates or when the catch is measured infrequently (Ref. 50).

Because of the different gages and different exposure methods used by various countries, their rainfall data currently are not directly comparable. To overcome this difficulty, the World Meteorological Organization has standardized on a Snowden gage with an Alter shield as the interim international reference precipitation gage.

(2) *Recording rain gage.* Recording rain gages can be divided into rainfall recorders that record the total amount of rain that has fallen since the record was started, and rainfall intensity recorders that record the intensity of rainfall at any instant. Rainfall recorders are used primarily to determine the time of onset and cessation of rain, and the amounts that have fallen in each part of the period covered—e.g., 1 hr, 6 hr. An approximation of intensity can be found by measuring the slope of the trace. Because of the large variation in rainfall intensity, a single intensity recorder is frequently inadequate to measure the whole range; a compromise usually has to be made on the basis of the relative frequencies of high and low rainfall.

The most common rainfall recorders are the float type, the tipping bucket type, and the weighing type. A description of each, with its advantages and disadvantages, is in the literature (Ref. 50).

(3) *Raindrop camera.* A raindrop camera makes it possible to photograph the drops

falling through a specific volume, and to measure drop size, drop size distribution, and raindrop concentration. By using calipers on enlargements of the images, the major and minor axes of the drops can also be measured (Refs. 5, 54).

(4) *Meteorological radar.* Radar is unique in providing synoptic data on the distribution, movement, structure, and development of rain clouds as well as the falling speeds and, hence, the size and growth of hydrometeors. The combination of conventional pulse radars with Doppler radars and the data from radiosondes and satellites are providing much more information on rain than heretofore was available.

Radars with wavelengths in the 3 to 10 cm range are employed. A variety of displays are employed including plan-position indicator and range height. A Doppler radar for weather observations may have a peak power of 10 kW with a pulse length of 0.8 μs, a range resolution of 150 m, and a velocity resolution of 1 m s^{-1}. A display of height versus velocity has been employed along with a variety of other displays and data processing equipment.

(5) *Photoelectric raindrop size spectrometer.* This instrument, sometimes called a disdrometer, makes photoelectric observations of a rain sample passing through an optically defined sensitive field. Output can be recorded by electronic readout devices. It is used to measure raindrop size and drop size distribution (Ref. 64).

7-4.2 LIMITATIONS

Most instruments and methods used to measure rain and rainfall are subject to problems and limitations. These limitations can produce inaccuracies in the measurement of a single parameter, and can lead to miscalculations when the values of computed parameters are based on their relationship to the measured parameters.

There are many possible sources of error in rain measurements. A major source is the limited volume of rain most instruments can sample. Rain may splash out of shallow gages, be blown over or out of a gage, or evaporate before being recorded. Improper exposure and errors in reading or recording (both human and instrument) also may produce inaccurate measurements.

The capability and limitations of individual instruments must be considered. Many instruments can be damaged if the collected water freezes. Several cannot record the entire range of values that may occur over a period of time.

Radar measurement errors can result from attenuation of the signals when passing through rain areas. At attenuation levels of over 10 dB, accurate measurement of rain intensity is doubtful (Ref. 71). Also, the rainfall intensity/radar reflectivity relationship varies with different rain types and local conditions, and even at different times during a single rainfall. Mueller and Sims (Ref. 5) found the limiting accuracy for estimation of rainfall rate by radar to be about ± 40 percent.

For these reasons, difficulties frequently arise in comparing the values of a parameter measured by different methods. For example, considerable differences were found between drop diameters measured by newer optical methods and by older methods in which the drops were caught on or in some material such as flour or filter paper (Ref. 6). Differences have been observed in the measurement of amounts and intensities of rainfall by radar and by rain gages, since radar samples the rain synoptically and aloft, while rain gages sample at a point on the ground.

Most limitations, however, can be partially or completely overcome through careful site selection and exposure of the instruments, precise reading of measurements, and proper selection, care, and protection of instruments.

7-5 EFFECTS ON MATERIEL

Rain—when falling, upon impact, and as

TABLE 7-17

EFFECTS OF RAIN

In the atmosphere:

1. Deteriorates radio communications
2. Limits radar effectiveness
3. Limits aircraft operations due to visibility restriction
4. Damages aircraft in flight
5. Affects artillery and missile accuracy
6. Degrades or negates optical surveillance
7. Decreases effectiveness of personnel in exposed activities

On impact:

1. Erodes surfaces
2. Imposes large forces on structures

After deposition:

1. Degrades strength of some materials
2. Promotes corrosion of metals
3. Deteriorates surface coatings
4. Restricts unpaved road and cross-country mobility
5. Causes flooding with destruction of structures
6. Destroys or deteriorates many exposed items of materiel--rations, clothing, repair parts, etc.
7. Can render electrical or electronic apparatus inoperative or dangerous if rain penetrates

deposited water–has a variety of effects on materiel, most of which are well known because of the pervasiveness of rain in the environment. In Table 7-17 some of these effects are categorized with respect to the life cycle of the rain. Most of these effects are sufficiently well known to be considered in the design and utilization of materiel and in military operations–structures are provided and designed to provide protection from rain, rainfall is a major factor in the design of transportation systems and vehicles, equipment is sealed against rain, personnel equipment and supplies are provided in waterproof packages, etc. Thus, many potential effects are not experienced except when the protective measures are compromised by error or operational expediency.

In Table 7-18, the effects of rain are categorized by characteristics of the rainfall. Two specific effects, erosion and electromagnetic wave reflection and attenuation, are discussed in the paragraphs that follow. Much related material is in Chap. 4, "Humidity"; Chap. 8, "Solid Precipitation"; and in other chapters of this handbook.

(1) *Rain erosion.* Erosion of materials (paint, earth) takes place during most rainfalls. However, major erosion problems occur when raindrops collide with objects traveling at very high speed. At high subsonic speeds, external parts of aircraft (such as radomes, windshields, and antenna insulators) are susceptible to rain erosion. As speeds increase above Mach 1, even metal surfaces begin to

TABLE 7-18

CORRELATION OF EFFECTS WITH RAIN CHARACTERISTICS

Characteristic	Effect	Refs.
Excessive amount	Structural weakening or collapse from heavy rainwater accumulations on roofs of buildings	72, 73
	Flooding from excess of rainfall over runoff	74, 75, 76
	Soil tractive ability decreases when excess accumulation of soil moisture causes mud	77, 78, 79
	Water deterioration effects increase where rainwater accumulates	
Deficient amount	Low water supply with poor quality	
	Airborne dust and sand increases	
	Water transportation impeded	
	Destructive flash floods become possible due to inadequate channelization	
Prolonged rain	Materiel absorbs large amount of moisture	
	Protective coatings dissolve or erode away; e.g., silicone coatings, insecticides, fire retardants, greases	80, 81, 82
	Saturation causes sandy soils to lose bearing and shear strength, and clay soils to become slippery	
	Airborne chemical and biological warfare agents lose effectiveness	
	Runoff becomes 100 percent after soil becomes saturated	
Intense rain	Erosion of terrain increases	72, 79, 83
	Penetration of rainwater increases	84
	Drainage systems become inadequate	18, 71
	Radar and communication systems are degraded	85
	Electric power systems affected by flashovers	
	Trajectories of artillery projectiles, rockets, etc. are inaccurate	
	Visibility reduced	
Large drops	Damage to high speed aircraft, missiles, and rockets increases	86
	Electromagnetic wave propagation interference is more severe	66
	Mud splatters onto materiel resulting in soiling, increased wear, and jamming of moving parts	

TABLE 7-18 (Continued)

CORRELATION OF EFFECTS WITH RAIN CHARACTERISTICS

Characteristics	Effect	Refs.
High liquid water content	Malfunctioning of jet engines due to water ingestion	5
High drop velocity	Erosion increases Penetration increases Artillery fire less accurate	83, 87, 88 89, 90, 91 22, 92
General	Extinguishes fire so that signal flares and smoke generating devices are less effective Provides safe drinking water and usable bathing water Increases some chemical reactions Active chemically Cleanses surfaces General deterioration of paper and wood, softens leather, shrinks some kinds of rope	84, 91

suffer severe damage when rain is encountered for more than a few seconds. Rain erosion is a critical problem for supersonic aircraft and especially for rockets and missiles that travel at very high Mach numbers. The rate and extent to which rain erosion will occur vary with such factors as the hardness of the material, configuration and finish of the surface, speed of the moving body, angle and force of the raindrop impact, number of raindrop impacts, and length of exposure (Ref. 93).

Laboratory experiments have shown that water drops shatter when they pass through the bow shock layer that precedes a body traveling at supersonic velocity if the time of traverse in the shock layer is greater than the break-up time, which is determined by the velocity of the drops relative to that of the body. The traverse time is determined by the velocity and geometry of the leading surface of the body. Available data indicate that raindrops of normal size will impact unshattered on the hemispherical nose cone of a missile traveling at 1,000 ft s^{-1}, if the nose cone radius is less than about 0.7 ft; at 2,000 ft s^{-1}, they will impact unshattered if the nose cone radius is less than about 1.6 ft; and at 10,000 ft s^{-1}, they will impact unshattered if the nose cone radius is less than about 2.8 ft. Therefore, it can be expected that raindrops will not be shattered in passing through the bow shock wave of most missiles. Results from several studies also indicate that raindrops have sufficient momentum to prevent them from being deflected by the lateral airflow at a nose cone; hence, all raindrops in the path of a nose cone will impact.

In the velocity range of 1,000 to 3,000 ft s^{-1}, erosion rather than cratering by raindrops is the dominant form of damage. When a raindrop impacts at supersonic velocities, a local pressure of about 10^5 to 10^6 psi is exerted on the target, which is greater than the compressive strength of most materials. As the impacting drop spreads out, the radial velocity of the water may be two to three times the impact velocity. This high-velocity radial flow creates intense erosive action on the target material.

As the impact velocity is increased above a few Mach numbers, the major damage (cratering) is caused by the extreme compressive forces of impinging raindrops. It has been demonstrated that a jet of water at 5,000 ft s^{-1} has sufficient force to cut metals. Its depth of penetration increases with velocity but at a decreasing rate. At 3,000 ft s^{-1}, the depth of penetration will be about 2.2 times that of 1,000 ft s^{-1} and, at at 20,000 ft s^{-1}, about 8 times that at 1,000 ft s^{-1}.

The effect of rain erosion has been tested on a large number of materials by different investigators. Materials tested include metals, glass, plastics, rubber, and some others. The findings of these tests are discussed in numerous publications (including Ref. 87 and 94). One part (Ref. 67) of an extensive study of the effect of rain erosion on various materials is cited because of its aptness. This series of reports covers most materials and is recommended for use by design engineers.

(2) *Attenuation and reflection of electromagnetic waves by rain.* Although radar has become a highly important tool for detection and measurement of rain, rain degrades the effectiveness of radar when used for detection of military targets and of communications based on electromagnetic propagation. For radar this degradation takes the form of unwanted radar reflections that limit the range of the radar and increase the noise background of the target signal. Theory shows the ratio between the power reflected by raindrops P_r and the power transmitted P_o takes the form

$$\frac{P_r}{P_o} \propto \frac{\Sigma N a^6}{\lambda^2} \tag{7-9}$$

where

N = number density of raindrops with radii between a and $a + \Delta a$, cm^{-4}

λ = wavelength, cm

a = radius of raindrop, cm

and the power is normally measured in watts. It can be seen that the degradation, i.e., the proportion of the power scattered or reflected by rain, increases very rapidly with increases in the population of larger diameter droplets in the rain and that longer wavelengths are less affected (Ref. 22).

Eq. 7-9 holds for raindrops with diameters much less than the wavelength of the electromagnetic waves. When this approximation holds, Rayleigh scattering takes place. Mie theory, which results in more complex functions, holds for larger diameter-to-wavelength ratios. For 10-cm radar wavelengths, the true scattering deviates from the Rayleigh value by only 20 percent (Ref. 22) and for longer wavelengths, this deviation decreases.

In the Rayleigh theory, the reflectivity η, defined as the sum of the scattering cross sections of the particles in a unit volume, is given by:

$$\eta = \frac{\pi^5}{\lambda^4} \times 10^{-12} \left[\frac{\epsilon - 1}{\epsilon + 2}\right]^2 \Sigma n D^6, \text{ cm}^{-1} \quad (7\text{-}10)$$

where

η = reflectivity, cm^{-1}

D = diameter = $2a$, mm

ϵ = relative dielectric constant of water, dimensionless

λ = wavelength, cm

n = number of raindrops with diameter D per unit volume, m^{-3}

The summation is over the full distribution of drop sizes in the unit volume (Ref. 22). (In some references ΣnD^6 is written as ΣD^6 with the same meaning, i.e., the sum of D^6 values for all particles in the unit volume.) The ΣnD^6 term is called the radar reflectivity factor, denoted by Z. For the Mie range of droplet sizes, an equivalent reflectivity factor Z_e is employed. The units of Z are conventionally $\text{mm}^6 \text{m}^{-3}$; and of η, cm^{-1}. Radar reflectivity Z can be related to rainfall intensity employing the Marshall-Palmer distribution of Eq. 7-1 to obtain

$$Z = 200 R^{1.6}, \text{mm}^6 \text{ m}^{-3} \quad (7\text{-}11)$$

which is found to apply over rainfall intensities R ranging from 0.5 to 70 mm hr^{-1} with an accuracy of ± 50 percent in most stratiform-type rainfall distributions found in nature. A more accurate equation for thunderstorms is (Ref. 43):

$$Z = 486 R^{1.37}, \text{mm}^6 \text{ m}^{-3} \quad (7\text{-}12)$$

Radar reflectivity thus varies with the wavelength of the radar (inversely as the fourth power), the rainfall intensity, and the distribution of drop sizes. Short wavelengths are more affected than longer ones. Drop size distributions vary with the type of rain, synoptic conditions, the amount of available moisture, and the stability of the atmosphere. Fig. 7-15 shows the relationships between radar reflectivity and rainfall rate at 0°C (32°F) for various wavelengths.

The intensity of plane parallel radiation in traversing a particular distance through uniform precipitation is reduced from I_o to I (Ref. 58):

$$I = I_o \exp\left(-10^{-2}\, x\, \Sigma Q_t\right), \text{W m}^{-2} \quad (7\text{-}13)$$

where

I = intensity, W m^{-2}

I_o = initial intensity, W m^{-2}

x = distance traversed, m

ΣQ_t = total attenuation cross section per cubic meter, $\text{cm}^2 \text{ m}^{-3}$

In practical units, the attenuation per kilometer of path length in precipitation or clouds is (Ref. 43):

$$\text{Attenuation} = 0.4343\, \Sigma Q_t, \text{ dB km}^{-1} \quad (7\text{-}14)$$

For particles that are small with respect to

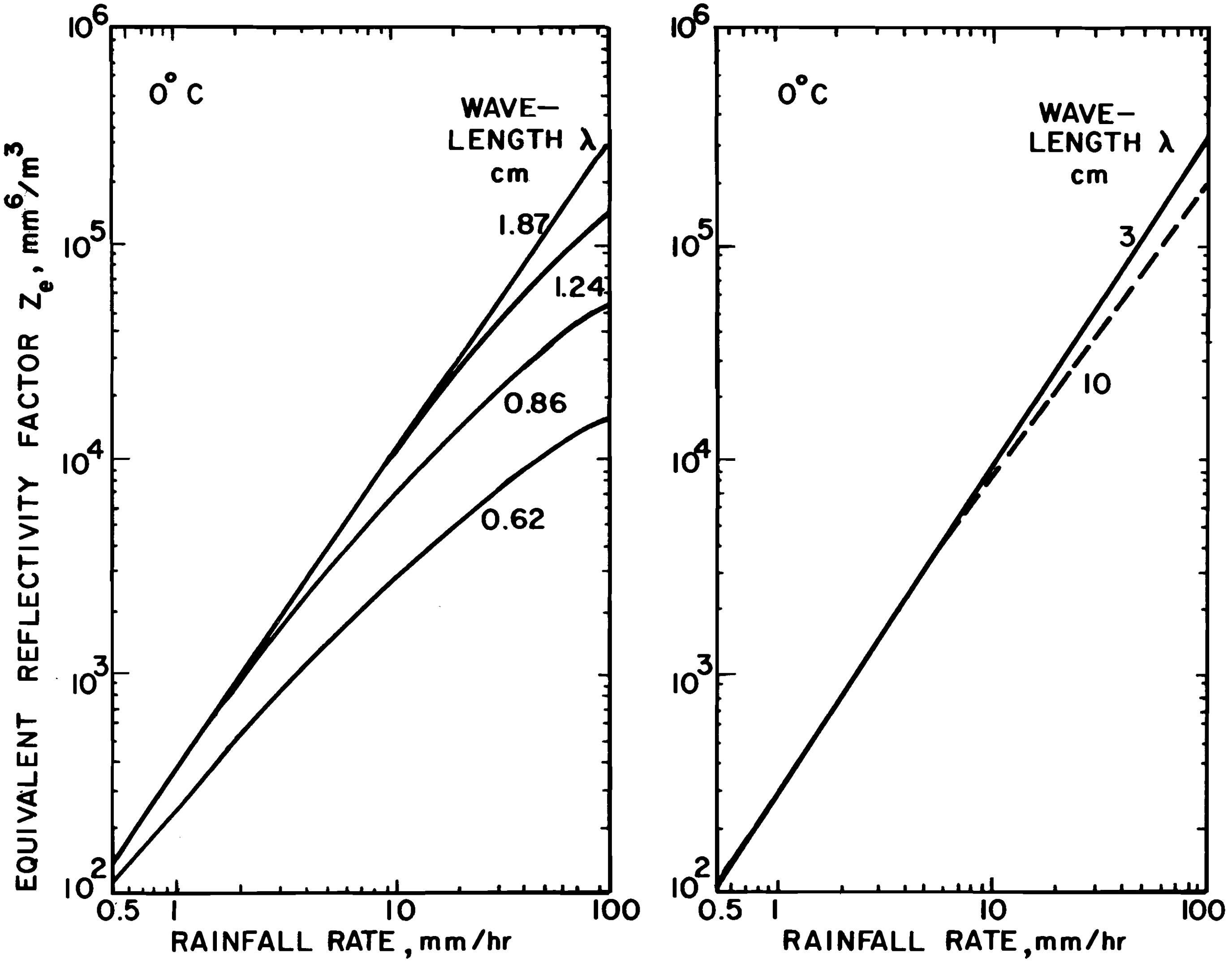


Figure 7-15. Dependence of Radar Reflectivity on Rainfall Rate (Ref. 43)

TABLE 7-19

ELECTROMAGNETIC WAVE ATTENUATION DUE TO RAIN* (Ref. 43)

Wavelength λ, cm	Attenuation at 18°C dB km^{-1}, one way
10.0	$0.0003\ R^{1.00}$
5.7	$0.0022\ R^{1.17}$
3.2	$0.0074\ R^{1.31}$
1.8	$0.045\ R^{1.14}$
1.24	$0.12\ R^{1.05}$
0.9	$0.22\ R^{1.00}$

*R is rainfall rate in mm hr^{-1}

wavelength ($D < 0.5\lambda$), the following equation can be used (Ref. 43):

$$\Sigma Q_t = \frac{6\pi}{\lambda} \frac{M}{\rho} \operatorname{Im}(-K), \text{ cm}^2 \text{ m}^{-3} \qquad (7\text{-}15)$$

where

λ = wavelength, cm

M = water content, g/m^3

ρ = density of water, g/cm^3

K = $\dfrac{\epsilon - 1}{\epsilon + 2}$

Im ($-K$) = imaginary part of minus K

ϵ = relative dielectric constant of water, dimensionless

In the case of radar, the actual attenuating path is twice the distance from radar to target. Although attenuation is generally proportional to rainfall intensity, the relationship varies with wavelength and temperature. Table 7-19 shows attenuation factors resulting from rain for different wavelengths.

7-6 DESIGN, SIMULATION, TESTING, AND SPECIFICATIONS

7-6.1 DESIGN

A primary requirement for design is an understanding of the extremes to which items may be exposed. Both AR 70-38, *Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions* (Ref. 95), and MIL-STD-210, *Climatic Extremes for Military Equipment* (Ref. 96), provide extreme values that general-purpose equipment can be expected to encounter in use.

The values shown are not the most extreme conditions that occur in an area; only a relatively small number of special-purpose items are designed for such "absolute" extreme conditions, in order to obviate the costs involved. Department of Army policy, as stated in AR 70-38, is to design, develop, and test materiel "to withstand extreme climatic conditions such that more severe climatic extremes are expected to occur only 1% of the time (hours) in the most extreme month in the most extreme parts of the appropriate areas". The "1% risk" policy is not applied to rain because of lack of necessary data for application. However, the values provided are somewhat less than absolute extremes.

Table 7-20 shows the rain extremes provided in AR 70-38 and MIL-STD-210 as a basis for normal design requirements. AR 70-38 provides criteria for eight climatic categories: wet-warm, wet-hot, humid-hot coastal desert, hot-dry, intermediate hot-dry, intermediate cold, cold, and extreme cold. MIL-STD-210 provides extreme values for seven spheres of operation: ground operations worldwide, arctic winter, moist tropics, hot desert, shipboard operations worldwide, airborne operations worldwide, and short-term storage and transit worldwide. The values in Table 7-20 are applicable to all spheres of operation of MIL-STD-210, and to all climatic categories of AR 70-38 except intermediate

TABLE 7-20

EXTREME RAIN CONDITIONS FOR GENERAL-PURPOSE MILITARY EQUIPMENT DESIGN (Ref. 95, 96)

AR 70-38: Applicable to wet-warm, wet-hot, humid-hot, hot-dry, intermediate hot-dry.

Drop size throughout: 0.6-4.0 mm, median of 2.5 mm
Windspeed throughout: 40 mph (35 kt)

Duration, hr:min	Amount, in.
0:01	0.45
0:05	1.00
0:10	1.50
1:00	4-5.5**
12:00*	9.50

*12 hr for wet-warm, wet-hot, intermediate hot-dry; 4 hr for humid-hot, hot-dry.

**4 in./hr for humid-hot, hot-dry; 5.5 in./hr for wet-warm, wet-hot, intermediate hot-dry.

MIL-STD-210: Applicable to ground operations, worldwide; ground operations, moist tropics; shipboard operations, worldwide; and short-term storage and transfer, packaging only.

Air and rain temperature throughout: 21.1°C (70°F)

			Drop size	
Duration, hr:min	Amount, in.	Rate, in./hr	Mean, mm	Standard deviation
0:55	2	24	4.0	1.68
1:00	7	7	3.2	1.10
11:00*	11	1	2.25	0.77
11:55	12	1	2.25	0.77
24:00	32	1-24	2.25-4	-

*Windspeed of 40 mph (35 kt) during this period cold, cold, and extreme cold, for which no values are provided.

Measures for the protection of materials against the effects of moisture are discussed in Chap. 4 of this handbook and against salt combined with moisture in Chap. 11. These measures are applicable equally to rain. The principal prevention and control measures discussed in these chapters may be summarized as:

(1) Proper selection of materials to minimize galvanic corrosion

(2) Use of protective finishes (plating, coatings)

(3) Use of preservatives, water repellents, and impregnants

(4) Proper insulation, hermetic sealing, and dehumidification.

Particular attention should be paid during design to the elimination of water traps, provision of easy access to areas of potential trouble due to moisture, and protection against wind-blown rain.

Proper fabrication and treatment of items–such as textiles, leather, and paper–that can be rendered useless by rain are important. Textiles must normally be protected against both penetration and wetting, with priority of protection based on use. Numerous processes are available for this purpose.

Protection against rain erosion at very high supersonic speeds still presents serious problems. Current methods appear to be the proper selection of material consistent with other operational requirements and the design. Erosion resistance increases (according to the best material in each class) through glasses, plastics, ceramics, and metals, with resistance increasing by more than 10^5 from glasses up to the most resistant hard metals (Ref. 87). Wheelahane (Ref. 94), in a state-of-the-art survey, notes that epoxy glass eroded rapidly and that neoprene and polyurethane elastomeric coatings were the only coatings that withstood erosion at speeds up to Mach 2.

Wheelahane also points out that, in the case of missiles, erosion is related to the radius of the nose cone and the thickness of its ablating material–the effect lessening with larger radii and thicker ablating material. Nose cone spikes have been found to be effective in reducing rain erosion damage at speeds of a few thousand feet per second. Design and placement of outside instrumentation must also consider rain impact and erosion as an environmental factor.

Protection against electromagnetic wave attenuation characteristics of rain consists principally of the use of appropriate wavelengths and signal strengths. As noted earlier, the relationships of rainfall to reflectivity and to attenuation vary with wavelength. Wavelength and signal strength selection must be related to rain conditions, mission requirements of radar and communication equipment, weight and cost limitations, topography, and other relevant factors.

Design for protection against the effects of rain is inherent in the construction of roads, airfields, buildings, transportation vehicles, and almost all items of Army materiel. Logistical and operational practices provide for protection of materiel against rain. This design and operational information is to be found dispersed throughout engineering and operational literature.

7-6.2 SIMULATION

Several methods are used to simulate rain and associated test conditions in a test facility. They can be divided into two major categories:

(1) Simulation of rain erosion conditions

(2) Simulation of vertical and wind-driven rainfall as encountered by ground-based materiel.

Method 506 in MIL-STD-810 (Ref. 97) describes the test apparatus and procedures to determine the effectiveness of protective covers or cases to shield equipment from rain. Simulation requirements include:

(a) Capability of producing both falling and wind-driven rain

(b) Droplet diameter range of 1 to 4 mm

(c) Water temperature of 11° to 35°C (52° to 95°F)

(d) Intensities up to 12 ± 1 in. hr^{-1} (304.8 ± 25.4 mm hr^{-1})

(e) Wind source capable of producing horizontal wind velocities up to 40 mph.

Various methods have been used to produce a vertical rainfall simulating capability, including stationary and rotating nozzles, perforated hoses, and even a chicken-wire/muslin arrangement with strings used as wicks. The rain chamber developed at Frankford Arsenal has been found to be highly effective. This facility has an 8- X 10-ft test area. Rainfall is produced by means of small, stainless steel capillary tubes of 0.014 to 0.017 in. in diameter, inserted on 1-in. centers into stainless steel feeder pans. The pans are fed through a pipe leader from a large water standpipe. Rainfall intensity can be controlled in increments of 0.5 in. hr^{-1} up to a 4-in. hr^{-1} rate, and in 1-in. hr^{-1} increments for rates from 4 to 24 in. hr^{-1} (Ref. 98).

The requirements to simulate wind-driven rain first appeared as a military test requirement with the publication of MIL-STD-810, which replaced MIL-E-5272. Consequently, most rain chambers developed prior to that time (June 1967) were incapable of meeting this requirement. Some military laboratories and test agencies modified their chambers in various ways to produce the required windspeed. Frankford Arsenal, for example, used a large fan to force air through a funnel. This produces the necessary windspeed but limits the effective test area in the chamber. Another approach was to use an airplane propeller as a wind source. In one chamber the specimen has been mounted on a rotating arm and moved through vertically-falling rain at the required speed, thus substituting the speed of the specimen for windspeed. Other chambers are being modified or replaced; many do not currently meet MIL-STD-810 requirements.

As noted, the simulation requirements of MIL-STD-810 relate only to testing protective covers and cases. Requirements for testing other materiel items are included in some, but not all, equipment specifications. For many items, moisture, humidity, salt spray, and immersion tests are considered adequate; and rain tests are not specified. Several rain simulation methods have been developed to test the resistance of textile fabrics to rain wetting and penetration. Some of these methods were approved by the American Association of Textile Chemists and Colorists and by the American Society for Testing Materials and are included in some of their publications, such as the *Book of ASTM Standards,* Part 24, "Textile Materials" (Ref. 99).

To test the effects of rain erosion, it is necessary to reproduce the appropriate rainfall conditions and high speeds. Rainfall conditions are met by producing a single water drop, drops made of other materials with density and size characteristics similar to those of rain, or simulated rainfall consisting of falling drops with a concentration, intensity, and size range corresponding to that encountered in natural rain. Required speeds are obtained by projecting a drop or drops at high speed against a stationary target, or by projecting an object at high speed against a stationary drop, or by simulating a vertically falling rain field. A number of methods have been used to reproduce these conditions (Ref. 98), namely:

(1) *Plastic pellet rain simulation device.* A Crossman CO_2 smoothbore cal .22 rifle has been used to propel polyethylene pellets at a

target. This test cannot duplicate repetition rates of raindrops in flight but does simulate erosion effects. Speeds obtained 6 in. from the muzzle are about 2,000 fps. Polyethylene of a density 0.9 that of water was chosen after comparison with raindrop impact and density characteristics.

(2) *Raindrop accelerator.* This apparatus, developed by the Naval Ordnance Laboratory at White Oak, Md., shoots a drop of water against a target at speeds from a few hundred to over 2,000 fps. The device consists of an air gun that shoots a lead pellet into a small chamber of liquid, forcing the liquid through a narrow nozzle. Using a double-flash light source, silhouette photographs are taken of the jet, from which the droplet speed can be computed. Only single drops can be fired, and reproducibility at the higher speeds can be difficult to maintain.

(3) *Whirling arm.* This is a zero-pitch horizontal propeller with a specimen attached to its leading edge near the tip. It rotates the specimen, normal to or at some predetermined angle of attack to the falling droplets. The droplet sizes used are 2-mm diameters for "normal" erosion testing and 5-mm diameters for "severe" erosion testing.

(4) *Ballistic method.* This method is unique in that it uses a captured projectile. The muzzle of a smoothbore gun (20 or 57 mm) is extended, and a perforated tube is inserted into it. Drops of water pass transversely through the perforations of the tube. At the end of the perforated tube is another tube into which a movable slug is placed. A projectile is fired through the perforated tube and impinges on the raindrops. The projectile enters the solid-walled tube and compresses air ahead of it, accelerating the slug and stopping the projectile.

(5) *Supersonic rocket track—US Naval Weapons Center.* This rain-producing equipment covers 2,500 ft and is divided into five 500-ft sections of 4-in.-diameter pipe. Each section is center-fed through its own gate valve from an 8-in.-diameter main. Pressure variations at the nozzles can be held to less than ± 1 psi at the nominal operating range of 5 to 15 psi. Alternate nozzles have a shut-off valve permitting a nominal rainfall of either 2.0 ± 0.7 in. hr^{-1} or 4.0 ± 0.7 in. hr^{-1}, with a 30-in.-wide distribution at the centerline of the rail. The drop size produced varies from 0.5 to 3 mm in diameter, with the mean drop size, based on volume, being 1.5 mm in diameter. Because of overlap, the maximum wind speed the system can tolerate is 5 mph; above this, the rainfall rate distribution is seriously affected. Speeds attained by the moving target range from subsonic to 3,500 fps.

(6) *High speed test track facility—Air Force Missile Development Center.* This facility provides an erosion test method similar to that at the Naval Weapons Center Rocket Track. The test track is 35,570 ft long, with a 6,000-ft rain simulation capability. Rain erosion tests using monorail sleds have been run at speeds up to Mach 5 (Ref. 100).

7-6.3 TESTING

The primary objective of rain testing is to determine the capability of materiel to withstand the deteriorative effects of rain under rainfall conditions that would probably be encountered in field operations. Such tests normally include operability, reliability, and resistance to penetration, wetting, erosion, and corrosion.

Most testing of the effects of rain on materiel is done in laboratories. Although testing in natural rain appears simple and economical, it presents problems, the most important of which are making accurate measurements of rain characteristics and duplicating test conditions. Control and reproducibility of conditions are particularly important so that even in areas where "it almost always rains", the rainfall conditions required for a particular test may not occur when personnel and equipment are on site and prepared. Such delays are costly as well as time consuming (Ref. 98).

The alternative to natural rain testing is simulated rain testing, which also has associated problems. These relate to the requirements for reproducing desired rain characteristics such as drop size, speed, shape, distribution, and intensity. Additionally, requirements to produce rainfall in combination with given temperatures (air and water) and windspeeds add to the complexity of rain simulation (Ref. 98).

In spite of the difficulties of testing the effects of rain on materiel under natural rain conditions, much testing is done under field conditions. Such tests make it possible to evaluate the effects of the total environment, including rain, on materiel. A considerable amount of field testing is accomplished at the US Army Tropic Test Center, Ft. Clayton, C.Z. At Ft. Sherman, also in the Canal Zone, rainfall exceeds 15 in./mo (381 mm/mo) in the rainy months and, even during the driest periods, rain falls on about 15 days per month (Ref. 101). Tests at the Tropic Test Center evaluate the effects of a humid tropical climate (where rain is one constituent) on equipment, but normally do not test the effects of rain as a single environmental factor.

Materiel reliability, operability, and maintainability tests are also performed under field conditions, and the capability of materiel to withstand rain is evaluated among other factors. Although such evaluations normally identify deficiencies, they cannot identify the precise rain parameter (drop size, intensity, windspeed, etc.) related to the failure. Equipment is also frequently evaluated in conjunction with maneuvers and other field exercises, but these evaluations likewise do not normally produce measurements of the specific rain conditions encountered.

Rain testing under natural conditions, of course, can be accomplished whenever rain occurs. In addition to the Tropic Test Center, rain testing and research have been performed on the gulf coast and the Pacific Northwest coast of the continental United States, the Aleutian Islands, southern Alaska, Hawaii, and many other areas.

Table 7-21 is a list of the military agencies whose rain chambers now comply with the rainfall rate requirements of MIL-STD-810. It is possible that recent modification of additional facilities may have expanded this list. Rain chambers with a rainfall rate less than 12 in. hr^{-1} or whose rate is not stated in Ref. 100 are located at the following agencies:

(1) USAF Packaging Evaluation Center, Wright-Patterson AFB, Ohio

(2) USAF Special Weapons Center, Kirtland AFB, N. Mex.

(3) Air Proving Ground Center, Eglin AFB, Fla. (chambers other than those in Table 7-21)

(4) Picatinny Arsenal, Dover, N.J.

(5) Tobyhanna Army Depot, Tobyhanna, Pa.

(6) Edgewood Arsenal, Aberdeen Proving Ground, Md.

(7) US Army Electronics Command, Ft. Monmouth, N.J.

(8) White Sands Missile Range, White Sands, N. Mex.

(9) US Naval Ammunition Depot, Crane, Ind.

(10) US Naval Ammunition Depot, Quality Evaluation Laboratory, Portsmouth, Va.

(11) US Naval Missile Center, Pt. Mugu, Calif.

(12) US Naval Ordnance Station, Indian Head, Md.

(13) US Naval Weapons Center, China Lake, Calif.

(14) US Naval Weapons Laboratory, Dahlgren, Va.

TABLE 7-21

RAIN CHAMBERS THAT MEET RAINFALL RATE REQUIREMENTS OF MIL-STD-810 (Ref. 100)

Agency	Dimensions, ft	Maximum rainfall rate, in./hr	Windspeed, mph
Air Proving Ground Center, Eglin AFB, Fla.			
Climatic Laboratory	252 x 201 x 70	15	-
All-Weather Room	19.83 x 34.75 x 10	15	40
Tropical Marine Room	12 x 12 x 9	12	-
Jungle Test Room	12 x 12 x 9	12	-
Dugway Proving Ground, Dugway, Utah	7 x 12 x 8.5	> 12	-
Frankford Arsenal, Philadelphia, Pa.	10 x 8 x 12	24	40 in part of area
Redstone Arsenal, Huntsville, Ala.	38 x 18 x 10	12	-

There are also rain chambers available in industrial facilities. Many large defense contractors have a rain test capability, although most such facilities listed in the *Institute of Environmental Sciences Facility Survey* of 1965 and the 1966 Supplement (Ref. 102) do not meet MIL-STD-810 requirements. It is probable that many of these chambers either have been or are being modified to meet these standards.

The rain erosion test facilities at the Air Force Missile Development Center, Holloman Air Force Base, N. Mex., and at the Naval Weapons Center, China Lake, Calif., have been described. A similar sled facility at Pendine, England, is operated by the Royal Aircraft Establishment. It has a 3,000-ft track passing through a 500-ft rain field. Average water drop size ranges from 1.2 to 2.8 mm, with a mean intensity of 5.8 in. hr^{-1} (147.3 mm hr^{-1}). Sleds reach a maximum velocity of approximately Mach 1.5 (Ref. 103).

Institutions having whirling-arm erosion test apparatus are:

	Maximum velocity, mph
(1) B. F. Goodrich Company Research Laboratory, Brecksville, Ohio	600
(2) Cornell Aeronautical Laboratory, Buffalo, N.Y.	600
(3) University of Cincinnati, Department of Mechanical Engineering, Cincinnati, Ohio	600
(4) Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio	6-ft blade, Mach 1; 20-ft blade, Mach 2.2

	Maximum velocity, mph
(5) Royal Aircraft Establishment, Farnborough, England	500-600
(6) Dornier System GmbH, Immenstaad, Germany	Mach 1.4

7-6.4 SPECIFICATIONS

The following basic documents contain directives, standards, and specifications related to the design, test, and operation of Army materiel under rain conditions:

(1) MIL-STD-810, *Environmental Test Methods,* 15 June 1967, with Notice 1, 20 October 1969, and Notice 2, 29 September 1969.

(2) MIL-STD-210, *Climatic Extremes for Military Equipment,* 2 August 1957, with Change Notice 1, 30 November 1958.

(3) Quadripartite Standardization Agreement 200, American-British-Canadian-Australian Armies Standardization Program, *Climatic Factors Affecting Design Criteria,* 18 March 1969.

(4) AR 70-38, *Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions,* 5 May 1969.

Rain test procedures for some items of equipment are contained in individual equipment specifications; these are listed in the *Index of Specifications and Standards,* Department of Defense, 1969.

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CHAPTER 8

SOLID PRECIPITATION*

8-1 INTRODUCTION AND DESCRIPTION

This chapter is concerned with those forms of ice that are derived from atmospheric moisture and that form on or are deposited on the earth or other solid surface. This broadens the meaning of "solid precipitation" to include those forms of ice that sublime from water vapor, and, thus, are not strictly precipitants, as well as those forms of ice that solidify from liquid precipitants after contact with a surface. Included in this discussion are the true precipitants—snow, snow pellets or graupel, ice pellets, ice crystals, and hail—as well as glaze, rime, and hoarfrost. These terms are defined in Table 8-1. It is apparent that these ice forms differ in their relative density and that the precipitants differ in size, largely determined by the natural processes of formation.

The effects of these various forms of ice on military materiel are diverse, ranging from severe limitations on mobility and destruction of communications to increased stresses on personnel, protective clothing, and man-equipment interactions. A summary of such effects includes:

(1) *Mobility restrictions.* Lost traction, road blockage, airfield obstruction, restricted personnel movement, visibility restrictions, hidden obstructions, and secondary flooding

(2) *Equipment outages.* Frozen mechanisms, ice-covered controls, overstressed vehicles, and ice-loaded aircraft

(3) *Personnel stresses.* Injuries, clothing burden, decreased energy reserves, and loss of manipulative dexterity

(4) *Snow and ice load.* Structure damage, loss of communication and powerlines, downed trees, and snow avalanches.

Closely related to the contents of this chapter are the discussions of ice fog and whiteout in Chap. 9, of cold temperatures in Chap. 4, of rain in Chap. 7, and portions of Chap. 2 on terrain. The prime discussions of flooding and quagmire, for example, are in Chap. 7, as caused by rain; and in Chap. 2, as a terrain-related problem. Ice formed on rivers or lakes is discussed in depth in Chap. 4. In this chapter, data are presented on all forms of ice derived directly from the atmosphere and found on the ground and on objects.

8-2 CHARACTERISTICS

The characterization of snow and other forms of deposited ice is complex because of the many conditions under which ice is formed from atmospheric moisture and the variety of physical forms that it can assume. Like other solids, ice is found in solid, dense forms such as rocks, in granular forms such as sand, and in varying soil-like textures. Unlike most solids, at certain ambient temperatures it is readily transformed to and from the liquid and gaseous phases. Approximately 2 percent of the water supply of the earth exists in the solid phase, primarily in glaciers formed from the snowpack, compared to 0.001 percent in the gas phase and approximately 98 percent in the liquid phase (Ref. 2). It is noteworthy, however, that 75 percent of the fresh water of the earth is deposited in the snowpack and glaciers.

For the discussion that follows, it is useful to categorize the various forms of ice derived from atmospheric water by their common generic names; snow, hail, glaze, rime, and hoarfrost. Other forms listed in Table 8-1 will be related to these.

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*Much of this chapter is based on a manuscript prepared by R. W. Gerdel of the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.

TABLE 8-1

TYPES OF SOLID PRECIPITANTS AND ICE DEPOSITS (Ref. 1)

Term	Definition
Snow	Precipitation composed of white or translucent ice crystals chiefly in complex dendritic, tabular, stellar, or columnar forms with hexagonal symmetry. Snow is formed directly from atmospheric water vapor.
Snow pellet or graupel	Precipitation consisting of white, opaque ice particles, usually round but sometimes with traces of crystallinity, ranging from 2 to 5 mm in diameter, and of a brittle texture. Ice pellets are easily crushed but can rebound when falling on hard surfaces. They are usually formed by riming of snow crystals.
Ice pellet	Precipitation consisting of transparent or translucent pellets of ice less than 5 mm in diameter. They may be formed by freezing of raindrops or consist of snow pellets encased in a thin layer of ice.
Sleet	A term formerly applied to ice pellets and now used colloquially and in British terminology to describe precipitation that is a mixture of snow and rain.
Hail	Precipitation in the form of rounded or irregular lumps of ice, called hailstones, which range in size from 5 to 50 mm or more in diameter and which are formed from frozen raindrops. Hailstones have a concentric layered structure usually alternating between clear and opaque ice.
Ice crystal	(diamond dust, ice needles, frost snow, snow mist) Precipitation in the form of slowly falling, very small ($\approx 30\ \mu m$) unbranched ice crystals in the form of needles, columns, or plates. Ice crystals do not reduce visibility, can be seen only in sunlight or an artificial light beam, and may precipitate from clouds or clear air.
Glaze	A dense, hard, transparent coating of ice formed on exposed objects by the freezing of supercooled rain or drizzle.
Rime	A white opaque granular deposit of ice formed by the rapid freezing of supercooled water drops as they impinge on an object. Rime is considerably less dense than glaze.
Hoarfrost	A light feathery deposit of ice consisting of interlocking ice crystals directly sublimed from water vapor onto a cold surface.

8-2.1 PROPERTIES OF SNOW

Snow has the lowest density of the various forms of deposited ice because, in the process of formation by sublimation from atmospheric water vapor, an open crystalline structure forms. After these crystals, usually in agglomerated masses or snowflakes, reach the surface of the earth, various processes increase the density of the snowpack and tend to form a solid, amorphous mass with the density of vitreous ice.

The characteristics of snow are conveniently separated into those of the precipitant and those of the deposited solid. The former is of import because, in many regions, it is the only snow encountered since the temperature is such that the snow rapidly melts. In the other extreme, snow is a permanent feature of the environment and its diverse physical properties are of interest.

8-2.1.1 PRECIPITANT SNOW

When ice crystals form in the free air through sublimation processes, they do so in a great variety of geometric shapes—all collectively called snow. These forms, falling as single or aggregated crystals (flakes), have been classified into seven basic types (Ref. 3):

(1) *Plates.* Thin, hexagonal plate, often with internal structure due to air inclusions

(2) *Stellar.* Thin, star-shaped snow crystal, generally with six arms; sometimes doubled, with two crystals connected by a short column.

(3) *Column.* Short, prismatic crystal, solid or hollow, often joined in various combinations.

(4) *Needle.* Very slender, needlelike snow particles, approximately cylindrical. Needles may combine in hollow bundles of parallel needles or other combinations.

(5) *Spatial dendrite.* Complex snow crystal, with fernlike arms that lie neither in a plane nor in parallel planes. It is roughly spherical but should not be confused with graupel, which has either a slight or no evidence of crystalline shape.

(6) *Capped column.* Column-type particle with hexagonal plates or stellar crystals at either end capping the column. Often additional plates occur at intermediate positions, but all intermediate and capping particles are arranged normal to the principal axis of the column.

(7) *Irregular crystal.* Snow particle made up of a number of crystals grown together in a random fashion. Often the component crystals can be seen only with magnification.

All natural snowflakes do not have the familiar and beautiful symmetries depicted in many publications. More often, snowflakes are broken, entangled, or rimed agglomerates resulting from growth accidents and their life cycles in the atmosphere. The small, ideal crystals present a great variety of forms which have been photographed extensively. Each of the simpler forms is related not only to the environment in which the crystal grew, primarily temperature and degree of supersaturation of the water vapor, but also to any contaminants present. Mixed forms represent crystals for which conditions changed during growth (Refs. 4, 5).

The size of the individual snow crystals varies considerably with form. Stellar crystals, for example, have an average diameter of 2.3 mm and average thickness of 0.08 mm but the diameter can be as large as 6 mm or as small as 0.12 mm. Columnar crystals, on the other hand, are typically 0.23 X 0.12 mm, and needles, 0.72 X 0.7 mm (Ref. 6). Aggregates of snow crystals, usually found at temperatures near the freezing point, are sometimes massive. In a given snowfall, average diameters of 3 cm have been reported with maximum diameters of 6 cm. In the other extreme, wind may break snow crystals into small fragments or, alternatively, evaporation while falling may reduce dimensions to a very fine snow dust. In a cold, blown snow, the grains typically fall in the 0.1- to 1-mm-diameter range (Ref. 7).

The average mass of a single snowflake in a snowstorm has been given as 3.1 mg, while the smallest particles, snow dust, weigh approximately 0.1 mg each. Larger agglomerated snowflakes may weigh as much as 0.8 g (Ref. 6).

Snowflakes fall with speeds up to 250 cm s^{-1} with the speed increasing with weight. Average speeds of 50 to 100 cm s^{-1} typify most snowstorms.

Rates of snowfall are given in terms of millimeters of water per unit time. Observations on one group of 15 snowstorms revealed rates from 0.3 to 2.88 mm water hr^{-1} (Ref. 8).

8-2.1.2 DEPOSITED SNOW

Soon after snow is deposited on a surface, it begins to lose the characteristic crystalline structure of the precipitant. Dependent on the temperature, this may be due to melting or to dry metamorphic (structure changing) processes. Even with subfreezing temperatures, the dry metamorphosis proceeds through a quasi-liquid surface layer on the snow crystal which facilitates molecular transport. Contacting snow grains can be fused or sintered by this process, thereby increasing the compressive strength of the fallen snow. Some of the various types of metamorphic transitions and their products are described in Table 8-2.

Deposited snow does not necessarily remain deposited. When falling snow is accompanied by wind or when wind blows over a surface of uncohesive snow crystals or grains, drifting can occur. The windspeed required for the onset of this wind-propelled or entrained movement is determined by the nature of the snow. With unidirectional windflow and a large volume of uncohesive snow available, high drifts may form wherever obstructions cause a change in windspeed or direction. In the extremely cold zones where the annual snowfall may be less than 2 ft, 8- to 20-ft drifts may accumulate at obstructions. In those regions where intermittent warm spells occur, drifts are rapidly stabilized and densified.

On level terrain with few obstructions, the drift pattern takes the form of concentric waves or V-shaped ridges, with the apex pointing into the prevailing wind as shown in Fig. 8-1. The angle of the legs of the "V" is indicative of the fluctuations in direction of dominant windflow. Another wind-produced feature is the choppy, wavelike feature called "sastruga", produced by etching and erosion as shown in Fig. 8-2.

The mechanisms of snow transport have been classified as creep, saltation, and turbulent diffusion (Ref. 9) and are similar to those for sand (Ref. 10). Creep describes movement in which the snow particles are in virtually continuous contact with the surface, seldom rising over 2 mm. Saltation refers to particle transport by leaping or bounding along the surface in a cycloidal-like trajectory. Saltation requires windspeeds of at least 15 to 30 km hr^{-1} and heights of as much as 100 cm are possible. Typically, in saltatory drifting, 90 percent of the mass of the snow is less than 25 cm above the surface. Turbulent diffusion, the third mechanism of snowdrifting, is most common during a snowstorm when snow on the ground is picked up by the turbulent air and held suspended by vertical mixing. Light, dry, and usually cold snow can continue to drift for several days after a new snowfall if the temperature remains low and windspeeds of above approximately 20 km hr^{-1} persist. Turbulent diffusion is the cause of most of the large drifts that disrupt transportation.

The physical properties of the snow cover are highly variable but are important since snow is often the characteristic and, at times, the only solid material in the operational environment. The properties of fallen snow have been studied extensively (Refs. 6, 11). The discussion of physical properties is separated into mechanical, thermodynamic,

TABLE 8-2

METAMORPHIC PROCESSES IN DEPOSITED SNOW

Type	Product	Description
Destructive	Powder snow (firn)	Sublimational growth on the snow surface as well as melting and freezing which leads to the formation of crystalline, rounded grains of snow, 0.5 to 1.0 mm in diameter and with a density of 0.15 to 0.25 g cm^{-3}. Powder snow forms a hard, bonded matrix under the load of succeeding snowfalls. Original crystal shapes are almost completely lost.
Constructive	Depth hoar	Subsurface sublimation growth of new and larger ice crystal forms, 2 to 15 mm or larger in dimensions with distinct structure often causing air pockets and a weak snow structure. Prismatic and hollow hexagon cups are common forms. Depth hoar snow has low strength and high viscosity often resulting in avalanches.
Melt	Spring snow (corn snow)	Coalescence of snow grains in presence of water to form larger, polycrystalline grains, 3 mm or larger. This coarse snow has a density of 0.3 to 0.5 g cm^{-3} and when bonded by frozen water films has a very high strength. Usually consists of coarse distinct grains, increasing in size with successive melt-freeze cycles.
Pressure	Snow concrete	Mechanical deformation of the structure of fallen snow through successive large loads in regions where the annual snowfall is not removed by summer melting. This causes a density approaching that of pure, solid ice, i.e., greater than 0.83 g cm^{-3}.

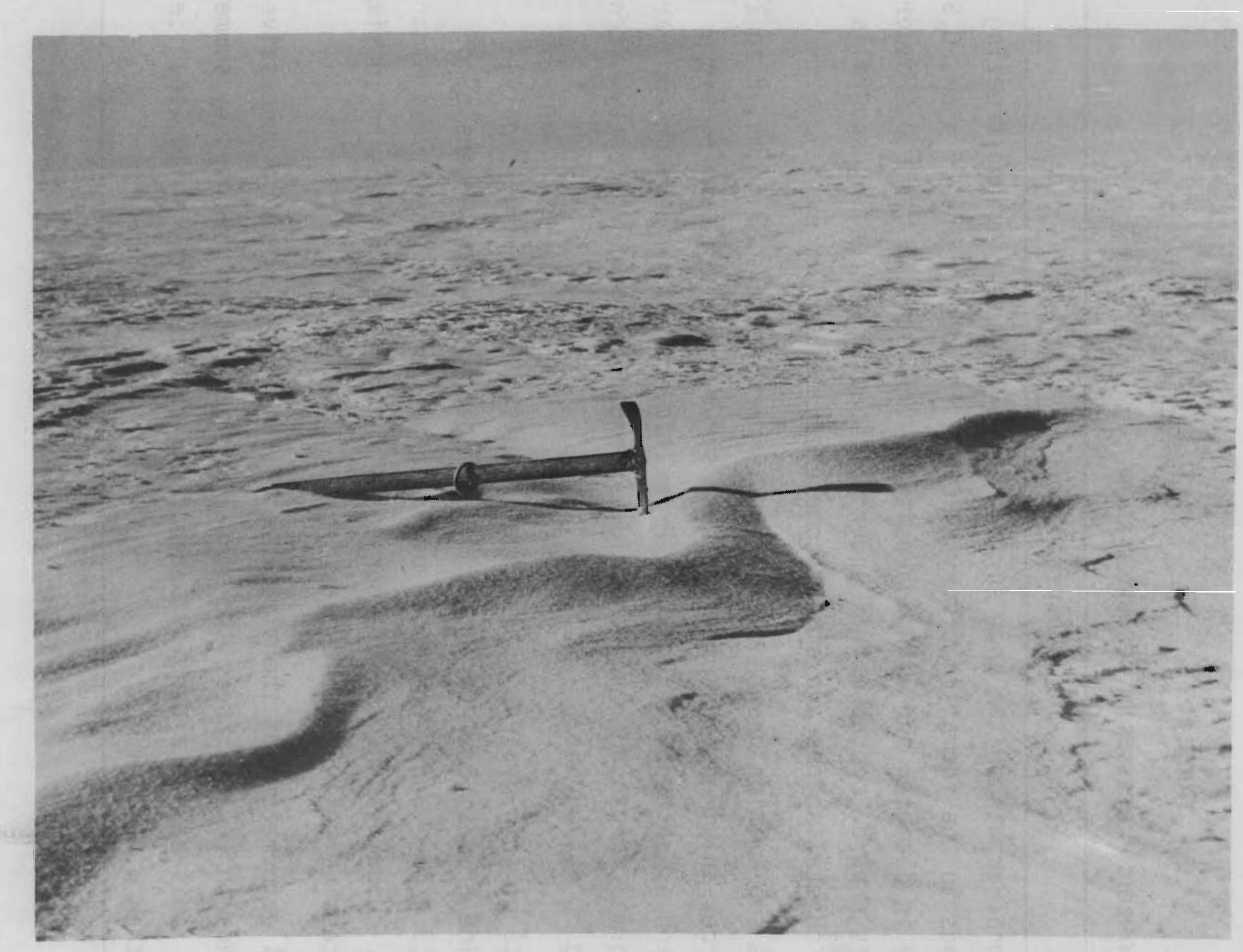

Figure 8-1. A Snow Wave (This is the characteristic drift pattern of cold, cohesionless snow. The wind direction is from the lower right.) (Photograph by R. L. Schuster)

and electromagnetic paragraphs.

8-2.1.2.1 MECHANICAL PROPERTIES OF SNOW*

Mechanical properties of snow depend on grain size, age, temperature, load history, and other environmental factors. Data included in the discussion that follows usually apply to one unique set of values for these variables but may be presented as a function of one variable. While the data are representative, care must be taken not to misapply them.

(1) *Density*. The density of fallen snow is the most useful single indicator of snow properties since density correlates well with many other properties. Snow density ranges from 0.1 g cm^{-3} or less for newly fallen snow consisting of large fluffy flakes to 0.83 g cm^{-3} for compacted snow. At higher densities, the compacted snow is classified as ice since it has lost most of those properties such as

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*This paragraph is based on *Properties of Snow* by M. Mellor (Ref. 12) with supplemental references as indicated.

Figure 8-2. Erosional Surface Features of Snow Cover (These "sastrugi" or "snow anvils" are produced by wind erosion of hardened snow. Since the "anvil" always points into the wind, northern bush pilots use these snow features for navigation and landing information.) (Photograph by R. W. Gerdel)

permeability that identify it as snow; pure ice has a density of 0.917 g cm^{-3}. Density, in all cases, is the mass of the snow divided by its volume, including pores or voids that are naturally present. Snow is more dense if it falls early in the season, has been broken up by the wind, has aged, has been exposed to relatively higher temperatures, or is deeper in the snowpack.

In Tables 8-3 through 8-6 typical density values and ranges are given for correlative variables associated with fallen snow (Ref. 6). In most cases, the tabulated data apply to fresh snow. Snow that has undergone metamorphic transition under pressure has a

TABLE 8-3

SNOW DENSITY CLASSIFICATIONS (Ref. 6)

Initial snow type	Density, g·cm^{-3}
Very loose	0.01-0.10
Loose	0.10-0.25
Medium	0.25-0.35
Dense	0.35-0.45
Very dense	Over 0.45

TABLE 8-4

DENSITY-TEMPERATURE VARIATIONS (Ref. 6)

(FOR NEWLY FALLEN SNOW)

Mean daily air temperature, °C	Density, g cm^{-3}
Below -10	0.01-0.23
-10 to -5	0.01-0.29
- 5 to -2	0.03-0.25
- 2 to 0	0.04-0.45
0 to +2	0.07-0.53
Above +2	0.16-0.59

TABLE 8-5

DENSITY-WIND VELOCITY VARIATIONS (Ref. 6)

(FOR NEWLY FALLEN SNOW)

Wind conditions during snowfall	Density, g cm^{-3}
Calm	0.04-0.07
Light breeze	0.04-0.13
Medium	0.12-0.18
Strong wind	0.15-0.22
Full gale	0.30-0.39

density approaching 0.83 g cm^{-3} and, dependent on the pressure and time since deposition, a full range of densities from those tabulated to this upper limiting value may be observed. In Table 8-3, density variation with depth in the snowpack is given.

(2) *Porosity and voids.* All deposited snow contains pores, and often voids, which cause its density to be less than that of ice. For newly fallen snow, porosity is determined by the nature of the snowflakes and the conditions during deposition. For established snowpacks, the pore distribution and larger voids are determined by metamorphic changes (particularly melting due to high ground temperature) or by solar radiation through translucent surface layers.

TABLE 8-6

DEPENDENCE OF DENSITY ON TYPE OF SNOW COVER

Type of snow cover	Density, g cm^{-3}		
	Min	Max	Usual range
Dry new snow	0.05	0.11	0.07-0.10
Dry settling snow	0.09	0.22	0.10-0.20
Wet settling snow	0.10	0.24	0.15-0.20
Dry settled snow	0.20	0.43	0.25-0.35
Loose, granular snow	0.11	0.30	0.18-0.28
Dry old snow	0.20	0.53	0.25-0.45
Wet old snow	0.28	0.52	0.35-0.45

Porosity n is defined as the ratio of pore volume V_p to total volume V_T or alternatively as the ratio of the difference between ice density ($\rho_i = 0.917$ g cm^{-3}) and snow density (ρ_s) to ice density.

$$n = \frac{V_p}{V_T} = \frac{\rho_i - \rho_s}{\rho_i} = 1 - 1.09\,\rho_s \qquad (8\text{-}1)$$

where

V_p = pore volume, cm^3
V_T = total volume, cm^3
ρ_i = ice density, g cm^{-3}
ρ_s = snow density, g cm^{-3}

Another parameter, void ratio r, is defined as the ratio of the void volume V_v to the snow volume ($V_T - V_v$).

Pores, defined as minute openings, are determined by the structure of the snow crystal or grain; the pore volume cannot be directly measured. For the measured porosity to have meaning, the snow sample must be homogeneous and free of larger voids. Voids, usually referring to larger openings in the snowpack, are formed by gross metamorphic processes.

Porous, low density snow thus has a porosity approaching 1. If the snow density approaches that of ice, the porosity is near zero. An actual lower limit for snow is 0.093. Values of r range from 90 to 0.1 as snow densities range from 0.01 to 0.83 g cm^{-3}.

(3) *Permeability.** The property of a material that allows another substance to pass through its pores or interstices under the influence of a pressure gradient is permeability. For snow, permeability is closely related to porosity and density and may refer to the flow of either a liquid or a gas through a solid snow barrier. This discussion is limited to air permeability, which is of interest as a possible basis for classification of snow types as well as for the practical importance of ventilation of under-snow installations.

Permeability of a substance is characterized by a permeability coefficient K, which is the proportionality constant expressed by the following equation:

$$Q = KAL^{-1}\,\Delta P,\ \text{cm}^3\ \text{s}^{-1} \qquad (8\text{-}2)$$

where

Q = volumetric airflow, cm^3 s^{-1}
A = cross-sectional area, cm^2
ΔP = differential pressure across the sample, cm of H_2O
L = sample length in direction of flow, cm
K = permeability coefficient, cm s^{-1}

Thus, K, the permeability coefficient, is the airflow speed in cm s^{-1} for a pressure gradient of 1 cm of water per cm of snow.

Permeability values for snow range from 0 to 350 cm s^{-1}; the higher value characterizes a large-grained new snow, and the zero value is the limiting value for impermeable snow or ice. Representative measured values are given in Table 8-7 and variations with depth are shown in Table 8-8.

The permeability of snow is evidenced by the ability of reindeer to smell moss, their chief food during winter, through snow 1 m or more in depth and also by the ability of carnivores to find mice beneath deep snow. Tracer gases released in a snowpack have demonstrated lateral gas speeds up to 10 m min^{-1} with no detectable release of the gas at the surface (Ref. 6).

(4) *Hardness.* For snow, hardness is a measure of its resistance to penetration by a solid object. It is dependent on the cohesive bonding between snow grains, which is a macroscopic function of the density of the snow, on the nature of the crust, if any, and on the type and progress of metamorphic changes. Hardness is expressed in terms

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*A general reference for this paragraph is Ref. 13.

TABLE 8-7

AIR PERMEABILITIES FOR NATURAL SNOW (Ref. 12)

Description	Permeability, K, cm s^{-1}	Density, ρ, g cm^{-3}	Porosity, n
Subsurface (Greenland)	5-230	0.76-0.42	0.16-0.55
Subsurface (South Pole)	15-100	0.65-0.48	0.30-0.47
Subsurface (Greenland)	20-340	0.6 -0.35	0.34-0.61
Fresh (Antarctica)	15-100	0.52-0.33	0.43-0.62
"Last winter's" (Antarctica)	25-135	0.56-0.43	0.40-0.53
Coarse grained (diameter > 1.2 mm)	15-340	0.6 -0.36	0.35-0.60
Top 4 m (Greenland)	40-240	0.48-0.37	0.49-0.60
Old	20-75	0.49-0.40	0.45-0.57
Granular	10-25	0.49-0.39	0.45-0.58
Naturally compacted	40-100	0.40-0.27	0.56-0.70
New	35-270	0.21-0.11	0.78-0.87
New	100-340	0.12-0.09	0.86-0.90

TABLE 8-8

PERMEABILITY AND DENSITY VARIATION WITH DEPTH (Ref. 14)

(IN THE GREENLAND SNOWPACK)

Depth, m	Density, g cm^{-3}	Permeability, cm s^{-1}
0	0.34	150
5	0.46	100
10	0.53	70
15	0.57	60
20	0.60	50
25	0.62	40
30	0.64	30

TABLE 8-9

HARDNESS OF SNOW

Type of snow cover	Hardness, g cm^{-2}		
	Min	Max	Mean range
Dry new	0.5	20	1- 10
Dry settling	5.0	200	10- 100
Wet settling	20.0	100	20- 100
Dry settled	25.0	8000	100- 6000
Loose granular	15.0	200	20- 100
Dry old	50.0	20000	100-20000
Wet old	20.0	500	50- 500

defined by the method by which it is measured. Most common is the index based on the pressure necessary to force a disc into the snow. An alternative hardness index, referred to as the ram hardness number, is based on the force required to drive a cone-tipped rod into the snow, using an instrument called the Swiss rammsonde. Ram hardness numbers are relative measures only.

Table 8-9 gives values of hardness for different types of snow in terms of the force per unit area required to force a disc into the snow. It has been found that, as snow cover density increases from 0.15 to 0.4 g cm^{-3}, the hardness increases from 20 g cm^{-2} to 50,000 g cm^{-2}, over four orders of magnitude. During the seasonal development of a snow cover, the hardness may increase, decrease, or remain the same, dependent on the climatic conditions. Under pressure, the hardness of snow increases with time at a rate that is temperature dependent. For a given snow cover, the hardness increases as the temperature decreases.

(5) *Grain size.* The initial grain size is that of the precipitant, but after deposition, grain growth normally occurs. The exception is a cold dry snowpack that is subjected to drifting; the churning action can reduce the grain size. The metamorphic processes contributing to grain growth are described in Table 8-2. Actual measurements are reported here.

Sizing of snow grains is accomplished with sieves; size distributions are reported in terms of the size of the sieve opening. Examples are shown in Fig. 8-3 for fresh snow and in Fig. 8-4 for old snow that had been milled by a snowplow. The increase in grain size of the milled snow during the first year is attributed to an increase in small grains during the disaggregation process employed in sieve analysis. Similar measurements on Alpine snows gave a median grain size of approximately 0.8 mm for new snow; the size increased to 1.3 mm in 96 days and to 2.0 mm in 118 days.

These data are for specific snow samples that are products of their specific environments. The progressive metamorphic growth of grains can proceed to depth hoar crystals with sizes as large as 15 mm. Competing with the increase in grain size is the trend toward formation of a continuous ice sheet. The old

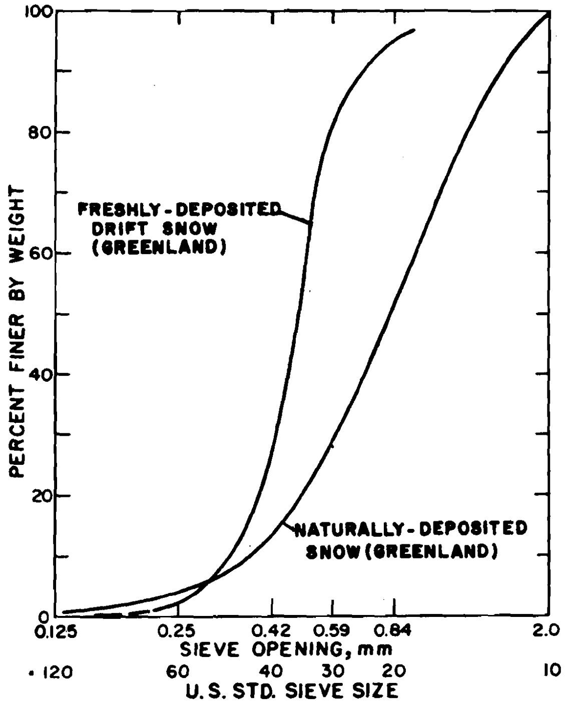
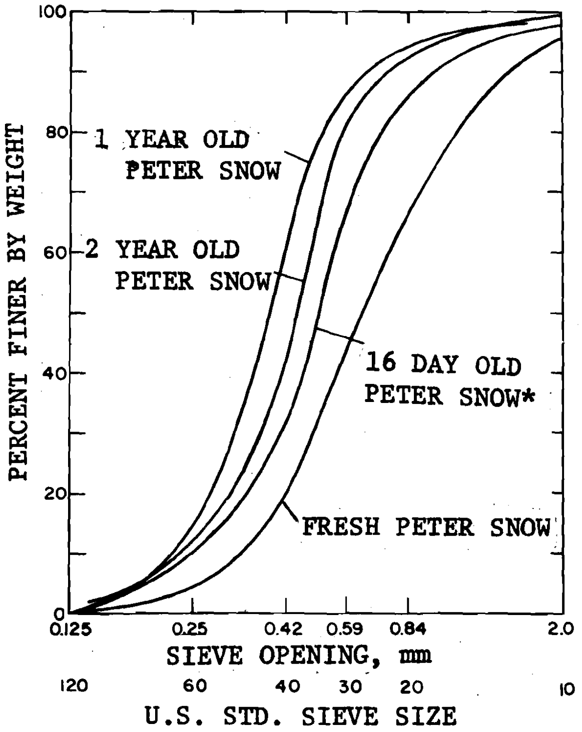


Figure 8-3. Grading Curves for Freshly Deposited and Subsurface Snows (Ref. 14)



***Ref. par. 8-2.1.2.1 (7) for information on "Peter snow"**

Figure 8-4. Grading Curves for Milled Snow (Ref. 14)

snow (sometimes called firn) eventually becomes glacier ice (Ref. 6).

(6) *Elastic properties.* The elastic properties of snow apply when small transient loads are applied to the snow by feet, skis, impacts, or explosions. They are also of import when small amplitude vibrations such as seismic or acoustic waves are applied. Elastic behavior results only when the strain is small enough so that the structure of the snow is not disrupted; otherwise, the strain exceeds the "ultimate strength" of the snow and it fails. Since snow is a viscoelastic material, the loading rate must be higher than some minimum value to observe elastic behavior. Butkovitch (Ref. 15) recommends 0.5 kg cm^{-2} s^{-1} for this minimum value although Mellor (Ref. 12) recommends twice this minimum for testing.

Young's modulus, which is the spring constant or the ratio of stress to strain for linear elongation, and Poisson's ratio, which is the ratio of transverse contraction to the concomitant elongation, are the common descriptors of elastic properties. Metals, for example, have Young's moduli from 10^{11} to 1.5×10^{12} dyn cm^{-2} and Poisson's ratios on the order of 0.3. The velocity of propagation of an elastic compression wave is closely related to these elastic properties. The values for dry snow given in Fig. 8-5 as a function of density represent a composite of measurements reported by Mellor. The data on Young's modulus were obtained for age-hardened snow for which there is a small spread in the available data. The Poisson's ratio was determined primarily by seismic tests on undisturbed snow. Below a density of 0.6 g cm^{-3}, the data showed considerable scatter, probably resulting from the measurement technique as well as the structural variations in less dense snow (Ref. 12).

(7) *Strength.* Snow can exhibit

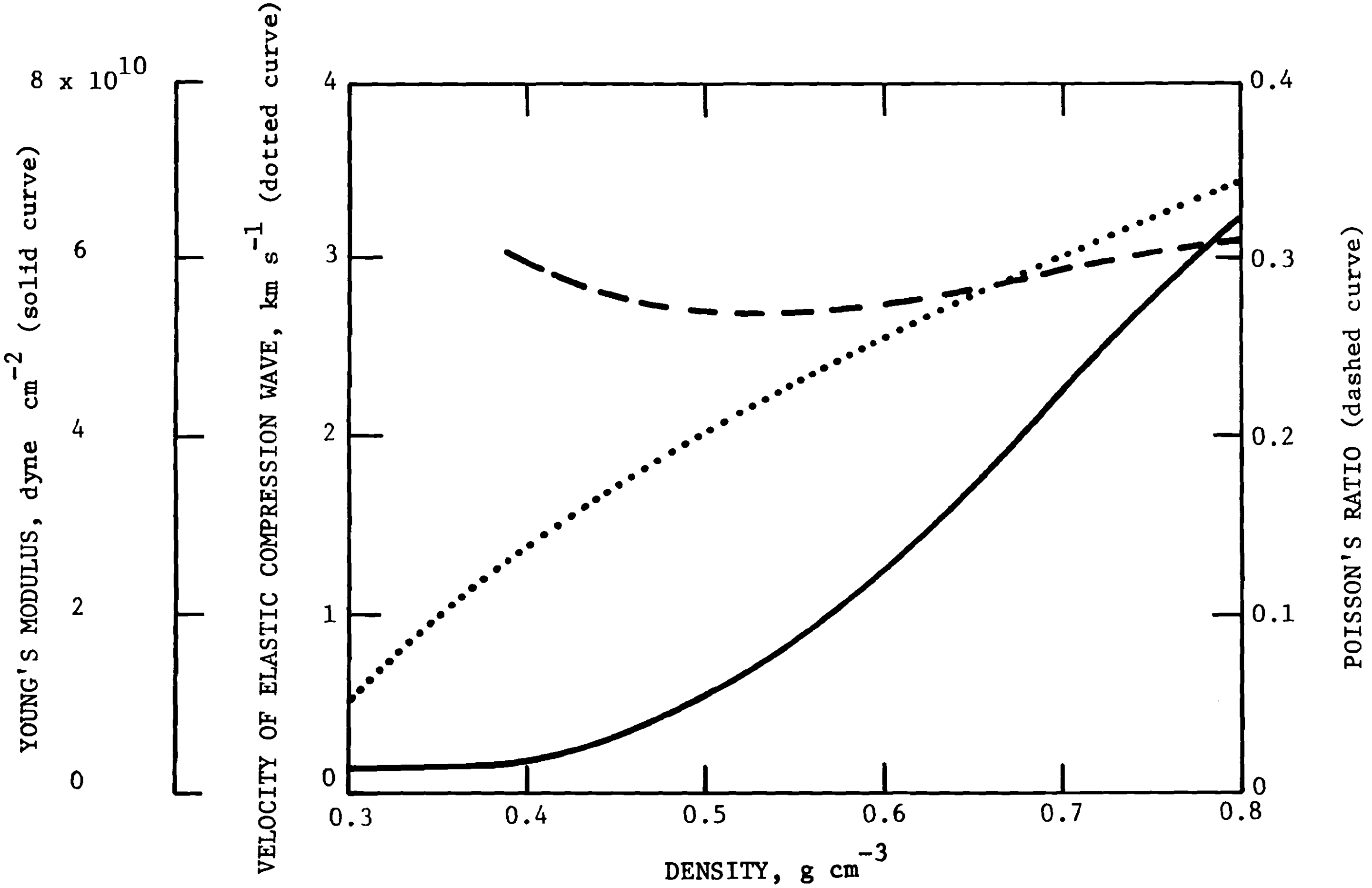


Figure 8-5. Dynamic Elastic Properties of Dry Snow

considerable mechanical strength under the proper conditions. For example, it may be used in construction of roads and shelters. This applies only in those regions of the world having sustained subfreezing temperatures and requires high density snow with much intergranular bond growth. Most often, aged snow is used. Before being used it is disaggregated with a Peter snow miller (a type of rotary snowplow), which produces relatively uniform fine particles. When employed as road filling or as structural elements, this type of snow is usually referred to as "Peter snow" and exhibits relatively predictable behavior. Other rotary snowplows may be used to disaggregate snow for construction, the resultant snow usually being described in terms of the particular equipment used since the resultant grain size and subsequent properties may differ.

Snow exhibits a spectrum of behavior under load, dependent on the nature of the load. Elastic behavior that is characteristic of small, transient loads and creep that is characteristic of sustained loads that are less than the failure strength are discussed subsequently. The ability of snow to sustain a load without immediate failure is referred to as the strength and is discussed in the paragraphs that follow.

With snow, as with other materials, strength can be described in many ways corresponding to the nature of the load and other conditions. For snow, the unconfined compressive strength, the tensile strength, and the shear strength are of prime importance.

Below a density of 0.4 g cm^{-3}, snow has little strength, the strength being principally dependent on grain structure and texture rather than density. Above 0.55 g cm^{-3}, the strength depends primarily on density so it is quite high because of the close packing of the grains and the many bonds between them. The 0.55 g cm^{-3} density is achievable with a well-milled snow, such as Peter snow. Under some conditions, a snow layer may change into the loosely bonded, coarse-grained aggregate known as depth hoar, which exhibits low strength in unconfined uniaxial loading.

The unconfined compressive strength of snow is measured by placing a cylindrical specimen in a press and compressing it to failure while controlling either the strain rate or the loading rate. The results are typically plotted against density, as in Fig. 8-6. However, the spread in the data shown, as well as in other data, indicates that uncontrolled variations result in a wide spread in the results obtained (Ref. 12). Generally, milled snow shows unconfined compressive strengths from 2 to 15 kg cm^{-2} for densities between 0.48 and 0.64 g cm^{-3} when the snow is 3 weeks or less in age. Older natural snows, giving data as in Fig. 8-6, have strengths extending above 30 kg cm^{-2}.

Tensile strength of snow—measured on cylinders, rings, and beams—shows wide dispersion in the data. Below snow densities of 0.42 g cm^{-3}, tensile strength does not exceed 1.2 kg cm^{-2}. At higher densities, tensile strength may be as high as 18 kg cm^{-2} and is a function of temperature, sometimes increasing as rapidly as the temperature decreases. Representative data are shown in Fig. 8-7.

Shear strength has been measured with a variety of apparatus. The resultant data are related primarily to the density of the specimen. Typically, for unconfined double shear, the strength increases from less than 1 to over 15 kg cm^{-2} as the sample density goes from 0.4 to 0.8 g cm^{-3}. Similar strengths are found for unconfined shear measurements as well as specimen under pressure. Torsional shear values do not exceed 8 kg cm^{-2}. All of these data were given by Butkovitch (Ref. 15) as reported by Mellor (Ref. 12).

(8) *Creep.* As noted in par. (7), after the initial transients a sustained constant stress tends to cause a continued strain or creep. This creep may continue for long periods if the stress is small but, if it is large, the cumulative strain will result in either densification of the snow and reduced creep or accelerated creep and collapse of the snow. For practical purposes, persistent creep under

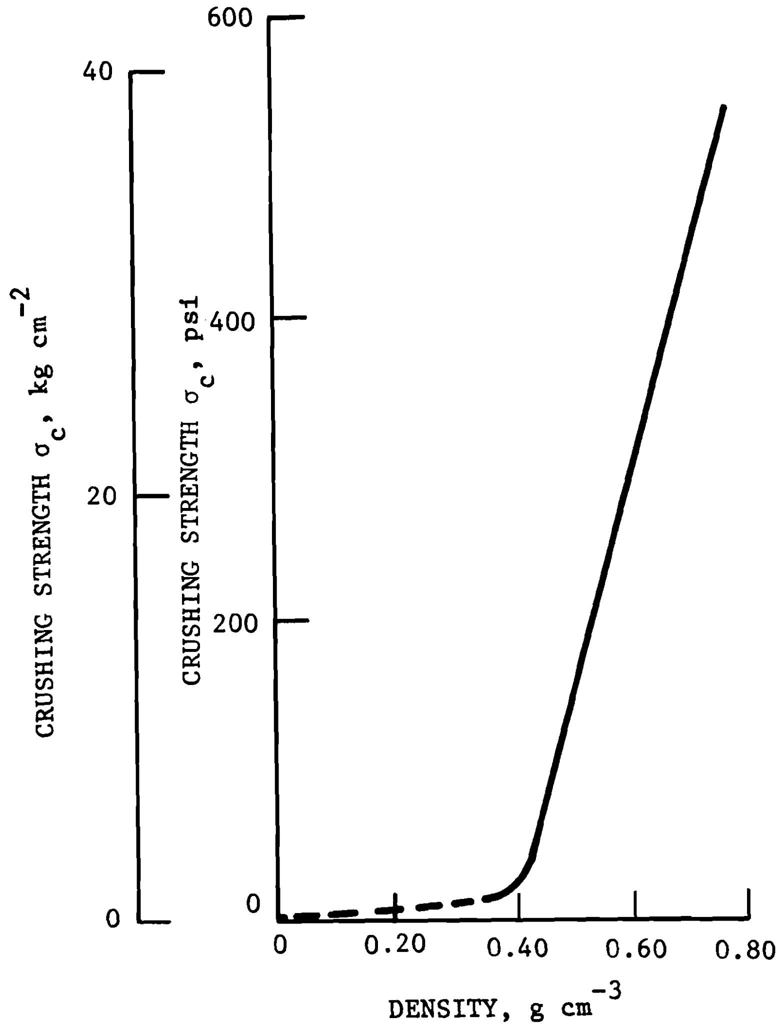


Figure 8-6. Unconfined Compressive Strength of Snow (Ref. 15) (Data, obtained in Greenland and adjusted to −10°C, represent a variety of data.)

relatively low stresses is of greatest interest.

Creep or strain in snow varies with time according to a power function of the form

$$\epsilon = \epsilon_0 + bt^n \text{, percent} \qquad (8\text{-}3)$$

where

ϵ = strain, percent
ϵ_0 = initial strain, percent
t = time, s
b and n = constants descriptive of the snow type and the method by which the stress is applied

The strain rate $\dot{\epsilon}$ thus takes the form

$$\dot{\epsilon} = nbt^{\,n-1} \text{, percent s}^{-1} \qquad (8\text{-}4)$$

In the usual case, the nonlinear initial strain behavior is ignored and $\dot{\epsilon}$ is a constant with respect to time, i.e., $\dot{\epsilon} = b$ for $n = 1$.

The load or stress dependence of strain rate is nonlinear for snow and is represented by a hyperbolic equation

$$\epsilon = \frac{\sigma_0}{\eta} \sinh\left(\frac{\sigma}{\sigma_0}\right) \text{, percent s}^{-1} \qquad (8\text{-}5)$$

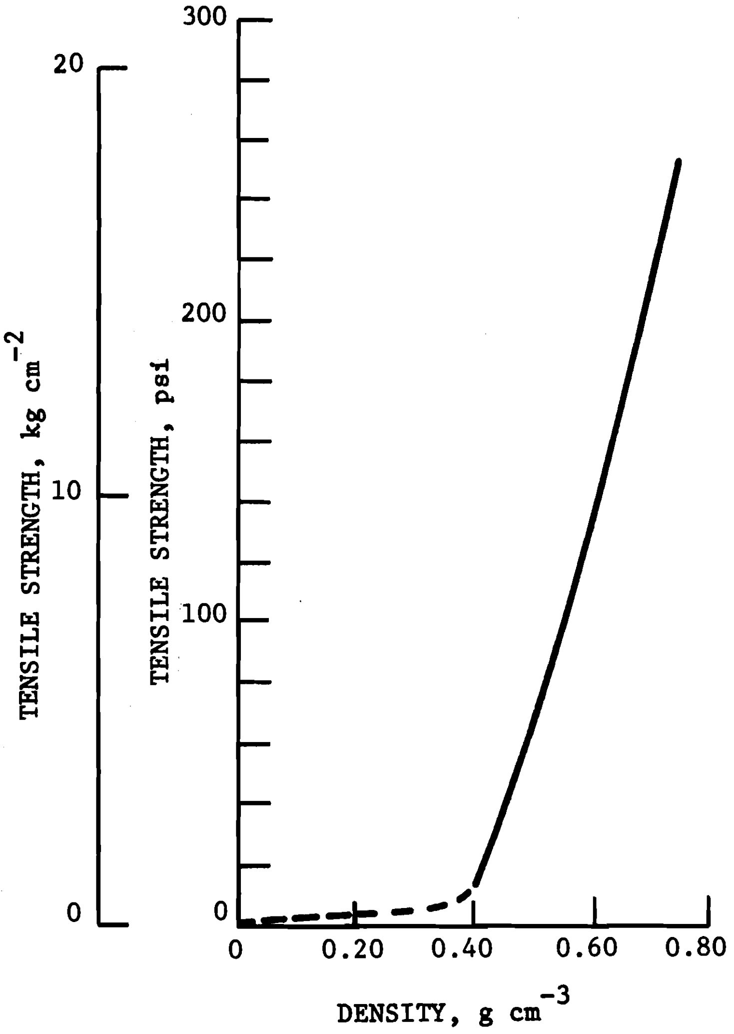


Figure 8-7. Tensile Strength of Snow (Ref. 15) (Test Temperature −10°C)

where

σ = the stress, g cm^{-2}

σ_0 = normalizing constant, g cm^{-2}

η = a viscosity coefficient, g cm^{-2} s

If $\sigma \leqslant 0.8\sigma_0$, then $\sinh\left(\frac{\sigma}{\sigma_0}\right) \approx \left(\frac{\sigma}{\sigma_0}\right)$ and

$$\dot{\epsilon} \approx \frac{\sigma}{\eta}, \text{percent s}^{-1} \qquad (8\text{-}6)$$

which is the behavior of a Newtonian viscous solid. Data indicate that Eq. 8-6 applies for stresses up to 550 g cm^{-2} ($\approx$ 8 psi) (Ref. 12). Large area structural footings can be designed close to these limits. The strain equation for these low stress conditions thus becomes

$$\epsilon = \epsilon_0 + \frac{\sigma}{\eta} t, \text{percent} \qquad (8\text{-}7)$$

allowing experimental determination of the coefficient of viscosity under known stresses.

Most observations of creep have employed compressive stresses, and the data are reported as a coefficient of compressive viscosity. This coefficient depends on the size, shape, and gradation of grains and on the bonds between grains. This is normally expressed as a function of snow density. Representative data on the compressive

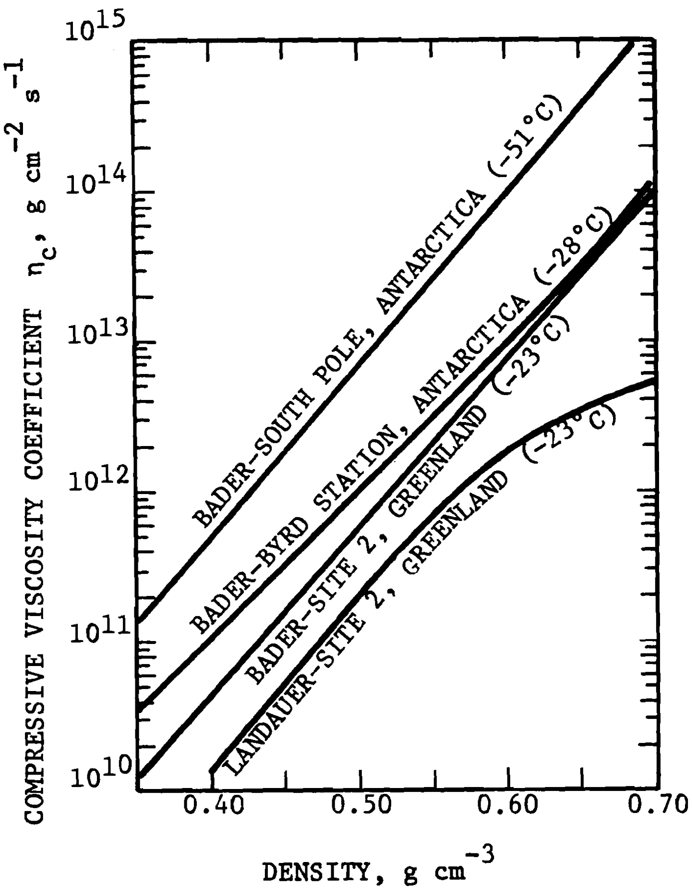


Figure 8-8. Compressive Viscosity of Snow (Refs. 11, 16)

viscosity coefficient are given in Fig. 8-8. Viscosity is temperature dependent; increasing with decreasing temperature. An activation process giving

$$\eta \propto \exp (A/T), \text{ g cm}^{-2} \text{ s}^{-1} \qquad (8\text{-}8)$$

where

A = constant, K^{-1}

T = absolute temperature, K

has been suggested to describe this temperature dependence.

(9) *Sliding friction and adhesion.* The common belief that snow provides a slippery surface is true only under certain conditions. Below −25°C, for example, loose snow is similar to dry sand in its reaction to a sliding object. At temperatures above freezing, the sliding resistance increases. The minimum coefficient of sliding friction is observed from −10° to 0°C.

The coefficient of sliding friction is the ratio of the force necessary to maintain a sliding object in motion to the normal gravitational force of the object on the surface. The coefficient of friction between snow and a solid slider varies with size, shape, bearing pressure, sliding speed, and temperature. Under conditions promoting easy sliding motion, the low coefficient of friction of snow is attributed to its self-lubricating property; i.e., the frictional heat generated by sliding causes a liquid film to form between the sliding object and the snow.

Resistance to sliding on snow is determined by factors other than the coefficient of sliding friction. The breakage of a crust, the move-

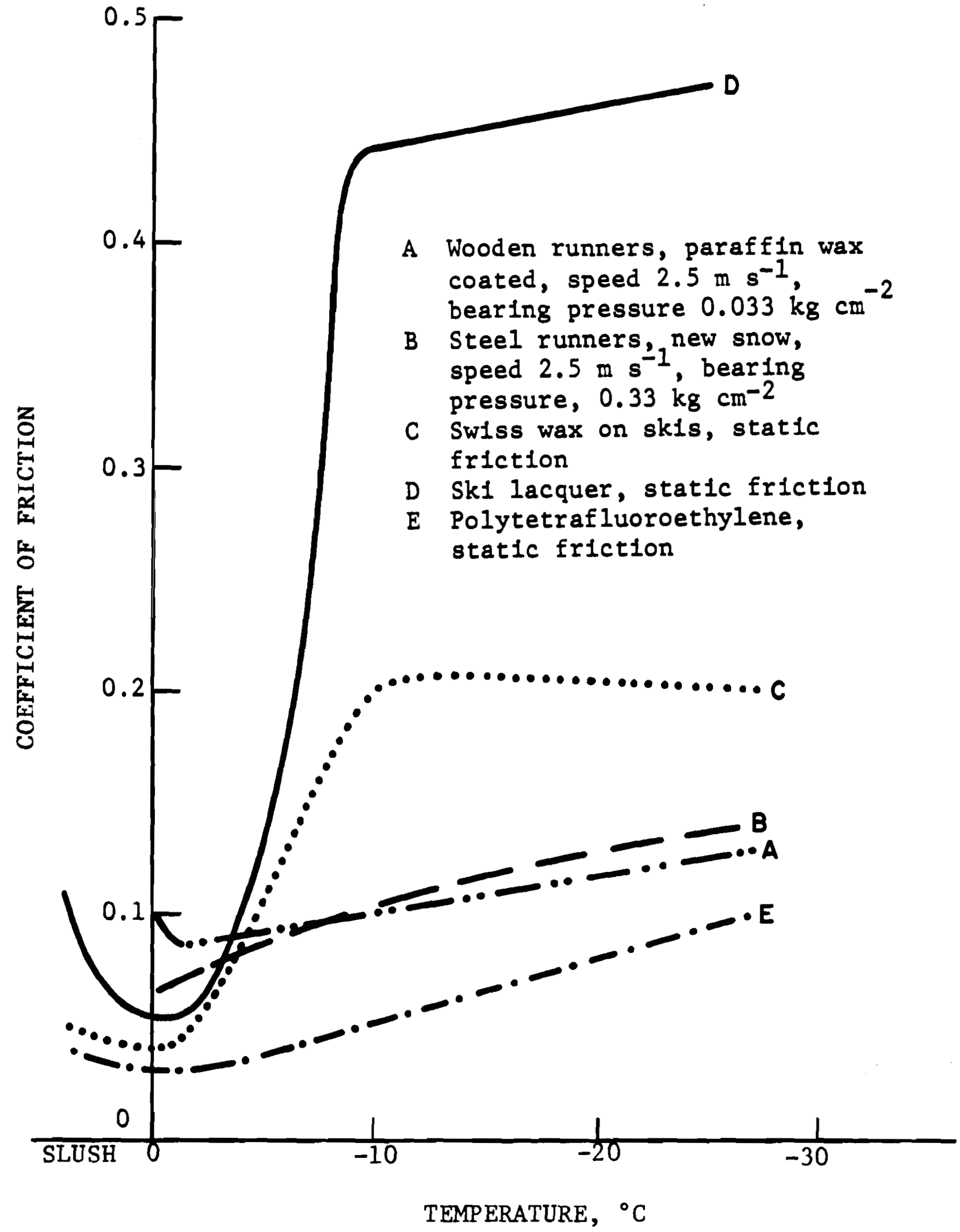


Figure 8-9. Coefficient of Friction on Snow (Ref. 12)

ment of snow in front of the slider, and the packing of the snow detract from the ease of motion. In dry, low density snow that is unable to sustain the slider load, mobility can be inhibited completely.

The coefficient of sliding friction for various materials on snow has been measured as a function of temperature under various conditions. Curves *A* and *B* of Fig. 8-9 show representative data. The coefficient of static friction—the ratio of the force required to initiate sliding to the normal gravitational force—is similarly presented in the other curves of Fig. 8-9. Although the polytetrafluororethylene curve *E* is an anomaly with its low coefficient of friction, curves *C* and *D* clearly show that static friction is higher than sliding friction. These data were compiled from various sources by Mellor (Ref. 12).

Static friction is the force necessary to restart a slider into motion immediately after it comes to rest. If the slider is left standing, the liquid film on the runner will freeze and considerable force may be required to free it.

8-2.1.2.2 THERMAL PROPERTIES OF SNOW*

Snow, as with most lightweight solids, is an excellent thermal insulator. It often prevents the ground and vegetation from freezing and can provide protection for men and animals from extreme cold. This low thermal conductivity is only one of the thermal properties of snow that are of practical importance. Other mechanisms of heat transport as well as the parameters of phase transition are equally important.

The thermal conductivity K is the ratio of the rate of heat flow $\dot{q}$ per unit area to the negative of the thermal gradient $\partial T/\partial x$ and it can be expressed by (Ref. 17)

$$K = -\dot{q}\left(\frac{\partial T}{\partial x}\right)^{-1}, \text{cal (cm s °C)}^{-1} \tag{8-9}$$

where

K = thermal conductivity, cal (cm s °C)$^{-1}$

$\dfrac{\partial T}{\partial x}$ = temperature gradient, °C cm^{-1}

$\dot{q}$ = rate of heat flow, cal (cm^2 s)$^{-1}$

A number of determinations of thermal conductivity have been made and are discussed by Mellor (Ref. 12). An envelope of these measurements is presented in Fig. 8-10 plotted against density†. The spread in the values probably results from variations in the granular structure of the snow.

For transient heat flow problems, the general equation is (Ref. 17)

$$\frac{\partial T}{\partial t} = \alpha\ \nabla^2 T \tag{8-10}$$

where

T = temperature, °C

t = time, s

α = thermal diffusivity, cm^2 s^{-1}

The thermal diffusivity is defined by

$$\alpha \equiv K/(\rho c_p), \text{cm}^2\ \text{s}^{-1} \tag{8-11}$$

where

ρ = snow density, g cm^{-3}

c_p = specific heat at constant pressure, cal (g °C)$^{-1}$

K = thermal conductivity, cal (cm s °C)$^{-1}$

Diffusivity may be calculated directly from thermal conductivity, density, and specific heat. The specific heat is usually taken as 0.50 cal (g °C)$^{-1}$ in practical problems, although it varies with the temperature and purity of the snow.

When a thermal gradient exists in the snowpack, heat may be transferred by processes other than thermal conduction. Vapor diffusion and forced convection are two such mechanisms. The former is described by the diffusion equation, which yields for one-dimensional vapor diffusion;

$$\dot{q} = -\beta D L_s \partial T/\partial x, \text{cal (cm}^2\ \text{s)}^{-1} \tag{8-12}$$

where

β = rate of change of vapor pressure of ice with temperature, 0.39×10^{-6} g (cm^3 °C)$^{-1}$

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*A general reference for this paragraph is Ref. 12.

†To convert from the units in Fig. 8-10, cal (cm s °C)$^{-1}$, to the international units, W (m K)$^{-1}$, divide by 41.868.

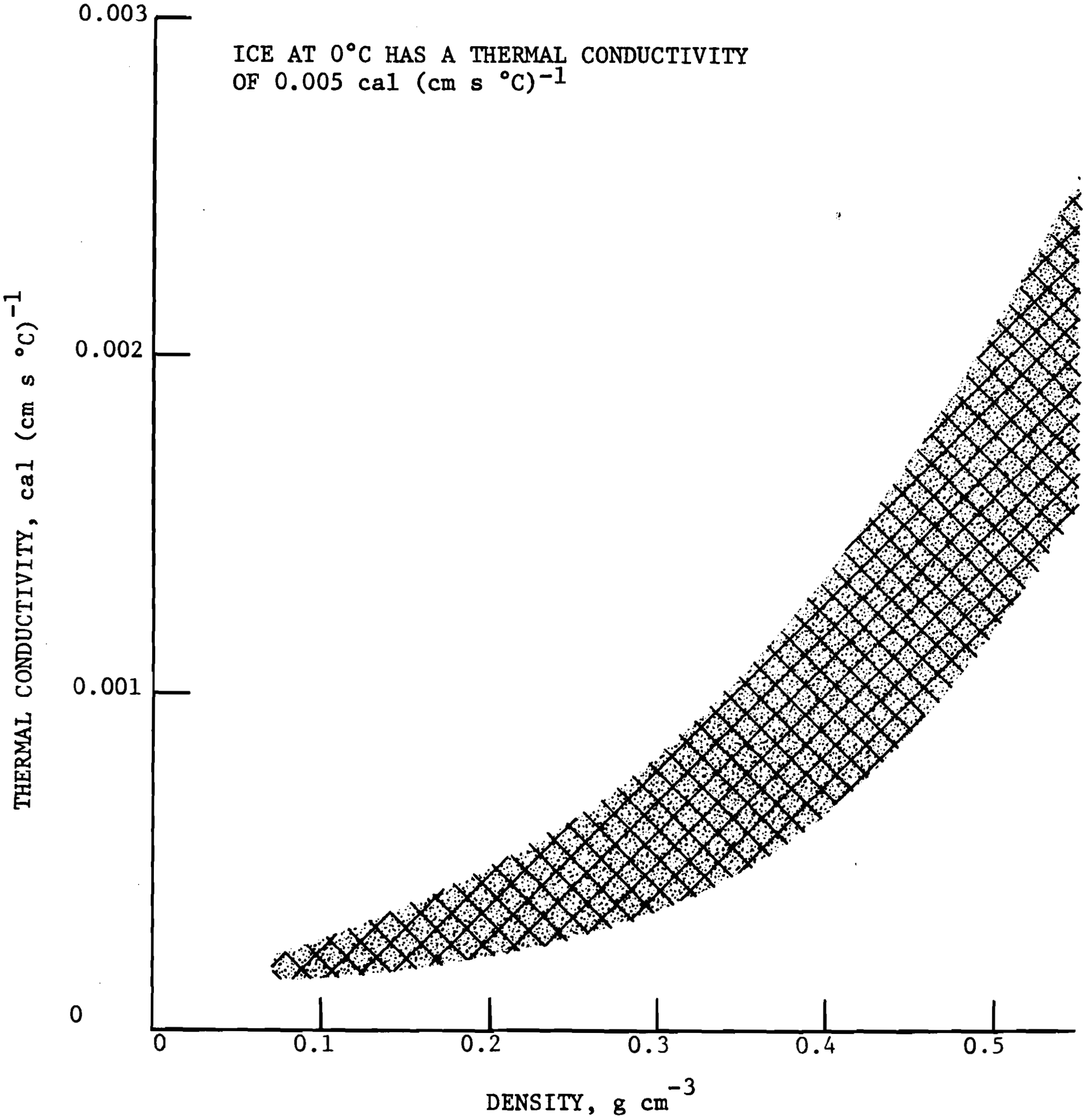

Figure 8-10. Thermal Conductivity of Dry Snow (Ref. 12)

D = diffusion constant, 0.85 cm^2 s^{-1}

L_s = latent heat of sublimation of ice, 677 cal g^{-1}

$\frac{\partial T}{\partial x}$ = thermal gradient, °C cm^{-1}

Substitution gives

$$\dot{q} = -2.2 \times 10^{-4}\ \partial T/\partial x, \text{cal (cm}^2\text{ s)}^{-1} \qquad (8\text{-}13)$$

Comparison with Eq. 8-9 shows that vapor diffusion contributes a small amount to the heat transfer processes in snow, except at very low snow densities.

Forced air and vapor convection can take place when undersnow structures are ventilated. Yen has considered this in terms of an equivalent thermal conductivity k_v, (Ref. 18),

$$\dot{q} = -k_v\ \partial T/\partial x, \text{cal (cm}^2\text{ s)}^{-1} \qquad (8\text{-}14)$$

where

$$k_v = 0.77 \times 10^{-4} + 0.314\,G - 89.4\,G^2 + 86.4\,G^3,\ \text{cal (cm s °C)}^{-1} \qquad (8\text{-}15)$$

G = mass flow rate per unit area for air through the snow, g (cm^2 s)$^{-1}$

For $G = 10^{-3}$ g (cm^2 s)$^{-1}$, the heat transfer due to forced convection is an appreciable portion of the total heat transfer and it rapidly becomes the dominant mechanism if the flow rate increases further.

The latent heat of fusion of snow is the same as that for ice particles, ranging from 79.4 to 79.8 cal g^{-1} at 0°C but decreasing with temperature (less energy is required to solidify supercooled water droplets). The latent heat of sublimation is greater, i.e., the sum of the latent heat of fusion and the latent heat of vaporization. This sum gives a value of 677.0 cal g^{-1} for the latent heat of sublimation at 0°C.

Thermal expansion is not a significant parameter for snow since it would be an integrated effect of the expansion of the individual grains. Grain expansion is compensated for by the rearrangement of the grains rather than by macroscopic dimensional changes.

The temperature at various levels in the permanent snowpack is dependent on the average surface temperature and, in fact, can be used to obtain estimates of the mean annual surface temperature. Daily temperature variations affect the temperature of only the top few centimeters of the snowpack.

8-2.1.2.3 ELECTRICAL PROPERTIES OF SNOW

The electrical properties of snow exhibit a wide variability due to variations in density, internal structure, chemical purity, temperature, and free water content. The available data indicate only the general nature of these electrical properties; the precise values of parameters cannot be predicted for a given snow sample. The dielectric and conductive parameters are of prime interest.

The dielectric constant* is the primary electrical descriptor for a poorly conducting material. It is the ratio of the electric field strength in a vacuum to that in the dielectric for the same distribution of charge. The dielectric constant ϵ may be defined and measured as the ratio of the capacitance C of an electrical condenser filled with the dielectric to the capacitance C_0 of the same condenser in a vacuum

$$\epsilon = C/C_0 \qquad (8\text{-}16)$$

The polarization of the dielectric by the applied electric field causes C to be larger than C_0.

When an alternating electric field is used, losses in the dielectric appear as heat. These losses can be described in terms of the angle δ between the phases of the loss current and the charging current, with the so-called loss tangent or dissipation factor defined as

$$\tan\delta = \frac{\text{loss current}}{\text{charging current}} = \frac{\epsilon''}{\epsilon'} \qquad (8\text{-}17)$$

where ϵ'' is the dielectric loss factor, also known as the imaginary part of the dielectric constant and ϵ' is the AC capacitivity. At frequencies where the polarization of the dielectric lags the applied electric field, the dielectric constant ϵ is expressed in a complex form,

$$\epsilon = \epsilon' - i\epsilon'' \qquad (8\text{-}18)$$

where $i = \sqrt{-1}$

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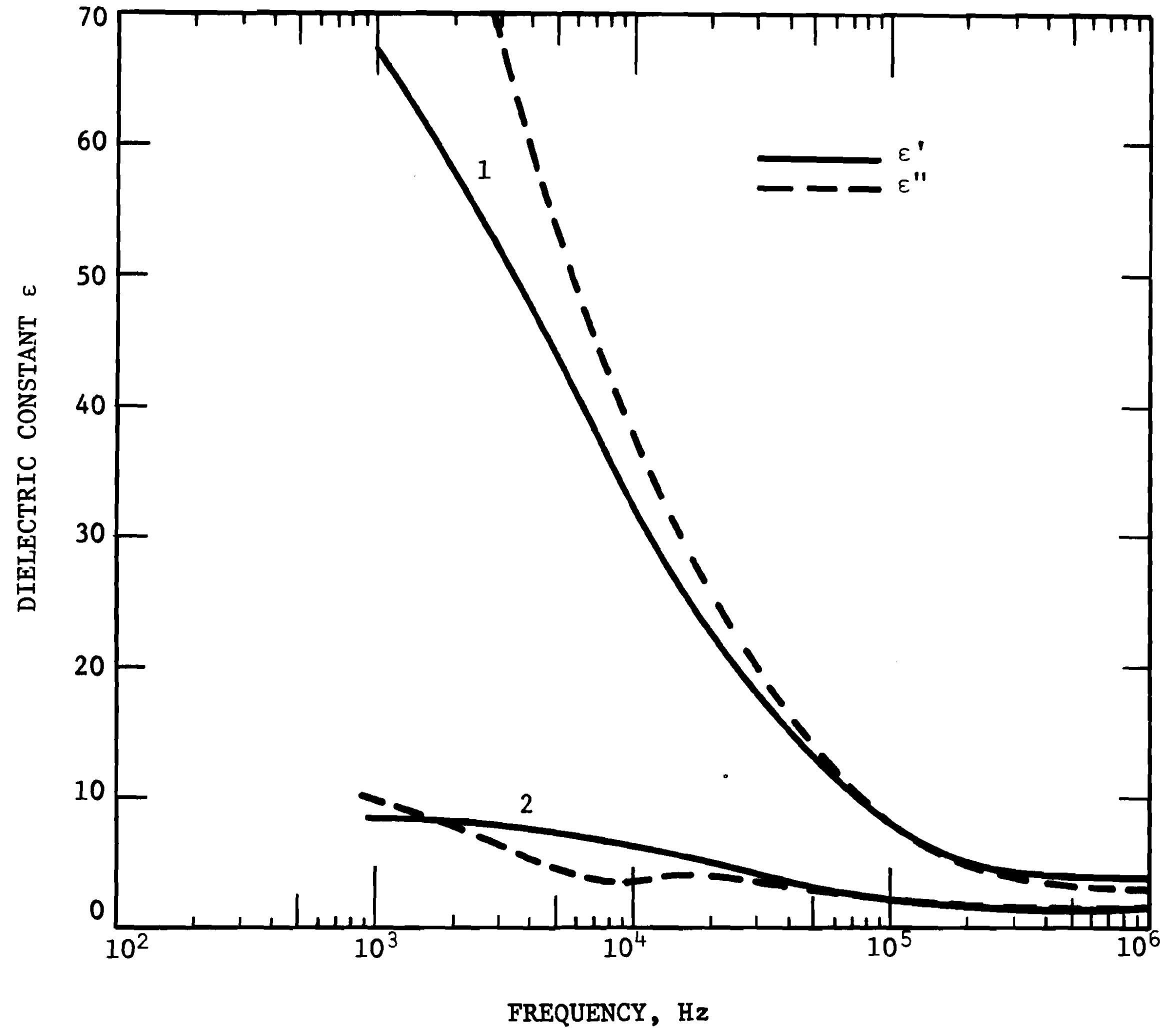
*The dielectric "constant" is, in fact, a constant only in a limited, but conventional, sense. It varies with frequency and material parameters, among other things. The dielectric constant is also called the capacitivity.



Curves	Type	Temperature, °C	Density, g cm^{-3}	Chlorine Content, ppm
1	Wet Snow	0	0.38	25
2	New Snow	-1	0.25	15

Figure 8-11. Dielectric Properties of Snow (Ref. 19)

The dielectric constant decreases with increasing frequency because the molecules of the dielectric cannot rotate into equilibrium with the electric field. This behavior is shown for snow in Fig. 8-11, where representative data on both the real and imaginary parts of the dielectric constant are plotted against frequency. A more complete report on experimental results is given by Mellor (Ref. 12). In Fig. 8-12, the dielectric constant at high frequencies is given with snow density as a parameter. In this range, the dielectric constant is closely related to the optical index of refraction n, so that, for a good approximation

$$\epsilon_\infty = n^2 \qquad (8\text{-}19)$$

In this frequency range, ϵ is designated ϵ_∞ and referred to as the optical dielectric constant. The dielectric constant increases with snow density at all frequencies and thus increases with the age of a packed snow. Free water in the snow also increases the dielectric constant. Although it is not obvious in the data of Fig. 8-11, the loss tangent is less than 1 and

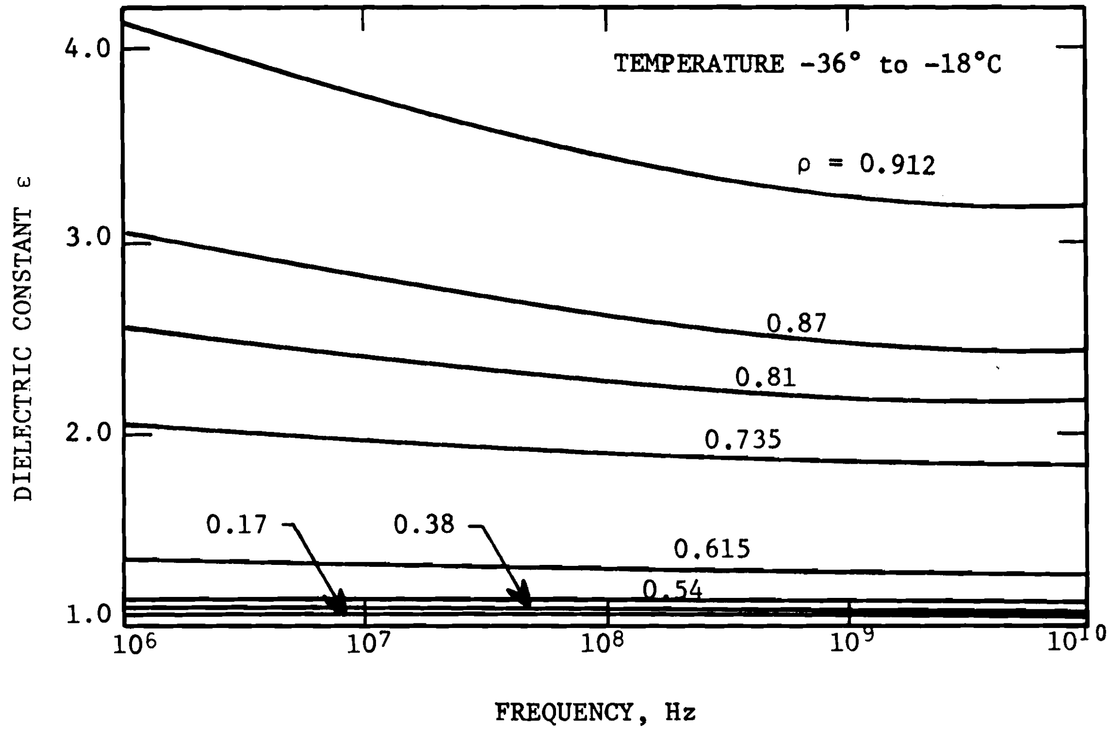


Figure 8-12. Dielectric Constant for Snow at High Frequencies (Ref. 20)

$\epsilon'' < \epsilon'$. Measured data on loss tangent are given in Fig. 8-13.

The electrical conductivity of snow generally lies in the range of 10^{-7} to 10^{-10} (ohm cm)$^{-1}$ with considerable spread in the data dependent on the density, granularity, purity, and temperature. Higher conductivity values are found for higher densities, higher liquid water content, or higher temperatures (Ref. 12). Wet snow, particularly when it is dirty, is a relatively good conductor similar to water, so care must be taken to adequately insulate electrical apparatus.

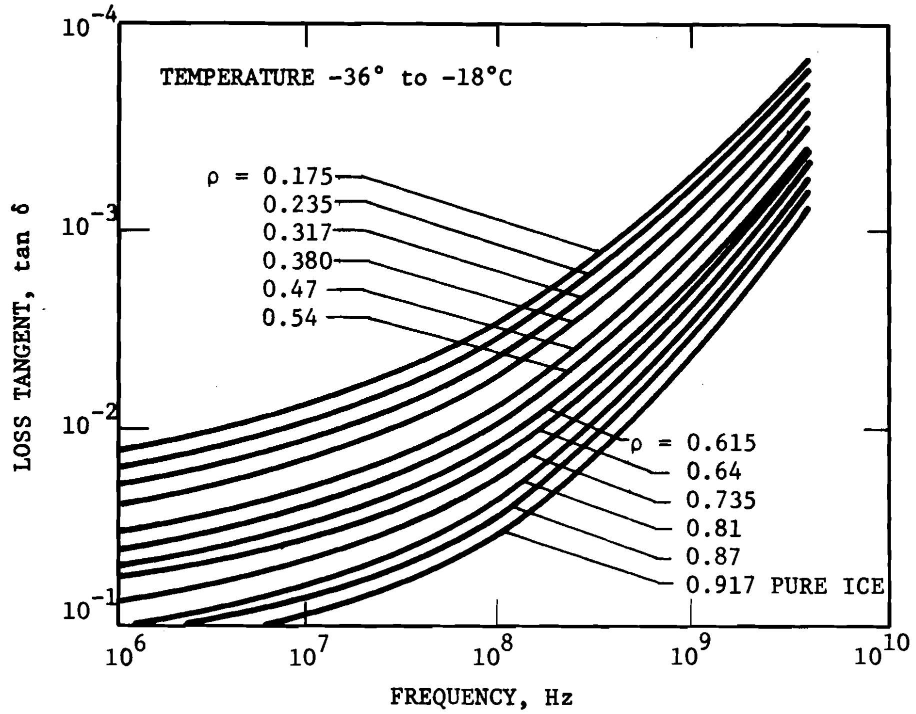
8-2.1.2.4 OPTICAL PROPERTIES OF SNOW

Electromagnetic radiation incident on a snow surface is largely reflected back into the atmosphere but the detailed nature of this reflectance is not clear. Most data indicate reflectance in excess of 70 percent throughout the visible range but the reflectance of all other natural ground cover is less than 50 percent. For comparison, the percent reflectances of various surfaces are given in Table 8-10. The reflectance of old snow decreases to 30-50 percent. Of prime interest is the spectral dependence of the reflectance. The

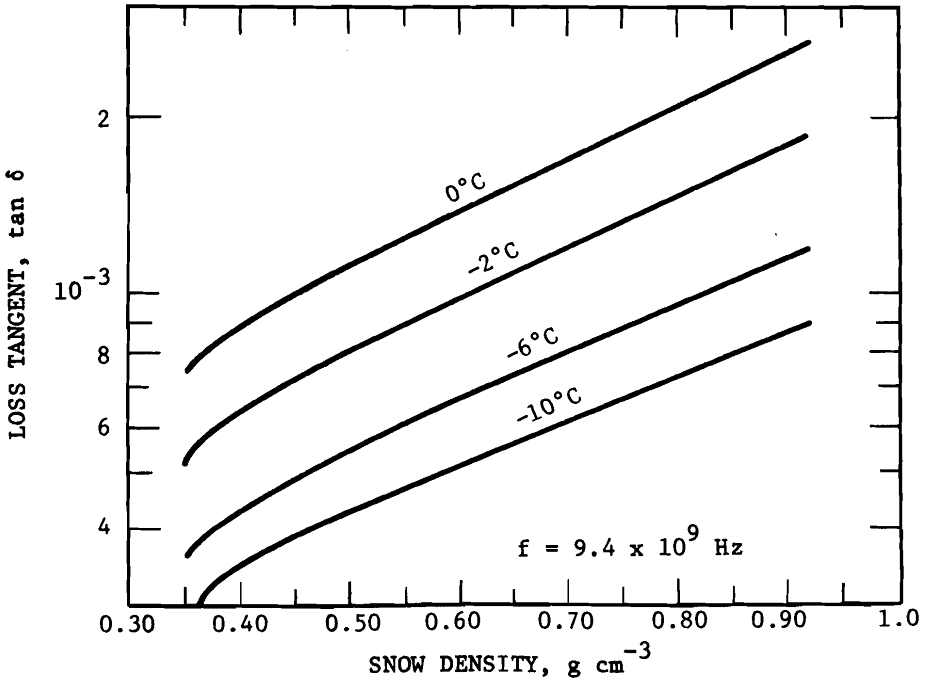
TABLE 8-10

REFLECTANCE OF VARIOUS SURFACES
(Ref. 6)

Surface	Reflectance, %
Snow	> 70
Sea ice	40-60
White sand	34
Green grass	26
Dry grass	19
Bare soil	10-30



(A) As a function of frequency for various densities



(B) As a function of density for various temperatures

Figure 8-13. Loss Tangent of Snow (Refs. 12, 20, 21) white color indicates a low spectral dependence in the visible region, but sufficient disagreement in the available data prevents any observation other than that the reflectance seems to gradually decrease as the wavelength increases from 0.4 to 0.7 μm (Ref. 12). At longer wavelengths in the electromagnetic spectrum—the microwave and UHF bands—the reflectance is considerably lower, approaching zero at 10 MHz. In all cases, the reflectance is dependent on the angle of incidence of the electromagnetic waves, on the surface texture of the snow, and on impurities.

The incident energy that is not reflected penetrates the snow, is scattered, and absorbed. The physical relation describing the attenuation of electromagnetic energy is

$$I = I_0 \exp(-\nu z),\ \mathrm{W\ cm^{-2}} \qquad (8\text{-}20)$$

where

I_0 = radiation intensity at surface ($z = 0$), W cm^{-2}

I = radiation intensity at depth z, W cm^{-2}

z = depth below surface, cm

ν = extinction coefficient or attenuation coefficient, cm^{-1}

ν is separated into an absorption coefficient a and a scattering coefficient β by the relation (Ref. 12)

$$\nu = a\sqrt{1 + 2\beta/a},\ \mathrm{cm^{-1}} \qquad (8\text{-}21)$$

The magnitude of the attenuation is such that 20 percent of the radiation entering dry snow reaches a depth of 10 cm. If the snow is wet, this percentage is decreased to 2.4 percent (Ref. 6).These percentages can vary considerably.

Extinction coefficients reported by Mellor range from 0.1 to 0.5 cm^{-1}. A general representation of the dependence of the extinction coefficient on wavelength and snow density is shown in Fig. 8-14. Generally, absorption is expected to decrease with increasing wavelength (Ref. 12).

8-2.2 PROPERTIES OF HAIL*

The most important properties of hail are size, weight, and falling speed. Its other properties are those of ice, which are documented extensively and will not be reviewed here (Refs. 24, 25, 26, 27).

Many large hailstones have been reported but most observers believe that hailstones of diameters greater than 3 cm occur in less than 5 percent of hailstorms. Hailstones as large as 13.7 cm in diameter and as heavy as 450 g have been reported in the United States, but most hailstones that are considered large are the size of baseballs. A frequency distribution of maximum hail size in the Denver area is given in Fig. 8-15 and of hailstone size in the United States in Table 8-11. The representative size distribution of hail in storms is shown in Fig. 8-16. Two types of distribution, unimodal and bimodal, are shown. Most hailstorms produce hailstones with diameters of 0.5 to 2.0 cm at ground level.

Hailstones are usually conical, spherical, or ellipsoidal, with irregular shapes less frequently observed. Some unusual forms are shown in Fig. 8-17. Hailstones consist of an ice nucleus, 0.2 to 0.5 cm in diameter, on which are formed 3 or 4 identifiable layers of ice. Transparent strata are two to three times the thickness of the intervening opaque layers. Radially oriented liquid water or air bubbles are found in hailstones. Hailstone densities are in the range 0.87 to 0.95 g cm^{-3}.

The terminal speed of hailstones varies greatly with meteorological conditions. For normal sizes, the speed is from 12 to 16 m s^{-1}, but calculations indicate that for the very large hailstones, speeds can reach 50 m s^{-1} or more.

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*Major references for this paragraph are Hull (Ref. 22) and Sulakvidze (Ref. 23).

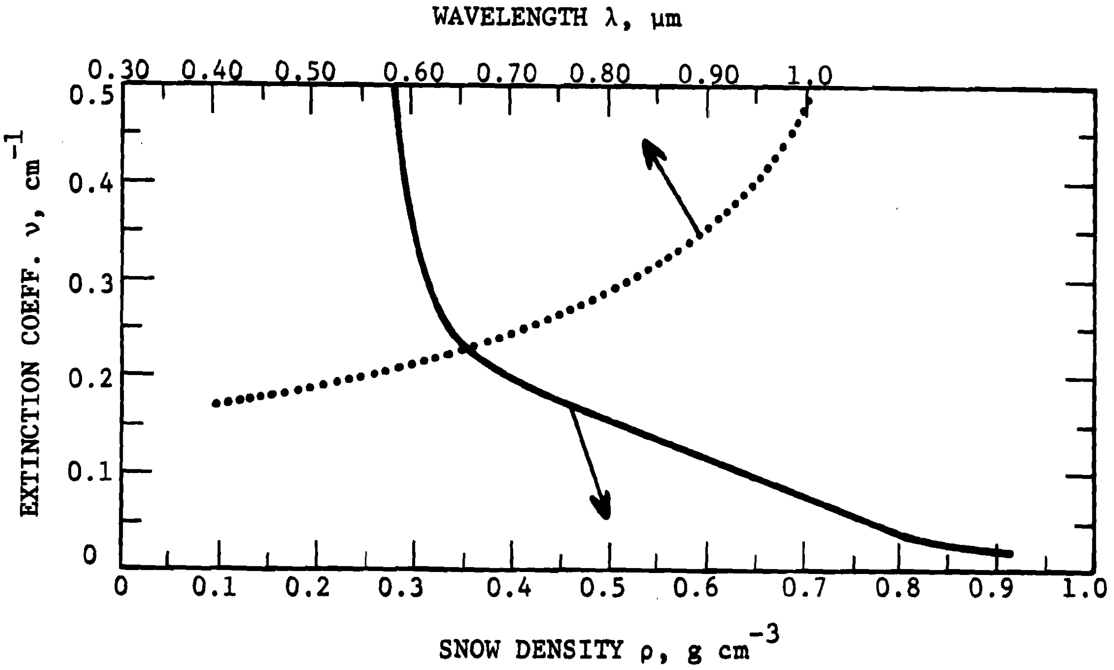

Figure 8-14. Extinction Coefficient in Snow

8-2.3 PROPERTIES OF GLAZE, RIME, AND HOARFROST

The density of glaze approaches that of pure ice (0.917 gm cm^{-3}). Rime has a density normally ranging from 0.1 to 0.6 g cm^{-3}. Examples of rime ice are shown in Fig. 8-18. "Hard rime", a form of precipitation between rime and glaze, has a density varying from 0.53 to 0.73 g cm^{-3}. The mass density of hoarfrost, which is almost impossible to measure, is probably less than 0.2 g cm^{-3}; however, the single "blades" or "cups" that give hoarfrost its striking patterns have a density approaching that of pure ice.

TABLE 8-11

FREQUENCY DISTRIBUTION OF HAILSTONE SIZE

Diameter, in.	Frequency, %
0.50-0.74	39
0.75-0.99	20
1.00-1.40	14
1.50-1.90	11
2.00-2.40	6
2.50-2.90	4
3.00-3.40	4
3.50-3.90	1
4 or more	1

Glaze is transparent or translucent and clings tenaciously to the surfaces on which it forms.

8-3 OCCURRENCE OF SOLID PRECIPITANTS

8-3.1 SNOWFALL AND ACCUMULATION*

Annual snowfall in the cold regions of the Northern Hemisphere varies from as little as 25.4 cm (10 in.) to more than 20.3 m (800 in.). In water equivalent terms, this is equal to about 3.8 cm to 3.05 m (1.5 to 120 in.) of precipitation. Orography plays an important

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*This paragraph is adapted directly from R. W. Gerdel, *Characteristics of the Cold Regions* (Ref. 30).

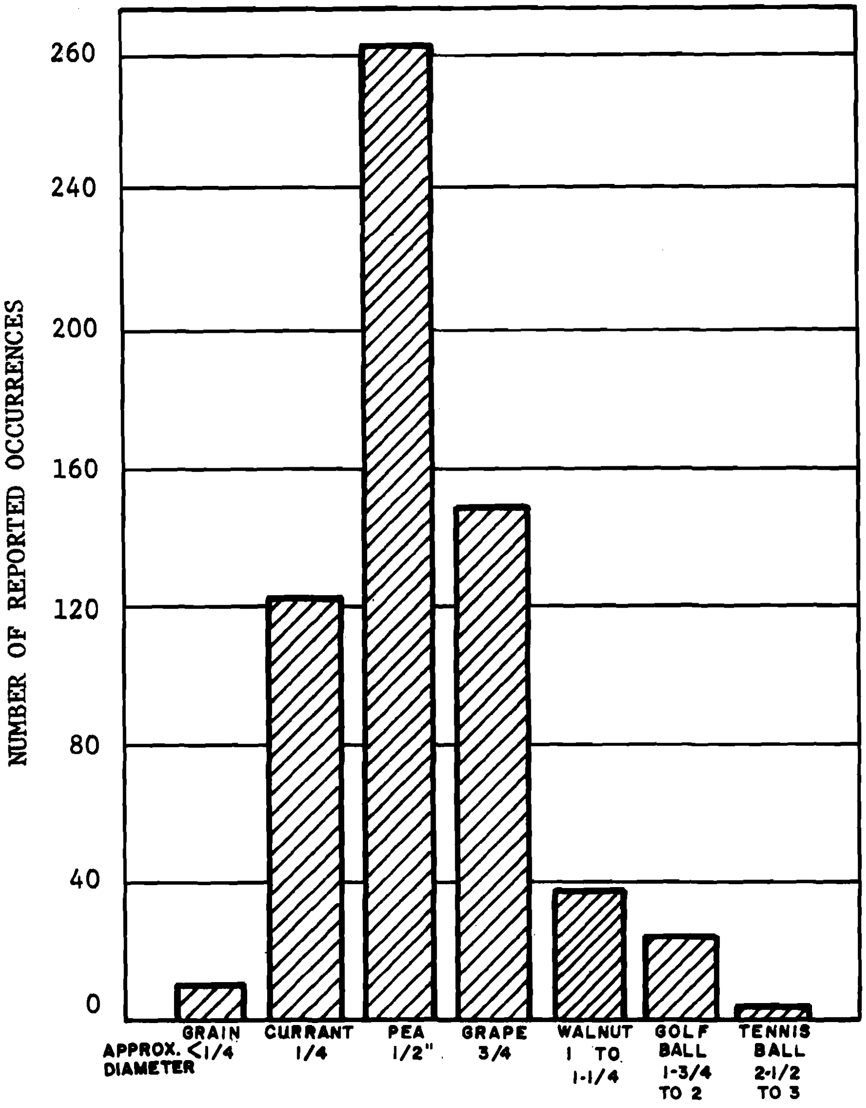


Figure 8-15. Frequency Distribution of Maximum Hail Size (Denver ≈ 1949–55)
(All dimensions in inches)

part in distribution of snowfall. The north-south axis of the Western Cordillera imposes a barrier to inflow of warm moist air from the Pacific Ocean into the continental area of North America. Some of the largest snowstorms of record are reported from locations along the western slope of the Sierra Nevada, Cascades, and mountains of Alaska. The single storm snowfall in this highland regime probably is not exceeded anywhere else in the world. At Donner Pass in the High Sierra, 2.1 m (84 in.) of snow fell in 24 hr–the highest snowfall rate on record. At Tamarack, Calif., also on the western slope of the Sierra, 9.9 m (390 in.) of snow fell in one month. At Thompson Pass, Alaska, on the Richardson Highway, 24.8 m (975 in.) of snow fell in one winter. All of these were in recent times. The mean annual snowfall for the United States is shown in Fig. 8-19.

The Himalayas, with their east-west axis, intercept the northward flow of warm moist air from the Indian Ocean. Since the Himalayas are close to the tropics, moist air must be lifted to a great elevation before snowfall occurs. Here the winter snowline is located at approximately 2,130 m (7,000 ft),

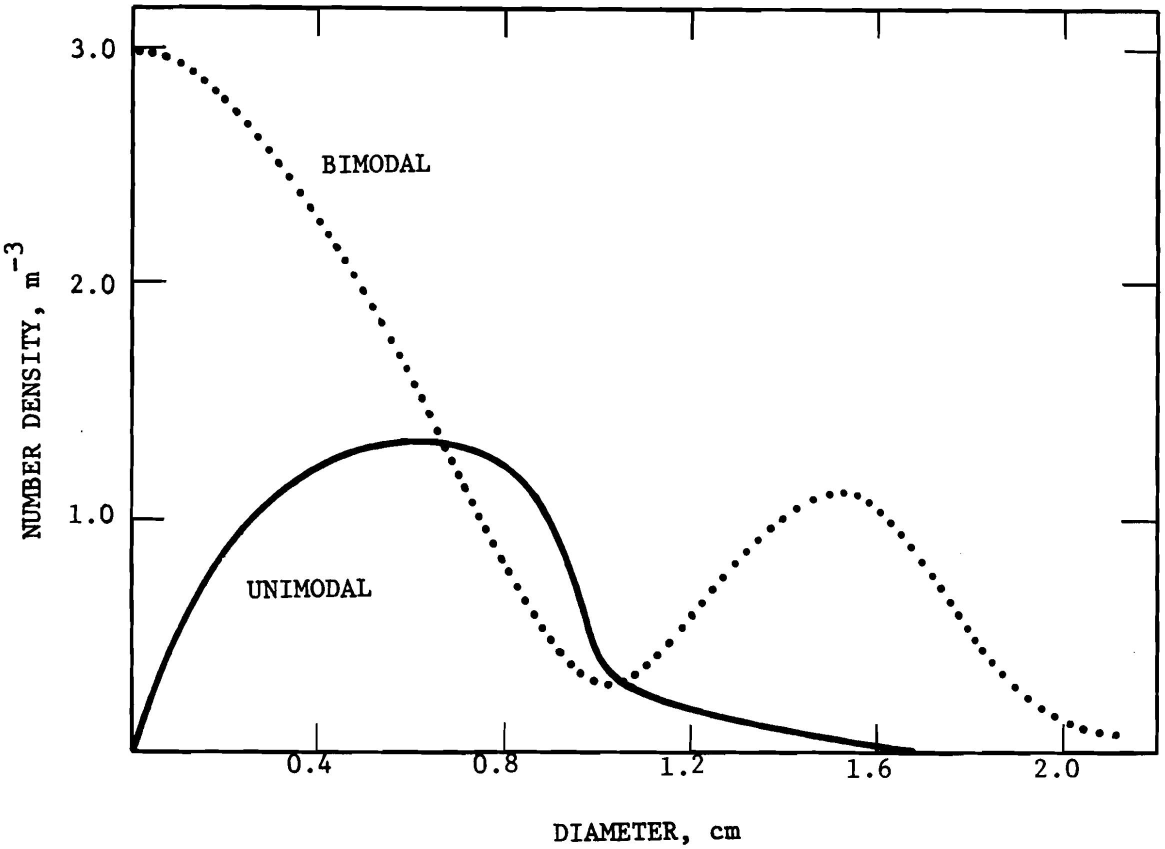


Figure 8-16. Observed Hailstone Size Distributions in Storms (Ref. 23)

but on the western slope of the Sierra Nevada it is about 1,200 m (4,000 ft). The orographic influence on snowfall may be observed in the Alps, the Appalachians, the mountains of central Quebec, and on the Greenland icedome.

The low annual precipitation in the form of snow during winter in midcontinental areas of both the Eastern and Western Hemispheres is due to the precipitation shadow effect of mountains, the low initial moisture capacity of the airmasses associated with the major winter storms, and the long trajectory of storm paths over dry continental areas with no opportunity for moisture pickup.

Large inland lakes also play an important role in the distribution and volume of annual snowfall. There is a region in southern Ontario and northern New York, south and east of the Great Lakes, where the average annual snowfall ranges from 1.52 to 5.1 m (60 to 200 in.) yr^{-1}; the large volume of snow is attributed to the introduction of moisture into polar continental or extratropical airmasses as they sweep across the lakes. The seasonal snowfall pattern east of Lakes Huron and Ontario is shown in Fig. 8-20. In upstate New York, the snowstorms attributed to the influence of the Great Lakes create serious maintenance problems on major highways and railroads. The "lake effect" may be expected anywhere in the cold regions where large bodies of water lie across major storm tracks.

Recording precipitation in the Antarctic is difficult because almost all of it is in the form of wind-driven snow in which the ordinary snow gage is ineffective. Best estimates of annual snowfall in this region are based on measuring stakes and on annual strata found in deep pits. Total precipitation is small, but with considerable variation from year to year. Annual snowfall varies from less than 5 cm water equivalent in the interior to above 40

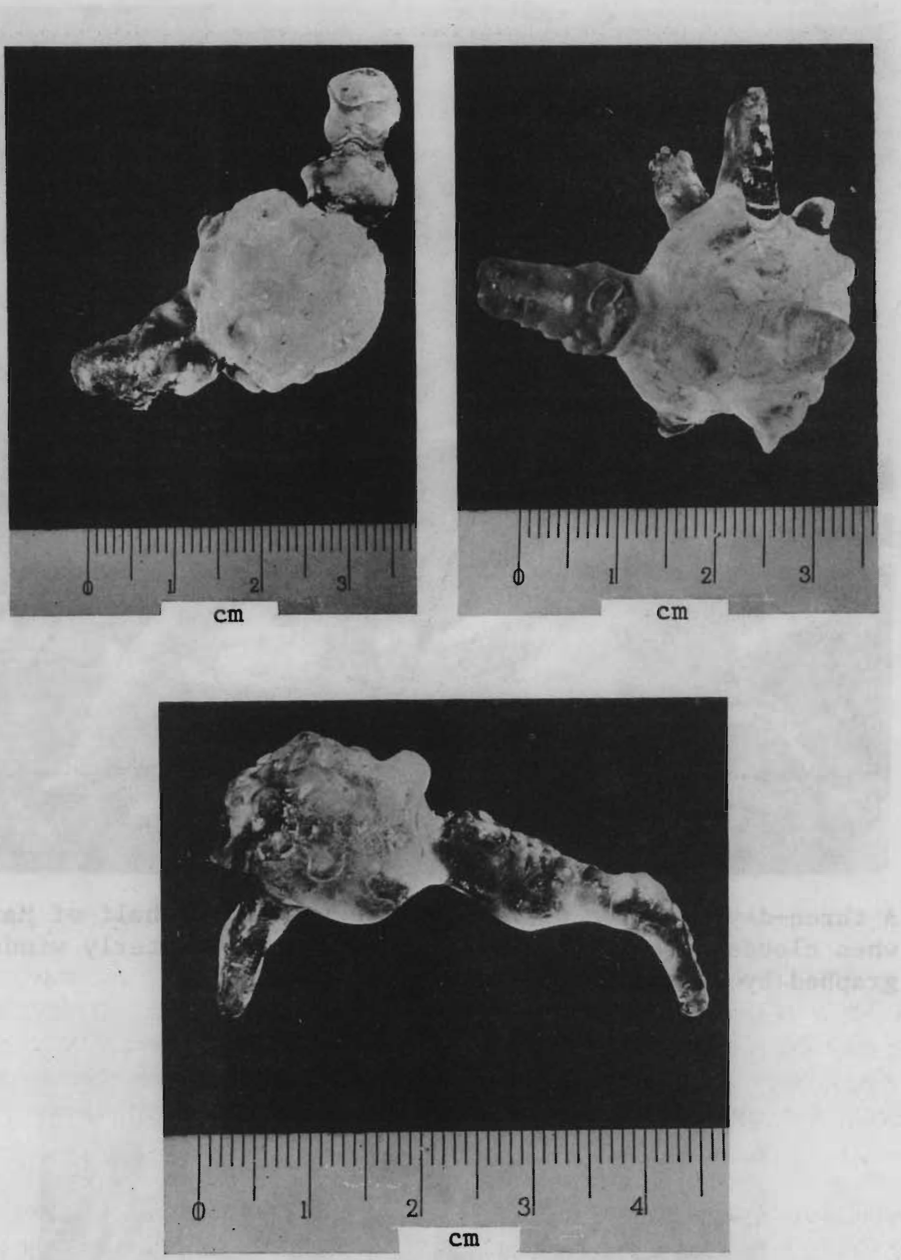
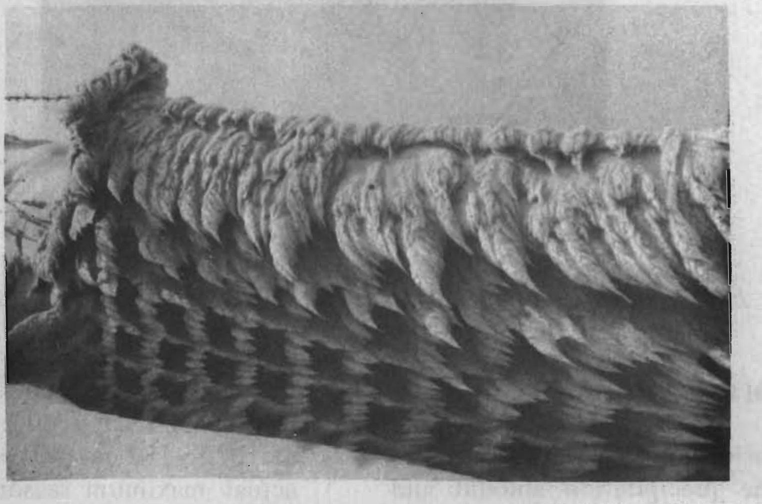


Figure 8-17. Unusual Hailstones (Ref. 28) (Hailstones that fell at Sydney, Australia, on 3 Jan 71.)

cm in the coastal regions (Ref. 32).

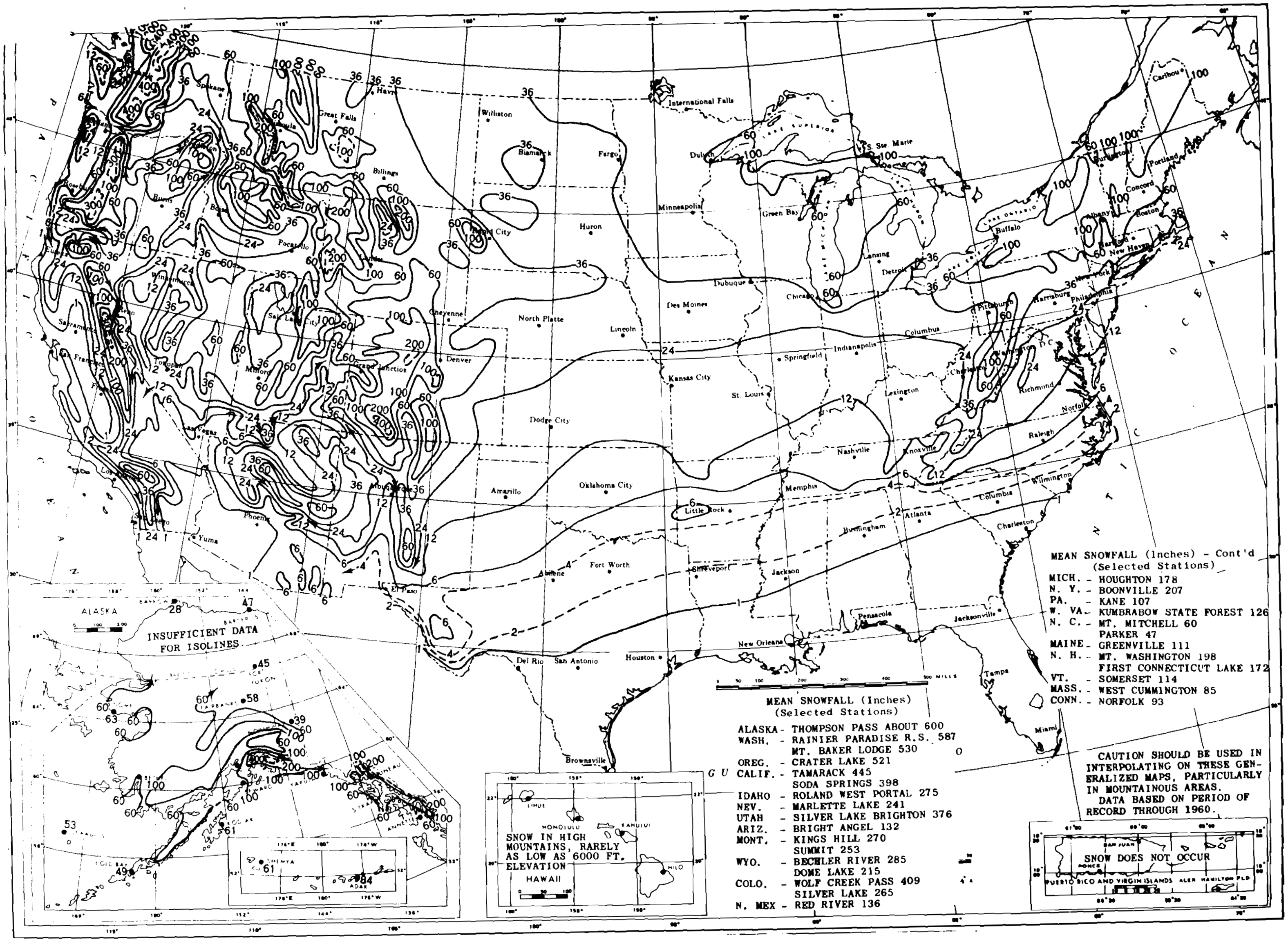
Accumulation of seasonal snow cover is a function of the precipitation amount and temperature cycles. In the extreme cold climate, the mean snow depth during the month of maximum depth on the ground may equal or exceed the mean depth for the corresponding period in the intermediate cold climate, in spite of much greater annual snowfall in the intermediate cold climate. Frequent winter thaws in the intermediate cold climate may reduce the seasonal snowfall of 102 to 152 cm (40 to 60 in.) or more to an actual maximum seasonal cover of 30.5 to 45.8 (12 to 18 in.) in undisturbed areas. In the extreme cold climate, where no melting occurs for 4 to 8 mo, a seasonal snowfall of 61 to 76.3 cm (24 to 30 in.) produces a maximum snow cover of 25.4 to 50.8 cm (10 to 20 in.) during the month of maximum depth. The difference between recorded

(A) A three-day build-up of rime during the latter half of March 1969, when clouds were super cooled in persistent easterly winds (Photographed by J. Dudley-Davies)



(B) The wire mesh fence is of 6 in. by 6 in. squares, and the icicles appear to be about 18 in. long at the top of the fence. It is also interesting to note that the length of the icicles reflects the change of wind speed with height (Photographed by W. Harper)

Figure 8-18. Rime Ice (Ref. 29)



MEAN SNOWFALL (Inches)
(Selected Stations)

ALASKA -	THOMPSON PASS ABOUT 600
WASH. -	RAINIER PARADISE R.S. 587
	MT. BAKER LODGE 530
OREG. -	CRATER LAKE 521
CALIF. -	TAMARACK 445
	SODA SPRINGS 398
IDAHO -	ROLAND WEST PORTAL 275
NEV. -	MARLETTE LAKE 241
UTAH -	SILVER LAKE BRIGHTON 376
ARIZ. -	BRIGHT ANGEL 132
MONT. -	KINGS HILL 270
	SUMMIT 253
WYO. -	BECHLER RIVER 285
	DOME LAKE 215
COLO. -	WOLF CREEK PASS 409
	SILVER LAKE 265
N. MEX -	RED RIVER 136

MEAN SNOWFALL (Inches) - Cont'd
(Selected Stations)

MICH. -	HOUGHTON 178
N. Y. -	BOONVILLE 207
PA. -	KANE 107
W. VA. -	KUMBRABOW STATE FOREST 126
N. C. -	MT. MITCHELL 60
	PARKER 47
MAINE -	GREENVILLE 111
N. H. -	MT. WASHINGTON 198
	FIRST CONNECTICUT LAKE 172
VT. -	SOMERSET 114
MASS. -	WEST CUMMINGTON 85
CONN. -	NORFOLK 93

CAUTION SHOULD BE USED IN INTERPOLATING ON THESE GENERALIZED MAPS, PARTICULARLY IN MOUNTAINOUS AREAS.

DATA BASED ON PERIOD OF RECORD THROUGH 1960.

Figure 8-19. Mean Annual Snowfall in the United States (Ref. 31)

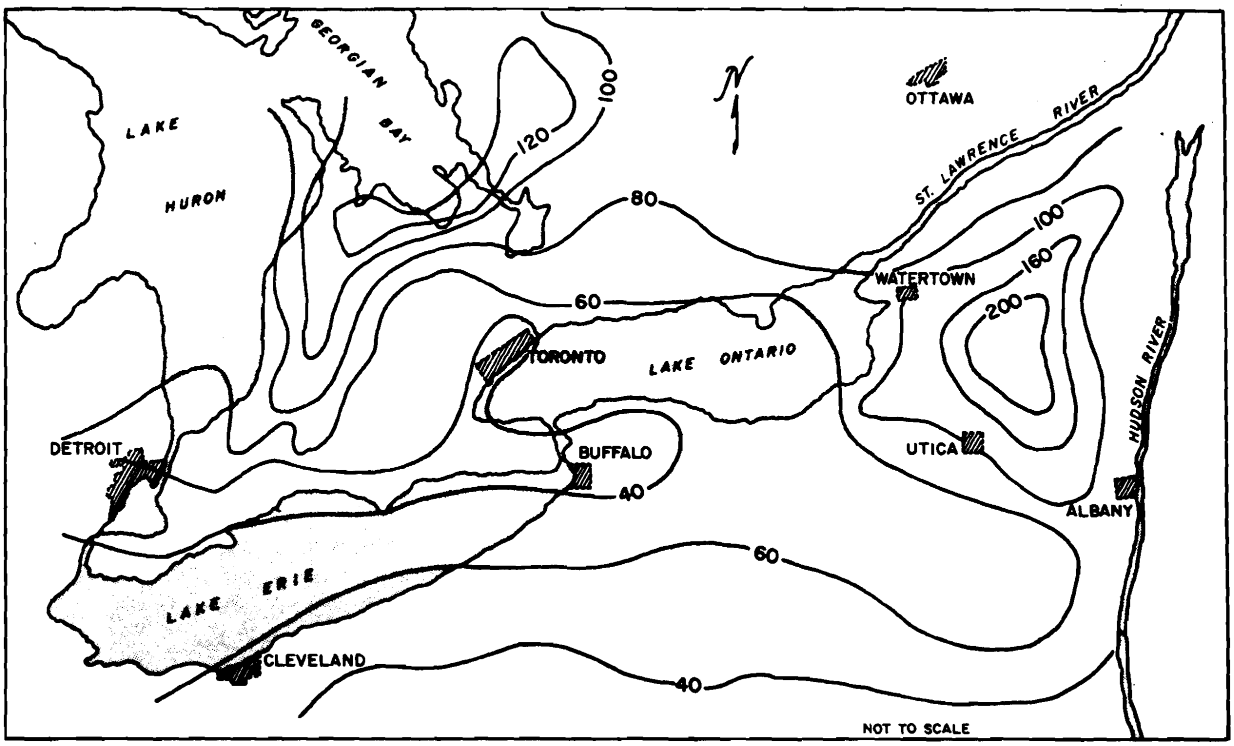


Figure 8-20. The "Lake Effect" Influence on Distribution of Annual Snowfall (Ref. 30)

annual snowfall and actual depth of snow on the ground in the extreme cold climate is due to settling, consolidation, and metamorphosis of the snow grains, not to melting, as it is in other parts of the cold regions. Sublimation also occurs but has less effect.

World distribution and duration of seasonal snow cover is shown in Fig. 8-21. This map shows that the major snow-caused problem areas of the world are in the northern cold regions. The zero-duration snow cover isoline in this figure does not identify the southern limit of snowfall; snowstorms of sufficient magnitude to create traffic and communication problems do occur occasionally south of this line.

The average seasonal maximum snow depth on the ground in the cold regions of the Northern Hemisphere is shown in Fig. 8-22. This map shows the maximum depth on the ground as recorded at the end of the month with maximum snow on the ground. Data used in preparation of this map were derived from climatological records covering periods up to 30 yr.

The largest month-end depth of snow reported for the winter season is usually less than the winter maximum since the heaviest snowfall producing the maximum winter depth may have occurred early in the month. Settling and possibly some melting with no subsequent snowfall during the month may reduce the record month-end depth to less than winter maximum.

In Canada, a factor of 1.236 must be used to convert end-of-month maxima to annual maxima when such information is needed for operational or design purposes. This conversion factor appears to be particularly applicable when the only available records of snow depth are those obtained from periodic snow surveys made for hydrologic purposes (Ref. 34).

Although the maps, Figs. 8-21 and 8-22, give some idea of the world distribution of

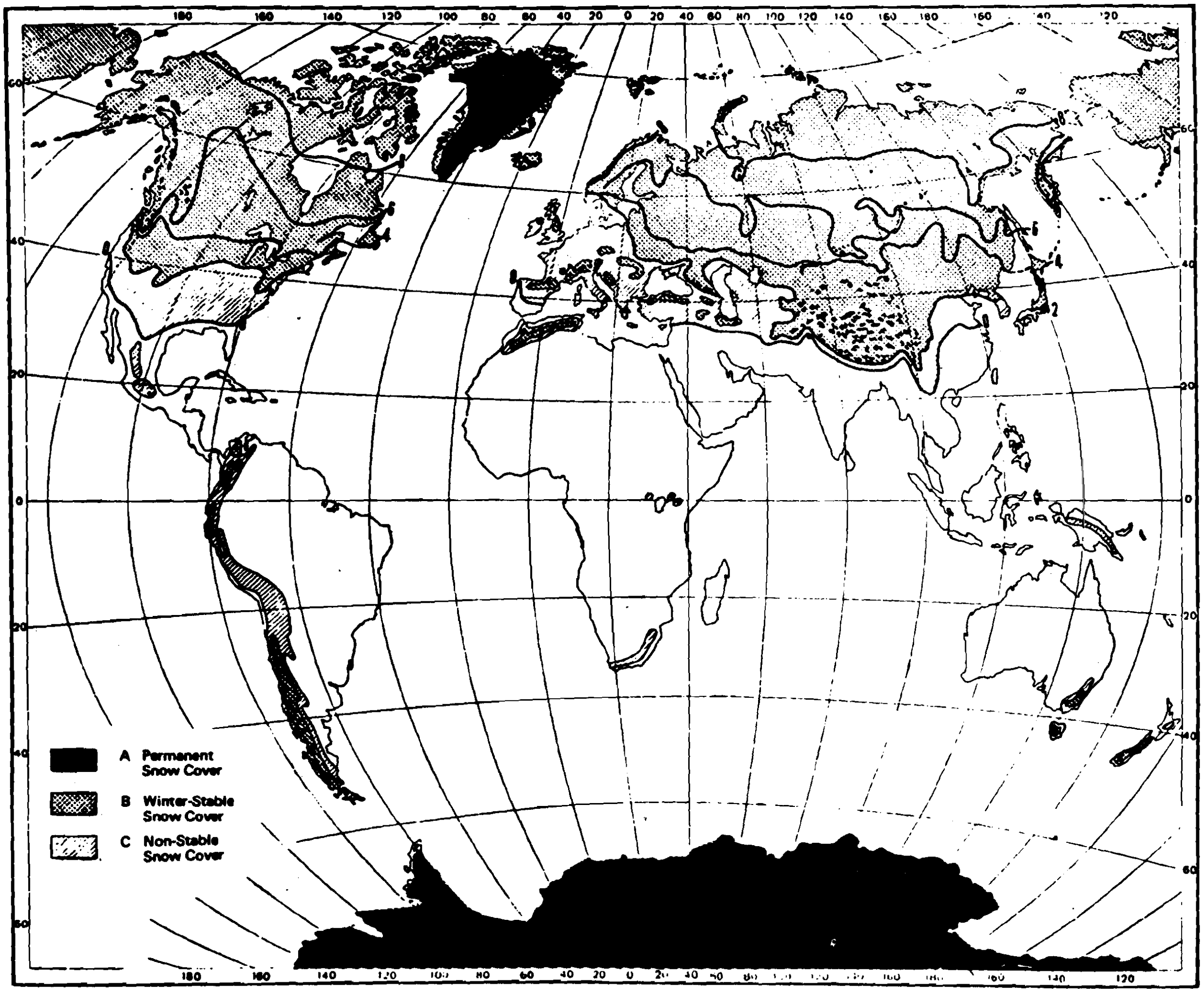


Figure 8-21. World Distribution and Duration of Snow Cover (Ref. 6)

depth and duration of snow cover, they fail to illustrate adequately the snow accumulation in the highlands of the cold regions. In the mountains, seasonal snowfall may accumulate to as much as 9.3 m (30 ft) or more and persist for 4 to 5 mo. Keeping highways, railroads, and airports open and maintaining communication services in these areas is a costly process justifiable only in a high level industrial economy or as a military necessity.

In the cold regions of the Northern Hemisphere, the greatest accumulation of seasonal snow occurs between 40 deg and 60 deg latitude. The decrease in accumulation northward is due to less annual precipitation and southward, to intermittent melting during the winter. There is also a decrease in seasonal accumulation with altitude above some elevation determined by the orographic and meteorological features of the region. The decrease in depth of snow on the ground at higher elevations may be masked by the effects of topography and exposure. High winds may sweep exposed areas clear of snow and deposit it in protected areas to depths several times the normal snowfall for the locality. The blown snow, deposited at lower elevations, may create snow removal problems for highways and railroads that are much greater than those that might be considered probable from a study of snowfall records for the area.

An excellent illustration of the effect of elevation, latitude, and exposure to prevailing

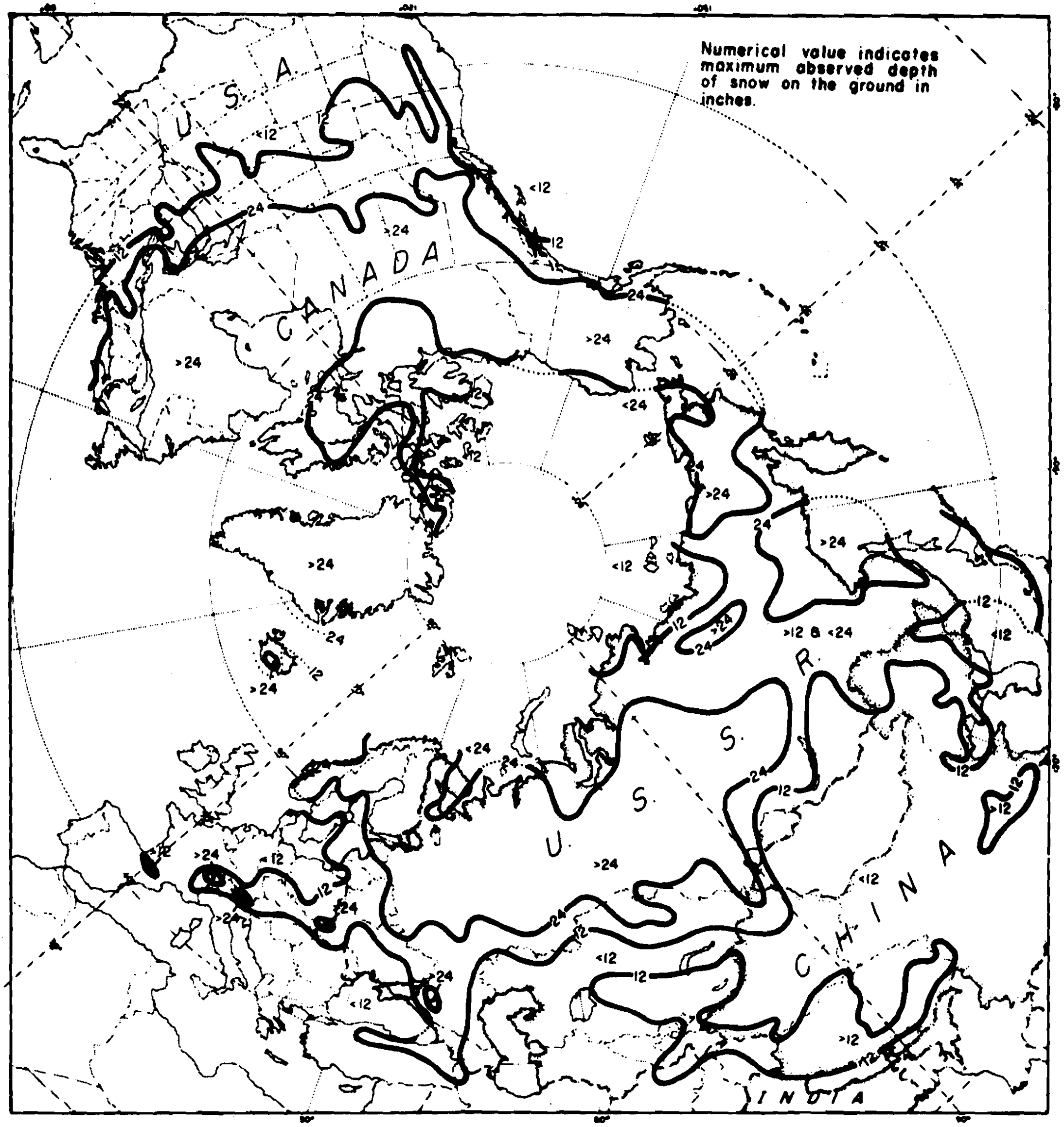


Figure 8-22. Maximum Annual Snow Cover in the Northern Hemisphere (Ref. 33)

storm tracks on seasonal snow accumulation is shown in Fig. 8-23. This map of annual snow accumulation in Greenland was prepared by Bader (Ref. 35), who used the snow stratigraphic studies reported by Benson (Ref. 36) and unpublished data from other sources to derive the annual isohyets for the icecap. It is apparent from this map that there is an increase in the annual accumulation of snow from about 30 cm (11.8 in.) of water equivalent near sea level to 60 cm (23.6 in.) water equivalent at an elevation of about 2,500 m (8,200 ft), then a decrease to 20 cm (7.9 in.) water equivalent snow above 3,000 m (9,850 ft) across central Greenland. Change in annual accumulation of snow with elevation along the western face of the icedome exhibits a uniform pattern which illustrates the orographic influence of the icedome on the prevailing westerly storms which pick up large supplies of moisture as they cross the open waters of the Labrador Sea and the Davis Strait. The effect of latitude is illustrated by the change in accumulation from about 90 cm (35.4 in.) water equivalent south of latitude 60 deg N.

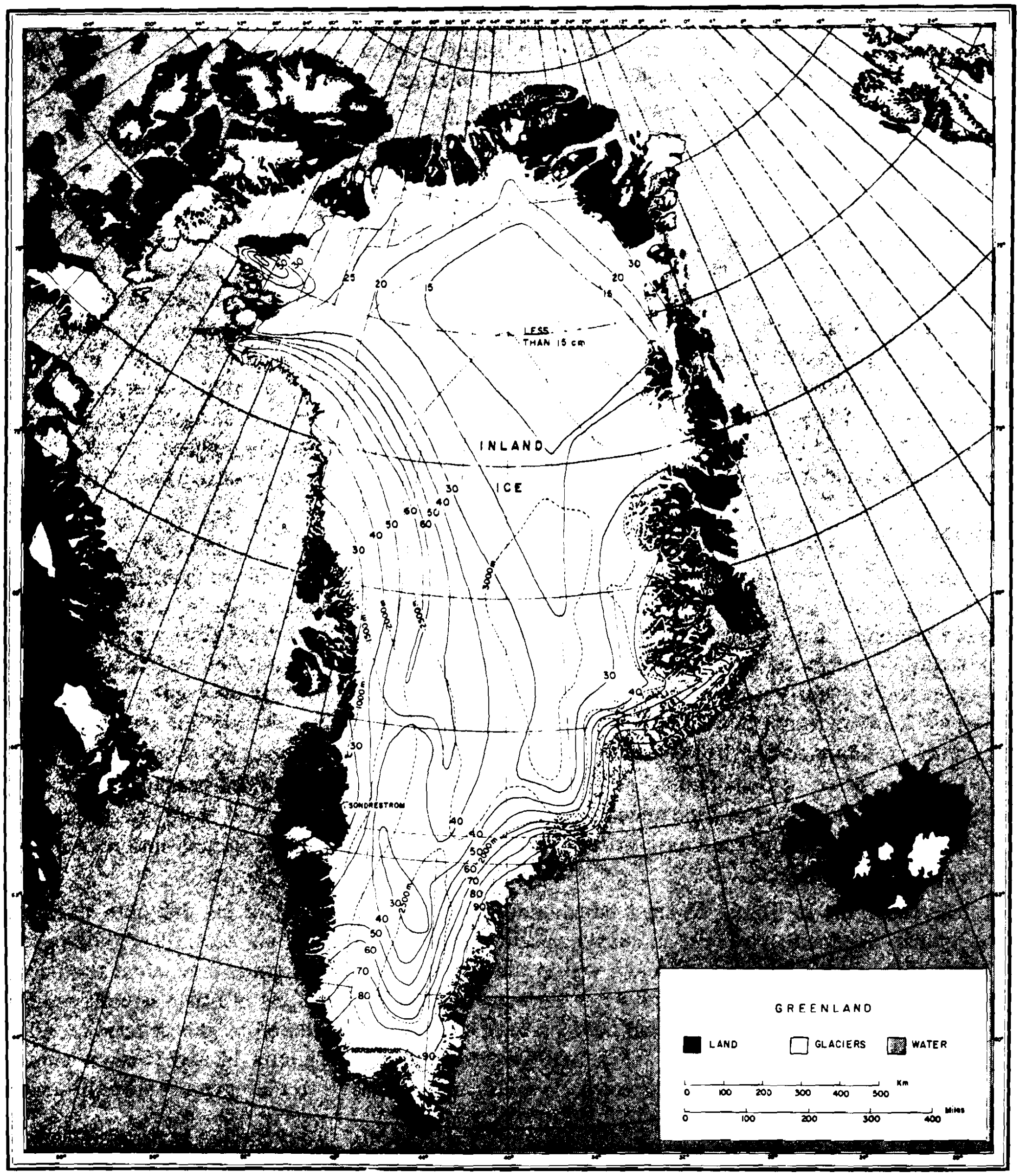


Figure 8-23. Annual Accumulation of Snow in Greenland (Ref. 35)

to 30 cm (11.8 in.) near 70 deg and to 10 cm (3.9 in.) near 80 deg along the crest of the icedome.

Although depth of snow on the ground imposes a physical barrier to mobility, the weight of the snow, or the snow load, is the most important consideration for design criteria in the cold regions. Conversion of depth of snow on the ground to weight from which snow load values may be computed is difficult. Newly fallen snow may have a density of less than 0.1 g cm^{-3}, but older snow density may exceed 0.5 g cm^{-3}. Boyd (Ref. 34) made a study of snow depths on the ground and snow loads on roofs in Canada, and the U S Weather Bureau made a similar study in the United States for the Housing and Home Finance Agency (Ref. 37). The map of Fig. 8-24, showing the maximum

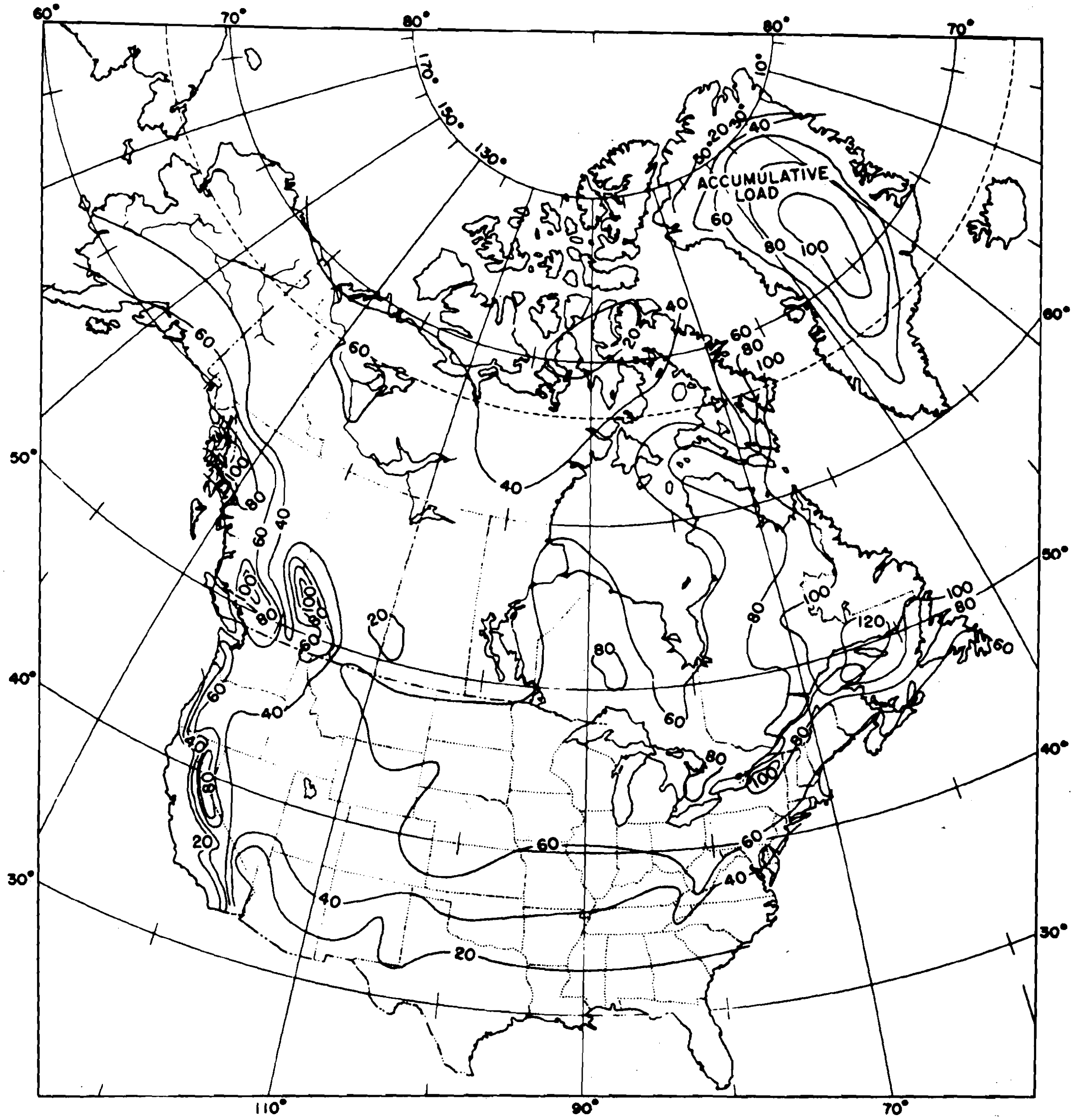


Figure 8-24. Maximum Probable Snow Load (lb ft^{-2}) on a Horizontal Surface in North America and Greenland (Ref. 61)

probable snow load to be expected in Canada and the United States was prepared from the data presented in these two reports. Additional records from snow surveys made in the western United States during the past 15 yr for water supply forecasts were used to extend the snow-load isolines into regions not covered by the two referenced reports.

The isopleths in Fig. 8-24 must be considered indicative only of the probable maximum snow load in any locality. Rain on snow can add appreciably to the load, particularly if the snow is cold enough to cause freezing of the rain in the snow cover. High winds may clear the snow load from some structures, or transfer and even increase the load on portions of other structures. Where the snow load is not removed by wind, the increased surface area created by accumulated snow may cause the snow load to be augmented by wind pressure.

In the extreme cold climate the annual snow load may accumulate year after year. On the Greenland ice sheet, above the firn line where there is little or no summer melting, the snow load increases at rates of 146 to 489 kg m^{-2} (30 to 100 lb ft^{-2}) yr^{-1}. Similar load accumulation problems are encountered at higher elevations in Alaska, Canada, and in the Antarctic.

Most of the available records on snow cover that may be used for computing regional snow loads are for snow depth only. Density or water equivalent values essential to satisfactory evaluation of potential snow loads are seldom measured or reported in standard climatological summaries. To compute snow loads from the regular weather station reports of depth on the ground, Boyd (Ref. 34) assumed that 1 in. of snow (2.5 cm) corresponded to a pressure of 1 lb ft^{-2} (4.88 kg m^{-2}). This assumption is based on a density of 0.2 which may be too low for some regions. A value of 1.5 lb ft^{-2}/in. depth of snow (3 kg m^{-2}/cm) might be a more realistic value for most of the cold regions of the Northern Hemisphere. Even that figure may be too low for a maritime climate where wet snowstorms are common.

8-3.2 HAILSTORM FREQUENCY*

Hailstorms may occur in global regions from the equator to the 65th parallel; they are associated with instabilities in warm humid airmasses that contain a sufficiently low quantity of giant condensation nuclei. However, the "hail belts", where the damaging effects of large hailstones are reported, are most often in midlatitude continental regions. Toward the equator and poles and over the oceans, the frequency of hailstorms decreases. The largest percentage of hailstorms is associated with the squall-line area of an active cold front; lower percentages are attributed to wave instabilities, occlusions, and convective currents as well as orographic lift. The incidence of hail can increase by a factor of two or more with 200- to 500-m increase in elevation, so local topography plays an important role.

The limited extent of hailstorms and reporting difficulties make it difficult to map frequencies of occurrence. In the United States, the "hail belt" consists of the high plains States east of the Rocky Mountains, and the Mississippi Valley plains States—where an annual average of four hailstorms is observed. The Pacific Northwestern States have reported up to 22 hailstorms per year, but the precipitation was actually snow pellets or graupel, not true hail.

In other parts of the Western Hemisphere, Canada experiences little hail; an average of only two incidents per year is reported in the Prairie Provinces and the Great Lakes region. In Mexico, hail incidence on the coast is about 1 yr^{-1}, but in Mexico City the average is 6 yr^{-1}, and at Saltillo it is 18. Both of these latter stations are above 6,000 ft in elevation. In South America, the lower elevations report an average incidence of 1 to 3 yr^{-1}, but 8 to 11 are reported in the Andes.

In Europe, snow pellets are reported as hail in the Scandinavian countries on from 1 to 8 days yr^{-1}, but they are of little importance. In the British Isles and western central Europe, an average of 4 yr^{-1} hailstorms occurs with a maximum in the winter months, although on the northern coast of Ireland, the average increases to 80. The Mediterranean countries show a similar incidence, i.e., 4 yr^{-1}; but in central Europe, where the continental airmass is dominant, hail frequency is highest in the summer, increasing to 5 or 6 yr^{-1}.

The U.S.S.R. has maximum hail frequencies of 8 to 10 yr^{-1} in the Transcaucasian region, the northern Caucasus, and in south Kazakhstan. Around Moscow, the average is 8 yr^{-1} but over 17 damaging hailstorms have been reported in the Moscow region in one season. (This statistic illustrates a characteristic of hailstorms also noted in a United

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*General references for this paragraph are Refs. 22 and 23.

Airlines study near Denver in the United States. Hailstorms leave "footprints" on the earth, which are characteristically 10 to 20 km long and 8 to 9 km wide. In a small area, hailstorms can occur daily, but a fixed weather station in the area can report zero incidence). The average hailstorm incidence for the entire U.S.S.R. is less than four annually.

China, Korea, and Japan, except for Hokkaido, report a frequency of no more than 2 hailstorms annually, but in the northern island of Hokkaido, 7 to 12 hailstorms occur each year. Africa has reported some of the larger and more destructive hailstorms but the records are poor. Hailstorms are infrequent in most of Australia and New Zealand, 1 to 2 yr^{-1}, but in Southern Australia, Melbourne and Adelaide, the averages are 7 and 6 yr^{-1}, respectively.

8-3.3 GLAZE, RIME, AND HOARFROST*

These three types of ice, which become solid upon deposition, are differentiated by their densities, as determined by the process of deposition. No clear dividing line distinguishes the three, and the conditions and geographic extent of their occurrence are very similar.

Glaze is common in most of the United States east of the Rocky Mountains, with the area of most frequent occurrence found in a broad belt extending from north-central Texas to southern New England. One storm every three years with ice 0.5 to 1.5 cm thick is experienced in this belt, and the entire United States east of the Rocky Mountains, except for the Southeast, experiences an average of one glaze storm every 6 yr.

While glaze is most often associated with the United States, it is not uncommon in Canada and Alaska and has been observed in northern Mexico. In the Southern Hemisphere, conditions favorable for glaze formation do not occur very often; however, it has been reported from New Zealand.

The pronounced anticyclonic circulation that dominates Asia in winter prevents the incursion of maritime tropical air into the mainland of Asia and keeps the incidence of glaze to a minimum. Data for eastern Asia are almost nonexistent, but one set of old data was obtained which shows that Vladivostok, Siberia, experiences 1 day with glaze in a 10-yr period. Due to a greater exposure to low pressure centers moving from the south, the Japanese islands undoubtedly experience more glaze than the mainland of Asia. Descriptions of two storms that struck Japan resemble conditions found along the eastern coast of the United States.

Glaze is common in many parts of Europe, particularly in the central and eastern sections, although frequencies apparently are considerably below those reported for the United States. The principal area of occurrence appears to be a broad belt lying to the north of the Pyrenees-Alp-Balkan mountain complex and extending from eastern France to south-central European U.S.S.R. Vienna, which is well within this area, had an average of more than 10 days yr^{-1} with glaze on the ground between 1905 and 1935. Data for the Soviet Union show at least one storm per year during a 10-yr period in an L-shaped area that runs from Leningrad to the southern Ukraine, eastward past Stalingrad, then northward as far as Moscow. Frequencies of two to three storms per year are common north of the Black Sea and Sea of Azov.

8-4 MEASUREMENTS AND INSTRUMENTATION

Snow, in particular among the solid precipitants, possesses a variety of measurable parameters for which there is ample incentive for obtaining data. Consequently, a variety of instruments have been developed and are being used. Since the same instrumentation is applicable with modified techniques to hail, glaze, rime, and hoarfrost, instruments for use with these solid precipitants will not be discussed separately.

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*A general reference for this paragraph is Ref. 38.

Snow research is a specialized activity carried out at locations where natural snow is available in sufficient quantities and for sufficient periods for long-range test programs. Test activities in the United States are primarily carried out by U S Government agencies at sites in Greenland, Alaska, Canada, Antarctica, and the northern coterminous States. Canada, Russia, Switzerland, Japan, and the Scandanavian countries also perform snow research. Tests are carried out at the field site or in laboratory cold rooms. The U S Army Cold Regions Research and Engineering Laboratory (CRREL) at Hanover, N.H., is a Government laboratory that is very active in snow research, development, and engineering.

The specialized nature of snow research and engineering and the relatively few participants in such activity have resulted in the development of relatively few commercially available measuring instruments. As a result, instrumentation is designed and developed by users. Descriptions of certain specialized snow-measuring equipment are available through CRREL to supplement the information provided in this paragraph.

The data that follow do not attempt to describe or list all instruments used in measurements of snow properties. Some are common to other aspects of meteorology and hydrology or to measurements of other environmental factors and are described in other chapters of this handbook. Thus, instruments designed to measure phenomena such as windspeed, air temperature, solar radiation, and other factors not peculiarly associated with snow characteristics are not described here, although they may be used extensively in obtaining associated measurements.

(1) *Snowfall and snow depth.* Snowfall and snow depth are more difficult to measure than would be expected. The blowing of snow while falling or on the ground, its settling and melting, and sampling and human errors create problems in obtaining accurate data (Ref. 39).

One method of measuring seasonal snow accumulation is through the use of long stakes (usually of bamboo) which are fixed in position (Ref. 40). The depth of snow on the ground is determined by measuring and averaging the accumulation at several places. A network of stakes is required; on an open snowfield, a large cross of stakes can be used, one line running at right angles to the prevailing wind direction and another along the wind direction. The spacing of stakes varies with the size of the area to be studied and the resources available. The Soil Conservation Service uses stakes on which are painted large numbers which can be observed from low-flying aircraft.

Measuring sticks thrust vertically into the snow to the ground level are also used. Measurements normally are taken at several spots and the results are averaged. New snowfall accumulation may be measured by placing snow boards on top of existing snow accumulations, then inserting sticks through the new snowfall to the snow boards. Subtraction of previous measurements after a new snowfall is also a means of determining new snowfall accumulation.

On permanent snowfields, often only the annual accumulation is measured. If annual layering can be identified (through snowpits which reveal a vertical profile), the thickness of an annual layer multiplied by its density provides the result in terms of mass or water equivalent. Core drilling may be used to provide samples which can be used for computations.

The rate at which snow falls can be obtained by periodically observing the accumulation of snow on a stake during snowfall. Snowfall rate in terms of equivalent rainfall is obtained by use of a collecting can or by use of a heated tipping-bucket rain gage; in it, the temperature of the receiving funnel is maintained at about 1°C with a thermostatically controlled heater (Ref. 41). A weighing rain gage can be similarly used. The radioactive snow gage is a device that automatically and continuously records the water equivalent of snow on a given surface as a function of time. The attenuation of the radiation from a small radioactive source is measured by a detector above the snow level. The attenuation is dependent on the water equivalent of the intervening snow (Ref. 1). An optical method has been evaluated and found to correlate well with other techniques; in it, the attenuation of light beam intensity over a short path is employed to continuously monitor the snowfall rate (Ref. 42).

(2) *Snow density.* Snow density is normally obtained by weighing a known volume of snow but occasionally the weight is obtained indirectly by measuring the volume of melt water from the sample. Open-ended sampling tubes are used in soft snow to remove a snow sample. Both vertical and horizontal samples are taken, depending on the type of data desired. Vertical samples provide average density of the snowpack and therefore the total equivalent water content. Horizontal samples provide data on density variation with depth and thus the metamorphic processes taking place. Samples are trimmed to size with a spatula or special cutoff plate in the tube and weighed on spring scales or a beam balance. A number of different types of vertical snow-sampling tubes are used in snow surveys; the type depends on the depth and density of the snow to be measured, including (Ref. 43):

(a) The Adirondack sampler, which is constructed of glass fiber with a smooth, sharp cutting point about 2.7 in. in diameter, is about 5 ft long, and is weighed on a specially calibrated scale. This sampler is used extensively in the eastern United States and Canada.

(b) The Federal snow sampler, almost universally used in the western United States and Canada and elsewhere, consists of aluminum sections, each 30 in. long with a 1.5-in. diameter steel cutting point. Tubular sections are coupled to permit sampling at depths of more than 200 in. Graduated slots permit reading of core length.

(c) The High Plains snow sampler, developed by the U S Army Corps of Engineers, is a stainless steel tube 48 in. long with steel driving handles brazed to the tube. The tube is ground to an edge at the lower end to give a core diameter of 2.5 in.

(d) The Bowman sampler is not commercially available, but several sets have been made for the Soil Conservation Service. It consists of threaded 30-in. plastic tube sections that can be coupled together to permit sampling at depths up to about 144 in., and it has a tool steel cutter with a diameter of about 1.5 in. and holes that permit core length observations.

(e) The Mt. Rose sampler consists of 30-in. threaded aluminum tubes that can be coupled for sampling at depths of 200 in. or more. It has a tool steel cutter with a diameter of 1.485 in. and is graduated for core length readings. With a core of this diameter, 1 in. of water weighs 1 oz (Ref. 1). Table 8-12 provides detailed characteristics of each sampler type.

For some of its field measurements of snow-cover density, CRREL uses small 500-cm^3 stainless steel tubes that have sharpened edges and are equipped with rubber caps. The Canadian sampler is similar, but has a volume of 250 cm^3 and is fitted with a handle. These are used for obtaining horizontal samples from various depths in the snowpack and should not be used in layers less than 2 in. thick (Ref. 44).

All snow sampler kits include scales for weighing the sample as it is removed from the snow site. The Chatillon spring balance scale and a tubular, aluminum barrel spring-activated scale (designed for the Federal snow sampler) are most commonly used. These are calibrated in terms of snow density or equivalent water content.

Other techniques have been considered for snow density measurements. Radioisotope techniques have been considered for snow

TABLE 8-12

CHARACTERISTICS OF VERTICAL SNOW SAMPLERS

Sampler	Characteristic							
	Material	Tube length, in.	Core diameter, in.	Depth capability, in.	Core length scale	OD at cutter, in.	OD at coupling, in.	Tube section weight, oz
Adirondack	Glass fiber	60.5	2.655	60.5	None		None	63
High Plains	Stainless steel	48	2.5	48	None		None	144
Mt. Rose	Aluminum	30	1.485	200+	3/8-in. hole with 1-in. spacing	1.75	1.75	30
Bowman	Plastic	30	1.485	144+	3/8-in. hole with 2-in. spacing	1.90	2.23	22
Federal	Aluminum	30	1.485	200+	Staggered slots 1/4 x 4 in.	1.75	2.00	19

density measurements. Radioisotope techniques include a radiotelemetering snow gage using the principle of absorption by water (liquid or solid phase) of the gamma emissions from a cobalt-60 source, detected by a Geiger-Mueller counter tube. Density has also been determined by measuring the attenuation of X rays, using photographic emulsions, photocells, fluorescent screens, and photomultipliers as detectors. Further studies of nuclear measurement techniques have indicated that there are severe limitations in the presently available instrumentation, but it is concluded that nuclear and electronic engineering will enable improvement of both resolution and accuracy of snow density measurements (Ref. 45).

(3) *Hardness.* The most commonly used snow hardness measuring device is the Rammsonde cone penetrometer (Ref. 46). It consists of a 1-m long, cone-tipped sonde, which is graduated in centimeters; four 1-m long extension rods; two pierced cylindrical hammers, which weigh 1 and 3 kg; and a graduated guide rod for the hammers. Snow hardness measurements produced by the rammsonde are expressed as ram hardness numbers, based on the equation

$$R = \frac{Wh}{s} + W + Q, \text{ kg} \qquad (8\text{-}22)$$

where

R = ram resistance, kg

W = weight of driving hammer, kg

h = height of fall of driving hammer, cm

s = depth of penetration per blow, cm

Q = weight of penetrometer, kg

The hammers can be dropped from different heights. Selection of the combination of height and weight is based on the conditions of the snow being measured.

The original rammsonde was found by CRREL researchers to be unsatisfactory for use in age-hardened snow of density over 0.5 g cm^{-3}. It has been modified by CRREL to provide a conical head with a 30-deg point for use in hard snow, in addition to the standard 60-deg point.

The Canadian hardness gage, a hand-pushed, spring-loaded circular plate, is used on softer snows to measure the crushing strength *in situ*. The Canadian hardness number is expressed in g cm^{-2}. The slow CBR (California Bearing Ratio) test developed for soils is used only in very hard snow.

(4) *Strength.* Various devices are used to measure the strength of snow and, generally, such measurements are made in laboratories.

Measurements of unconfined compression under varying density and temperature conditions were made by Mellor and Smith using snow molds to prepare snow samples of different densities and using a portable manual screw press with calibrated proving ring and dial micrometer (Ref. 47). For measurements of samples at higher temperatures, it was found that a rapid creep, rather than a brittle fracture, occurred; however, an electric drill attached to the spindle normally turned by a handcrank approximately doubled the press speed and resolved this problem. The effect of strain rate variations on unconfined compressive strength was measured during the same tests using a variable speed Tinius-Olsen testing machine.

Unconfined compressive strength tests have also been made using a motorized mechanical loading press. This press has a swivel head that assures loading normal to the surface of the sample, and a gear transmission that permits the rate of deformation to be varied from 0 to 2 in. min^{-1} (Ref. 48).

Tensile strength has been measured by use of a snow disaggregator designed and constructed at CRREL. The disaggregator is portable and requires no electric power, although it can be operated with an electric drill. The disaggregator wheel is about 8 in. in diameter and has a large number of small spikes attached to its outer rim. As the snow sample is forced into the rotating spiked wheel, the specimen is disaggregated, one crystal at a time. The force of the spikes causes a proportional phase lag between the outer rim and the primary drive shaft, which causes translation of the ball carriage of a ball-disc mechanical integrator. Its displacement from the disc center is proportional to the applied torque. The disc is coupled to the primary drive shaft and both the integrator output shaft and the drive shaft are coupled to numerical counters. The drive-shaft counter permits judging shaft speed and, even more important, enables the investigator to determine, prior to the test, the integrator counts due to mechanism friction by comparing integrator counts to shaft counts at no load. The resulting ratio is applied as a correction factor.

Ballard, Feldt, and Toth performed measurements of shear strength of snow under varying conditions of temperature and density (Ref. 49). Snow molds were used for sample preparation. The modified SOILTEST direct shear test apparatus that was used is described in their report. Consolidation, frictional resistance, and strain data were also recorded during the direct shear test.

(5) *Temperature*. Most measurements of temperature are made with thermometers, thermohms, and thermistors that are readily obtainable from industrial sources and generally are not peculiar to snow measurements. Mercury-in-glass thermometers are accurate down to about −35°C, and spirit-in-glass thermometers can be used to the lowest natural temperatures. Metal casings should be used to provide mechanical strength for glass thermometers pushed into snow. More precision is possible with platinum resistance thermometers or thermocouples.

The measurement of temperature is subject to a variety of possible errors arising from the particular type of thermometer and from its method of application. Each device has a characteristic lag coefficient of anywhere from 50 to 100 s, which is the time required to reduce the difference between the temperature of the thermometer and that of the environment to $1/e$ of its initial value. Measuring air temperature over snowfields is subjected to radiation and wind-induced errors of various types. It is necessary to shield the measuring instrument from direct radiation, but even then significant errors can occur. An extensive discussion of applicable thermometric techniques is given by Middleton and Spilhaus (Ref. 50).

(6) *Free water content.* Free water content is usually measured by melting a snow sample in warm water inside a vacuum flask calorimeter. Repeated weighings give the weight of wet snow added. Temperature measurements give the temperature drop of the water after the sample has been melted. Knowing the specific heat of water and its latent heat of fusion, the technician uses the depression of the water temperature in the calorimeter to make a direct calculation of the mass of added frozen water when the total added mass is known. The percentage of free water in the snow can then be calculated if the water equivalent of the calorimeter is known.

Wet snow can also be melted while totally enclosed in a calorimeter by passing a metered current through it. By knowing the precise rate at which heat is added, a technician can plot temperature as a function of time; note when the temperature rise indicates that all of the snow is melted; and, from the total heat added, compute the mass of snow originally present. The design of such a calorimeter has been described (Ref. 51).

(7) *Transport of blowing snow.* The rate at which blowing snow is transported horizontally at any given level is found by extracting snow from a narrow airstream during a timed interval. Gages extend a slim nozzle upstream into the wind and orient in the wind direction by means of a pivot and vane. Snow grains can be extracted from the air inside the gage by expanding the stream and reducing the velocity so that grains settle out.

To find the drift density, or mass, of snow present per cubic meter of air, wind velocity measurements at the gage height must be made simultaneously. Drift density can also be measured by means of light beams shining on photoelectric cells. The amount of drifting snow between the light source and the cell governs the intensity of light received by the cell. Experiments have also been made using gamma rays instead of visible light.

(8) *Internal structure of snow.* Measurements of the size, shape, orientation, and bonding of grains and crystals in snow and ice are accomplished by preparing thin sections and photographing them in transmitted polarized light. The snow sample is generally impregnated with a water-soluble aniline dye at a temperature between $-10°$ and $-5°C$ and frozen into a solid block at $-20°C$, with a glass plate frozen on one side. The sample can then be shaved to a thickness of about 0.1 mm with a microtome or a carpenter's plane. Measurements are made using a low-power polarizing petrographic microscope. Photomicrographs are made by attaching a camera to the eyepiece end. The design of a four-axle universal stage with camera mount and camera has been described (Ref. 52).

(9) *Optical measurements.* The optical properties of snow are profoundly influenced by metamorphism and ablation, that, in turn, determine mechanical properties of snow. Aside from albedo measurements (made with albedometers), few studies have been made of optical effects in snow. Mellor measured extinction coefficient for the visual range as a function of wavelength, grain size, and snow density, and reflectance as a function of wavelength. Instrumentation consisted of an internally blackened stovepipe to hold snow samples, a cold-white fluorescent lamp consisting of 11 concentric tubes, and an ultrasensitive brightness meter. A detailed description of this, as well as a means used to test wet snow in the field, have been described by Mellor (Ref. 53) and by O'Brien (Ref. 54).

(10) *Permeability.* The permeability coefficient is measured with apparatus either assembled in the laboratory or, alternatively, a commercial snow permeameter is available. With the commercial instrument*, snow samples of 500 cm^3 or less, in the form of a cylinder 5.8 cm in diameter and 18.9 cm or less in length can be tested. The apparatus consists of a cylinder in which the sample is sealed. Air is forced through the snow by a sealed piston traveling at various speeds as controlled by a variable speed electric drive. The volume of air passing through the snow per unit of time is measured by noting the length of piston travel on a graduated scale. Pressure developed in the void between the piston and the bottom of the snow sample is measured by a micromanometer equipped with an optical readout, accurate to ± 0.0002 in. of water. The practical range of the instrument is limited to wind-drift snow or hoar depth of 0.25 g cm^{-3} density, where the coefficient of permeability ranges from approximately 150 to 400 cm s^{-1}.

Apparatus assembled in the laboratory for measurement of snow permeability can measure snow permeabilities as low as the 10 cm s^{-1} characteristic of older compact snows (Fig. 8-25). The apparatus used for measuring small rates of flow, 0.06 to 0.8 cm^3 s^{-1}, is similar to most constant head permeameters, except that a liquid is used to displace the air that is forced through the sample. The rate of flow of the liquid is measured by weighing and timing with a stopwatch. In practice, the one regulator valve was replaced by a manifold of three valves that were left at different rates of flow and checked only at the beginning and end of the operation on a given sample.

For greater rates of flow, 0.5 to over 2,000 cm^3 s^{-1}, the apparatus consists of three concentric cylinders. The inner A, and outer C, cylinders are fixed and the space between holds kerosene. The middle cylinder B moves up and down, with the kerosene acting as an air seal. Air is drawn or forced through the sample by moving the middle cylinder up or down. The movable cylinder is raised or lowered by winding or unwinding a wire on a

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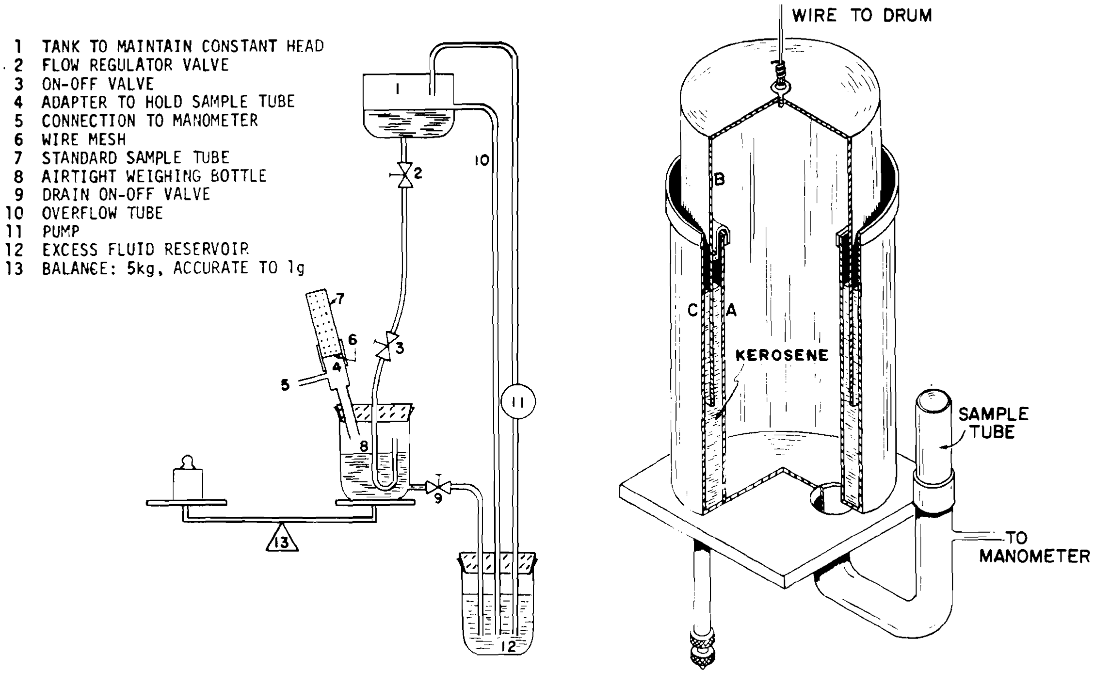
*Available from SOILTEST, Inc., Chicago, Ill.



(A) Permeameter using liquid to displace air. Used for rates of flow 0.06-0.8 $cm^3 s^{-1}$

(B) Constant velocity permeameter. Used for rates of flow 0.5 to over 2000 $cm^3 s^{-1}$

Figure 8-25. Laboratory Permeameters (Ref. 13)

drum. The sample tube for the measurements is a polished stainless steel snow tube, length 18.9 cm (7.4 in.) and inner diameter 5.8 cm (2.28 in).

(11) *Remote sensing.* A variety of techniques for obtaining data on snow from an aircraft or satellite platform are being developed and evaluated. The objective is to acquire capability for obtaining larger amounts of data than is now practical by laborious, point-by-point sampling and to obtain synoptic information on the snow cover that is not now possible. The two principal classes of techniques are (1) the passive techniques of photography, infrared scanning, and radiometry and (2) the active sensors employing primarily radar. Examples of satellite photography in observing snow cover are shown in Figs. 8-26 and 8-27. Considerable data using solarimeters have been obtained on the surface albedo using aircraft surveys (Ref. 55). Remote instrumentation, although now in the early developmental stage, will provide an invaluable source of data on the nature, extent, and temporal changes of the global snow cover.

8-5 EFFECTS OF THE SOLID PRECIPITANTS

The effects of the several solid precipitants are sufficiently different to discuss them separately. There are, however, common features based on the fact that they are all atmospherically derived frozen water. For example, all can result in excessive loading of suspended wires, all can make a surface slippery, and all can interfere with the operation of exposed mechanical assemblies. Furthermore, each of the solid precipitants can occur in combination with other environmental factors, such as wind, rain, temperature, solar radiation, or humidity, in such a way as to enhance detrimental effects.

Much of the information on the effects of solid precipitants is qualitative. Either the effect is not quantifiable or its quantification has not been accomplished. Exceptions are

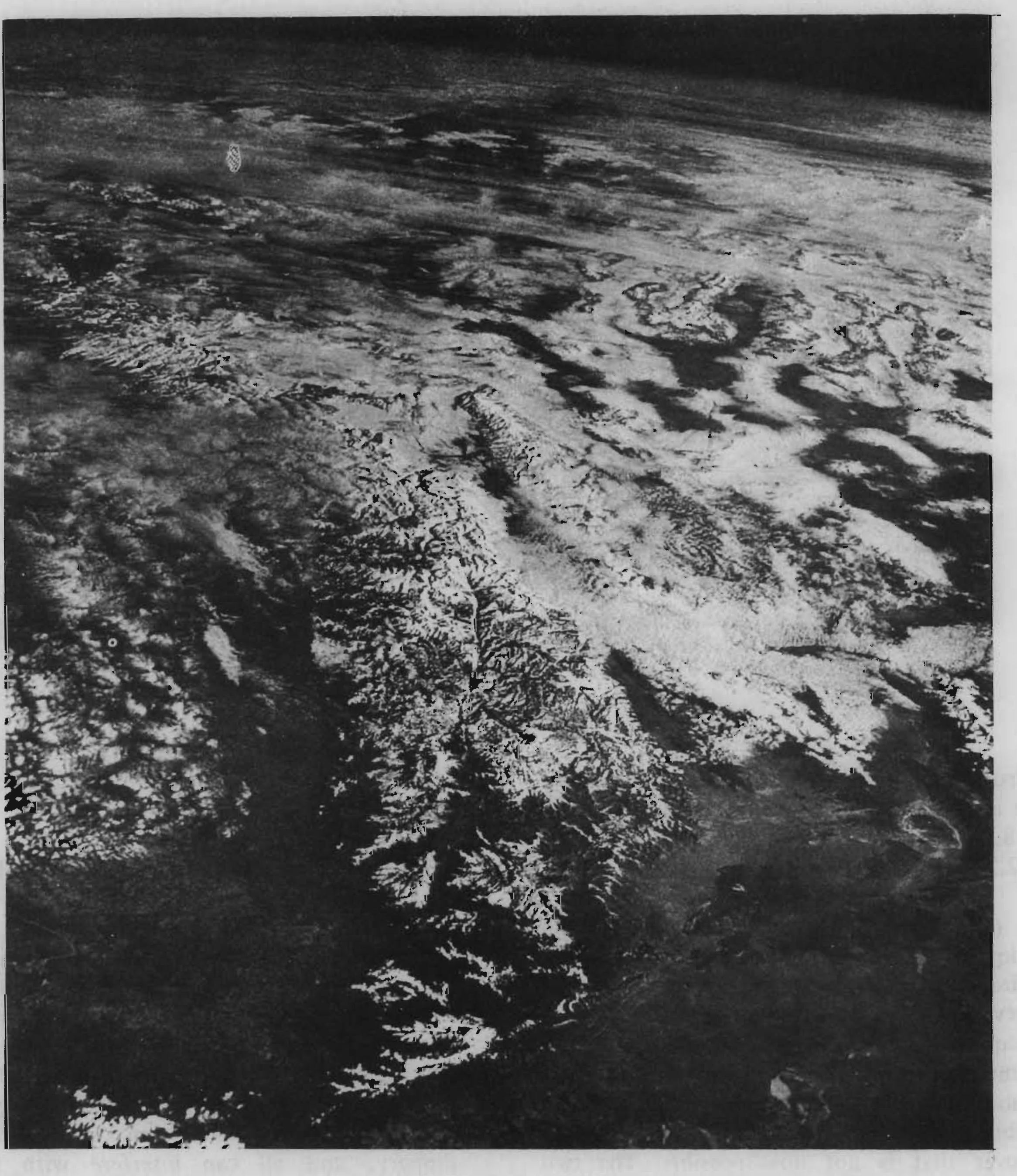
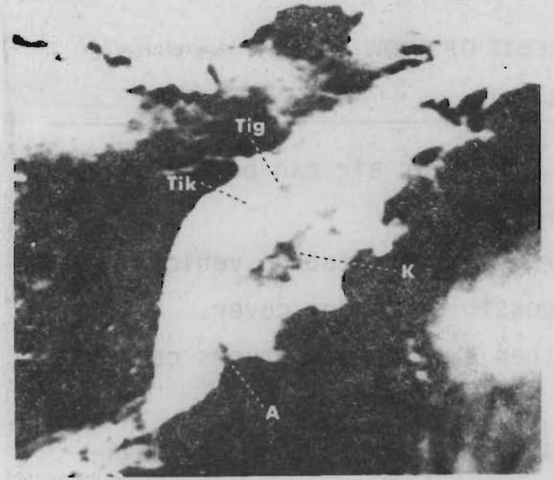
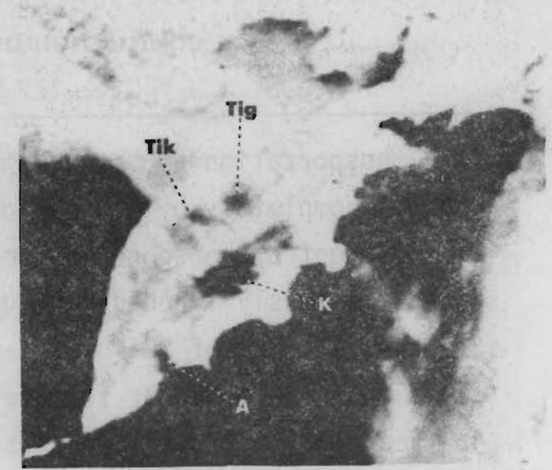


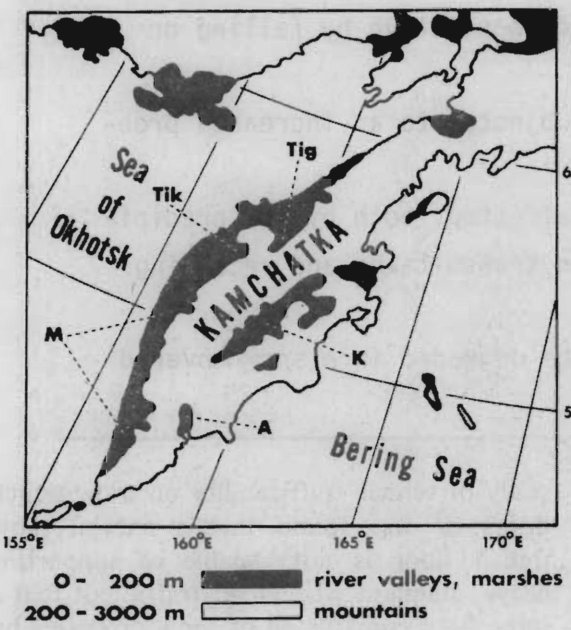
Figure 8-26. Satellite Photograph of Sierra Snow Cover (Ref. 56) (Apollo 9 photograph (Mar 69) showing mountain snow cover in Southern Sierras Region, United States. The ground resolution in this photograph is of the order of that proposed for future Earth Resources Satellites Systems (NASA photo).)

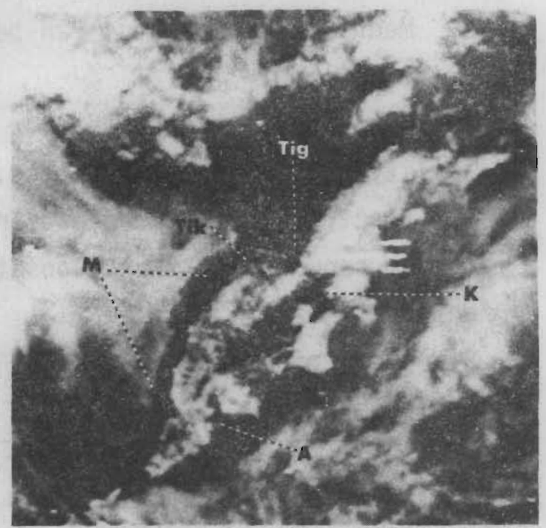


22 April 1970 - Snow melt has begun in the Kamchatka (K), Avacha (A), Tikhaya (Tik), and Tigil (Tig) river valleys.



27 April 1970 - Further snow melt in these river valleys is evident. Note also, overall peninsula reflectances have decreased.





27 May 1970 - All river valleys (K, A, Tik, Tig) and marshland (M) snow cover has melted.

Figure 8-27. Snow Melt Surveillance (Ref. 56) (Kamchatka, U.S.S.R., Nimbus 4 Image Dissector Camera System (IDCS))

found in considerations of snow loadings on structures, which comprise engineering data of considerable economic importance and in transportation-related data required for important practical applications.

8-5.1 MATERIEL PROBLEMS CAUSED BY SNOW

The effects of snow on materiel (summarized in Table 8-13) are discussed:

TABLE 8-13.

COMPILATION OF EFFECTS OF SNOW

1. Transportation by motor vehicle, rail, or air can be slowed or stopped completely by deposited snow.
2. Movement of personnel by foot or by transportation vehicles can be seriously impeded or made impossible by snow cover.
3. Snow loading of buildings and other exposed structures can cause their collapse or failure.
4. Features of the terrain obscured by snow cover can make navigation or position location difficult.
5. Requirements on camouflage are altered in a snow cover environment.
6. Mechanical apparatus can be made inoperative by falling or drifting snow.
7. Personnel activity on snow is subjected to an increased probability of accidental injuries.
8. Electromagnetic propagation is affected, both by the precipitating snow and by that deposited on transmitting and receiving antennas.
9. The performance of weapons can be degraded in a snow covered environment.

(1) *Conventional transport vehicles.* When a snowfall accumulates to a depth where the tractive force at the wheels is insufficient to overcome the resistance of the snow, conventional wheeled vehicles are immobilized. Mobility depends on the wheel diameter; a wheel diameter at least four times the snow depth is required in soft snow. On old snow, the bearing strength of the snow and the vehicle load must be such that the wheels sink to less than 25 percent of their diameter (Ref. 57). Light vehicles with high-flotation tires can usually travel over wind-packed snow at temperatures below −12°C, but prepared trails are required on new soft drift snow or on old snow when the temperature approaches 0°C (Ref. 58). In a study of vehicle trafficability on snow trench floors, it was found that a natural snow trench floor is not capable of supporting heavy, standard wheel-load traffic but that a snow floor constructed of snow processed by a Peter snow miller is capable of supporting 7,000-lb wheel loads for at least 500 coverages without any indication of failure or surface wear (Ref. 59).

(2) *Tracked vehicles.* Tracked vehicles may operate either by flotation or by ground support. For snow up to 25 cm in depth, ground support, whereby the snow is compressed against the unyielding ground, allows movement by farm tractors, construction equipment, and all types of tracked

combat vehicles. When the snow depth increases to 75 cm, small tracked vehicles (gross weight less than 6,000 lb) must float on the snow surface, but heavy vehicles still obtain ground support and thus are more effective. For snow depths greater than 100 cm, only vehicles with light track pressure and uniform pressure distribution can operate consistently.

(3) *Personnel movement.* In addition to limitations placed on personnel movement by vehicular movement restrictions, personnel on foot are severely limited by soft snow cover. When snow reaches a depth of 10 cm, the additional energy required to walk through it reduces operational effectiveness of troops. As the depth increases further, a point is reached at which activities cease because the effort of moving through the snow cover does not permit additional productive activities. The synergistic influence of other environment factors—temperature, wind, fog, or rain—can accelerate this deterioration of personnel mobility. Where these factors are present, additional items of materiel, such as skis and special vehicles, can partially alleviate the restrictions.

(4) *Snow load.* As noted in par. 8-2.1.2.1 snow density varies from 0.1 to 0.83 g cm^{-3}. If 0.20 g cm^{-3} is taken as a value for a newly fallen snow, then a 10-cm (≈4-in.) snowfall produces a load of approximately 20 kg m^{-2} or 4 lb ft^{-2}, which is a load of 3.6 tons on a 30- by 60-ft structure. In construction of buildings in the cold and extreme cold regions, the potential snow load often determines the design strength and thus is a major factor in the cost of a building. Building codes in New York State, for example, require roofs designed for snow loads between 20 and 60 lb ft^{-2} with the design load reduced for roof pitch over 20 deg (Ref. 60).

The snow load that occurs in various regions is discussed in par. 8-3.1. Specifications on snow load in AR 70-38 require a load-sustaining capability of 40 lb ft^{-2} in the intermediate cold, the cold, and the extreme cold climates unless the installation is cleared between or during snowfalls. In this case, the specification is modified to 20 and 10 lb ft^{-2}, respectively.

Structural failure under heavy snow loads occurs most frequently in the intermediate cold zone, particularly where wet snow predominates. The infrequent heavy wet snows create an extreme loading condition, often not provided for in design of structures. Over 100 people were killed in 1922 by the collapse of the Knickerbocker Theater in Washington, D.C., after a 28-in. wet snowfall; the dome of the Seattle Cathedral collapsed in 1916 under a 32-in. load of wet snow; and in 1960 many buildings in Georgia, Tennessee, and Kentucky were similarly damaged (Ref. 30).

Wet snow, particularly when alternate thawing and freezing occur, can present a critical problem to utility lines. Broken lines can result from a single storm and interruptions often occur due to the rapid unloading of lines, causing them to snap and whip with consequent arcing.

In the extreme cold climate, the snow load accumulates at a rate of 20 to 100 lb ft^{-2} per year and presents a unique loading problem for permanent structures.

(5) *Obscuration.* Falling snow often cleanses the air and improves visibility. While snow is falling, however, visibility can be extremely low; during blizzards, it is sometimes necessary to provide indoor illumination. In a natural environment, fallen dust cannot return to the air until after the snow melts and the ground dries; thus the best atmospheric visibility is found in the winter months. In industrialized environments, however, the atmospheric cleansing by snow is more than offset by increased combustion of fossil fuels. Large quantities of particulate pollutants are discharged into the atmosphere, so visibility in winter is lower than that in summer (Ref. 6).

Obscuration of aerial landmarks with snow cover, as tabulated by Kulakov and Shtal and reported by Rihkter, is given in Table 8-14 (Ref. 6).

Spring fogs are often associated with remnants of the snow cover. These fogs form either as a result of cooling of the moisture-laden air over the snow or by mixing of air cooled by the snow with warmer air (see Chap. 9 for further discussion of fog formation). In any case, visibility can fluctuate rapidly during the spring thaw of the snow cover.

The high reflectivity of the snow cover can have significant effects on observations and operations (Ref. 61). An observer can be made completely ineffective by the reflected rays of the sun and, in the extreme cold regions, may suffer eye damage without protective glasses. The white background makes it difficult to determine range and, under conditions producing whiteout, depth perception is lost (see Chap. 9). The large changes in illumination of the ground brought about by reflection of the snow cover and the changing angle of incidence of solar radiation are of great importance in aerial photography.

(6) *Camouflage*. The normal colors of military equipment stand out with particular sharpness against the white of the snow cover. Even if a protective white cover is provided, the shadows produced by sunlight are easily seen. Tracks left by vehicular or other activity are also readily discerned from the air, particularly where the snow cover is light and the snow is mixed with the underlying soil. The normal varied backgrounds of the natural environment allow concealment of installations, materiel, or activity but are completely lost in the uniform landscape of the snow cover (Ref. 6).

(7) *Mechanical assemblies*. Drifting, falling, or splashed snow can jam mechanical apparatus and prevent it from operating normally. A simple example of this problem is wet snow that blows into a door latch, freezes, and prevents opening of the door (Ref. 62). Tracked vehicles sometimes require periodic cleaning of the suspension and track mechanism to allow continued operation and to prevent breakage. Additional maintenance is required on aircraft exposed to snow to assure operation of the airfoil control surfaces. Rifle and gun mechanisms can be made inoperable by snow. Many of these effects are particularly severe when the snow is partially melted and refreezes, thus producing a stronger mass.

Ice crystals increase rapidly in hardness as the temperature goes down. They approach 6 on Mohs' scale at −60°C, which is a hardness equivalent to that of feldspar. An erosive effect noted on the lower faces of cliffs in the extreme cold region has been attributed to blowing snow, but may actually result from sand mixed with the snow. The destructive effect of snow grains impacting a surface at high speeds must be considered, particularly for delicate instruments or apparatus (Ref. 6).

(8) *Personnel injury*. Snow surfaces are often slippery and injuries resulting from falls are common. Of equal concern is the added exertion required during personnel activities in the snow which often result in heart attacks. Additional personnel hazards arise from vehicular accidents caused by snow and by obscuration of terrain hazards such as bodies of water, crevasses, and concealed obstacles.

An important source of peril in mountainous regions is the avalanche. Avalanches can be classified as loose snow or slab, full depth or surface, dry or wet snow, open slope or gully, and airborne or flowing. They are caused by an unstable accumulation of snow on a slope, and they travel at between 50 and 190 kt ($1 \text{ kt} = 0.51 \text{ m s}^{-1}$). Factors contributing to the buildup and release of avalanches include angle of slope, topography, vegetation, and meteorological conditions. In mountainous regions where snowfall or drifting has caused snow to accumulate, avalanches are to be considered an important factor in operations. They can be triggered, sometimes very easily, by slight perturbations of the snow. It has been noted that even the

TABLE 8-14

AERIAL LANDMARK VISIBILITY

			Electrically lighted cities	Large railroad stations	Nonelectrified villages	Railroads	Highways	Dirt roads	Lakes	Large rivers	Streams	Lighthouses	Aviation beacons	Campfires	Woods
Daytime	In clear weather	Below	5 5	5 5	5 5	5 5	5 5	5 5	5 2	5 2	5 3	2 2	2 2	1 1	5 5
		To the side	5 5	4 4	5 5	3 4	4 4	3 4	5 1	5 2	4 1	3 3	3 3	1 1	5 5
	In cloudy weather	Below	5 5	5 5	5 5	5 5	5 5	5 5	5 2	5 3	5 3	4 2	4 2	1 1	5 5
		To the side	4 4	4 4	4 4	2 3	3 3	2 3	5 1	5 1	5 1	5 3	5 3	1 1	3 4
Night	Moonlit and clear	Below	4 4	4 4	3 3	2 3	4 4	3 4	3 1	3 2	2 2	3 3	5 5	3 3	3 4
		To the side	4 4	4 4	2 2	1 2	2 2	1 2	5 1	5 1	4 1	5 5	5 5	4 4	3 3
		Beneath moon	3 3	3 3	2 2	1 2	2 2	1 2	5 1	5 1	4 1	5 5	5 5	4 4	3 3
	No moon and clear	Below	3 3	3 3	2 2	1 2	2 4	1 2	1 1	1 1	1 1	3 3	5 5	3 3	1 3
		To the side	3 3	3 3	2 2	1 1	1 2	1 1	2 1	2 1	1 1	5 5	5 5	5 5	1 2
	Cloudy	Below	3 3	3 3	2 2	1 1	1 2	1 1	1 1	1 1	1 1	5 3	5 5	4 3	1 1
		To the side	3 3	3 3	2 2	1 1	1 1	1 1	1 1	1 1	1 1	5 5	5 5	4 4	1 1

Visibility index

1. Zero
2. Poor
3. Fair
4. Good
5. Excellent

The upper index is for visibility without snow cover; the lower for visibility with snow cover.

shadow of a skier has been sufficient to initiate an avalanche by causing water in the snow to freeze—its resultant expansion triggering the event (Ref. 63).

(9) *Electromagnetic.* Radar meteorology based on the backscatter of electromagnetic waves by hydrometeors is a useful technique for the study of clouds and precipitation (Ref. 64). The theory, techniques, and data of radar meteorology comprise a complex, active branch of meteorology (see, for example, papers presented at the *Thirteenth Radar Meteorology Conference,* Ref. 65). In discussing effects of the solid precipitants, the scattering and attenuation of electromagnetic waves, which is useful for the study of meteorology, must be recognized as detrimental effects. Precipitating snow interferes with the normal use of electromagnetic waves for detection by radar and for radio communication as well as providing obscuration relative to the electronic intelligence derived from uncooperative emitting sources.

The detailed characterization of electromagnetic propagation in the presence of snow is sufficiently complex to prevent treatment in this handbook. The cited references should be consulted for further information.

(10) *Weapon effects.* Fragmentation ammunition using point-detonating fuzes does not receive sufficient resistance from the snow cover to detonate at the surface. The result is burial before detonation, with a large deterioration in the effectiveness of the ammunition (Ref. 66). Should the projectile function, fragment speed will be degraded—as a function of the depth and density of the snow. These observations illustrate the type of problem encountered in use of weapons on snow cover. Snow cover affects the ability to deliver a weapon to the target and to produce the desired effect on delivery. Similarly, precipitating snow can affect the performance of those weapons dependent on optical or electromagnetic guidance or fuzing. These adverse effects result because weapons were designed for the more common nonsnow environment; if weapons are to be used in snow, compensatory modifications in design, application, and performance of such materiel are often required.

8-5.2 MATERIEL PROBLEMS CAUSED BY HAIL

Hail is similar to snow in its effects on electromagnetic propagation, but in most other respects it is different. This is primarily because hail rarely persists as a groundcover; however, as a precipitating solid, it can produce much more damage than that caused by snow. The most well-known damage is that to crops. Such losses are sufficient to merit special insurance coverage in the United States and extensive weather modification studies in the U.S.S.R. (Refs. 22, 23). Almost equally well known is the damage to aircraft. Broken windshields, denting of wings and stabilizers, broken lights, nose section cracks, and other incidents of major damage have been tabulated (Ref. 22). Damage to equipment and structures on the ground is less common. Although spectacular damage may sometimes occur, the larger, more destructive hailstones are sufficiently rare and limited that protective design is not warranted.

8-5.3 MATERIEL PROBLEMS CAUSED BY GLAZE, RIME, AND HOARFROST*

Of these three forms of deposited ice, glaze causes the major damage to materiel because of its higher density. Hoarfrost can sufficiently load suspended utility wires that their mechanical vibration is affected, allowing, in rare incidences, "dancing" of the wires which can be destructive. Under unusual meteorological conditions, rime may so accumulate that it has a considerable loading effect. Unusual rime deposits of this type are shown in Fig. 8-18. Utility and communication wires, particularly in mountainous regions, can be broken by such accumulations. Rime deposits up to 1 ft in diameter have been observed on utility wires crossing the Continental Divide in the United States.

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*This paragraph is abstracted from Ref. 38.

True glaze causes more damage to exposed utility installations than do all other environmental factors combined because of its greater density and its tenacity. Utility damage is not the only effect of glaze. Either by itself or with snow, it can cause major disruptions in transportation, although usually for relatively short time intervals. Glaze can temporarily incapacitate exposed machinery or weapons as well as present an increased injury hazard to personnel carrying out activities in a glaze storm.

The collapsing and breaking of exposed wires, structures, and trees by glaze loads constitute the most important effect of glaze on materiel. The thickness of the glaze coating on the object is not predictable since it varies with the amount of precipitation, with the height of the exposed surface above ground level, with temperature, and with other meteorological variables. Loads of 10 lb or more per foot of wire have been reported.

Modern design of power distribution systems allows little direct damage from the ice load on the wire. More often, damage results from secondary effects—from wind action on ice-coated wires or from the motion induced by unloading ice from the lines. In most cases, however, it is the breakage by falling trees or the electrical shorts resulting from falling tree branches that results in major damage to the lines. Uneven loading of wires, decreasing their spacing so that electrical shorts occur, and asymmetrical stress on the supporting towers are also caused by glaze.

Tree damage due to glaze storms is a major factor in the configuration of forest, orchard, and shade trees in the glaze belt. Glaze is one of the most important hazards to normal healthy tree growth. In forested regions, trees or branches that have fallen due to ice load not only disrupt utility systems but also make roads impassable and damage structures. A large tree can be coated with 50 tons of ice in a glaze storm. In many cases, snow following the glaze adds to the load and to the resulting damage. Forests, after glaze storms, can be impassable due to the mass of fallen trees and branches.

8-5.4 SYNERGISM OF ENVIRONMENTAL FACTORS

Solid precipitation may occur in combination with most other environmental factors. However, from a practical standpoint, most impact on materials and structures results from combinations of solid precipitation, wind, and temperature. Although solar radiation, humidity, and pressure are commonly found in combination with solid precipitation, their synergistic effects are slight.

The combination of solid precipitation, wind, and temperature occurs as a synergistic total of environmental factors, with many variations possible. Thus, strong winds at low temperatures may produce large-scale problems from drifting and blowing of snow which would not occur at higher temperatures. Strong winds at higher temperatures produce major damage to transmission lines. Therefore, it is the various combinations of wind and temperature with solid precipitation that must be considered in design of materiel for use in climates subject to solid precipitation.

Snow frequently occurs in combination with wind, and its effects are significantly increased under these conditions. However, the effect of blowing snow on materials of construction, parts, components, and assemblies is not as great as on equipment, transportation facilities, structures, and personnel. The blowing of snow which results in drifts increases the snow loading on structures and may cause damage that would not have occurred under conditions of normal accumulation. Damage is increased when wind-driven, wet, heavy snow is caused to adhere to transmission lines. In one reported case, wet, heavy snow combined with average windspeeds of 35 to 40 mi hr^{-1} and gusts up to 60 mi hr^{-1} produced major disruption of utility services; the storm broke wooden poles that had previously withstood the fury of hurricanes, 77 of 110 33-kV transmission lines tripped and 57 of them had major faults (Ref. 67).

Blowing snow affects the operation of radio antennas. Snow crystals in the air are electrically charged. When the snow is blowing, the charges on the particles may become quite large, tending to increase with increasing windspeed and decreasing temperature. The electrical field of the atmosphere is drastically modified, usually by increasing the normal positive potential gradient. Conductors exposed to the blowing snow become strongly charged and spark discharges occur where there are large potential differences. The repeated discharges are a source of serious radio noise at lower radio frequencies (Ref. 9).

Temperature dictates, to a large extent, the duration of snow on the ground and the properties of the accumulated snow. It affects snow density, viscosity, water content, hardness, and strength. When temperatures rise above the melting point, snow becomes water; its effect in this phase on materials of construction, parts, components, and assemblies is discussed in Chap. 7, "Rain".

8-6 DESIGN GUIDANCE

For the several cold climates, the design of many items of materiel must take into account the effects of snow and the other solid precipitants as environmental factors. This applies to buildings, clothing, vehicles, and weapons. Limitations placed on operations by the solid precipitants require special materiel items. Procedures and activities must be modified to protect against and to adapt to the environments of the solid precipitants. The extensiveness of such materiel considerations forbids complete coverage in this handbook. Thus, attention is focused on three considerations that are peculiar to snow; i.e., snow removal, oversnow transport, and control of drifting snow. In addition, the use of snow as a construction material is discussed in par. 8-6.4.

8-6.1 SNOW REMOVAL

The dependence of the civil economy and the military capability on wheeled vehicles, including aircraft, has imposed a demand for rapid snow removal from city streets, highways, airports, railroads and their marshalling yards, civic and industrial parking areas, and loading docks. Most wheeled vehicles are immobilized by 8 to 10 in. of snow on the ground. Even light tracked vehicles and military tanks cannot maintain satisfactory mobility in snow more than 25 in. deep. Propeller-type aircraft may be able to take off and land in 4 in. of snow, but commercial aircraft are limited by FAA requirements to operation on not more than 0.5 in. of slush. Except in very cold weather, 1 or 2 in. of new snow on an airport are rapidly converted to sufficient slush to prohibit jet aircraft operation.

A bare pavement is the ultimate goal in snow removal operations on heavily travelled highways and city streets, and at all airports with regularly scheduled commercial airline services. The U S Air Force has a prime requirement for snow- and ice-free runways at all times. A requirement by the Air Force in 1949 for complete clearance of a 300-by 10,000-ft runway in 30 min with snow falling at the rate of 2 in. hr^{-1} cannot be achieved yet with existing equipment and techniques. At advanced fields, where sufficient equipment or personnel are unavailable for snow removal, compacted snow runways may be used.

Maps showing the duration, distribution, and amounts of the seasonal snow cover, such as those presented in par. 8-3, are not sound bases for establishment of a snow removal program or for selection of appropriate snow removal equipment. Rapid snowfalls create a more serious removal problem than slow accumulations because snow depths may increase beyond the available plow capacity (Ref. 68). As automobiles and trucks become immobilized by rapidly accumulating snow,

Figure 8-28. High Snowbank (at Blue Canyon Airport, Calif., elevation 5,400 ft) (Photograph by R. W. Gerdel)

they impede plow operations. Drifting may lead to the rapid return of hazardous traffic conditions and may even immobilize the best snow removal equipment because of mechanical inability to cope with the volume of snow or the inability to refuel snowplows.

Airfield maintenance presents some peculiar problems. In regions where dry, cold snow prevails during much of the winter, wind-blown snow lifted from plowed snowbanks along airport runways often reduces visibility to 10 or 15 yd. When high, plowed snowbanks alongside runways start to thaw, the drains are often unable to handle the volume of melt water, and runways flood to depths sufficient to prevent aircraft operations. Snow can be just as dangerous alongside as on runways so that effective snow removal may require not only plows but also conveyors and dump trucks (Ref. 69). An example of a 16-ft snowbank is shown in Fig. 8-28; the embankment was produced by a seasonal removal program based on the use of high-speed displacement plows during a snowstorm and on rotary plow cutback when the storm had ceased.

Construction of roads without sufficient right-of-way or control of building encroachment along the highway can lead to major snow removal problems. Fig. 8-29 effectively

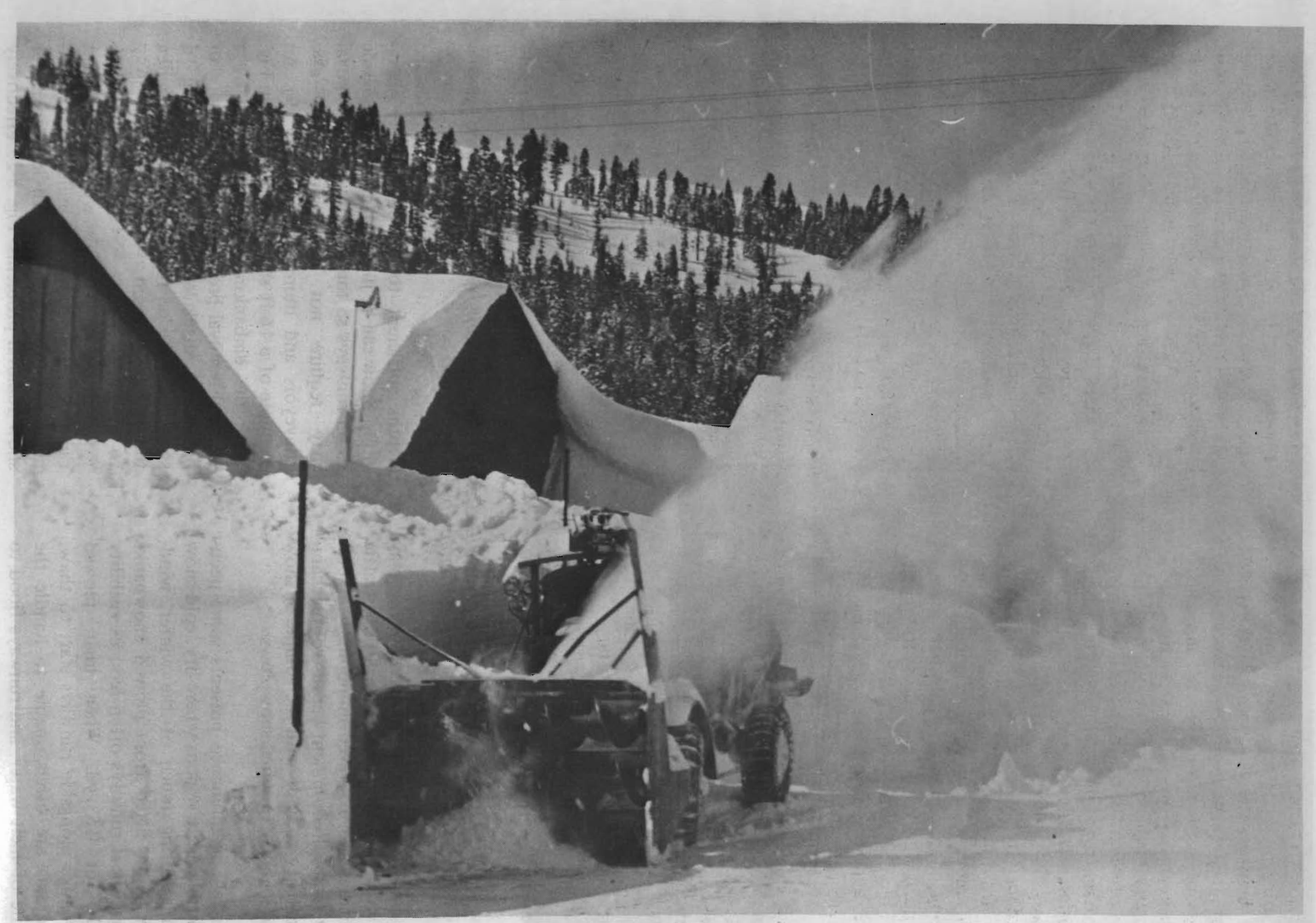

Figure 8-29. Snow Removal Problem (Donner Summit, Calif.) (Photograph by R. W. Gerdel)

illustrates a primary and secondary problem. The primary problem results from lack of room between the roadway and the service station, restaurant, and garage complex for storage of snow moved off the highway by displacement plows during a storm. The secondary problem is created by the extreme width of roadway over which the cast from the rotary plow must be made under such conditions. Light snow deposited on the roadway by fallout from the cast creates hazardous traffic conditions. The blowing snow from the plow reduces visibility for traffic moving in both directions. Modern highway construction programs have eliminated much of this type of interference with snow removal; however, on older roads, in cities, and on many military bases, such problems are still prevalent.

Mechanical removal of snow is most commonly accomplished with truck- or tractor-mounted blades or with rotary-blower systems that mill the snow and blower-cast it a considerable distance from roadway or runway. With suitable attachments, the milled snow may be discharged directly into trucks for removal from the area. Rotary brooms may be used in conjunction with plows or alone to remove a very light snowfall. Minsk presents a comprehensive survey of snow and ice removal equipment used by civilian and military agencies in the United States, Canada, and several European countries (Ref. 70). A type classification of snow removal equipment developed by Minsk and presented by Mellor is given in Table 8-15 (Ref. 68).

The most commonly used snowplows may be separated into three basic types—pushers, high-speed displacement plows, and rotary plows.

(1) *Pushers.* Blade systems are mounted on low-speed wheeled or tracked vehicles that operate like bulldozers. Effective in close quarters, tractor types often are used to push snow to rotary plows operating in narrow passes or in places where high banks must be cut down to widen the roadway.

(2) *High-speed displacement plows.* These are wedge or "V" plows and blade-type plows with conical or hydrodynamically designed shapes attached to vehicles of 25 to 60 tons gross weight and operated at speeds of 20 to 40 mph. Vehicles may have positive four-wheel drive and four-wheel steering. Wedge plows may have movable wings on either or both sides. Depending on snow density, some of the heavy-duty, high-speed plows can clear a 28-ft width of highway or airport runway when operating in 2 ft of snow at 30 mph. Single blades set at a 40-deg angle and pushed at 35 to 40 mph, can cast snow 50 to 75 ft, depending on windspeed and wind direction. Wedge types are used on railroads to clear single track lines, and angle-mounted blades are used to clear multiple track lines.

(3) *Rotary plows.* Rotary plows are equipped with powered front-mounted augers and with rotating cleated drum or "scoop wheels" that disaggregate heavy snow and deliver the comminuted snow to a chute that can be controlled for height, distance, and direction of cast. An axial-flow impeller fan is used in the collection and ejection chamber on most rotary plows. Rotary plows used on railroads are high-speed fans with reinforced cutting edges that serve as disaggregators, collectors, and blowers. Rotary plows are used in deep, high-density, or hard snow to open roads not cleared by blade plows during a storm and to widen roadways and runways following high-speed blade removal. Rotary plows used in cities frequently are equipped with discharge chutes adapted to truck loading to prevent uncontrolled discharge of hard icy fragments, stones, and gutter debris.

The two most commonly used snowplows are shown in Figs. 8-29 and 8-30. There are many variations of each type. The Air Force prefers a 54,000-lb gross vehicle weight for high-speed blade or blade and wing plows, but the Army uses a lighter weight, more maneuverable vehicle with a maximum gross weight not over 34,000 lb.

There are a number of commercial

TABLE 8-15

CLASSIFICATION OF SNOW REMOVAL EQUIPMENT

Blade or displacement plows

- Front mounted
  - V-blade
  - One-way blade
    - Fixed position, right or left cast
    - Reversible, swivel or roll-over

- Underbody
  - Truck mounted
  - Road grader

- Side mounted (wings)

- Towed (drags)

Rotary plows

- Two-element type (impeller-booster fan)
  - Auger
    - Horizontal axis
    - Vertical axis
    - Swept-back axis
  - Cutters
    - Helical
    - Horizontal breakers (rakes)

- Single-element type (no impeller)
  - Scoop wheel
  - Drum

Pure blowers

- Compressor fed, compressed air jet
- Combustion jet, (aircraft jet engine)

Power brooms

Hybrid machines

- Combination blade and impeller
- Combination blade and cutter
- Combination broom and blower

Specialized devices (For compacted or refrozen snow, etc.)

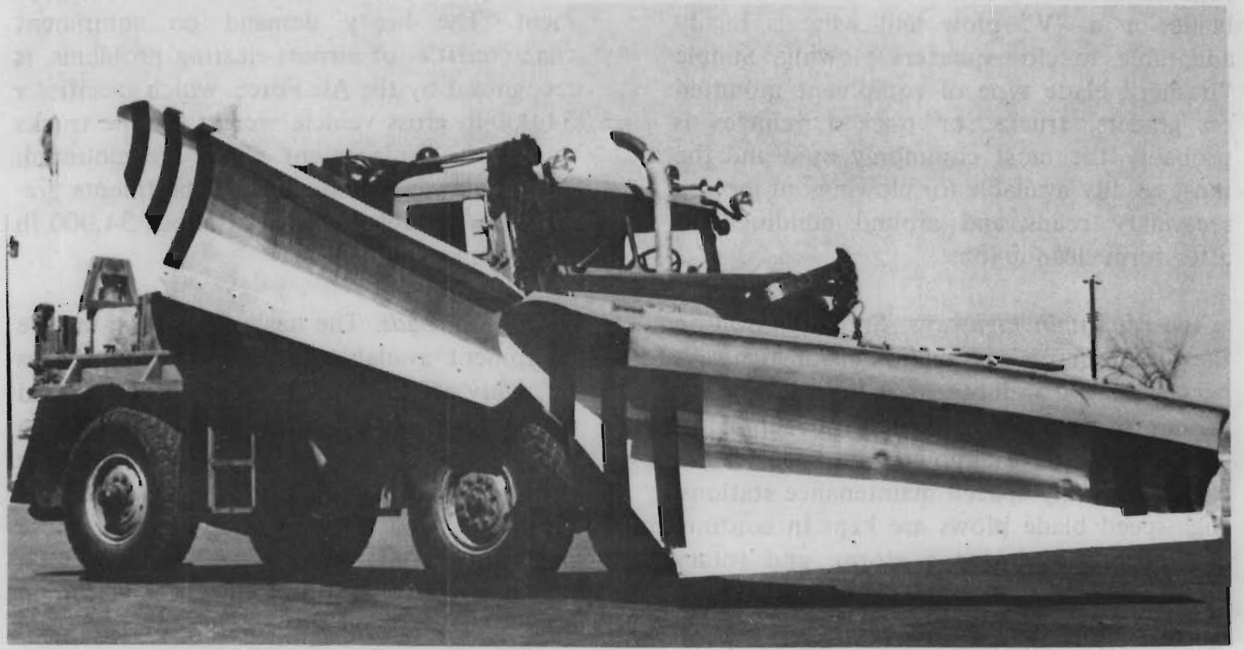

Figure 8-30. Blade Plow With Wing (The wing may be removed when not required. It is used to widen roadways and shape banks during clean-up operations.) (Photograph by L. D. Minsk)

products for surfacing moldboards, augers, and impeller fans that are claimed to reduce friction and to increase plow performance. Their efficacy and economy under heavy-duty operations and over a wide range of snow conditions have not been fully demonstrated.

Miscellaneous and specially adapted equipment designed for use where commercially available plows do not provide satisfactory snow removal are not uncommon. They include power brooms, jet snow blowers, and special ice removal devices.

Effective snow removal requires that an efficient program, applicable to a specific area, be established and that it be activated at the first indications of a storm or on receipt of a storm warning from weather services. Equipment and operators should be on duty before the storm arrives. By starting removal operations while the snowfall is light, equipment can be operated at high speeds for more effective roadway clearance. By staying ahead of the storm, less equipment is needed and a more satisfactory roadway and runway clearance job is accomplished. These axioms apply to railroads as well as to highways and airports.

(1) *Open highway clearance.* High-speed blade plows on four-wheel-drive trucks are operated at speeds up to 40 mph to provide maximum length of cast. On secondary roads, "V" or wedge plows with or without side wings may be used. Normally, plowing should be in the direction of traffic movement. If plowed snow sets for even 1 hr, it will start to harden and, in a few hours, removal of the previously plowed snow to widen a highway may require twice the mechanical effort needed for removal of an equal amount of undisturbed snow.

(2) *Secondary roads, villages, military posts, and bases.* The clearing of secondary roads, streets, and parking areas, where long casts cannot be made or where storage space for plowed snow is limited, is often delayed until after the storm. Plows designed for maneuvering in a limited space are most efficient for such areas. A four-wheel-drive,

four-wheel-steer grader with either a front blade or a "V" plow and wing is highly adaptable to close-quarters plowing. Simple "pusher" blade type of equipment mounted on graders, trucks, or tracked vehicles is probably the most commonly used and the most readily available for plowing-out jobs on secondary roads and around buildings for afterstorm cleanup jobs.

(3) *Mountain highways.* Snow removal on the mountainous sections of major highways has become a well-organized operation. The prime requirement is a plentiful supply of equipment and manpower strategically located in closely spaced maintenance stations. High-speed blade plows are kept in continuous operation during a storm, and rotary plows are often placed in operation before a storm is over to widen the shoulders, provide additional storage area, and open up access lanes to parking areas. Every effort is made to keep ahead of the storm. Once the road is "lost", only slow-operating rotary plows can cope with the 10- to 40-ft accumulation of snow in cuts and passes; days, weeks, or even months may be required to open a major road. An example of a snow removal problem caused by "losing" a major highway to a snowstorm is shown in Fig. 8-31. Since mountain roads frequently have storage space only on one side, powerful rotary plows capable of making very long casts are required to move the snow across wide, four-lane highways.

(4) *Airfields.* Runways on major airfields are usually cleared with high-speed displacement plows operating in echelon to move the snow to the side of the runway. Rotary plows are then used to clear runway markers, to aid in early opening of drains, and to deliver snow to trucks for transportation to disposal areas when local storage space is not available. Since airfields are located in wide-open areas, wind may create more serious problems there than on highways. Clearing of wide airstrips involves more rehandling of the snow than required on most highway clearing jobs. Rehandling contributes to sintering that increases the snow density, thus imposing a much greater load on snow removal equipment. The heavy demand on equipment characteristic of airport-clearing problems is recognized by the Air Force, which specifies a 54,000-lb gross vehicle weight for the trucks on which displacement plows are mounted. Most highway maintenance departments prefer more flexible vehicles of about 34,000 lb maximum weight.

(5) *Railroads.* The heavy, powerful motive equipment available to railroads contributes to highly effective snow removal with V- and blade plows. The plow may be mounted on an independent unit provided with hydraulic control of height and throwing aspect of the plow and may be pushed by one or more powerful locomotives. Speeds up to 60 mph may be attained by the plows. On mountain divisions, very powerful rotary plows are used to clear cuts, remove heavy drifts, and open up double track and switchyard areas. Flangers are used to provide clearance for wheel flanges at the rail to avoid compaction of the snow against the rail with possible derailment. The flanger is a small V-scoop plow either fitted to a standard railroad freight or passenger car or operated as a specialized, independent unit pushed by an engine or by its own motive power.

(6) *Chemical removal.* The objective in the use of chemicals for control and removal of snow is to depress the freezing point of the snow-water-chemical mixture. By depressing the freezing point by several degrees, snow and ice can be melted considerably below 0°C (32°F). The melt water will flow off roads or runways and, unless the temperature falls below the freezing point of the solution, ice will not form on the traffic surface. Even when snowfall exceeds the melting rate of the chemicals applied, plowing is facilitated by the reduction in adherence of the snow and ice to the pavement, and a clean roadway surface without hazardous spots of compacted snow or ice is more readily achieved.

The chemicals most commonly used for snow removal are sodium chloride ($NaCl$) and calcium chloride ($CaCl_2$). They may be

Figure 8-31. Rotary Plow Opening a Mountain Highway (Donner Summit, Calif., following a major snowstorm) (Photograph by R. W. Gerdel)

applied for snow removal, with or without admixture with abrasives. For rapid removal of snow on vehicles, aircraft, and equipment when temperatures are below freezing, a force-spray of an ethylene glycol solution often is used. It has the advantage of being noncorrosive and leaves a temporary film to which snow does not readily freeze. The freezing point depressions for sodium chloride, calcium chloride, and ethylene glycol solutions are shown in Fig. 8-32.

Both sodium and calcium chlorides are commonly applied at rates of 300 to 600 lb mi^{-1} of two-lane highway. Many types of commercial spreaders are available for rear-end attachment to dump trucks. The chlorides are commonly applied at the start of a storm. If the snowfall does not exceed 3 in. (less than 0.3 in. water equivalent), the

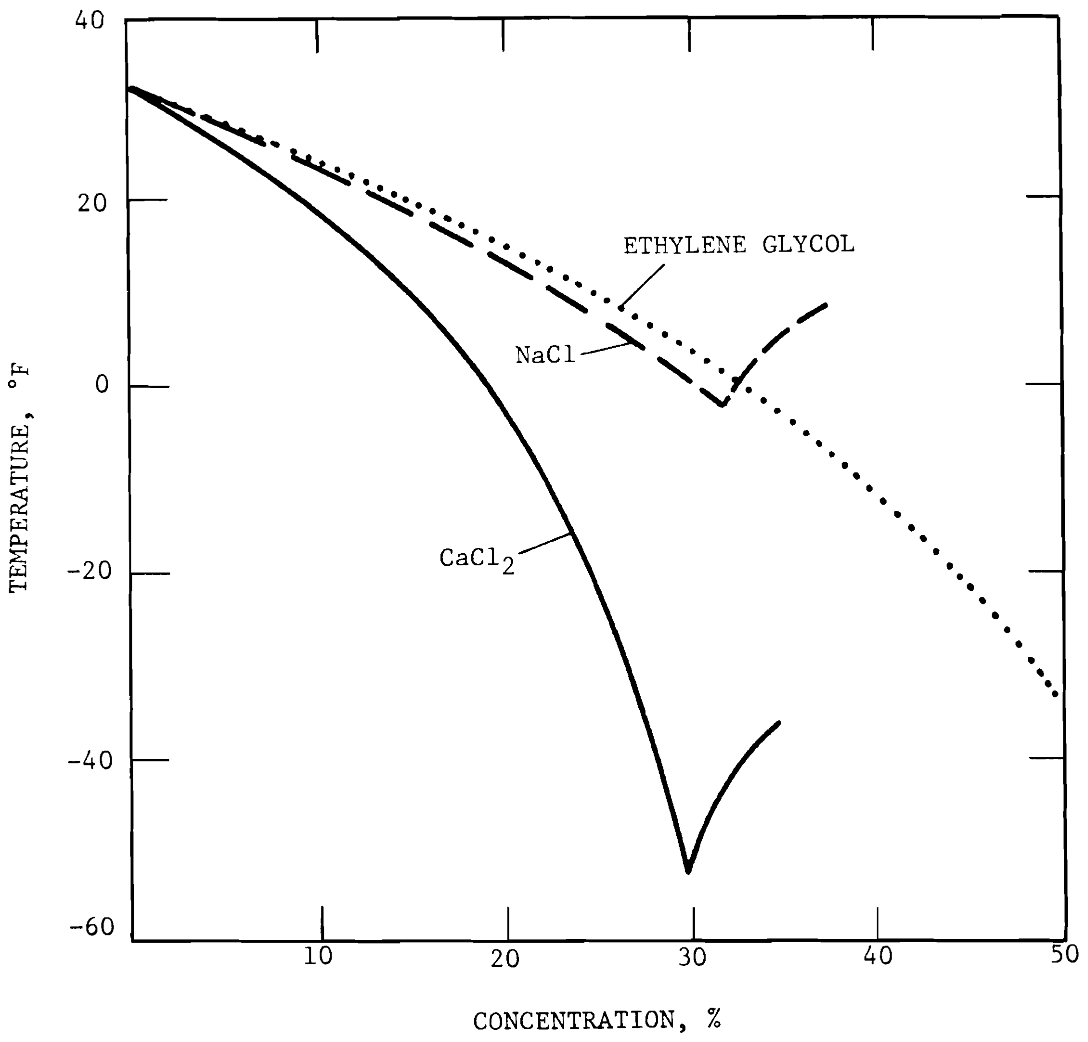

Figure 8-32. Freezing Temperatures of Aqueous Solutions

chlorides alone may produce a bare pavement. The rate of snowfall and the amount of equipment available determine the extent of pavement clearance without recourse to plows. When plowing alone is used to remove deep snow after a heavy storm, chlorides frequently are applied to the traffic-packed snow on the road surface to improve tractive ability. If insufficient chlorides are applied, producing a weak brine solution on the pavement, a sudden drop in temperature may lead to an extremely hazardous ice surface on the pavement. Sodium chloride brines on a pavement usually form an ice surface at temperatures below −7°C (+20°F). The residual concentration of a sodium chloride solution on a pavement seldom exceeds 15 percent. A similar concentration of calcium chloride brine starts to freeze at about −9.5°C (15°F).

The chlorides have a detrimental effect on concrete pavement; new concrete is more susceptible than older concrete. Temperature cycling during the period when the brine is in contact with the pavement aggravates the deterioration. Curbing, gutters, and pockets where brine may accumulate and concentrate are particularly susceptible. Spalling and general disintegration of the surface by the chlorides are difficult to control. The highly corrosive action of the chlorides tends to limit their use on airfields to emergency conditions and necessitates the subsequent washing of equipment to remove the chloride.

Sodium chloride, in the rock salt form, is most commonly used in highway maintenance. Calcium chloride is effective at a lower temperature than sodium chloride. Calcium chloride requires special storage procedures because it absorbs moisture and cakes readily. Also, it has well-known properties as a dust layer on dirt roads, leaving a continuous moisture film on pavements when used as a snow or ice remover. Calcium chloride has an advantage over sodium chloride because its solution process is exothermic; it releases 123 Btu lb^{-1} as the heat of solution, or enough heat to melt about 0.9 lb of ice per pound of calcium chloride leading to a more rapid liquefaction of snow and ice. (The full exothermic heat is seldom attained since commercial calcium chloride is hydrated.)

8-6.2 OVERSNOW TRANSPORT*

While snow removal is a prime requirement in populated areas and on many military bases, it does not meet the mobility requirements of the Army for cross-country winter operations in some parts of the intermediate cold regions and for all types of winter operations in the cold and extreme cold regions. For these requirements, oversnow transport mobility is required.

The snow terrain for which transport capabilities must be developed can be divided into three main categories: (1) seasonal snow covers with an average maximum depth of about 30 in. (0.75 m), typical of the subarctic and arctic barrens, (2) deep permanent snowfields of the icecap type, and (3) the high-mountain snowfields.

The performance of a vehicle in a soft terrain is limited by the strength of the material beneath it. Snow must be capable of supporting a vehicle without excessive sinkage and must be able to withstand the tractive thrust of wheels or tracks. The deeper a vehicle sinks, the greater its motion resistance increases; consequently, the proportion of the total tractive effort available for useful work decreases. If a vehicle is to travel over virgin snow, it must be designed so that it has high flotation (little sinkage) and good traction.

Both the bearing capacity of snow and its resistance to tractive thrust depend on the shear strength. The shear strength of an undisturbed snow is made up of a cohesive component, resulting from intergranular bonding, and a component dependent on internal friction.

Movement of vehicles over undisturbed snow may destroy the intergranular bonding, with the snow beneath the track behaving as a predominantly granular material. Under appropriate climatic conditions, particularly when the air temperature is near the melting point, tracks may compact the snow thus producing an increase in shear strength and improvement in trafficability of the surface.

Oversnow vehicles fall into two categories from an operational point of view—reconnaissance and personnel-carrying vehicles, and freight-hauling vehicles. Personnel vehicles are usually light or medium tractors, carrying 1 to 12 men at speeds up to 25 mph; some half-tracked machines with front-end skis, as shown in Fig. 8-33, are in use, and in favorable situations, airscrew-driven sleds may be operated. Most heavy freight is still carried on sleds that have load capacities from 1 to 20 tons and a speed of about 4 mph. The most common prime movers are tractors equipped with wide tracks or more extensively modified for low ground pressure. Large-wheeled prime movers and trailers are in the test-evaluation stage. These allow the traveling speed of an oversnow freight train to be raised appreciably. One such wheeled vehicle train is shown in Fig. 8-34.

While oversnow vehicles should be capable of traversing virgin snow, they may use trails "broken" by earlier traffic. These trails can vary from unimproved vehicle tracks to prepared snow roads.

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*Much of this paragraph is based on CRREL Report IIA4, *Oversnow Transport* by M. Mellor as abstracted by R. W. Gerdel (Ref. 71). A more comprehensive discussion may be found in that reference.

Figure 8-33. Bombardier Snowmobile (Used by the RCMP for transportation in the Canadian Arctic) (Photograph by R. W. Gerdel)

A major hazard on high polar snowfields is concealed crevasses. Since electronic detectors for locating crevasses are seldom available when needed, probing by a roped-up team of men is still the most commonly used method. If not avoidable by a short detour, a crevasse may be filled or bridged with snow.

In the high mountains, extremely heavy snowstorms may deposit 4 to 12 ft of snow in a single continuous period of precipitation. Density of the new snow is usually less than 0.15 g cm^{-3}. Only the very lightest weight, one- or two-man motorized toboggans can travel over the deep snows that fill the passes and obscure many hazardous features of the terrain. Deep drifts, massive cornices, and steep slopes all contribute to poor trafficability in all mountainous regions.

The properties of a seasonal snowpack change through the winter as the new snow is metamorphosed, but it is generally soft, with a density in the range 0.1 to 0.3 g cm^{-3}.

Icecap snows are generally denser, in the range 0.3 to 0.4 g cm^{-3} or more, and harder than seasonal snows. Hard snows give ample support and traction to most oversnow vehicles, but the dunes and sastrugi of a wind-sculptured surface are often big enough to constitute a serious roughness problem. To traverse such a surface, a vehicle must have adequate suspension and freedom from excessive pitching, in addition to the usual flotation and traction requirements.

One important difference between seasonal snow and icecap snow is the firm ground surface that underlies the former. For snow covers that are up to 75 cm (30 in.) deep, many types of tracked vehicles pick up ground support by compressing snow against the unyielding ground. Over snows of great depth, this advantage does not exist. Tracked oversnow vehicles are illustrated in Figs. 8-35 and 8-36.

A shallow seasonal snow cover, where snow

Figure 8-34. Overland Train (A U.S. Army logistic carrier. Front unit houses a current generator and controls for power delivered to independent motors in each wheel on power unit and trailers.) (Photograph by R. W. Gerdel)

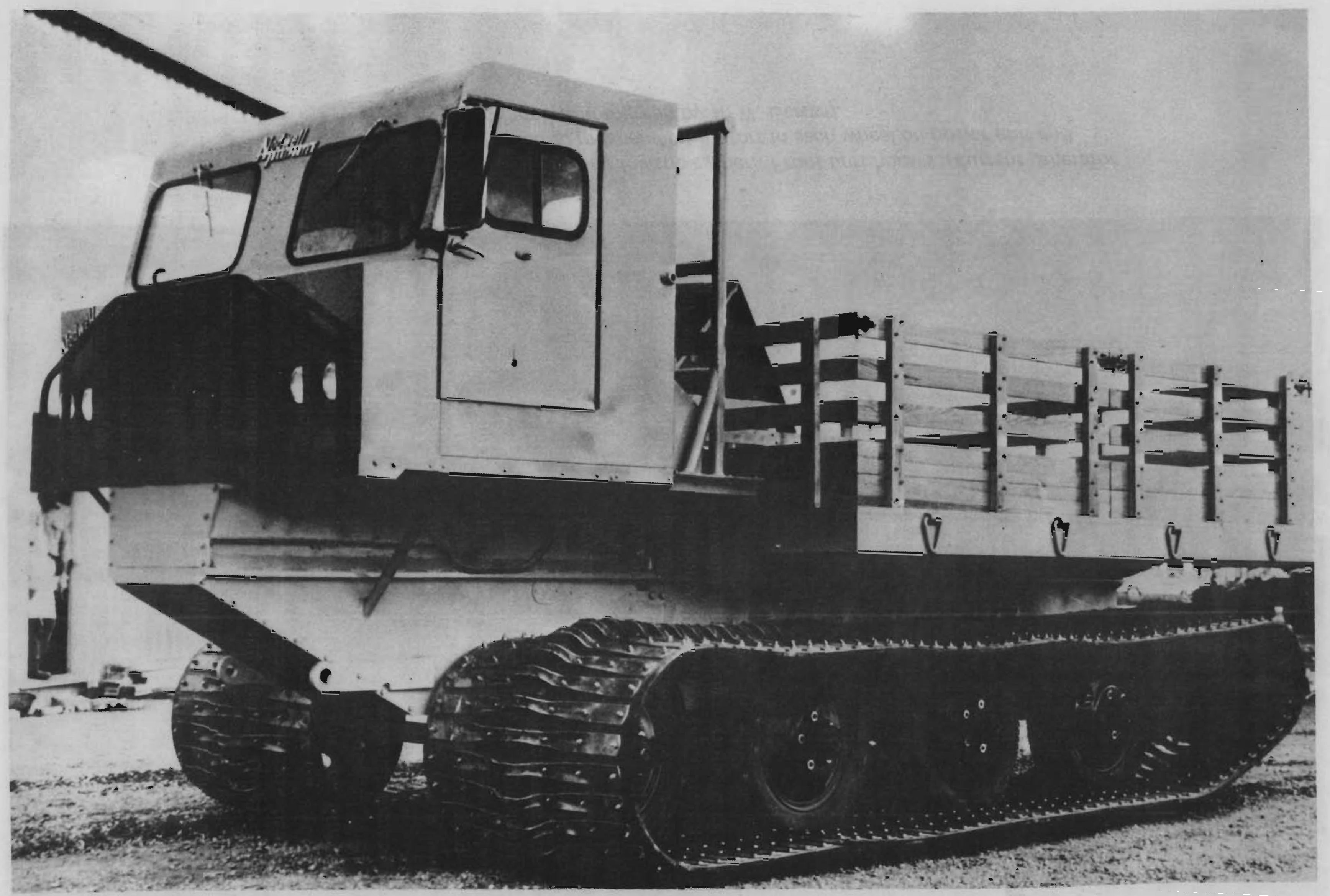


Figure 8-35. Nodwell 4-axle Tracked Carrier (Ref. 71)

Figure 8-36. Polecat Train in Greenland (Front and rear tractors in this train have power units in front portion of articulated carrier. Center tractor has power unit in rear portion of articulated carrier.) (Photograph by R. W. Gerdel)

up to 10 in. (25 cm) deep lies on firm ground, can usually be negotiated by jeeps, trucks, farm tractors, construction equipment, and combat vehicles. Occasional immobilization of rubber-tired vehicles may result from slipperiness.

In deep seasonal snow, where 25 to 75 cm (10 to 30 in.) of snow lies on firm ground, only tracked vehicles and special wheeled vehicles having wheel diameters four times as great as the snow depth are satisfactory. On snow 30 in. (75 cm) deep, small tracked vehicles (gross weight less than 6,000 lb) depend entirely on the flotation principle, but heavy vehicles can pick up ground traction and thus are relatively more efficient.

In very deep soft snow (depth greater than 30 in., surface density less than 0.25 g cm^{-3}), only vehicles with light track loading and uniform pressure distribution can operate consistently. The effects of the environment on oversnow transport may be classified into two categories: operational and mechanical. An operational effect does not necessarily cause a system to fail but does prevent it from fulfilling its mission. A mechanical effect prevents the system from functioning. A deep, low density snow may provide sufficient resistance to forward motion to cause operational failure of an oversnow vehicle. Snow, packing in the drive sprockets and stretching the track linkage to the breaking point, will cause a mechanical failure. Either or both types of failure may be limiting in different environments.

The adaptability of vehicles most commonly used for oversnow transport to snow-terrain conditions is shown in Table 8-16.

Density and temperature information is often available for snowfields whose trafficability properties are unknown. Since mechanical properties are influenced by density and temperature, it should eventually be possible to make predictions of shear and sinkage parameters from information about density, temperature, and grain structure.

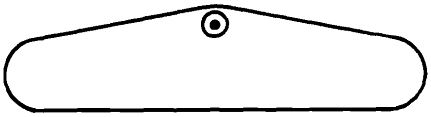
For a machine to be considered an oversnow vehicle, a number of basic requirements must be met. The vehicle must have

TABLE 8-16

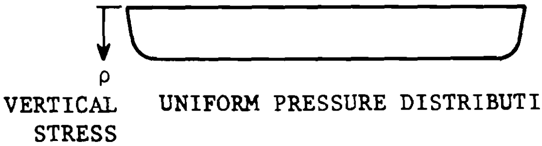
VEHICLES FOR OVERSNOW TRANSPORT (Ref. 71)

Type of snow terrain		Suitable vehicle types
Shallow seasonal snow cover lying on firm ground. Snow up to 10 in. deep	Flat or small gradients	Tracked LGP* vehicles, wheeled LGP vehicles, high-ground-pressure tracked and wheeled cross-country vehicles (combat vehicles, construction equipment), farm tractors, 4 x 4 and 6 x 6 jeeps and trucks
	Steep grades	Tracked LGP vehicles, wheeled LGP vehicles, high ground pressure tracked and wheeled cross-country vehicles (combat vehicles, construction equipment), farm tractors
Deep seasonal snow cover lying on firm ground. Snow from 10 to 30 in. deep	Flat or small gradients	Tracked LGP vehicles, LGP vehicles with large-diameter wheels, medium ground pressure tracked vehicles with high ground clearance, very large tracked and wheeled vehicles
	Steep grades	Tracked LGP vehicles, special vehicles with large-diameter wheels, some medium-ground-pressure tracked vehicles (construction tractors, some combat vehicles)
Permanent icecap snows. Depth is effectively unlimited	Flat or small gradients	Tracked LGP vehicles, LGP vehicles with large-diameter wheels, some medium-ground-pressure tracked vehicles (construction tractors, some combat vehicles)
	Steep grades	Tracked LGP vehicles, LGP vehicles with large-diameter wheels
Very deep seasonal snow. Depth greater than 30 in.	Flat or small gradients	Good tracked LGP vehicles
	Steep grades	High-performance LGP tracked vehicles

*LGP - low ground pressure (up to 4 psi for tracked vehicles)

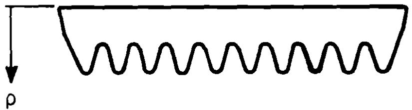


(A) RIGID PONTOON

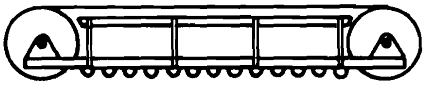


UNIFORM PRESSURE DISTRIBUTION

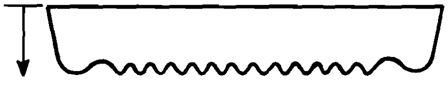
(C) FLEXIBLE TRACK WITH SEPARATE BOGIES



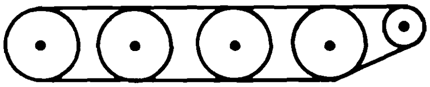
CONSIDERABLE STRESS CONCENTRATION BENEATH EACH BOGIE WHEEL



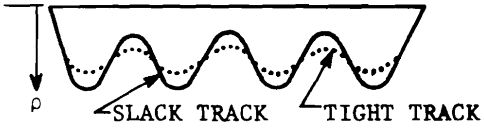
(B) STIFF, ALL-STEEL GIRDERIZED TRACK



PRESSURE DISTRIBUTION CLOSE TO UNIFORM



(D) FLEXIBLE TRACK AROUND LARGE-DIAMETER WHEELS



SEVERE STRESS CONCENTRATIONS BENEATH THE WHEELS

Figure 8-37. Common Track Systems Used on Oversnow Vehicles (Ref. 71) (A schematic representation of their stress distribution is shown.)

good flotation and traction characteristics if it is to operate on all kinds of snow. It should be capable not only of moving when lightly laden but also of carrying or pulling a load. It should also have sufficient power and riding stability to permit reasonable speeds.

Theory shows that total tractive effort depends on track area and contact pressure, but it does not take grouser features into account. Diamond and Lanyon show grousers to be effective (Refs. 72, 73). It has been suggested that there should be an optimal spacing for grousers, but vehicle tests have indicated that performance is best with a grouser on every track pad; this may be related to the fact that horizontal stress on and against a track pad increases sharply when it passes a bogie.

Tests show that maximum traction is usually obtained with track slips of about 15 to 30 percent. This may be attributed to increase of shear resistance with increasing deformation and strain rate. It is thought that long tracks give best performance in this respect. Some common types of track systems used on oversnow vehicles are shown in Fig. 8-37, with a schematic representation of their stress distribution.

When the sinkage of a track is deep in relation to its vertical dimensions, the track will bulldoze (shear the snow horizontally). This is indicative of inefficient operation. For a track to compact the snow rather than bulldoze it, a gentle angle of approach is needed. Bulldozing resistance is also proportional to track width; it is minimized by a narrow track.

Very deep sinkage allows the underside of the vehicle to scrape the snow, causing additional bulldozing and possibly taking some of the weight off the tracks. In extreme conditions the vehicle can become immobile.

The following features improve tractive performance over deep snow:

(1) Low basic ground pressure to permit negotiation of soft snow (drawbar pull can be improved on hard snow by adding payload to increase ground pressure)

(2) Even pressure distribution (avoidance of stress concentrations)

(3) Long narrow tracks rather than short wide ones

(4) Shallow grousers, one for each track joint

(5) Nose-heavy position for center of gravity

(6) Configuration to minimize bellying resistance.

Many standard tractors, some ordnance tracked vehicles, and some self-propelled weapons may operate satisfactorily on very hard snow but they are not reliable prime movers for oversnow transport.

Generalizations about comparative pulling powers of different snow vehicles are likely to be misleading, mainly because of the strong dependence on snow type and the inherent shortcomings of the drawbar coefficient. Fig. 8-38 gives some idea of drawbar coefficients commonly found for operation over firm snow; these data do *not* indicate relative merit for the vehicles shown since there is great variation in their design and usage.

Vehicle speed often is limited by surface roughness such as the hard wind-sculptured dunes and sastrugi. Vehicles pitch and roll severely, causing acute passenger discomfort and structural damage to the vehicle. The two-unit articulated vehicle has an advantage—it damps the pitching. The Sno-Cat configuration permits some conformance to the terrain. Simple robust construction in the track system helps to minimize vehicle damage in rough terrain.

The traction principles applicable to tracked vehicles apply also to wheeled vehicles; i.e., there should be low ground pressure evenly distributed, a long narrow gearing area, and little relative sinkage. The wheel does not meet these requirements easily—it has little bearing area compared to its size, several wheels must be run in train to give a long narrow area, and it can only sink to about one-fourth of its diameter before it begins to bulldoze. On the other hand, the internal friction of a wheel is negligible compared to that of a track and it has a high-speed potential.

Large (8- to 10-ft diameter) wheeled vehicles, both small and large sleds, oversnow wheeled and tracked trailers, aerosleds, and snowmobiles are employed for oversnow transport under various conditions. Air-cushioned vehicles have been operated over an undisturbed snow surface at speeds up to 35 mph, but their ultimate potential for oversnow transport is yet to be determined (Ref. 74).

To quote from Army Field Manual, FM 31-71 (1963) (Ref. 75), "It is impractical to establish definite rules for oversnow operations due to the varied snow conditions encountered. Most tracked vehicles are immobilized by 1 to 2 meters of wet snow. Heavy tracked vehicles may negotiate fine, dry snow of 1 to 2 meters in depth. Normal speeds may be maintained after a packed snow trail has been formed by the passage of several vehicles. Dry snow causes few operating difficulties as it has little tendency to pack on suspension systems. Wet, clinging snow has a tendency to accumulate on the track, suspension idler wheels, and sprockets and may require occasional halts for removal."

There is no one vehicle, nor family of vehicles, that will provide unqualified mobility in the snow-covered regions of the world.

8-6.3 CONTROL OF DRIFTING SNOW

In those regions where drifting snow

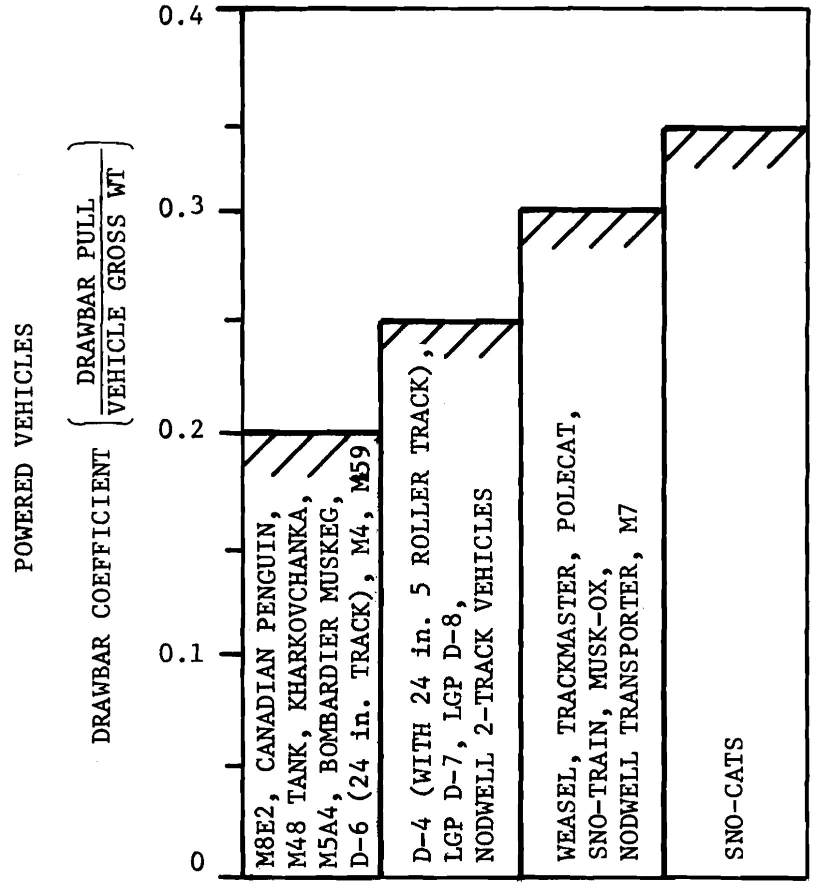


Figure 8-38. Drawbar Coefficients for Some Common Snow Vehicles (Ref. 71)

constitutes a significant feature of the environment, control of drifting by various types of barriers is used to much advantage. Thousands of miles of snow fence are in use in the United States and Canada to protect highways and railroads from drifting snow. Russia, the Scandinavian countries, Germany, and England make such extensive use of snow fences that intensive laboratory and field investigations have been conducted in these countries as well as in the United States and Canada to determine the most effective type, height, and spacing of fences for drift control.

In remote areas where commercial materials suitable for snow fence construction are difficult to obtain, fences have been constructed from material such as tree boughs woven into mats. Probably the most extensively used snow fence is the 4-ft high, wirebound, wood lath fence. It is readily transported in large rolls, easily erected using ordinary iron fence posts for single height and longer wood posts for multiple section heights, and easily dismantled for summer storage. A fence widely accepted in recent years is made of corrugated, galvanized, sheet metal strips mounted on a collapsible, angle-iron A-frame. It is commercially available in 8- or 10-ft sections, easily transported in knockdown form, and readily erected on site; it can be fastened down with pins through the angle-iron base or, in mountain regions, the base may be weighted down with stone. This type of fence has been used extensively along the transcontinental railroads and highways in the United States and Canada. The U S Army has used effectively this highly portable metal fence for protection of installations on the Greenland Ice Cap (Fig. 8-39) and for the deliberate accumulation of snow during the winter to provide

Figure 8-39. All Metal Drift Fences (These are commonly used by railroads and some State Highway Departments. In this photograph the fences are being installed to protect a Greenland Ice Cap facility.) (Photograph by R. W. Gerdel)

insulation during the summer and thus reduce the amount of thaw along access roads.

A higher collection efficiency has been attributed to inclined fences such as the A-frame fence (Ref. 76). It is claimed that a fence erected at a 30-deg angle from the vertical and inclined in the direction of windflow produces longer, lower profile drifts. There is, however, no evidence that the total volume of drift catch is increased by inclined fences.

Paper-strip fences have been tried in some areas. The paper comes in rolls of two-layered, heavy kraft paper, bonded with asphalt and reinforced with sisal or synthetic fibers. A photograph of a paper-strip fence in use along a highway in Northern Michigan is shown in Fig. 8-40. The use of paper or other disposable material for drift control fencing appears to be satisfactory where extremely high winds are not expected. Special fasteners are available for mounting on iron fence posts. More than usual care is required to

Figure 8-40. Paper Drift Fence (This is shown erected along a highway in Northern Michigan. Note that many more iron fence posts are used than normally required for the common wood slat fence.) (Photograph supplied by R. W. Gerdel)

avoid tearing the paper when erecting the fence. Tests in Greenland indicate that the paper fence is not satisfactory at fence heights above 3 ft.

Regardless of the type of fence used, research indicates that the "density" of a fence should be between 40 and 60 percent for the most effective control of drifting snow; i.e., the solid area of the fence should constitute about 40 to 60 percent of the total area, regardless of whether the slats or strips are installed vertically or horizontally. This open construction produces long, shallow eddy zones, that contribute to the deposition of greater volumes of snow on the lee side of the fence compared to a high density or solid fence (Refs. 76, 77, 78).

A gap beneath the fence improves drift control for the same reason that an open slat or panel fence increases the volume of the controlled drift. In most highway drift control practice, a gap of 6 to 8 in. is

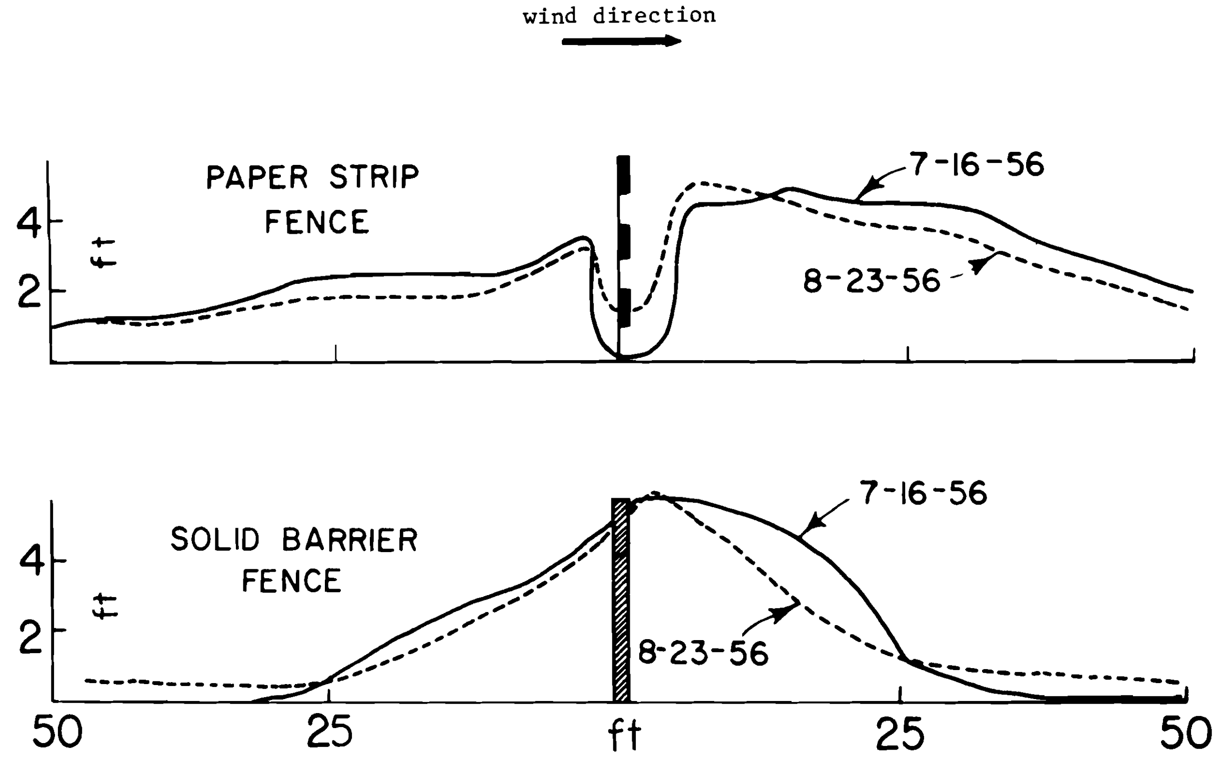


Figure 8-41. Snow Accumulation Patterns at Snow Fences (Paper strip fence has a 50-percent density. Actual experience in Greenland, 1956) (Ref. 79)

provided between the bottom of the fence and the ground. Along some of the transcontinental railroads in the western region of deep snow, gaps as large as 30 in. may be used. The height of the gap between the fence and the ground appears to be determined by local experience gained from many years of observance of snow fence effectiveness since few experiments with scale model fences in wind tunnels have indicated any major advantage to large gaps (more than 12 in.) beneath fences.

Cross sections of drift accumulation patterns for a 50-percent density paper-strip fence with 10-in. bottom gap and for a solid drift fence erected in Greenland in 1956 are presented in Fig. 8-41. The solid barrier fence was saturated after the first storm and the drift accumulation was subjected to erosion from the windward side. It was no longer an effective drift control structure 2 weeks after erection at an installation on the Greenland Ice Cap. The 50-percent density fence had not only accumulated slightly more drift snow in the same period of time but also had a residual capacity equal to the amount of drifting snow that had already accumulated.

Fence height is usually determined by local conditions. Multiple rows of low fencing are more effective than a single high fence. Western railroads often use three to ten rows of 6-ft-high wood or metal slat fencing with spacing from 25 to 100 ft between rows, depending on snowfall and drifting peculiarities of the locality. A very high fence can be very effective if properly erected to withstand major stormwinds. Fig. 8-42 shows the volume of drift snow accumulated on the lee side of a 12-ft, wood slat fence erected as a permanent structure along a main highway in Northern Michigan. An extremely high fence of this type may be required where drift control structures must be kept within right-of-way boundaries or where easements on private land are unobtainable.

Figure 8-42. Snow Accumulation at a High Snow Fence (12-ft, wood slat drift fence erected permanently along a major highway in Northern Michigan. Note "blow-out" when a section of the fence was removed and not replaced to permit access to cultivated field.) (Photograph supplied by R. W. Gerdel)

Snow fences are usually erected in single or multiple rows on the upwind side and parallel to a highway or a railroad track. When erected in long rows, they need not be perpendicular to the prevailing wind, but the greater the divergence of the wind from a 90-deg angle with the fence, the less effective is the control. To protect a large installation, a drift fence should always be erected with the long axis as nearly normal to the wind direction prevalent during major snowstorms as conditions permit.

Where windflow is at an angle to a highway or airport runway, a staggered system of fences with unit axis normal to the wind or nearly so is more effective than a single fence. The staggered system is also more effective where the prevailing wind may be almost parallel with the roadway or runway, particularly if heavy drifting follows deposition during the stormwind and if prevailing wind directions are different from windstorms. An example of the effectiveness of a staggered system of drift fences is shown in Fig. 8-43.

Spacing of fences depends on the overall environment. If possible, each situation should be examined with respect to annual precipitation in the form of snow, wind direction, windspeed, prevalence of windspeeds high enough to cause drifting, topographic peculiarities, and usage of the area to be protected. A parallel fence or the nearest edge of a series of staggered fences should be about 80 ft from the centerline of a highway. Where a series of fences are erected, the first fence should be at a distance from the road 15 times its height; i.e., a standard 4-ft, wood slat fence should be erected 60 ft from the road edge. Additional rows of fence may be erected at intervals 10 times the fence height (Ref. 78).

Hicks (cited in Ref. 9) found that, by moving the portable A-frame, metal slat fences to the top of either the windward or the lee drift accumulation before the fence became saturated with snow, very effective drift control was attained. By a series of three moves during the snow season, a drift 15 ft high was accumulated with a single row of the metal fences, which were only 6 ft high.

When an obstacle projects into an airstream that is transporting snow, eddies are formed and a turbulent wake develops around the obstacle. The eddy pattern and, accordingly, the snow drift pattern that develop around a structure or natural obstacle are related to the shape of the barrier. Sketches of the eddy currents and the snow accumulation patterns around typically shaped obstacles are shown in Fig. 8-44.

A detailed discussion and review of the pertinent literature of the problem of boundary layer separation, turbulent wake formation, and snow-drift patterns produced by obstacles projecting into the blowing snow stream is presented by Mellor (Ref. 9). Practical applications to engineering design and facilities construction of the empirically derived information on drift patterns produced by obstacles are presented by Gerdel and by Hicks and Bolsenga (Refs. 79, 80).

Proper design of highways and railroads can reduce snow removal requirements considerably. Finney studied the effects of bank height and the deepness of cuts on snow accumulation (Ref. 81) and found that elevated road sections were self-clearing when the bank slope was about 1:6.5, regardless of windspeed. Rikhter observed that in the eastern part of European Russia the top of railroad embankments between 1 and 2 m high were blown clear of snow and that highways elevated 1 m or more tended to be free of blocking snowdrifts (Ref. 6). Test sections of roadway constructed in Northern Michigan with 1:2, 1:3, and 1:4 side slopes on an embankment 6 ft high were found to be largely self-clearing throughout the winter (Ref. 79). For all embankment slopes, snow accumulated on both sides of the roadway until the effective side slope was reduced to 1:9. Fig. 8-45 shows a cross section of one test section and the snow accumulation profile during the major snowfall and the drifting period of the winter. A similar section only 3 ft high was not fully self-clearing. The results of this test indicate that the elevation of a roadway must be greater than the local, normal accumulation of seasonal snowfall.

It is probable that narrow aircraft runways might be largely self-clearing if appropriately elevated and located in an area where a free flow of stormwinds can be utilized to aid in maintaining a clear landing surface.

Studies of drift-accumulation patterns lead to the following suggestions for snowdrift control:

(1) Objects may be kept free of snow by supporting them above the surface.

(2) Buildings and stores should be erected with their long axis normal to the wind. The

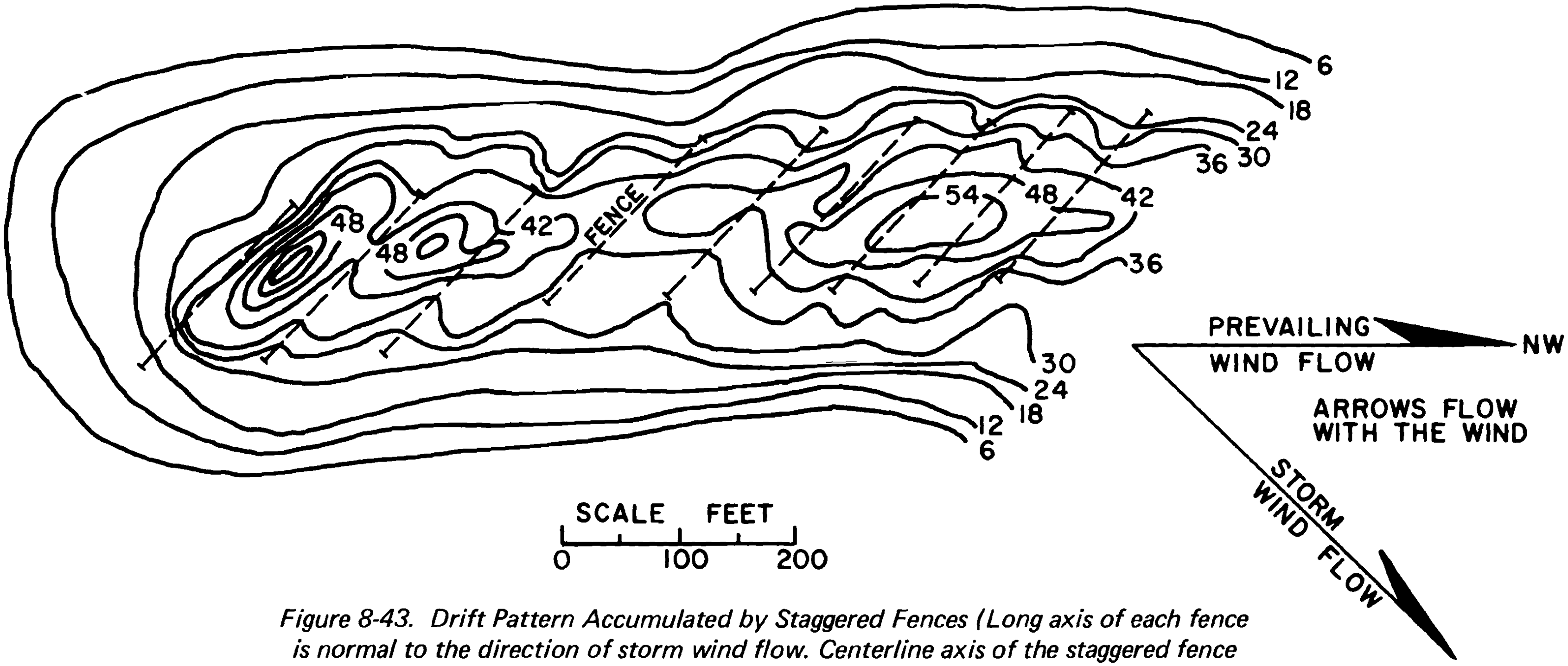
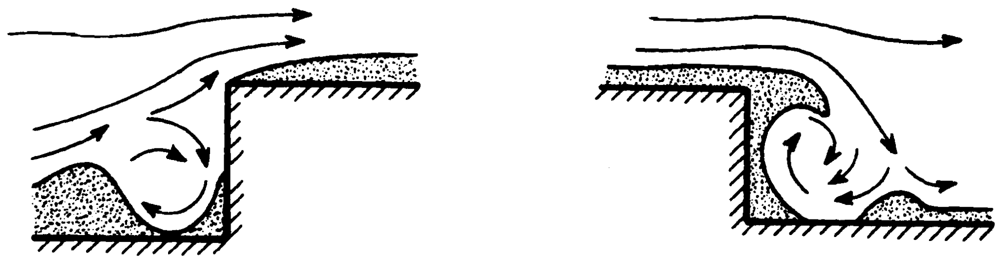
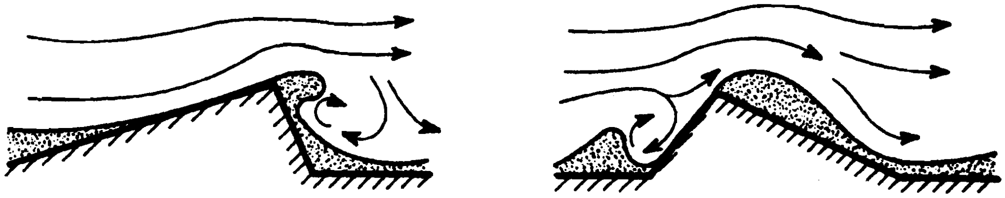


Figure 8-43. Drift Pattern Accumulated by Staggered Fences (Long axis of each fence is normal to the direction of storm wind flow. Centerline axis of the staggered fence group is parallel to prevailing wind. This system can be adapted to achieve effective drift control along highways and railroads.) (Ref. 79)



(A) ACCUMULATION OF SNOW AT A SHEER WALL FACING THE WIND

(B) ACCUMULATION OF SNOW AT A SHEER WALL FACING AWAY FROM THE WIND



(C) ACCUMULATION OF SNOW AROUND A NARROW RIDGE WITH GRADUAL WINDWARD SLOPE AND A STEEP LEEWARD SLOPE

(D) ACCUMULATION OF SNOW AROUND A NARROW RIDGE WITH A STEEP WINDWARD SLOPE AND A GRADUAL LEEWARD SLOPE

(E) ACCUMULATION OF SNOW AROUND A LOW RIDGE OF SYMMETRICAL SLOPE

(F) ACCUMULATION OF SNOW AROUND A HIGH RIDGE OF SYMMETRICAL SLOPE

Figure 8-44. Eddy Currents and Drift Accumulation Around Typical Obstacles (Ref. 6)

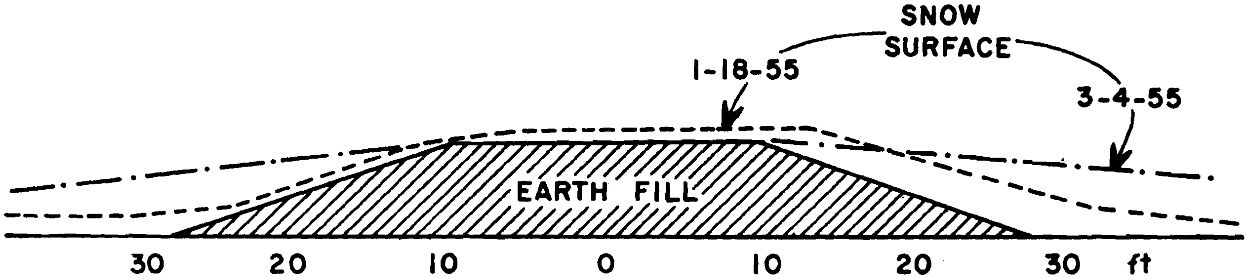


Figure 8-45. Accumulation of Snow on Elevated Roadway (6-ft test section with 3:1 bank slope) (Ref. 79)

long axis should be as short as possible.

(3) The upper surface of objects should be smooth. A false, smooth roof should be erected over stacked oil drums, crates, and other irregular stores.

(4) Where numerous buildings and roofed stores are spaced at random, to avoid drift coalescence spacing should be not less than 30 times the height of the object.

(5) Objects should be spaced along a line normal to the prevailing wind to avoid overlap of lee drifts from one object with the windward drift of another object.

(6) Where it is desired to have objects completely buried by snow, they should be placed in a compact group to insure rapid coalescence of drifts and subsequent coverage by normal snow accumulation.

These six suggestions are applicable when modified to meet the requirements of the local environment. The reliability of any program for drift control will depend on the amount of detailed, available information on windspeed, prevailing direction and volume of storm, and annual snowfall.

8-6.4 SNOW AS A CONSTRUCTION MATERIAL

While snow often acts as a deteriorating environmental factor for military operations and materiel, it can also be employed for useful purposes. Its abundance and the scarcity of alternative materials make it particularly useful as a construction material for temporary or permanent facilities in extreme cold climates. The wide variation in the physical properties of snow and the continuing metamorphism that determine its strength characteristics at any given time and that vary in rate under even light loading imposes certain limitations on its use as a construction material and, at the same time, permits unique construction practices. Camp Century in Greenland and other similar subsurface facilities that have been constructed in the Arctic and Antarctic are outstanding examples of the unique practices that may be used when an unlimited supply of snow *in situ* is available. The construction of compacted snow landing strips capable of supporting wheeled landing and takeoff of 135,000-lb LC-130F tanker aircraft in the Antarctic is another example of the application of the unique properties of snow to military requirements (Ref. 82).

In those portions of the cold regions where annual snowfall may not exceed 3 or 4 ft, there is usually sufficient densification and hardening of the snow to a depth of 8 to 20 in. to permit quarrying of snow blocks for use in the construction of windbreaks and self-supporting walls for habitable structures. The construction of an igloolike structure with a domed roof requires only a little ingenuity in shaping and fitting the snow blocks. Loose snow packed into the joints between blocks rapidly hardens and increases the strength of the structure. Where drifts are sufficiently large, snow caves may be readily excavated which will provide comfortable protection from the weather as well as concealment. The inside walls of a cave or snowblock structure quickly glaze from the melting induced by body warmth, exhaled breath, and artificial heating so that the strength of the structure is thus further increased. Troops on winter maneuvers in the Canadian Barrens who had never seen an igloo or other snow structures quickly developed techniques for the construction from snow, the only available material, of sophisticated facilities to protect themselves from the cold, high winds, and blowing snow.

Basic construction principles for erection of snow walls and for excavation of snow caves are given in Department of the Army FM 31-70 (1959) (Ref. 83). This manual shows plans for 16- to 20-man snow caves. A structure of such dimensions might be considered semipermanent and should be provided with a minimum of heat to avoid too rapid deformation of the roof and walls.

Some concealment is achieved by covering

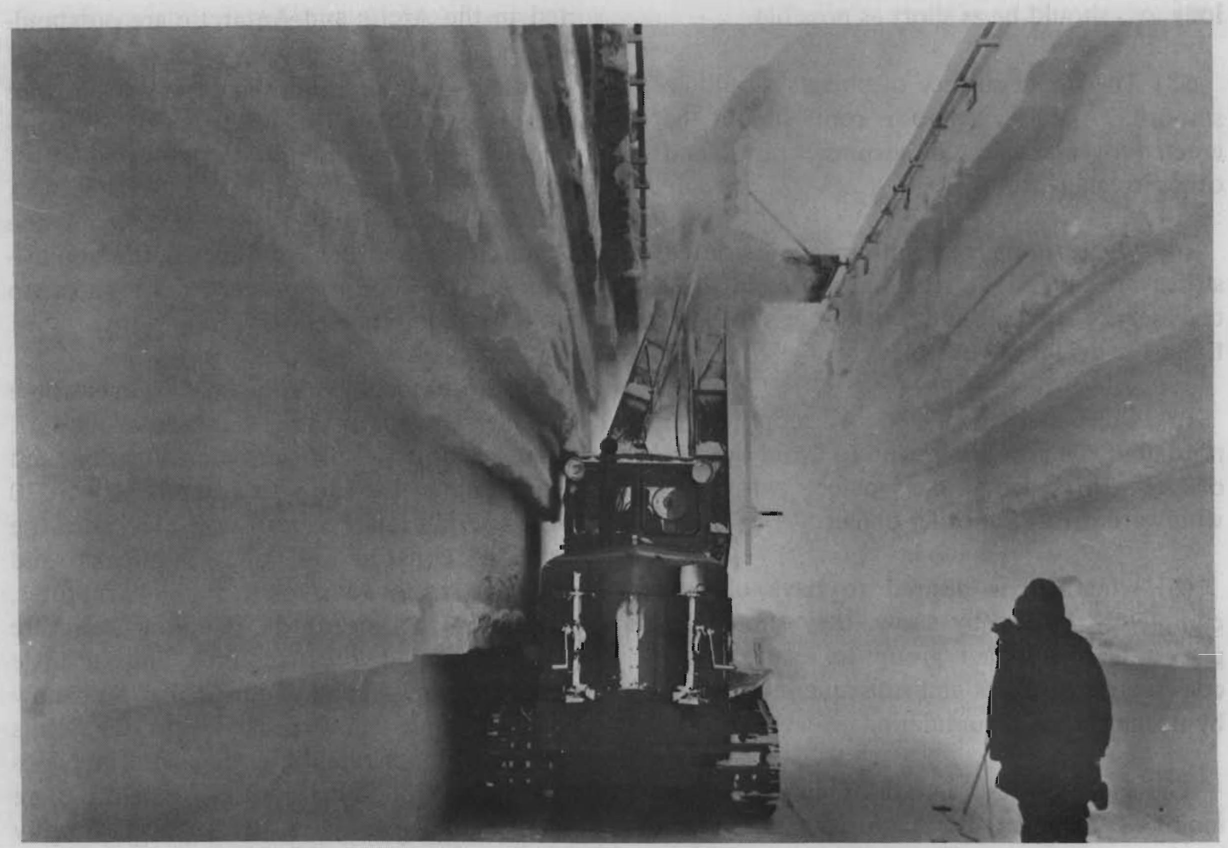


Figure 8-46. Cutting a Trench at Camp Century, Greenland (Photograph by Waterhouse)

vehicles and equipment with snow; however, any disturbance of the natural snow surface is readily detected by visual or infrared surveillance. Too much reliance should not be placed on the use of a thin snow cover for camouflage or concealment.

A technique for the construction of more or less permanent subsurface military bases within the deep snow cover of the Greenland Ice Cap was developed by the U S Army Cold Regions Research and Engineering Laboratory in 1955. The concept, which is based upon a cut-and-cover trenching technique, has been used to construct the 200-man facility, Camp Century, on the northern Greenland Ice Cap, at an elevation of 6,200 ft and 130 mi east of Thule, and Byrd Station in the Antarctic.

Detailed discussions of the cut-and-cover trenching process are presented by Waterhouse, Abele, and Clark (Refs. 84, 85, 86). A brief description of the construction of Camp Century is contained in Army Technical Manual TM 5-349 (1962) (Ref. 87).

The trenches are cut with a Peter snow miller, a snowplow made in Switzerland. The finely pulverized snow excavated by this machine is discharged through adjustable ducts to a stockpile on the surface parallel to the cut (Fig. 8-46), and repeated passes are made to produce a trench of the desired width and depth for the planned usage of the trench. By undercutting on each pass, a trench is produced with a uniform trapezoidal cross section that is 14 ft wide at the top, 24 to 40 ft wide at the bottom, and 20 to 30 ft deep. Fourteen-ft metal arch roof forms are set on pins to span the open cut (Fig. 8-47) and the stockpiled snow blown back over the roofed trench (Fig. 8-48). After 24 to 72 hr, the backfilled snow becomes sufficiently self-supporting due to sintering to permit removal of the arch roof forms for reuse (Fig. 8-49). The completed trench is then ready for

Figure 8-47. Installing Metal Arch Roof Forms at Camp Century, Greenland (Photograph by Waterhouse)

installation of prefab T-5 buildings that are erected on piles set deep into a denser snow. The installation of nuclear power plants at the Camp Century and the Byrd facilities permitted year-round operation of these undersnow bases. An interesting, well-illustrated, nontechnical book dealing with the use of snow as a construction material is available (Ref. 88).

Since snow on the Greenland Ice Cap has a density of less than 0.6 g cm^{-3} to a depth of at least 40 ft, both vertical and horizontal deformation of the snow walls and trench roof takes place. This deformation is accelerated by the heat used in maintaining living quarters at a comfortable temperature. Periodic shaving of the walls and roof is required to offset trench closure and ultimate destruction of installed facilities.

Compacted snow roads have been used by the logging industry in the United States and Canada for more than 100 yr. Compaction was used to increase the load-carrying capacity of large, horse-drawn logging sleds. Large, horse-drawn wooden rollers were used to achieve initial compaction, and the passable surface was maintained during the snow season by drag-leveling and by the natural compacting resulting from continued use of the logging sleds during storms. Compacted snow roads provide winter season communication over muskeg and tundra that are impassable during all other seasons.

From the military standpoint, compaction of snow in cold and extreme cold climates is, at best, a temporary expedient, inefficient in its use by man and machines. The only exception may be the temporary improvement of mobility over muskeg. Even in the extreme cold region, muskeg seldom freezes to sufficient depth beneath a packed snow

Figure 8-48. Covering Roof Forms at Camp Century, Greenland (Photograph by Waterhouse)

road to permit movement of heavy wheeled vehicles, but repeated movement of tracked vehicles over muskeg during the winter may produce a suitable roadway without prior compaction.

On the polar icecaps where perennial snowfields are subject to little melting and light annual snow accumulation (6 to 30 in.), the construction and maintenance of compacted snow roads and aircraft runways contribute to effective year-round operation of facilities.

The equipment used to achieve satisfactory bearing capacity of compacted snow includes pulvimixers for depth processing, large rollers for compressive compacting of the pulverized snow mass, and drags or planers for producing a relatively smooth surface. Pulvimixers may be combined with flame-type heaters (Fig. 8-50) to warm the comminuted snow mass as an aid to better compaction and more rapid hardening or a water spray system may be used to increase the binding capacity of the pulvimixed snow. The pulvimixers are standard or modified types of agricultural rotary tillers, usually self-powered or towed-type construction mixers. Commercially available mixers, with or without modification, are capable of comminuting 2 to 40 in. of snow, and they operate at rotor speeds of 500 to 800 rpm. Use of such mixers is considered essential to the acceleration of the natural age-hardening process in snow and to the rapid development of a snow mat that has sufficient strength to support heavy aircraft or wheeled automotive vehicles.

Bender describes the results of tests on compacted snow runways in Greenland where successful landings were made with wheeled C-47, C-54, and C-124 aircraft (Ref. 89). The runway—which was prepared with pulvimixers, auxiliary heaters, rollers, and drags—consisted of a hard, processed layer of high-

Figure 8-49. Completed Trench With Roof Forms Removed and Ready for Installation of Buildings at Camp Century, Greenland (End-wall treatment to provide for escape hatch is shown in this photograph.) (Photograph by Waterhouse)

Figure 8-50. Pulvimixer With Flame Heater Attached (This equipment is used to disaggregate and raise the temperature of the snow to a depth of 12 in. prior to compaction. This mixer was used on the Greenland Ice Cap to prepare a runway on which wheeled C-124 aircraft were able to land and take off.) (Photograph by R. W. Gerdel)

density, high-strength snow on top of a layer of compacted snow of lower density and strength which had been built up on a subgrade of weak unprocessed snow. His report indicates that obtaining uniform heat distribution was difficult in the pulverized snow, and that there were areas of poor cohesion and other areas with large ice clumps.

Easton describes the equipment and techniques used to construct aircraft runways in the Antarctic by the U S Navy and a 12,000-car parking lot in the High Sierra for the 1960 Winter Olympic Games (Ref. 90). Six techniques have been developed: (1) precompaction preparation to level drifts and reduce surface irregularities, using a 925-lb wood drag equipped with metal cutting edges; (2) compressive compaction with 5-ton steel rollers, 8 ft in diameter and 8 ft wide; (3) depth processing with snow mixers; (4) double depth processing with snow mixers; (5) surface hardening with water spraying; and (6) overnight freezing of the surface and layered compaction. Separately, the techniques are limited in application, but most or all may be required to build a runway suitable for heavy wheeled aircraft. The choice and the sequence for initial construction and subsequent maintenance depend on snow and atmospheric conditions. Use of the combined techniques produced a runway capable of handling wheeled aircraft up to 135,000 lb. This runway had an average bearing capacity of 62.4 psi on the surface and 80.9 psi at a depth of 16 in. The lesser strength at the surface was due to a newly compacted 3-in. layer of drift snow.

Due to the extreme variability in the properties of old snow and new virgin snow and due to the effects of ambient temperature, wind, and radiation on these properties, no standard technique for the construction of compacted roadways and aircraft runways has been developed. Equipment for construction of high bearing capacity runways, such as those built by the U S Navy in the Antarctic, is seldom available and has high initial cost and high maintenance requirements. Well-trained operators are required to insure a uniformly processed surface that will prevent major damage to the aircraft by "break-throughs". In the cold and very cold regions, a compacted snow surface over hard roadways and runways must be removed rapidly when spring thaw starts. This is a major operation that requires very heavy equipment for breaking up and transporting the thick layer of icelike snow produced by the winter compaction program.

Additional information is available for a post engineer faced with the problem of constructing compacted roadways and runways (Refs. 87, 91, 92, 93, 94, 95, 96).

8-7 TESTING, SIMULATION, AND SPECIFICATIONS

Most testing to determine the effects of solid precipitation on materiel is related to the effects of snow on major items of equipment, facilities, and personnel. Major test objectives are thus directed toward the operability and survivability of equipment, facilities, and personnel in snow and to the trafficability of equipment over snow. Little testing is related specifically to the operation of materials of construction, parts, components, and assemblies, except as they perform as part of a major equipment item or facility.

Much of the testing of materiel under snow conditions is done in the field and is frequently combined with tests of equipment under related environments, such as cold temperature. Military maneuvers, normal military operations, or other types of activities in snow areas are frequently used as sources of test data; thus, test results and evaluations are based on the actual experience and measurements obtained during such operations.

The use of simulation is limited. Most simulations are performed to determine the characteristics and properties of blowing snow and the effects of the drifting resulting from obstacles in its path. A considerable amount of effort has been devoted to this type of simulation in attempts to determine optimal facility layout in areas where blowing snow is a major, recurring problem.

8-7.1 TEST RANGES

Testing of materiel under snow conditions is accomplished in many locations. The extensive use of field testing establishes the requirement for test locations to be in areas where snow is available in large quantities over relatively long periods of time and where the various characteristics and properties of snow can be expected to be present. Some of the field facilities used by the United States testing agencies have included Alaska Field Station, USACRREL, Fairbanks, Alaska; Camp Century and other installations (such as Dewline stations), Greenland; the South Pole Station, New Byrd Station, and other installations, Antarctica; the U S Army Arctic Test Center, Ft. Greely, Alaska; and the U S Army Natick Laboratories, Natick, Mass. Tests have been performed at and supported by numerous other installations; this list includes only some of those used for this purpose. At present, Antarctica, by treaty, is unavailable for military use and Camp Century has been deactivated.

8-7.2 SIMULATION EQUIPMENT

The largest facility in the United States capable of snow simulation is the climatic hangar at the Air Proving Ground Center, Eglin Air Force Base, Fla. The larger chamber of this facility is 201 by 252 ft, has a maximum height of 70 ft, and is accessible through 60-ft-high doors. Temperature control ranges from −65° to +165°F, windspeed may be varied from 0 to 5 mph, and snow and rain can be produced in the facility. It is used primarily for testing major items of equipment that can be readily placed and, to some extent, operated in the hangar. A smaller chamber, 34 ft by 19 ft 10 in. by 10 ft high, is also available at Eglin. Temperature in this chamber can be controlled between −80° and +170°F, and windspeed can be varied from 5 to 35 mph.

The Navy Missile Center, Point Mugu, Calif., has a climatic chamber capable of producing a maximum of 2 in. of snow per hour. The chamber is 60 by 63 by 25 ft, has a temperature control range of −60° to +165°F, and is large enough for testing full-scale models of most items of military equipment in a simulated cold region environment.

Much of the snow simulation involves wind-tunnel testing of blowing snow (Ref. 90). Numerous wind tunnels in the United States can be adapted for snow testing. The baffles necessary to simulate turbulent fluctuations and eddies must be constructed so that they do not obstruct the transport of particles in the test area. All problems in wind-tunnel testing have not yet been resolved.

The wind tunnel at Colorado State University, Ft. Collins, Colo., has a test section 88 ft long with a 6- by 6-ft cross section. The controlled temperature range is −40° to 200°F, and the windspeed range is 5 to 120 fps (3.5 to 80 mph). Relative humidity may be controlled between 20 and 80 percent. A simulated snow may be used in this wind tunnel, although it is not specifically constructed for such tests.

New York University has a wind tunnel which has been used for simulated snowdrifting studies. The test chamber is 3.5 ft high, 7 ft wide, and 30 ft long, and it operates at the ambient temperature and humidity, with windspeed controlled up to 20 mph. Crystalline borax is used in the tunnel to simulate snow. Although the tunnel has not been used recently for snow simulation, the required equipment is available, and test and evaluation programs could be initiated on short notice.

An interesting environmental test facility for research and evaluation of snow removal equipment is the tow basin at the Road Research Laboratory, Harmondsworth, Middlesex, England. Scale models of snow removal equipment are tested in a salt-filled towing basin. The snow, a special dendritic form of sodium chloride developed by Imperial Chemical Industries, is available, when specified, from Morton International in the United States.

8-7.3 SPECIFICATIONS

The following documents contain directives, standards, and specifications related to testing the effects of snow on materiel:

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CHAPTER 9

FOG AND WHITEOUT

9-1 INTRODUCTION

Fog is defined as a hydrometeor consisting of a visible aggregate of minute water droplets suspended in the atmosphere near the surface of the earth, reducing visibility to below 1 km (0.62 mi). Fog differs from cloud only in that the base of the fog is at the surface of the earth, while clouds are above the surface. Ice fog is composed of suspended particles of ice. It occurs at very low temperatures, usually in clear, calm weather at high latitudes (Refs. 1, 2).

Whiteout is a weather condition in the polar regions in which no object casts a shadow, the horizon is not discernible, and light-colored objects are very difficult to see. Visibility is reduced and the senses of depth and orientation are lost (Refs. 1, 2).

Fog and whiteout are discussed together in this chapter because both have important effects on visibility.

The design engineer requires knowledge of fog and whiteout in order to include the following considerations in the design of materiel:

(1) The primary effect of fog and whiteout is reduction of visibility which restricts operations of both air and ground vehicles as well as other activities dependent on observations.

(2) In fog, propagation losses of acoustic and electromagnetic energies increase but not as rapidly as losses of optical energy.

(3) Both fog and ice fog may cause deterioration in the performance of materiel as do other high humidity environments.

(4) The effects of fog and ice fog may be aggravated or dissipated by the operation or use of specific items of materiel.

This chapter on fog, ice fog, and whiteout overlaps, in some instances, the information in other chapters of this Environmental Handbook Series, as follows:

Part Two:	Chapter 4:	Humidity
	Chapter 7:	Rain
	Chapter 8:	Solid Precipitation
	Chapter 11:	Salt, Salt Fog, and Salt Water
Part Three:	Chapter 2:	Atmospheric Pollutants.

Refer to these chapters for supplementary information.

9-2 CHARACTERISTICS OF FOG

Condensation and sublimation of water vapor in atmospheric air form minute water droplets and ice crystals. When such particles aggregate directly above the ground, they produce fog. Saturation of the air with water vapor and the presence of condensation nuclei are usually necessary for fog formation. In some cases, however, deliquescent nuclei produce fog when the relative humidity is considerably below 100 percent. For example, as noted in Chap. 11, salt fogs form well below the saturation point because hygroscopic sea-salt nuclei may begin to absorb moisture at relative humidities as low as 76 percent. Condensation nuclei composed of sulfur compounds and other combustion products are usually concentrated in industrial areas and may also produce fog at relative humidities considerably below 100 percent. When the temperature is sufficiently low, ice fogs may occur (Refs. 1, 3).

9-2.1 TYPES OF FOG

Fogs may be classified on the basis of their intensity, the physical processes leading to their formation, or the aggregate state of the fog particles.

Fog classification by intensity has varied often since the original definition by the U.S. Weather Bureau in 1892 when a foggy day was one "on which fog surrounds the station for one hour or more, and is dense enough to obscure objects at a distance of 1000 ft". *Light, moderate, dense,* and *thick* were employed at various times to describe different intensities of fogs until 1949 when all descriptive terms were eliminated (Ref. 4). Climatic summaries are based on either *heavy fog* with visibility of 400 m (1/4 mi) or less, or *fog* with visibility of 1 km (0.62 mi) or less. A more precise description requires the specification of visibility usually in increments of 1/4 mi. Delineation among fog, smog, and haze is left to the discrimination of the observer.

In the classification of fogs by the physical process of formation, there are two broad classifications: evaporation fogs, formed when moisture is added to cold air, and cooling fogs, formed when moist air is cooled below its dewpoint. These can be subdivided into types based on more specific formation processes as follows (Refs. 1, 2, 5).

9-2.1.1 EVAPORATION FOGS

These fogs occur when water vapor enters the air upon evaporation from a warm underlying surface and is subsequently chilled by the cold air overlying that surface. For this to occur, the evaporating surface must be appreciably warmer than the air. Fog resulting from this process is commonly called steam fog, but is also known in arctic areas as "arctic sea smoke". Steam fog is an unstable type which occurs when very cold air drifts across relatively warm water; it is particularly common over relatively warm seas adjacent to regions of cold arctic air (e.g., the Aleutian Islands); and it is frequently observed in the autumn in the middle latitudes when cool land air advances over the warmer lakes and rivers. Steam fog is characterized by much turbulence and may be as much as 5,000 ft thick.

9-2.1.2 COOLING FOGS

Cooling fogs are the most common and most extensive fogs. They result from chilling of the air and occur when moist air contacts a colder surface. Cooling fogs are classed into three types, according to the cause of chilling:

(1) *Radiation fogs.* These fogs occur over land areas cooled by radiation. This cools the adjacent air to or below its dewpoint. A radiation fog is strictly a nighttime occurrence, although it may begin to form by evening twilight and often does not dissipate until after sunrise. Favorable conditions for radiation fog formation include the absence of a cloud cover, high relative humidity, and low windspeed.

(2) *Advection fogs.* The movement of moist air over a cold surface and the subsequent cooling of this air below its dewpoint produce advection fogs. A common type is the sea fog, formed when air that has been lying over a warm water surface is transported over a colder water or land surface which cools the lower layer of air below its dewpoint. Advection fogs are particularly common along seacoasts in the cold season when air advances over land from the warm surface of the water; they also frequently form over cool ocean currents.

(3) *Upslope fogs.* These are formed when air flows upward over rising terrain and consequently is cooled adiabatically to or below its dewpoint. A specific upslope fog is the so-called "high fog" associated with the coastal mountains of California.

9-2.1.3 MIXING FOGS

Mixing fogs result from the horizontal

mixing of air masses of different temperatures and humidities and also, under certain conditions, from turbulent vertical motion. Calculations show that the mixing causes fogs only if the relative humidities of the air masses involved are 95 percent or higher and the temperature difference between them is 10 deg C (18 deg F) or more. These fogs are usually of limited intensity.

9-2.1.4 OTHER FOG TERMINOLOGY

In addition to the previous types, "ground fog" is a term used to describe a fog, usually a radiation fog, that obscures less than 0.6 of sky but does not extend to the base of any cloud, and "shallow fog" is a term describing a radiation fog that does not obstruct visibility at a level 6 ft or more above the surface of the earth. The term "frontal fog" describes fogs associated with frontal zones or frontal passages. In warm-front prefrontal fogs and cold-front postfrontal fogs, the fogs result from rain falling into cold stable air and raising the dewpoint temperature. Frontal-passage fogs can be mixing fogs or can result from sudden cooling of air over moist ground (Ref. 1). Several fog types are shown in Fig. 9-1 (Ref. 6).

9-2.1.5 ICE FOG

Ice fog is unique because it is usually a manmade phenomenon, a form of air pollution in which the pollutant is water vapor. In a city such as Fairbanks, Alaska, where ice fog is common, the water vapor originates from automobile exhausts (3 percent), the combustion of coal and oil (29 percent), power plant cooling water (64 percent), and miscellaneous sources (4 percent) (Ref. 7). In Fairbanks in January when the temperature is below −40°C (−40°F) 10 percent of the time, water droplets formed in the air freeze in several seconds (Ref. 8). The nucleation process is accelerated by the presence of condensation nuclei but, at the lower temperatures, does not depend on them. Denser ice fog is seen at the lower temperatures because of the growth of a larger number of small crystals (Refs. 9, 10). The appearance of ice fog over Ft. Wainwright near Fairbanks is shown in Fig. 9-2, and a midday ice fog in Fairbanks is shown in Fig. 9-3.

9-2.1.6 FOG COMPOSITION

Above 0°C (32°F), all fogs consist primarily of water droplets, with melting snowflakes or hailstones which have fallen from overlying layers only occasionally observed. As the temperature drops below 0°C (32°F), both supercooled droplets and ice crystals begin to appear. Finally, at very low temperatures (−40°C (−40°F) and lower), fog consists only of the solid phase of water, ice crystals in various forms. Thus, fogs may be categorized as:

(1) Droplet (or liquid) fog, consisting of droplets of water. (Droplet fogs may be supercooled fogs, composed of unfrozen droplets at temperatures below 0°C (32°F), or warm fogs, with droplet temperatures above 0°C (32°F).)

(2) Mixed structure fogs, containing both supercooled droplets and ice crystals

(3) Ice fog, consisting entirely of ice crystals.

9-2.2 PROPERTIES OF FOG

The generation, development, and dissipation of fog depend on thermodynamic conditions in the atmosphere that determine the condensation (sublimation) of water vapor. The macroprocesses have been described in the preceding paragraphs; the microprocesses inside the fog are equally important. Macro- and microprocesses operate simultaneously.

The most important microphysical characteristics of clouds and fogs are:

(1) The aggregate state of the hydrometeors

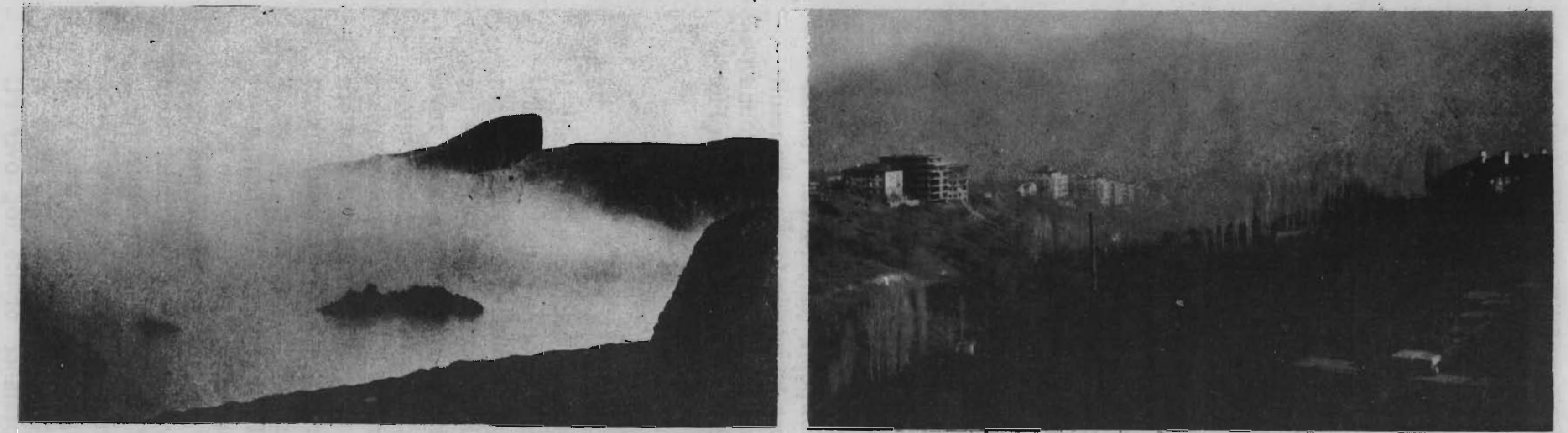
(2) The predominant size and size spectra of the droplets or the form and size of the ice crystals

Photograph by J. R. C. Young

(A) Radiation Fog

Photograph by R. W. Longley

(B) Steam Fog



Photograph by K. Williamson

(C) Sea Fog at Fair Isle

Photograph by Gr. Capt. R. F. Hitchcock

(D) Smog Over Ankara

Figure 9-1. Some Representative Types of Fog (Ref. 6)

(A) Over Ft. Wainwright, Near Fairbanks, Alaska

(B) Same Location on a Clear Winter Day

Figure 9-2. Ice Fog Produced by Power Plant and Other Water-vapor Sources of Contamination (Photographs by Motoi Kumai)

Photograph by Robert M. Chapman

Figure 9-3. Fairbanks at Midday During a Typical Ice Fog (The sign shows temperature and time with alternating flashes of the lights. The temperature it shows (−41°F here) is usually 5 deg C warmer than recorded by the U S Weather Bureau at the airport.)

(3) The concentration of condensed moisture per unit volume, or liquid water content (LWC)

(4) The droplet concentration, or number of particles per unit volume

(5) Effect on visibility

(6) The chemical composition

(7) The vertical depth.

An extensive survey of the literature by Pilie (Ref. 11) resulted in the physical models for radiation and advection fogs given in Table 9-1.

9-2.2.1 DROPLET SIZE

The droplet size in fogs varies over wide ranges dependent on the number and size of nucleation centers, temperature of the air, rate of cooling of the air, liquid water content, and the age of the fog. For example, if an active salt particle with a diameter of 1 μm serves as the nucleation center, it can grow, through water vapor condensation, to a diameter of 10 μm in 1 s. However, about 500 s are required for the droplet to grow to a diameter of 100 μm (Ref. 12). In still air, the terminal velocity at which a droplet falls due to gravity is 0.04 mm s^{-1} for a 1-μm-diameter droplet but increases to 3 and 300 mm s^{-1} for 10- and 100-μm-diameter droplets, respectively (Ref. 12). In fog, droplets either are held suspended by rising air currents or are continually replaced by new droplets condensing from the water vapor in the air. In any case, a decreasing population is observed as the drop diameter increases, and in some regions, falling fog droplets provide more water to vegetation than does rainfall.

The distribution of raindrop diameters (see Chap. 7) ranges from 0.5 to over 5 mm; in clouds, raindrops grow in size through coalescence of droplets by capture processes as-

TABLE 9-1

PHYSICAL FOG MODELS

Fog parameters at the surface	Radiation (inland) fog	Advection (coastal) fog
Average droplet diameter	10 μm	20 μm
Typical droplet size range	5-35 μm	7-65 μm
Liquid water content	110 mg m^{-3}	170 mg m^{-3}
Droplet concentration	200 cm^{-3}	40 cm^{-3}
Vertical depth of fog		
a. Typical	100 m	200 m
b. Severe	300 m	600 m
Horizontal visibility	100 m	300 m

sociated with their relative motion.

The fog droplet size distribution is from 2 to 60 μm diameter with some larger diameters reported. Table 9-2 provides representative values for droplet sizes in various types of fogs.

Tverskoi (Ref. 5) states that the range of droplet sizes narrows in evaporation fogs (r = 1 to 20 μm predominate). Dergach (Ref. 13) concludes that droplet size may relate to the stage of development, with size increasing with age.

The rate of change of the droplet mass due to evaporation and condensation is proportional to its radius r. The scattering of light on a droplet is proportional to the square of the radius r^2. The change in its volume or mass is proportional to r^3. Reflection of radio waves is proportional to r^6 (Ref. 5).

Eldridge (Refs. 18,19) discusses the size distribution of droplets in fog and notes the biases inherent in the measurement techniques. These tend to truncate the reported distributions at either the small or large diameters. Middleton (Ref. 20) has also discussed the measurement problem and offers the size distribution curves shown in Fig. 9-4. Kocmond (Ref. 21) has obtained the data in Fig. 9-5 showing the expected variation in drop size distributions with altitude in a representative "valley" fog.

9-2.2.2 ICE CRYSTAL SIZE

Ice fog is composed of many minute ice crystals; most are spherical but some are in the form of hexagonal columns or irregular crystals (Ref. 10). Shapes, concentrations, and sizes vary with temperature and conditions of formation. Ice-fog crystals, formed at around –40°C (–40°F), are small, ranging from about 2 to 30 μm in diameter. Kumai (Ref. 22) reports that ice-fog crystals in the Fairbanks area of Alaska in 1962 at –42°C (–44°F), –37°C (–35°F), and –39°C (–38°F) were mainly spherical, 2 to 15 μm in diameter, with rudimentary crystal faces (5 to 30 μm) and some hexagonal plates and columnar forms (5 to 30 μm). Robinson et al. (Ref. 23) also found that the diameter range of ice-fog crystals fell mainly in the 2- to 15-μm range. The difference in size distribution of ice crystals formed between –37°C (–35°F) and –42°C (–44°F) indicates that size decreases with decreasing air temperature.

TABLE 9-2

FOG DROPLET SIZE

Fog type	Mean Radius, μm	Modal Radius, μm	Range, μm	Place and date	Ref. No.
Ground	-	-	4.0-32.0	Greenland 1956	14
Ground	-	-	3.0-21.0	Greenland 1957	14
Ground	-	-	5.0-59.0	Greenland 1957	14
Ground	8.6	7.3	1.0-33.0	Greenland 1960	15
Ground	8.0	-	10.0-25.0	Greenland 1960	17
Ground	8.5	-	8.0-30.0	Greenland 1960	17
Sea	9.0	7.0	1.0-33.0	Greenland 1960	15
Sea	8.7	6.0	1.0-37.0	Greenland 1960	15
Sea	-	-	2.0-60.0	Hokkaido 1951	16
Sea	5.0- 7.0	10.0	1.0-35.0	U.S.S.R. 1956	13

Larger ice crystals, which are the initial stage of snow crystals, form at around −25°C (−13°F) and range from about 20 to 300 μm in diameter. Ice crystals collected by Kumai (Ref. 22) in both heavy and light ice fog showed a diameter of about 100 μm. They had a well-developed crystal shape and were a slow type of precipitation. Benson (Ref. 7) distinguishes these larger crystals from those found in ice fog and attributes their more highly developed crystallinity and their size to the slower growth rate in the free atmosphere, as opposed to the rapid growth of crystals when water vapor is injected into extremely cold air. The larger crystals form in cirrus clouds and are observed in the so-called diamond dust displays (Ref. 7).

9-2.2.3 LIQUID WATER CONTENT (LWC)

The LWC of droplet fogs normally is between 0.01 and 1.0 g m^{-3}, with most measurements ranging from 0.015 to 0.5 g m^{-3}. Tverskoi (Ref. 5) states that low values (0.02 to 0.03 g m^{-3}) are found in evaporation fogs at low temperatures and that high values (0.3 to 0.9 g m^{-3}) are found in radiation and advection fogs. Dergach (Ref. 13) observed a direct relationship between liquid water content and temperature, and also found the liquid water content is higher in the middle and upper fog layers. Table 9-3 shows the liquid water content measured in various types of fog at different locations and times. Petterssen (Ref. 12) notes that in a dense sea

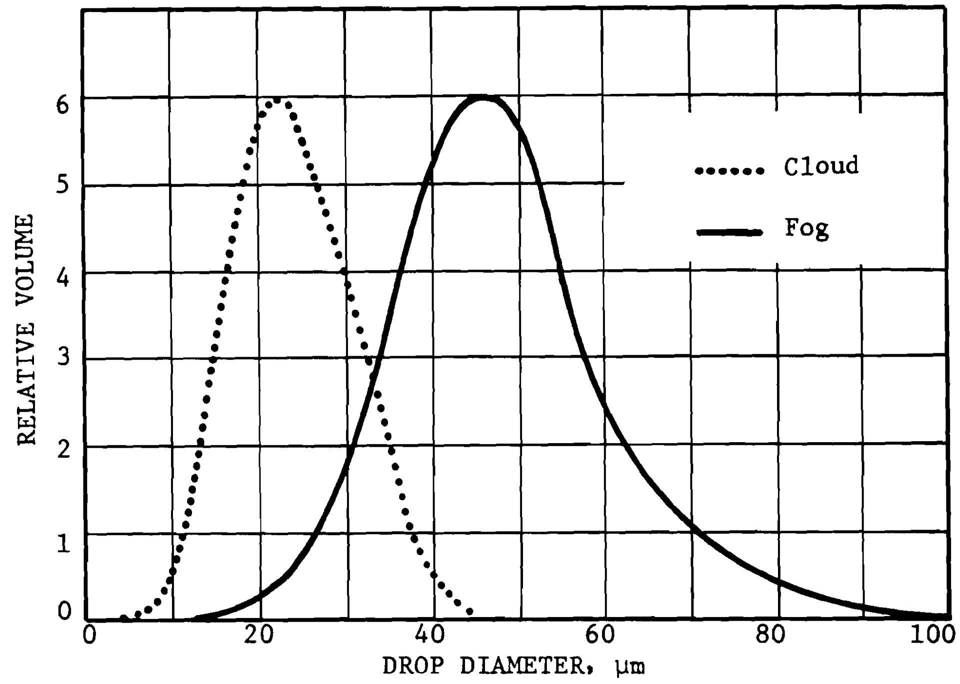


Figure 9-4. Drop Size Distribution (Ref. 20) (Typical distributions for a cloud (or mountain fog) and coastal fog showing relative volume of water distributed among drop sizes.)

fog (visibility less than 50 m), there may be as much as 3 g m^{-3}, but in a light city fog (visibility of about 1,000 m), the water content may be less than 0.02 g m^{-3}.

Little data are available on the liquid water content of ice fog. Tverskoi (Ref. 5) states that the liquid content of ice-crystal and mixed fogs is 0.03 g m^{-3}. Kumai (Ref. 22) reported liquid water content of 0.02 to 0.07 g m^{-3} for ice fogs observed in the Fairbanks area in 1962. Benson (Ref. 10) states that a conservative measure of the liquid water content of ice fogs in the Fairbanks area is 0.21 g m^{-3} in the central area over the city where the fog is densest, and 0.07 g m^{-3} in the outlying areas of less dense fog. He further estimates that an input to the atmosphere of 4 X 10^6 kg water per day occurs in Fairbanks and maintains a maximum ice fog volume of 3 X 10^9 m^3 over an area of nearly 200 km^2 (Ref. 7).

9-2.2.4 DROPLET CONCENTRATION

The droplet concentration or number density reported for fogs depends on the method and conditions of measurement. In Fig. 9-5, for example, it can be seen that the droplet concentration depends on the altitude within the fog at which the observation is made. Myers (Ref. 26) gives a range of 20 to 500 droplets cm^{-3}, Tverskoi (Ref. 5) gives a range of 1 to 10 cm^{-3} for thin fogs and 400 to 600 cm^{-3} for thick fogs, and Wright (Ref. 27) gives 100 to 200 cm^{-3} for light fogs and 500 to 600 cm^{-3} for dense fogs.

Studies by Kumai indicate that the crystal concentration in ice fogs ranges from about 100 to 200 crystals cm^{-3}, based on measurements in the Fairbanks area in midwinter 1962 (Ref. 22). He reported the same ranges based on measurements in downtown Fairbanks in January and February 1963 (Ref.

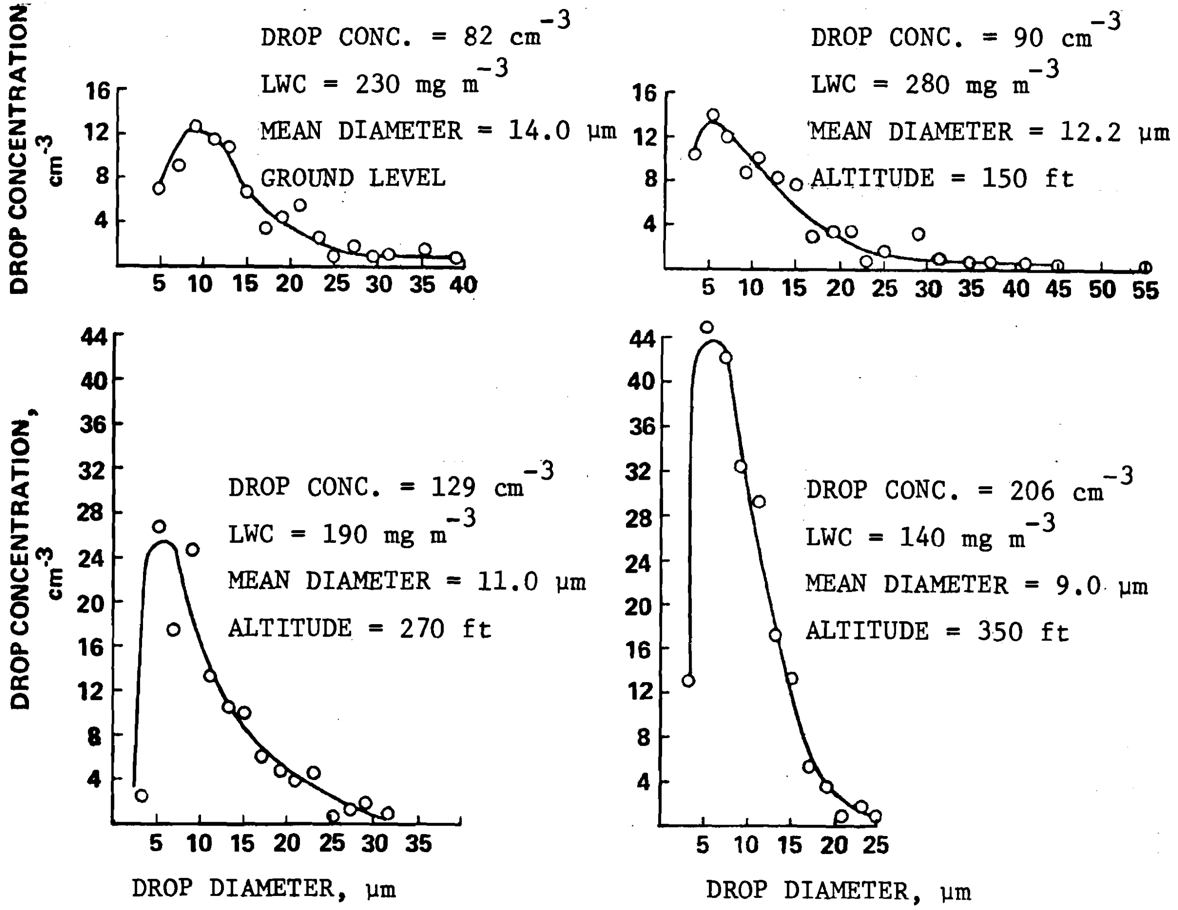


Figure 9-5. Drop Size Distributions at Four Levels in a Valley Fog at Elmira, N.Y., 30 Aug 68 (Ref. 24)

28) and, in measurements taken at Eielson Air Force Base near Fairbanks in February 1964, a concentration of 100 crystals cm^{-3} was recorded (Ref. 29).

9-2.2.5 VISIBILITY*

Meteorological visibility is defined as the greatest distance at which a black object of suitable dimensions can be seen and recognized against the horizon sky, or, in the case of night observations, could be seen and recognized if the general illumination were raised to normal daylight levels (Ref. 28).

Observations show that the more distant an object is from the viewer, the brighter it appears. When objects are viewed against the horizon sky, a distance will be reached at which the brightness of the object and the sky become so nearly alike that the contrast between the object and the horizon is lost; hence, the object becomes invisible.

9-2.2.5.1 VISIBILITY-RESTRICTING PARAMETERS

A few basic elements of the theory of visibility may be considered. Visibility is dependent on:

(1) *The intensity of light (sunlight and skylight).* Light intensity is approximately constant along the optical path if the sky is either perfectly clear or uniformly clouded. In fog, the sky seen by the ground level observer is generally uniformly covered so that constant illumination along the optical path can

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*General references for this paragraph are Refs. 3, 5, 15, 20, 30, and 31.

TABLE 9-3

LIQUID WATER CONTENT (LWC) OF DROPLET FOG

Fog type	LWC, $g\ m^{-3}$	Place and date	Ref. No.
Ground	0.015	Greenland 1960	15
Ground	0.034	Greenland 1956	14
Ground	0.108	Greenland 1957	14
Ground	0.061	Greenland 1957	14
Radiation	0.3-0.5	Travis AFB 1968	24
Sea	0.1-0.15	U.S.S.R. 1956	13
Sea	0.6	U.S.S.R. 1956	13
Radiation	0.06-0.5	U.S.S.R. 1962	25

be assumed.

(2) *The coefficient of attenuation (also known as the coefficient of extinction).* The coefficient of attenuation is the proportion of the light flux removed from a beam of light in a unit of distance. The removal of light flux is primarily the result of scattering. The light scattered back to the observer by the atmospheric suspensoids in the optical path increases the apparent brightness of the viewed object as the distance from the observer increases. Scattering particles include (in order of increasing size) air molecules, condensation nuclei, smoke, dust, fog, and precipitation elements.

(3) *The brightness-contrast threshold.* This is the smallest contrast of luminance that is perceptible to the human eye under specified conditions of adaptive luminance and target visual angle. For the average eye under daylight conditions, most authorities have taken 0.02 as the threshold at which the object becomes visible, however; the value is set at 0.05 by the World Meteorological Organization based on the definition of meteorological visibility cited in par. 9-2.2.5, which requires both seeing and recognizing the object (Ref. 30).

Although treated as a constant, the actual threshold ratio varies considerably under certain conditions primarily related to the level of illumination and the size of the angle subtended by the object at the eye. As the general illumination decreases below a critical minimum at twilight and at night, the value of the brightness-contrast threshold increases sharply (to 0.6 – 0.7). Under daylight conditions, the threshold value remains practically constant for objects with angular dimensions exceeding 20 min (Ref. 5). The World Meteorological Organization in its guide (Ref. 30) recommends that viewed objects should be large enough to subtend an angle of 0.5 deg at the observer's eye.

9-2.2.5.2 VISUAL RANGE

Koschmieder's theory, which is generally accepted, states that the meteorological visual range for a black object is equal to the distance at which the brightness contrast is equal to the threshold value, or

$$V = \frac{1}{\sigma} \ln\left(\frac{1}{\epsilon}\right) = -\frac{\ln \epsilon}{\sigma}, \text{ m} \qquad (9\text{-}1)$$

where

V = meteorological visual range, m

σ = attenuation coefficient or extinction coefficient, m^{-1}

ϵ = brightness-contrast threshold, dimensionless

Substituting 0.05 for ϵ gives

$$V = \frac{3.0}{\sigma}, \text{ m} \qquad (9\text{-}2)$$

The Koschmieder equation applies to an absolutely black object, which absorbs all of the incident light, so that its brightness is zero when measured directly at the object. The World Meteorological Organization in its guide notes that if the albedo of the object does not exceed about 0.25, no error larger than 3 percent will be caused if the sky is overcast, as is common in fog.

The deterioration of visibility in fog results from the large light-scattering effect of the fog droplets. The effect of air molecules on light scattering in fog is so small compared to fog particles that it can be neglected.

The meteorological visual range in fog depends on the number of particles per unit volume and on their size. For the droplet sizes usually found in fog, according to Mie's theory, the attenuation coefficient σ is expressed by:

$$\sigma = \sum_{i=1}^{n} \pi r_i^2 N_i K = 2\pi \sum_{i=1}^{n} N_i r_i^2 = 2\pi N r_{rms}^2, \text{ m}^{-1} \qquad (9\text{-}3)$$

where

r_i = droplet radius, m

r_{rms} = root mean square radius of droplets, n

N_i = number of droplets per unit volume with radii $r_i + \Delta r$, m^{-3}

N = total number of droplets per unit volume, m^{-3}

K = a scattering function, ≈ 2 for $r > 0.05$ μm, dimensionless

The value of N can be determined from the liquid water content of the fog, using the equation

$$W = \frac{4}{3} \pi \rho \sum_{i=1}^{n} N_i r_i^3 = \frac{4}{3} \pi \rho N r_{mvr}^3, \text{ g m}^{-3} \qquad (9\text{-}4)$$

where

W = liquid water content, g m^{-3}

r_{mvr} = mean volume radius, m

ρ = density of water, g m^{-3}

From this,

$$\sigma = \frac{3W}{2\rho}\left(\frac{r_{rms}^2}{r_{mvr}^3}\right), \text{ m}^{-1} \qquad (9\text{-}5)$$

and the meteorological visual range V can be given as

$$V = \frac{2\rho}{W}\left(\frac{r_{mvr}^3}{r_{rms}^2}\right) \approx \frac{2\rho}{W} r, \text{ m}^{-1} \qquad (9\text{-}6)$$

where if W and ρ are in the same units, then V is in the same units as r. Substituting the values of the radiation fog model from Table 9-1, i.e., $r = 5$ μm $= 5 \times 10^{-4}$ cm and $W = 0.11 \times 10^{-6}$ g cm^{-3}, the visual range is

$$V = \frac{2 \times 5 \times 10^{-4}}{0.11 \times 10^{-6}} \text{ cm} = 9090 \text{ cm} = 90.9 \text{ m} \qquad (9\text{-}7)$$

which is in reasonable conformity with the model value of 100 m. The model advection fog in Table 9-1 does not agree with Eq. 9-5, probably because its droplet sizes are dispersed over a wide range and $r_{rms} \neq r_{mvr}$ as assumed.

From Eq. 9-5, it can be seen that the visual range in fog is inversely proportional to the liquid water content and directly proportional to the radius of the fog droplets. (These two parameters are not independent, of course.) Thus, for the same liquid water content, the visual range in a fine-droplet fog will be lower than in a large-droplet fog; in fact, the visual range drops to zero in thick fog and to 1 km in light fog. For polydisperse fogs allowance must be made for the size distribution of the droplets.

For ice fogs, the meteorological visual range depends on the number of ice crystals per unit volume and on their size. As shown earlier, Koschmieder's equation requires only the determination of the attenuation coefficient to establish the meteorological visual range V. For ice fog the attenuation coefficient σ is expressed by Prudden and Wardlaw (Ref. 31) as.

$$\sigma = \frac{1.97\, M_p K}{P(N)\, d}, \mathrm{m}^{-1} \tag{9-8}$$

where

σ = attenuation coefficient, m^{-1}

M_p = ice mass concentration per unit volume, $\mathrm{g\ m}^{-3}$

K = a scattering function (≈ 2 for $d \geqslant 0.1\ \mu\mathrm{m}$)

$P(N)$ = crystal size distribution parameter, relating volume mean diameter to area mean diameter which can vary from ≈ 0.4 to 1.3, depending on the skewness of the crystal size spectrum. For practical purposes, a median value of ≈ 1.0 can be used.

d = crystal diameter, $\mu\mathrm{m}$

Applying these values to the expression for the meteorological visual range, Eq. 9-2 ($V = 3.0/\sigma$) results in the expression

$$V = \frac{0.76\, d}{M_p}, \mathrm{m} \tag{9-9}$$

Thus, for ice fogs, as with droplet fogs, the visual range is directly proportional to the diameter of the fog crystals and inversely proportional to the concentration per unit volume.

9-2.2.6 CHEMICAL COMPOSITION

Condensation of water vapor on nuclei is the principal mechanism for the atmospheric formation of embryonic droplets, which may grow and form fog or other forms of precipitation. The relative humidity at which condensation on nuclei takes place depends on how hygroscopic these nuclei are and on their radii. As noted in Chap. 11, salt nuclei initiate condensation at relative humidities of 76 percent. Atmospheric nuclei are generally categorized by size (Ref. 32):

(1) Aitken nuclei	$r \leqslant 0.1\ \mu\mathrm{m}$
(2) Large nuclei	$0.1\ \mu\mathrm{m} < r \leqslant 1.0\ \mu\mathrm{m}$
(3) Giant nuclei	$r > 1.0\ \mu\mathrm{m}$

Of the three categories, the large nuclei play the most important role in the formation of atmospheric droplets (clouds and fog). Although giant nuclei also produce droplets, their low concentration makes their effect insignificant except in the formation of rain (Ref. 32).

The concentration of large nuclei is greatest at lower levels of the atmosphere, particularly over cities and industrial areas. The concentration distribution results primarily from the following mechanisms by which the nuclei are produced (Ref. 32):

(1) *Combustion.* In natural (volcanic eruptions, brush, and forest fires) or artificial (domestic, industrial) combustion, volatile

combustion products evaporate or sublime and emerge into the atmosphere at an elevated temperature. These vapors cool quickly by mixing with the air and become highly supersaturated. As a result, nuclei are formed by either homogeneous or heterogeneous nucleation, most of which are Aitken nuclei. The nonvolatile combustion products that emerge are either partially or completely burned; being friable they break easily under the action of the wind; nuclei thus formed are mostly large nuclei.

(2) *Chemical reaction.* The atmosphere contains a wide variety of gases of low concentration. Under the action of heat, humidity, or short wavelength radiation, certain of these gases can interreact. For example, NH_4Cl can be formed by the reaction of NH_3 and HCl, or SO_2 can be oxidized to H_2SO_4. Most nuclei formed by this mechanism are Aitken nuclei.

(3) *Release of liquid particles.* Atomization of water thrust upward from the sea as spray and bursting of air bubbles at the surface of the sea result in the release of droplets into the air. Evaporation, if complete, results in crystallization of the sea salt and produces mostly large nuclei, with some giant nuclei. A discussion of this mechanism and the resulting nuclei size is given in Chap. 11.

(4) *Solid particles.* Wind action lifts solid particles (sand, dust, etc.) from the ground and disperses them into the atmosphere. In general these particles are either large or giant nuclei. Giant nuclei fall rapidly to the ground with their zone of dispersion being limited to the vicinity of their source.

Studies of condensation nuclei indicate that they are composed principally of sea salt, combustion products, and particles released from the ground. Little information is available on the relative percentages of these condensation nuclei or on the relative amounts of various chemical elements and compounds in them. The most common nuclei appear to be those containing compounds of chlorine, sulfur, nitrogen, carbon, magnesium, sodium, and calcium. Salt nuclei are encountered quite frequently. The chemical composition of nuclei varies, to some extent, from one area to another—e.g., nuclei consisting of sulfur compounds are concentrated in industrial areas; salt nuclei, in areas near the sea; and sand and dust nuclei, in desert and arid areas (Ref. 5).

Although precise measurements are not available, the design engineer needs to know that a high percentage of nuclei in fog droplets are chloride or sulfur compounds, both of which have a marked effect on metal corrosion.

The presence or absence of large numbers of condensation nuclei can have important effects on fog. Fog frequencies are believed to have increased considerably due to increased air pollution; thus, fogs are more prevalent in polluted industrial areas than in areas having cleaner air. Myers (Ref. 26) notes that at an observation station in Prague, Czechoslovakia, where 150 yr of records have been taken, twice as many fogs have been recorded since 1881 compared to the preceding 80-yr period. The visual range in fog in industrial areas is less than that in unpolluted areas because of the added constituents. In the "dirty fog" or smog in London in 1952, the composition was estimated to be that shown in Table 9-4. Despite the very low percentages of smoke and sulfur dioxide, the smog was very dirty and resulted in many deaths.

Although concentration of condensation nuclei in most uninhabited arctic areas is low, it can become high in urban areas. The lack of wind and the temperature inversions that accompany ice fog contribute to the concentration. Condensation nuclei measurements made by Kumai and O'Brien (Ref. 28) in the Fairbanks, Alaska, area, during three winter seasons (1962, 1963, 1964) showed that concentrations in the fog-free areas ranged between 450 and 2,400 particles cm^{-3} while in the areas where fogs occur, they ranged

TABLE 9-4

COMPOSITION OF LONDON SMOG OF 1952 (Ref. 20)

Component	Density, tons km^{-3}
Dry air	500,000
Liquid water	4,500
Water vapor	17,000
Smoke particles	10
Sulfur dioxide	10

between 22,500 and 26,000 particles cm^{-3}.

Since ice fogs are produced by the discharge of water vapor, sulfur dioxide, and other combustion products from engines and heating devices, the nuclei in ice-fog crystals are mainly products of combustion. During his midwinter 1962 observations, Kumai counted and identified the nuclei in ice-fog crystals formed from jet aircraft exhaust gases, from flue gases of coal-burning power plants, and from an open water site kept clear by warm waste water from industrial plants (Ref. 22); 74 to 90 percent of the nuclei were combustion byproducts, 10 to 21 percent were combustion byproducts combined with silicate minerals, and 0 to 3 percent were combustion byproducts combined with a hygroscopic substance. Kumai and O'Brien (Ref. 28) reported at Fairbanks in 1962 and 1963, that of 409 crystals collected 80 percent of the nuclei were combustion byproducts, 9.8 percent were a hygroscopic substance combined with combustion byproducts, 8.5 percent were clay minerals, and 1.7 percent were unidentified. Thus, for ice fogs in urban areas, 90 percent or more of the ice crystals are expected to contain nuclei resulting from combustion processes. The principal combustion products produced by coal, fuel oil, and gasoline are carbon dioxide, sulfur dioxide, water, and in the case of coal, ash.

9-2.2.7 VERTICAL DEPTH

The vertical depth or thickness of fog is important and varies widely with fog type and local conditions. Pilie (Ref. 11) cites, as representative, ranges of 100 to 300 m for radiation fogs and 200 to 600 m for advection fogs. The London fog (smog) of 1952 was about 150 m deep, while an advection fog over the Grand Banks has been observed to be 210 deep (Ref. 12). Bakhanova and Solyanek (Ref. 33) described steam fogs over water which are from approximately 5 to 20 m deep, while Jiusto (Ref. 34) reported coastal, radiation, and sea fogs to be, respectively, 130, 150, and 500 m deep. From these and previous discussion, the range of fog depth extends from a few meters to 1,500 m or more.

9-2.3 OCCURRENCE OF FOG

Fog over land is usually a localized phenomenon greatly influenced by local terrain or geography, but in large regions of the oceans and in certain land areas, conditions are such as to give a persistent widespread fog pattern. For example, the Grand Banks area is noted for its fog and icebergs. Here, the Labrador Current brings large masses of cold water adjacent to the northward flowing warm Gulf Stream to produce ideal conditions for frequent advection fogs. This regime extends from as far south as the Carolinas, up along the New England coast to Greenland, the northern Norwegian sea, and the Barents Sea. In winter, fogs are frequent along the edge of the arctic ice, and in summer they are frequent all over the Arctic (Ref. 12).

In the United States, the west coast experiences high fog frequencies (> 45 days yr^{-1}) due to the orographic lift provided by the mountains to the moist air from the Pacific Ocean. In the Rocky Mountain region, the moisture is lower and fogs are less frequent (< 20 days yr^{-1}). The vast regions of the Great Plains and the Mississippi Valley are also relatively free of fog (< 20 days yr^{-1}), but the Great Lakes provide sufficient moisture for that region to have about 30 days yr^{-1} of fog. The irregular terrain and abundant moisture in the Appalachian region result in 20 to 60 days yr^{-1} of fog with a few years as high as 100 days. The average incidence drops to about 25 days yr^{-1} along the Atlantic and Gulf Coasts. A fog frequency map compiled by Peace (Ref. 35) from the U S Weather Bureau's "Local Climatological Data Summaries" is shown in Fig. 9-6.

Cold currents similar to the Labrador Current are found along the eastern coast of Asia, while the western coasts of South America and southern Africa have high fog frequencies similar to those of the U S Pacific coast. Worldwide frequencies of fog in any form are shown in Fig. 9-7 as compiled by the U S Environmental Data Service (Ref. 36). For comparison, a similar fog isopleth map is shown in Fig. 9-8 for supercooled fogs in October.

Seasonal maps indicating percent frequency of occurrence of surface visibility less than 2 nautical miles for the arctic region are shown in Fig. 9-9 (Ref. 37). Fog is only one contributor to this low visibility, as indicated in the bar graph in Fig. 9-10 showing causes of obscuration at three arctic observing stations.

The influence of industrial activity on fog occurrence is becoming more pronounced. The most visible example is the direct supply of moisture to the atmosphere by electric power generation stations, either from cooling towers or from warm water discharges into lakes or streams. Under favorable meteorological conditions, fogs created by such sources can extend over large areas. Similarly, as previously noted, localized fogs are observed near large emission sources of air pollutants which provide concentrations of condensation nuclei (Ref. 26).

Fogs have clear-cut daily and annual marches. The daily march is particularly well defined for radiation fogs, which develop at night, reach maximum intensity by morning (at the time of minimum temperature and maximum relative humidity), and dissipate after sunrise. Other types of fog are intensified by radiation processes; therefore, their frequency of occurrence also displays a maximum at night and minimum by day (near the temperature maximum).

The annual march depends on geographic conditions. In middle latitudes, maxima in fog frequency are observed in autumn and spring. Over continents, a fog is most common in autumn, and over seas and oceans in spring when the water surface is coolest.

Ice-fog formation depends on temperature levels of about –35°C (–31°F) or lower, so it occurs only during the winter months in areas subject to such temperature extremes. Its occurrence also depends on an adequate supply of water vapor in the atmosphere, usually provided by human activities. Therefore, ice fog is normally confined to limited areas in and around urban centers and military installations located in areas where sufficiently low temperatures occur.

Temperatures allowing formation of ice fog are shown in Figs. 9-11 through 9-14 for the Northern Hemisphere (Refs. 8, 38). Percent frequencies of temperatures below –32°C (–25°F) are shown in Figs. 9-11 and 9-12 at which ice fog may form while, given a source of moisture, ice fog will certainly form at or

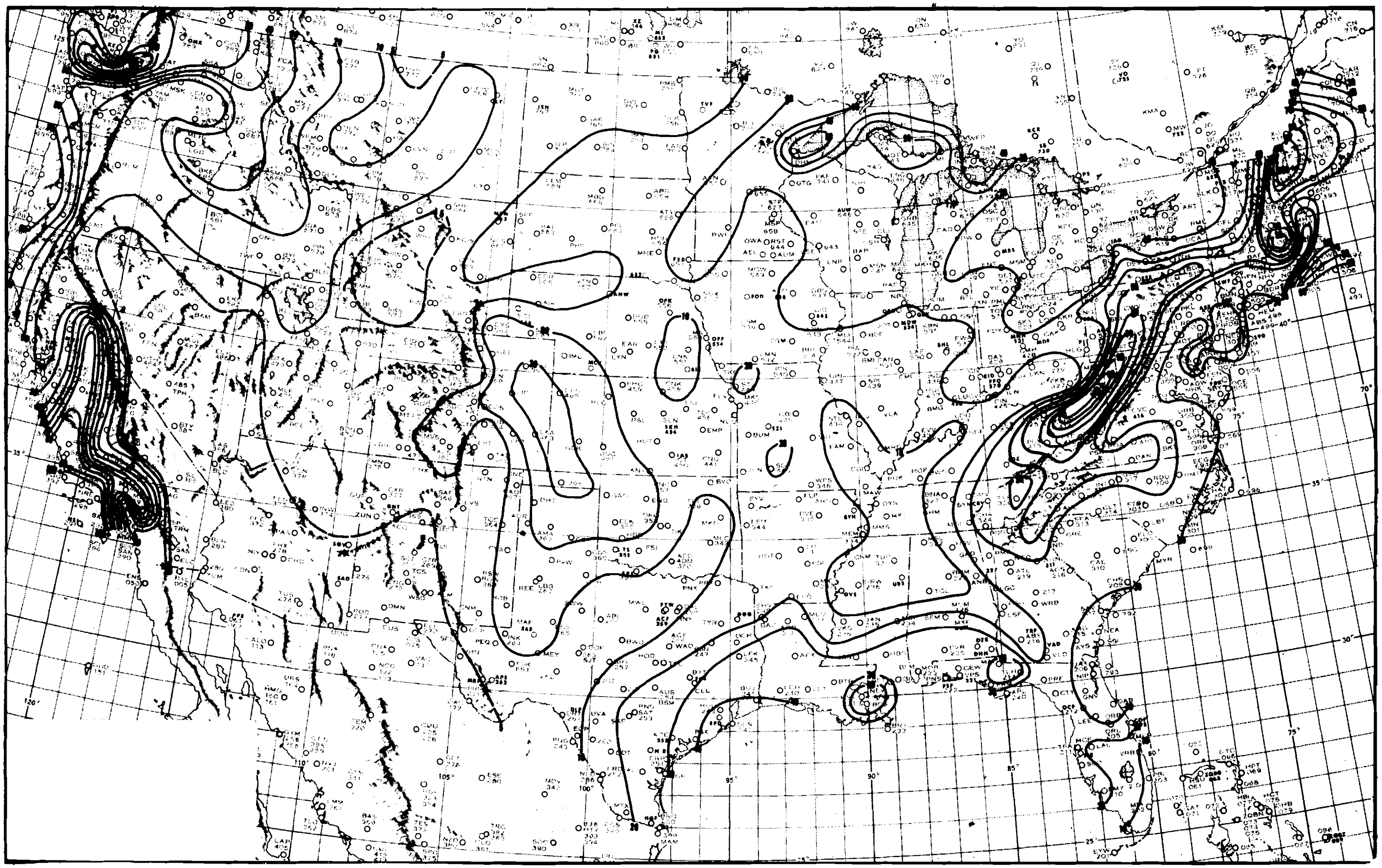


Figure 9-6. Mean Annual Heavy-fog Frequency (days/year) (The isopleths show the mean annual number of days with fogs that reduced visibility to one-fourth mile or less.) (Ref. 35)

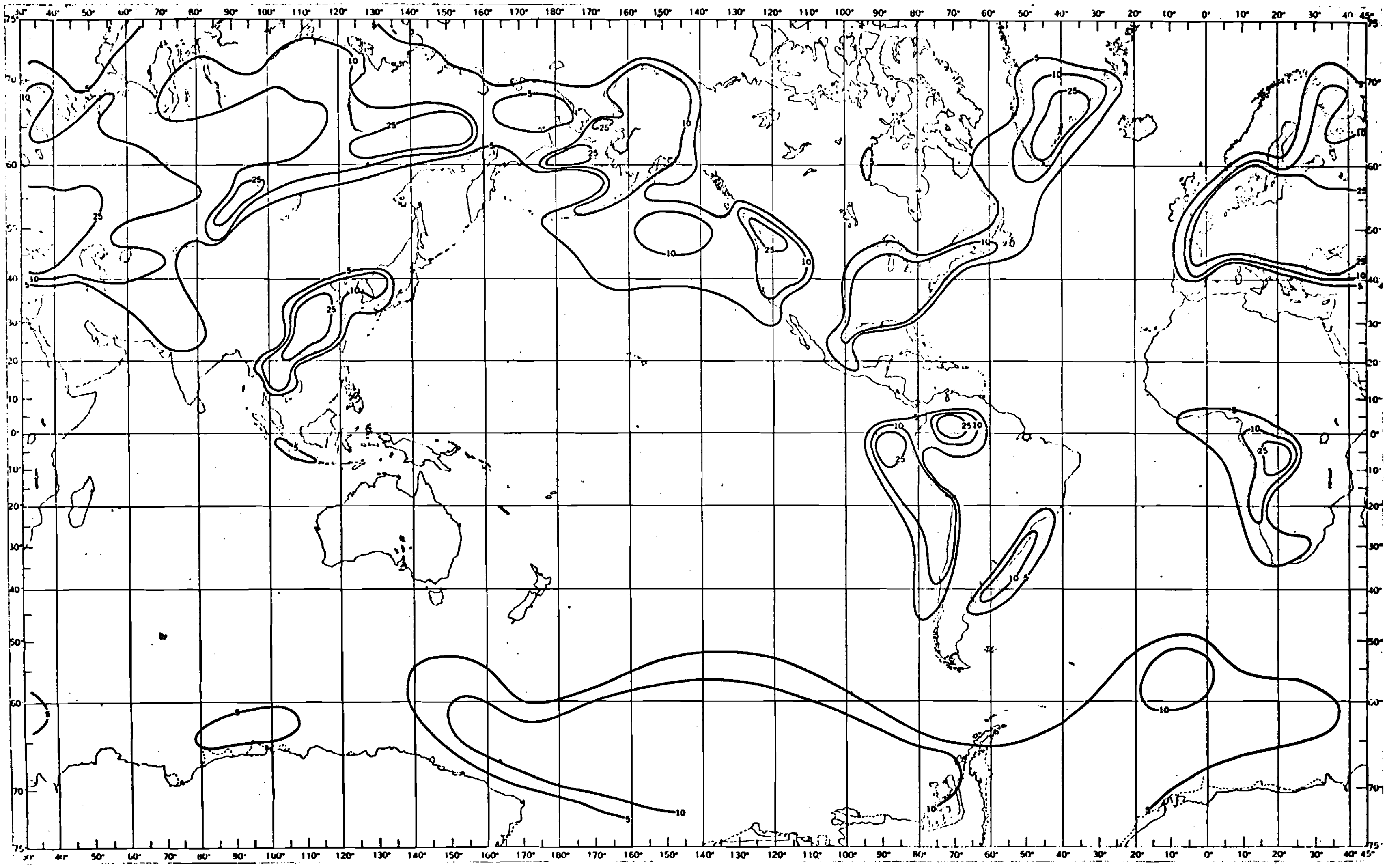


Figure 9-7. Percent Frequency of Occurrence of Fog in Any Form (A) January

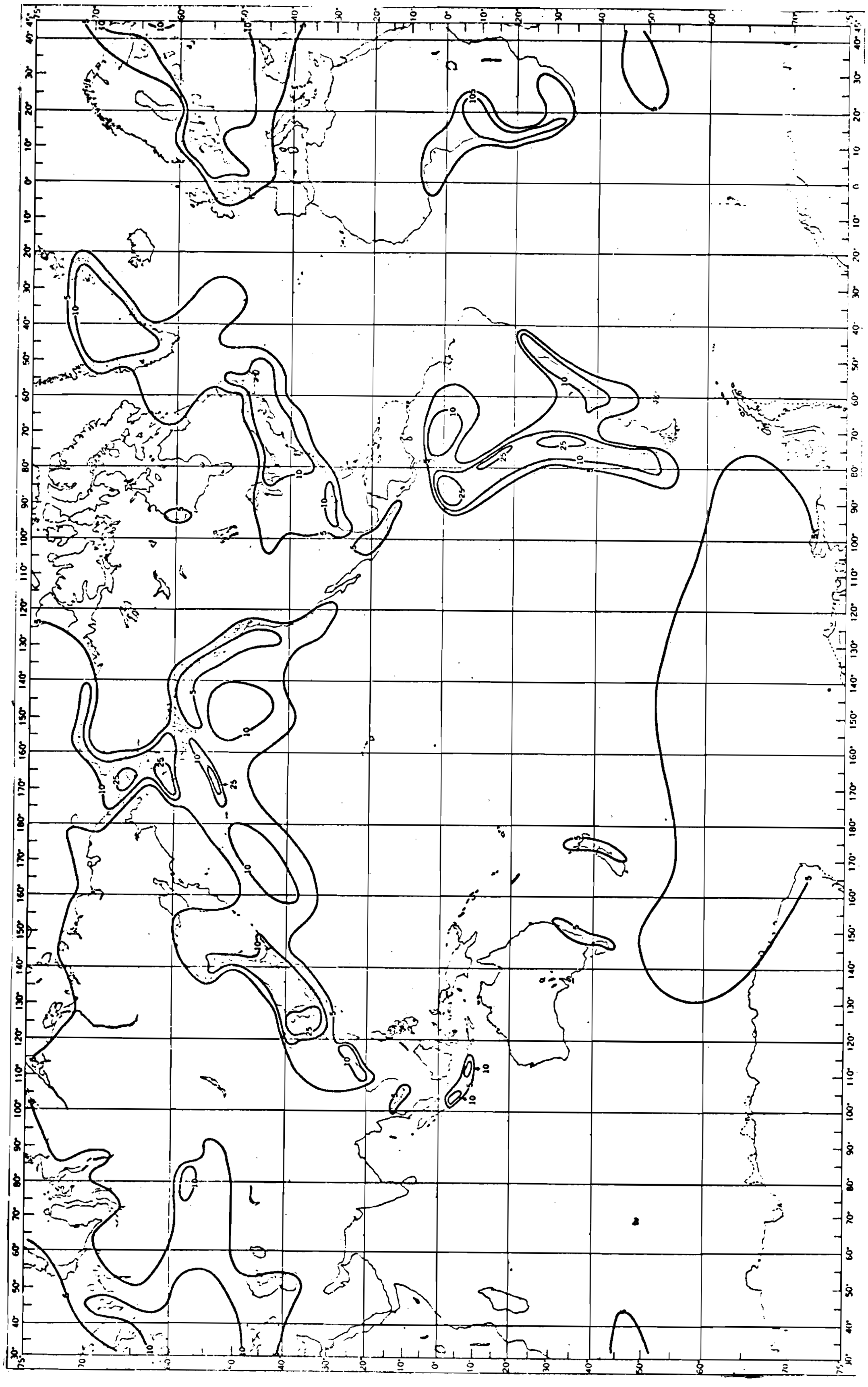


Figure 9-7 (continued). Percent Frequency of Occurrence of Fog in Any Form (B) April

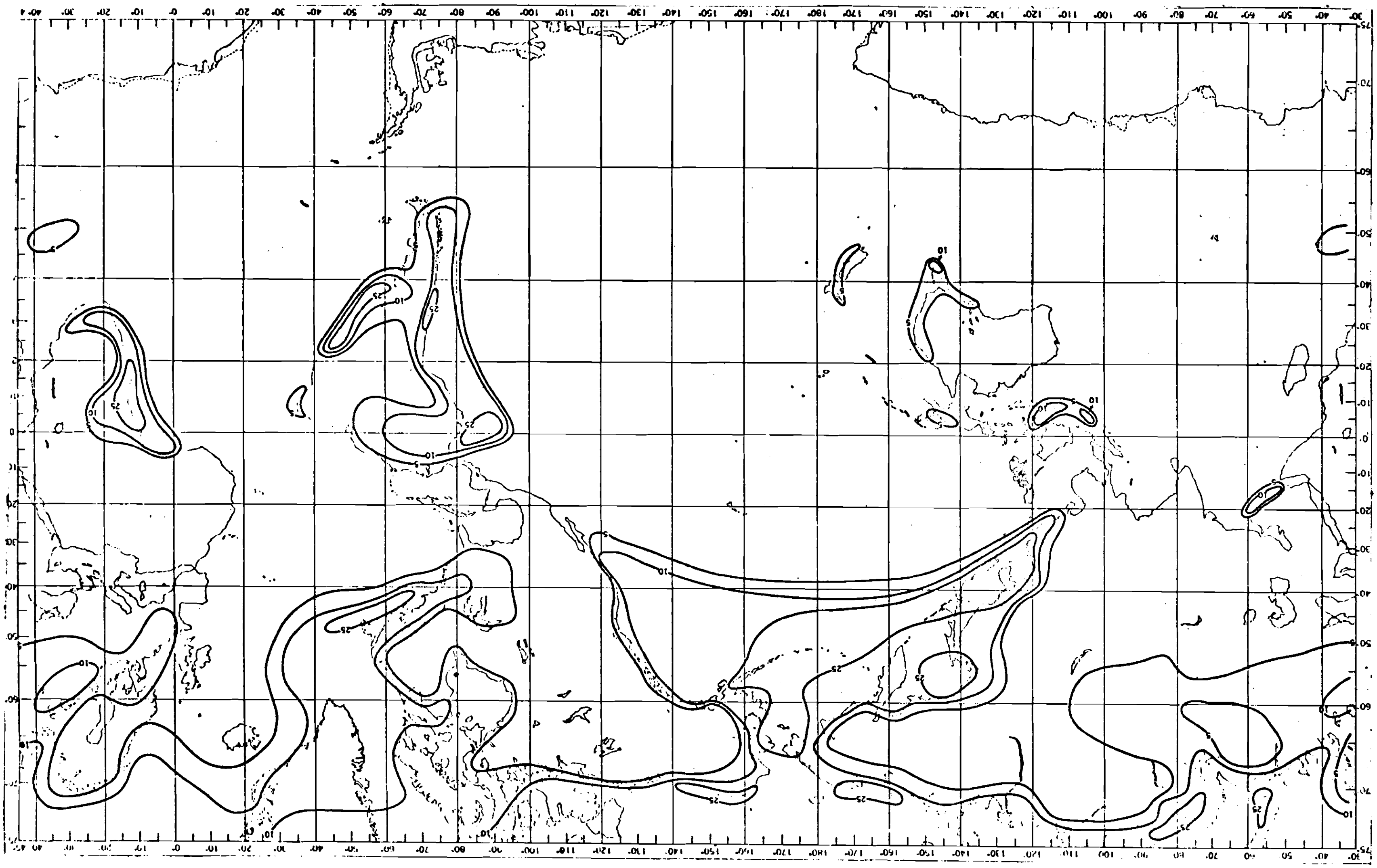


Figure 9-7 (continued). Percent Frequency of Occurrence of Fog in Any Form (C) July

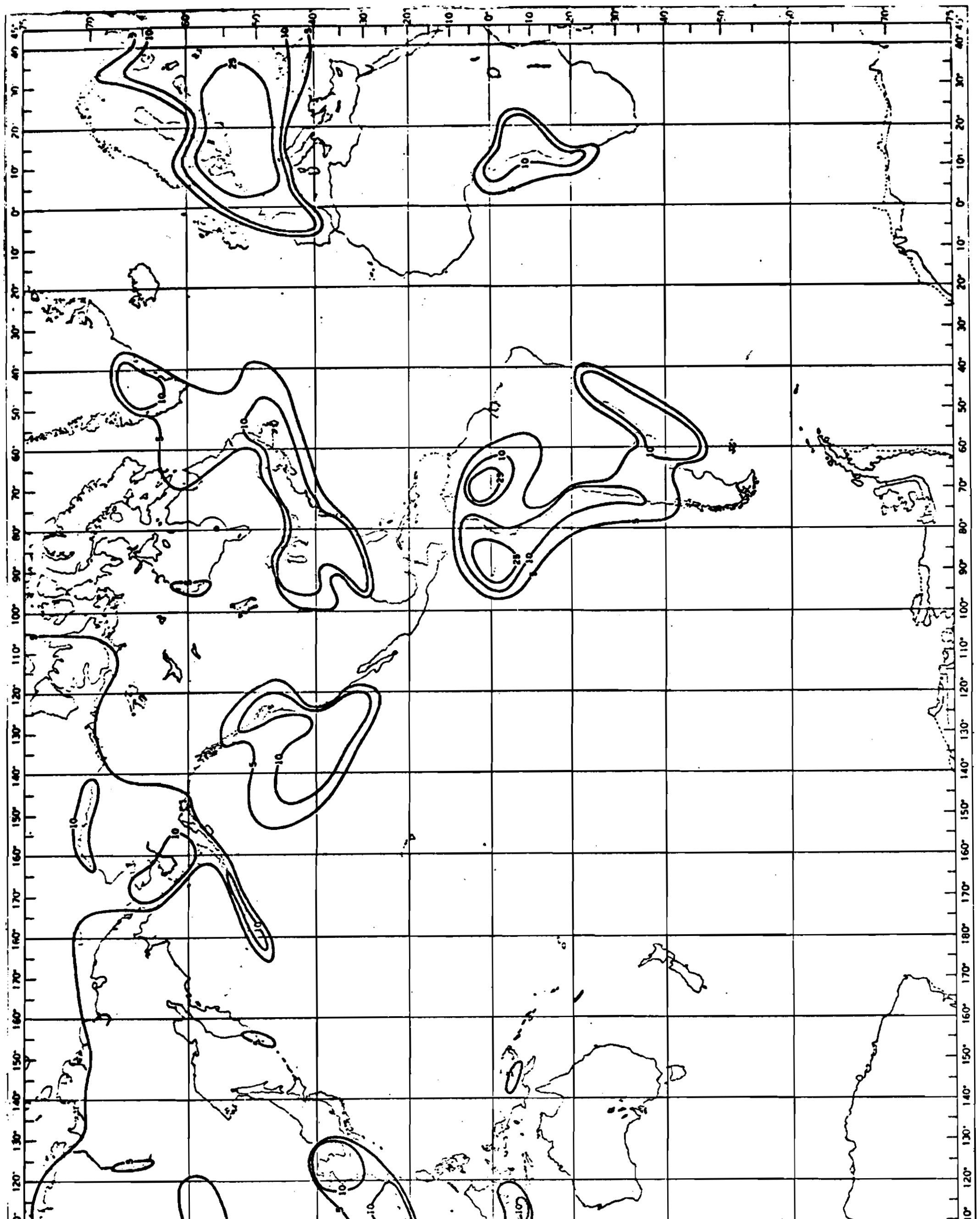


Figure 9-7 (continued). Percent Frequency of Occurrence of Fog in Any Form (D) October

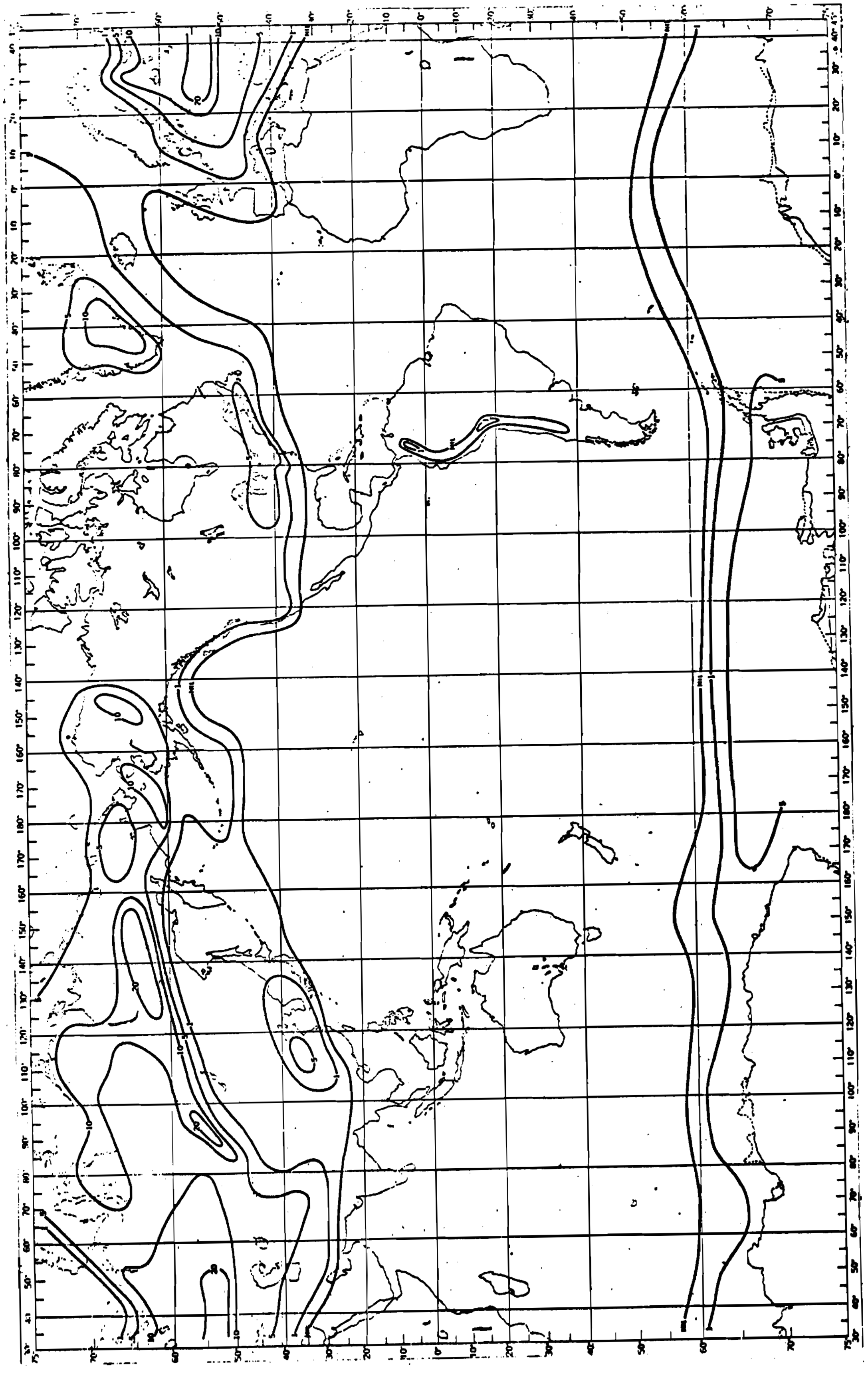
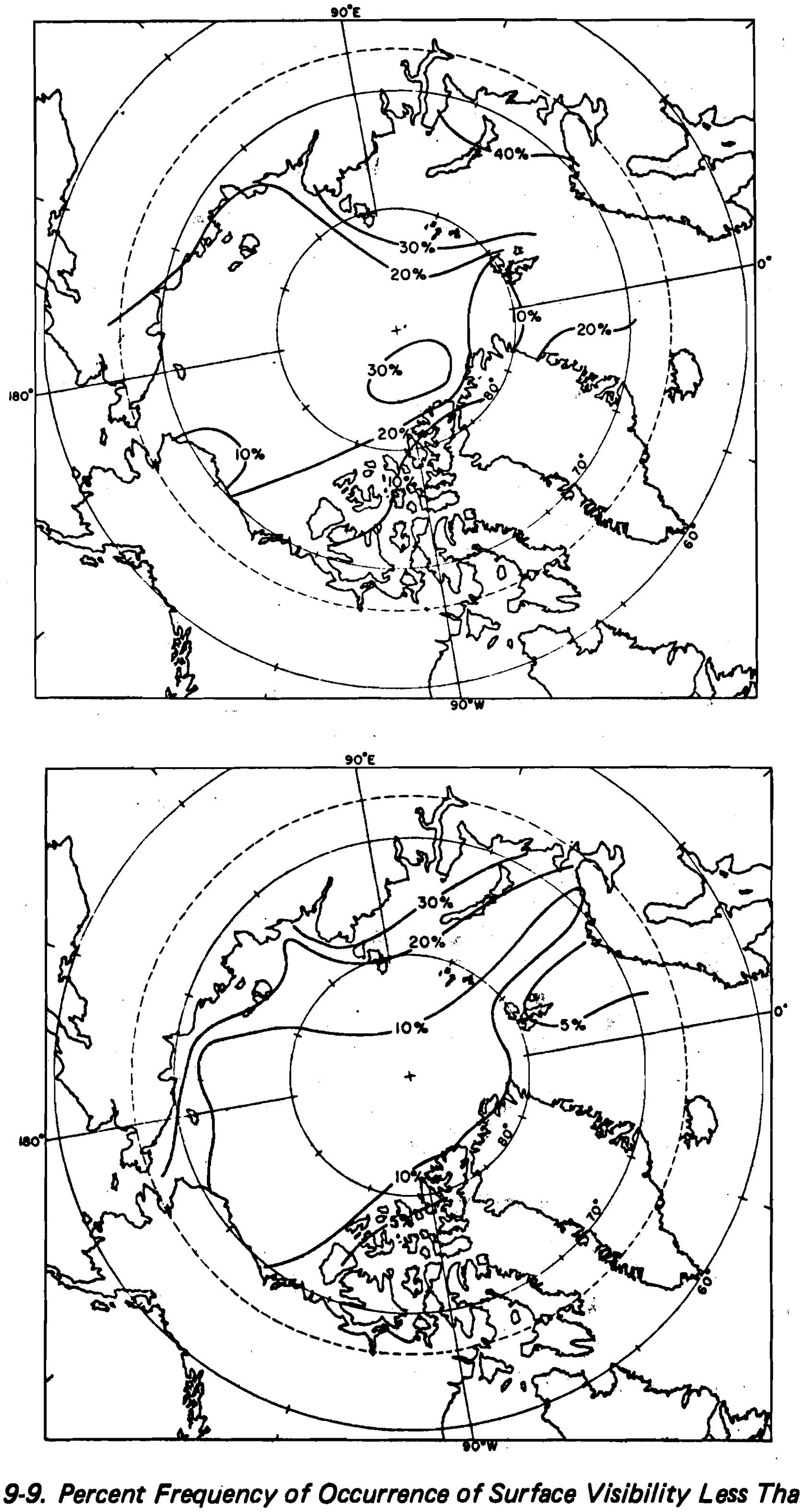


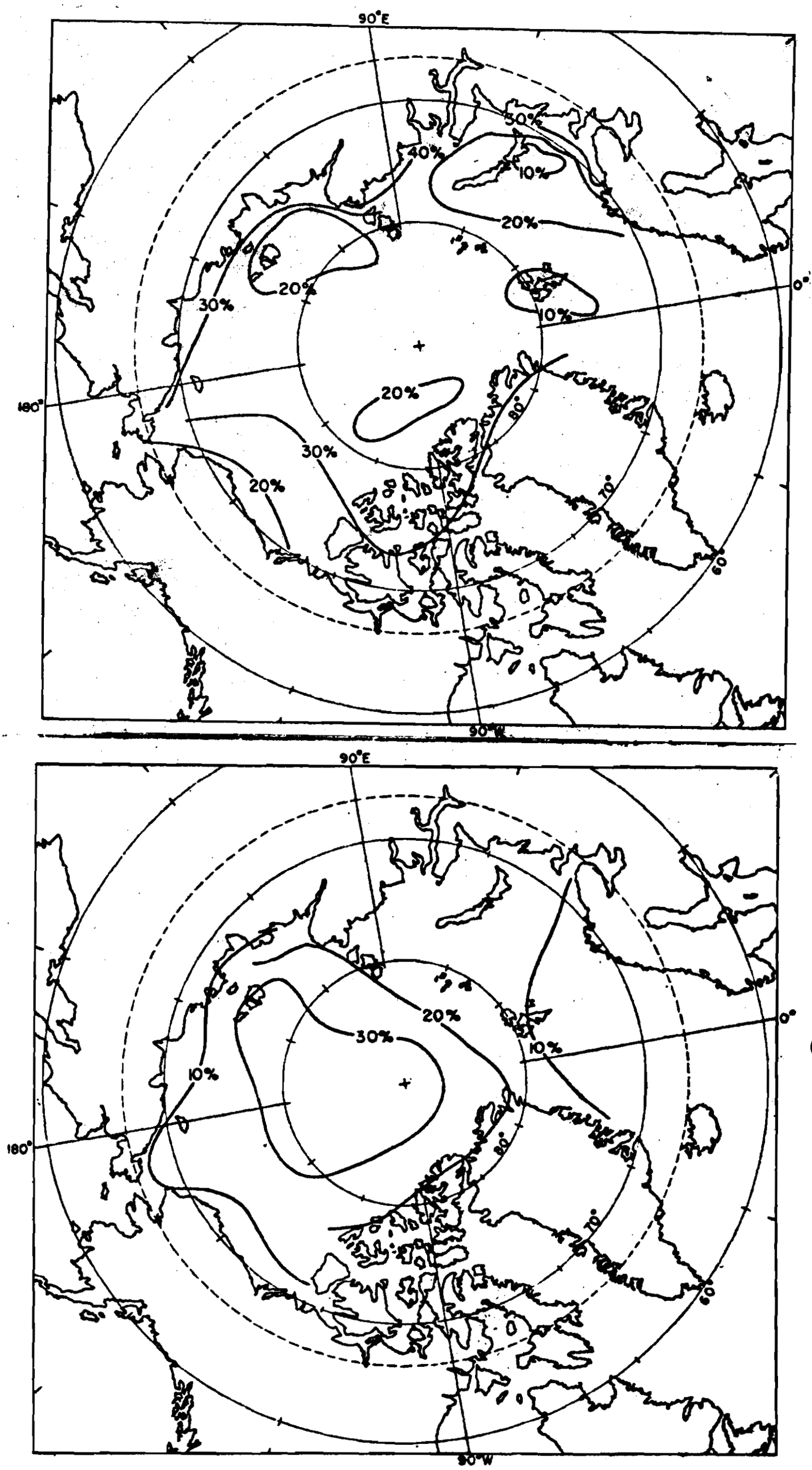
Figure 9-8. Percent Frequency of Occurrence of Supercooled Fog—October



(A) January

(B) February

Figure 9-9. Percent Frequency of Occurrence of Surface Visibility Less Than Two Nautical Miles, in Arctic (Ref. 37)



(C) July

(D) October

Figure 9-9 (continued). Percent Frequency of Occurrence of Surface Visibility Less Than Two Nautical Miles, in Arctic (Ref. 37)

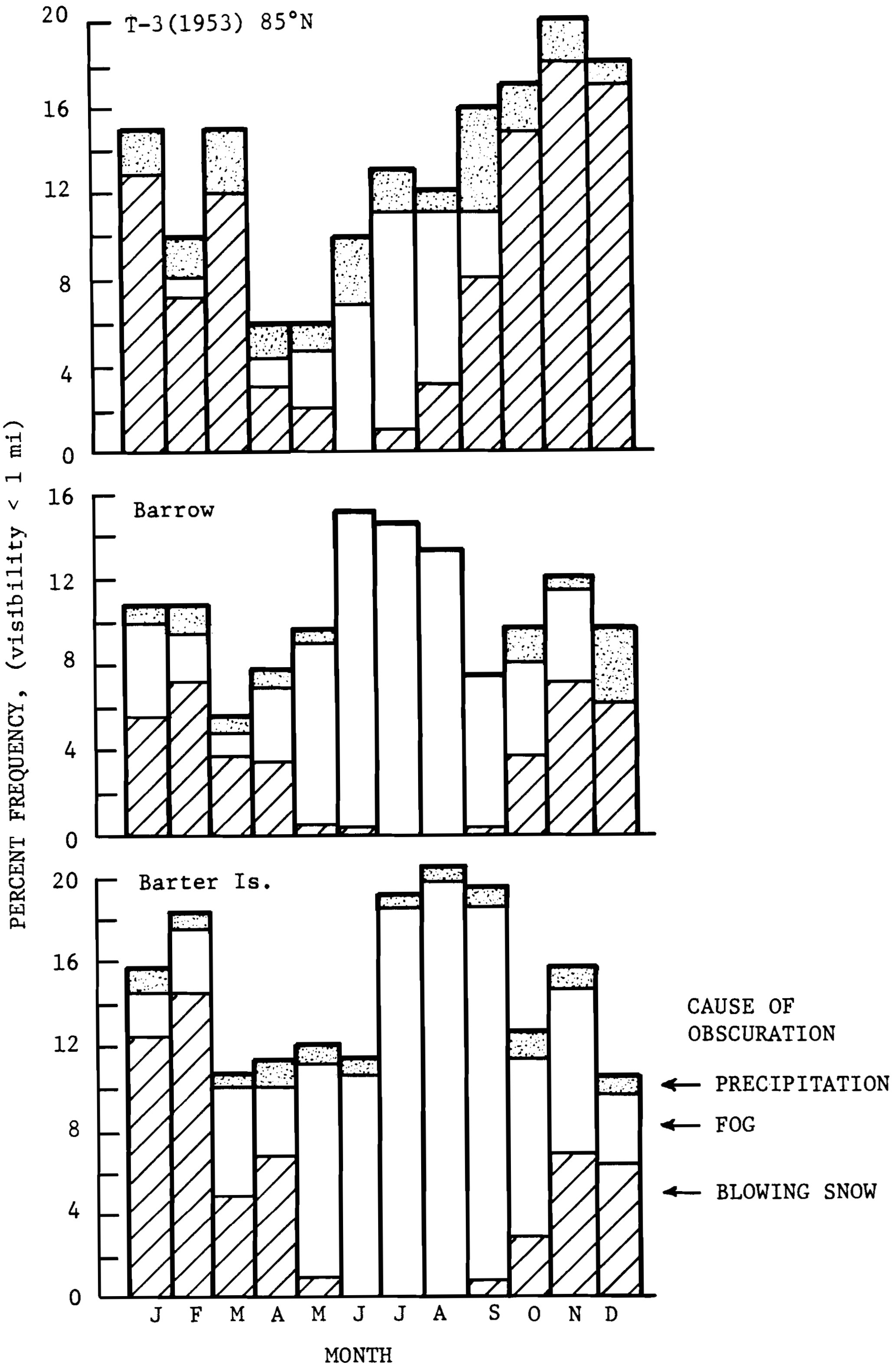


Figure 9-10. Frequency of Occurrence of Low Visibility and Its Cause (Ref. 37)

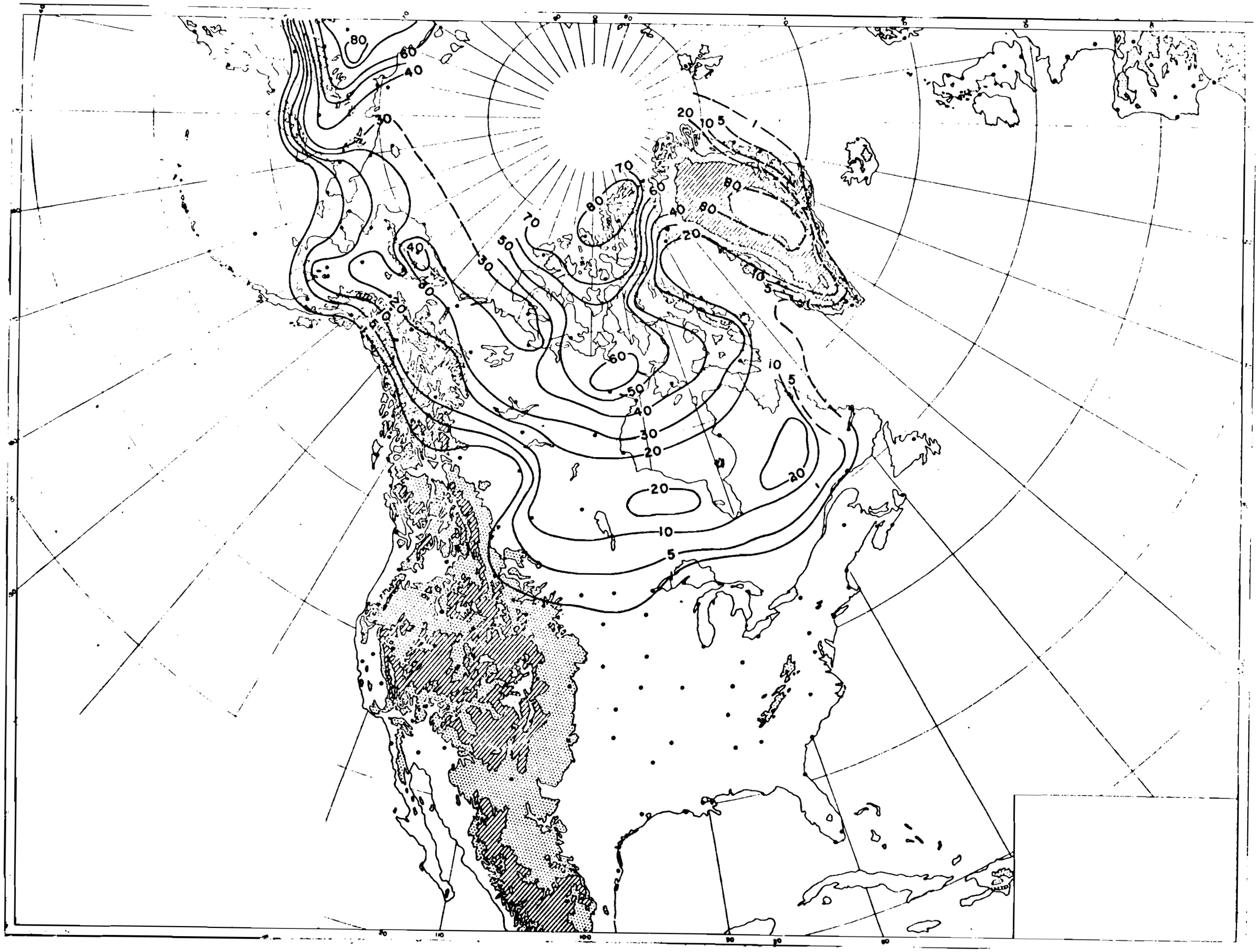


Figure 9-11. Percent Frequency of Temperatures Below −25°F in North America–January (Ref. 8)

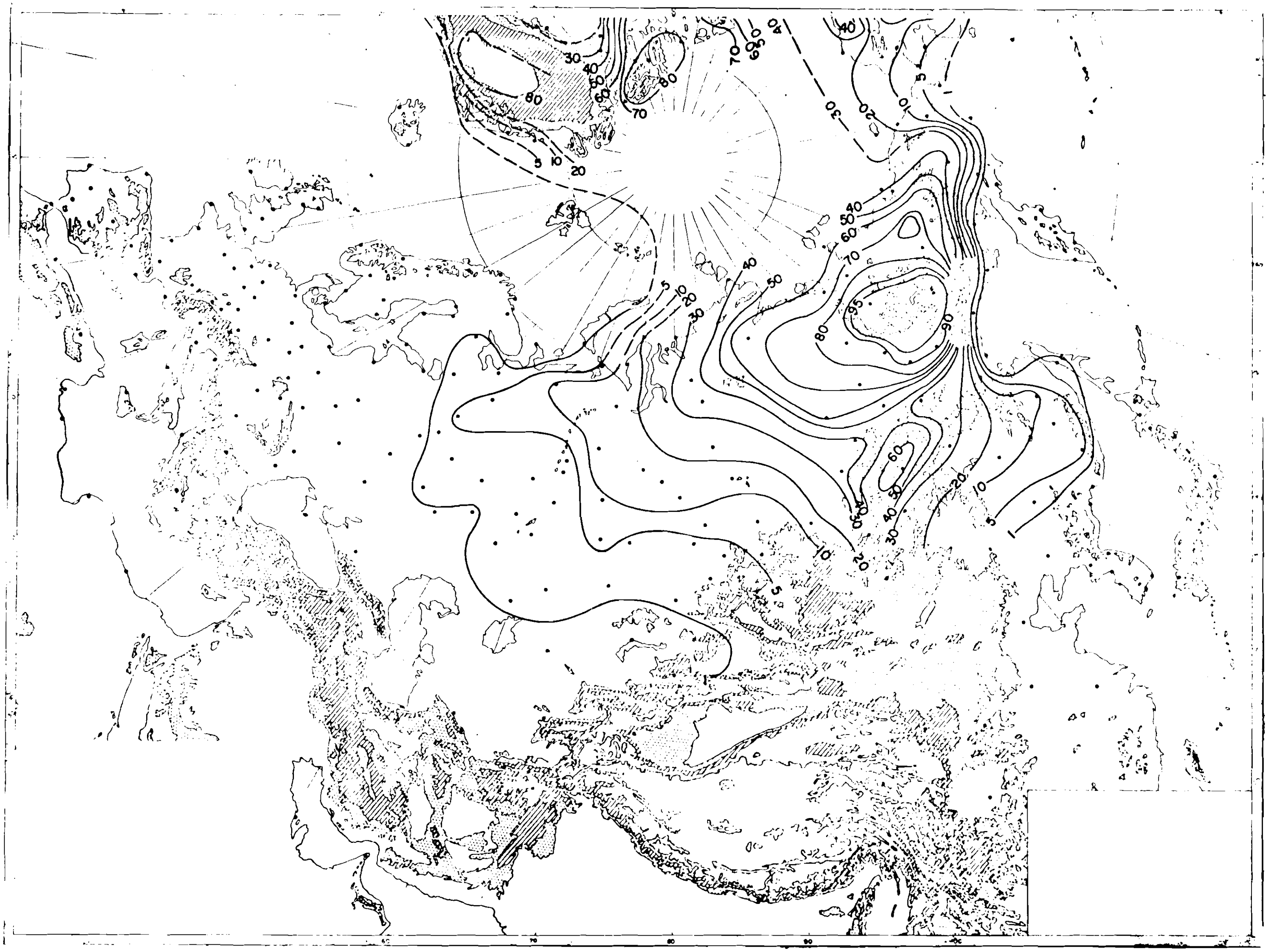


Figure 9-12. Percent of Temperatures Below −25°F in Eurasia–January (Ref. 38)

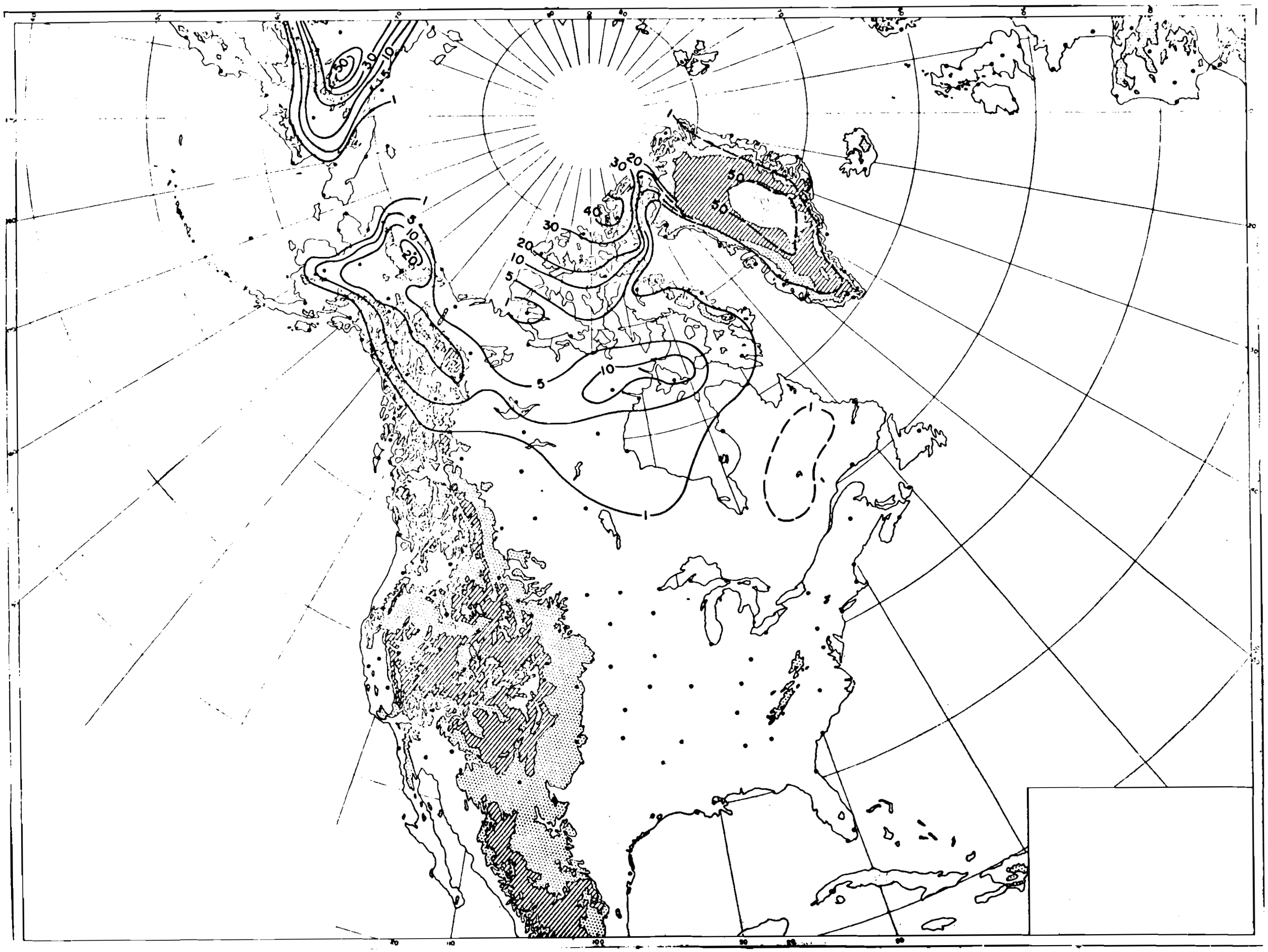


Figure 9-13. Percent Frequency of Temperatures Below –40°F in North America –January (Ref. 8)

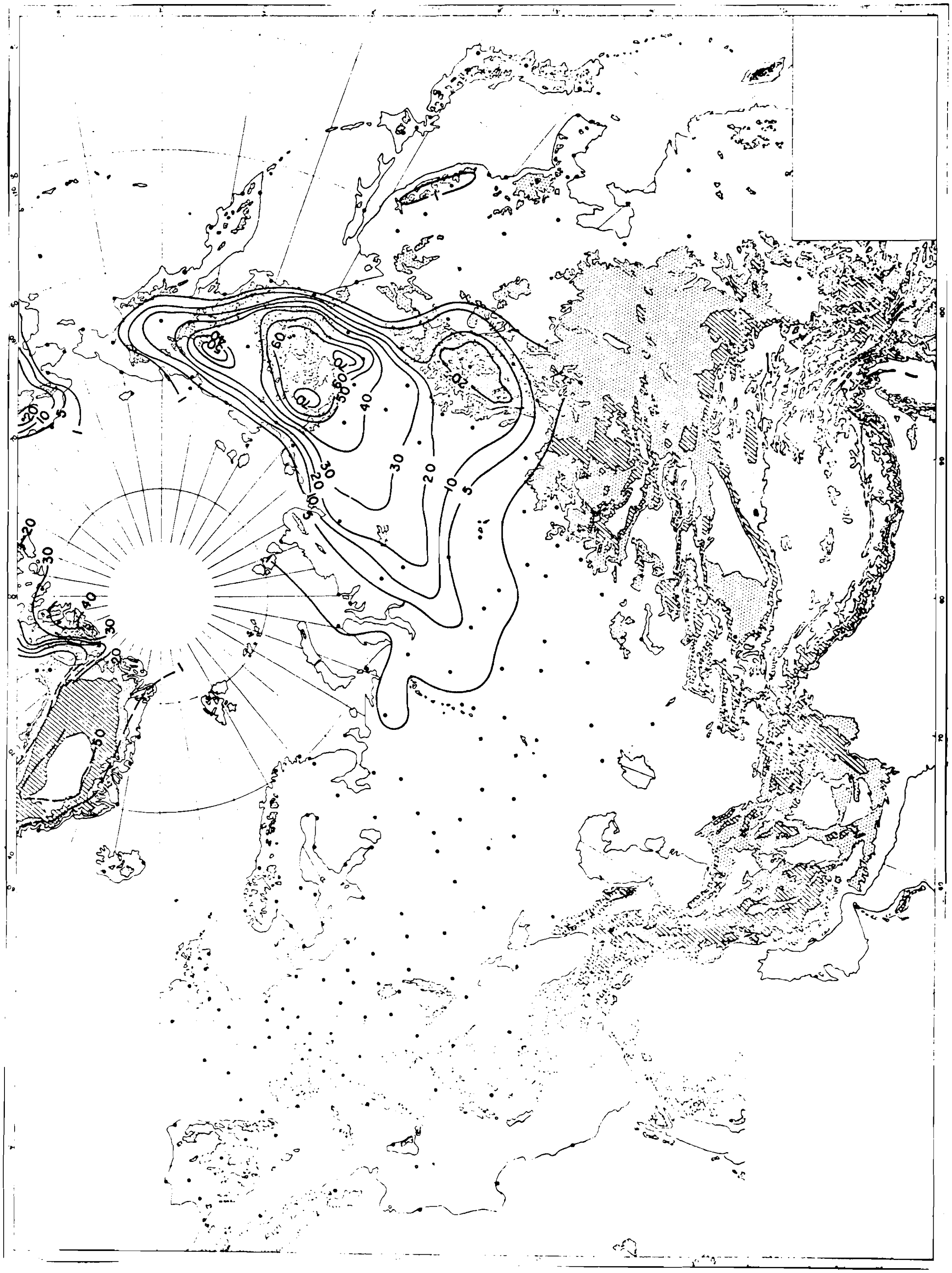


Figure 9-14. Percent Frequency of Temperatures Below –40°F in Eurasia—January (Ref. 38)

below –40°C (–40°F), the percent frequencies of which are shown in Figs. 9-13 and 9-14.

Table 9-5 provides a 6-yr history of ice-fog frequency and duration at Fairbanks, Alaska. Fogs occurred with the highest frequency and longest duration during December and January; none was observed in October and April.

9-3 WHITEOUT

When the surface and cloud albedos* for visible radiation are uniformly high (> 80 percent), whiteout occurs in either sunlight or moonlight. Upward and downward fluxes of light are almost identical and the horizon cannot be seen. Because objects are uniformly illuminated, there are no shadows; hence, many features of the landscape and of objects cannot be seen. In particular, snow and ice appear perfectly level and a person can collide with a waist high ice cake or stumble over a 1-ft snowdrift (Ref. 39).

Gerdel and Diamond (Ref. 40) have classified whiteouts by sources as follows:

(1) *Overcast whiteout*. Produced by a complete cloud cover with light reflected between snow surface and cloud base.

(2) *Water-fog whiteout*. Produced by thin clouds containing super-cooled, almost microscopic water droplets, with the cloud base usually in contact with the cold snow surface.

(3) *Ice-fog whiteout*. Produced by clouds containing minute ice crystals, with the cloud base usually in contact with the snow surface. This type of whiteout is frequently combined with the water-fog type.

(4) *Blowing-snow whiteout*. Produced by fine blowing snow plucked from the snow surface and suspended in the lower 3 to 4 ft of air by winds of 20 kt or more.

(5) *Precipitation whiteout*. Produced by storms characterized by very small, wind-driven snow crystals falling from clouds above which the sun is shining.

The first three classifications are the most important. The last two may be present and worsen visibility, but do not themselves cause whiteout in the sense usually employed. Whiteout is primarily an optical phenomenon, and all of these sources of whiteout can be considered as physical conditions of the atmosphere which cause incident sunlight or moonlight to be diffused. Since the light is almost completely and diffusely reflected from a clean snow surface, an observer finds himself in a nearly equally bright "whitened" environment, or whiteout (Ref. 41).

The visibility factors related to fog and ice fog are discussed in par. 9-2.2. Meteorological visibility (or visual range) is defined as the distance at which a black object of suitable dimensions can be seen and recognized against the horizon sky. The factors that determine the visual range relate to the object size and its reflectance for visible light (visual albedo), the optical conditions of the surroundings (brightness of different parts of the sky, visual albedo of the ground, turbidity of the air), and the brightness contrast threshold of the eye.

The Koschmieder equation assumes the use of a completely black object, so that its brightness when measured directly at the object is equal to zero. The brightness of the black object is independent of illumination and hence independent of sky conditions. The Koschmieder formula, therefore, is a function of the attenuation coefficient of the air and thus a measure of the turbidity of the air.

The visual range of nonblack objects, however, is more difficult to determine. These reflect part of the incident light, so their brightness, their brightness contrast against the horizon, and, consequently, their visual range depends on illumination. In general, the illumination of the object depends on the cloudiness of the sky and the position of the sun. However, when the sky is completely

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*The albedo is the ratio of the electromagnetic radiation reflected by a body to the amount incident on it.

TABLE 9-5

ICE FOG AT FAIRBANKS, ALASKA: FREQUENCY AND DURATION 1 JAN 57 TO 10 FEB 63 (Ref. 28)

	November		December		January		February		March		Total	
Winter	No.	Hr	No.	Hr	No.	Hr	No.	Hr	No.	Hr	No.	Hr
1956-1957	-	-	-	-	1	42	4	59	0	0	5	101
1957-1958	0	0	7	186	1	1	0	0	0	0	8	187
1958-1959	3	20	1	41	9	153	0	0	4	29	17	243
1959-1960	0	0	7	59	2	95	0	0	0	0	9	154
1960-1961	4	26	0	0	3	10	1	2	3	12	11	50
1961-1962	6	28	6	323	5	98	1	6	2	9	20	464
1962-1963	5	48	8	136	4	74	2	89	-	-	19	347
Total	18	122	29	745	25	473	8	156	9	50	89	1546

No. = Number of occurrences during month.
Hr = Total number of hours during month.

overcast by a cloud or fog layer of sufficient thickness so that the sun is invisible and no cloud texture can be perceived, the incident skylight is completely diffuse. Under these conditions, the visual range of an object of a given diameter is a function of its own visual albedo, the visual albedo of the ground, and the scattering coefficient of the air (Ref. 41).

Two factors of vital importance to visibility under completely overcast conditions are (Ref. 41):

(1) The visual range of objects of low or medium albedo, regardless of color, is almost independent of the visual ground albedo, so that they may be considered as equivalent to black objects.

(2) The visual range of very bright objects exhibits a strong dependence on the visual ground albedo. The visual range of white objects tends to approach zero when the visual ground albedo is greater than 0.94; this is independent of air turbidity and applies even to clear air.

Clean snow has a visual albedo of over 0.9. Therefore, according to theory, bright objects on or just above a snow surface and under an overcast sky can be seen only with difficulty, and white objects cannot be seen at all. Thus, one cannot perceive snow drifts, the snow surface as a whole observed against the horizon sky is invisible, there is no horizon line, and the sky and snow surfaces merge into each other indistinguishably even in clear air. In contrast, dark or black objects can be well perceived since their visual range is affected only by the turbidity of the air, such as caused by fog or blowing snow.

Gerdel and Diamond (Ref. 40) recognized these two factors in their discussion of whiteout observed in Greenland, in which they noted that "Perspective, involving the judgment of distance, was limited to a few feet but actual horizontal visibility of dark objects was not materially reduced".

Whiteout has been observed in Greenland, in Alaska, and in northern Canada but no information on the frequency of occurrence is available. A series of photographs illustrating the onset of whiteout is shown in Fig. 9-15 (Ref. 42).

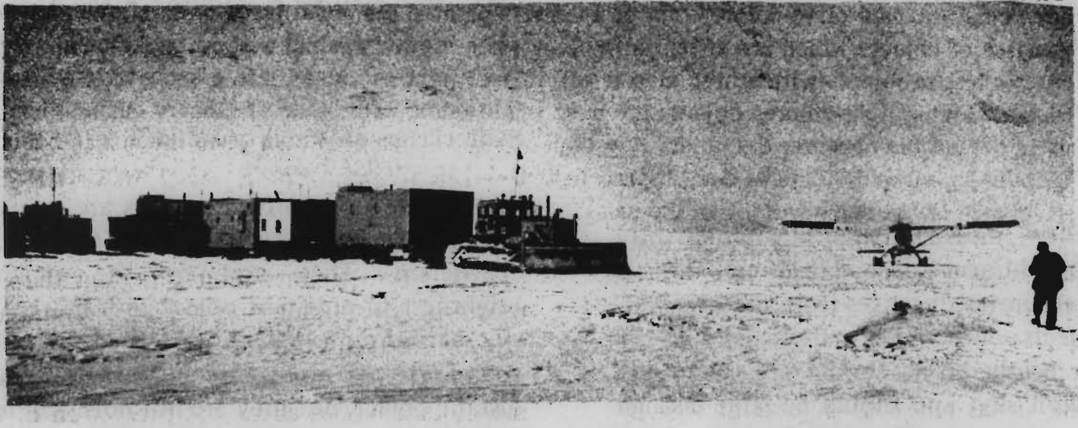
9-4 MEASUREMENTS AND INSTRUMENTATION

The measurements related to fogs that are useful in considering operational and materiel effects are often difficult to accomplish with precision. Most important would be measurements that would allow the prediction of the occurrence and duration of fog. Of secondary importance are measurements of those parameters described in par. 9-2.2 related directly to the visibility and extent of a fog. Next in importance are droplet size, number density, physical state, and chemical composition and the liquid water content of fog. The measurements of these parameters are important for fog analysis, but the resultant data can only be indirectly related to materiel effects or operations. Finally, fog detection instruments for unattended operations are also desirable.

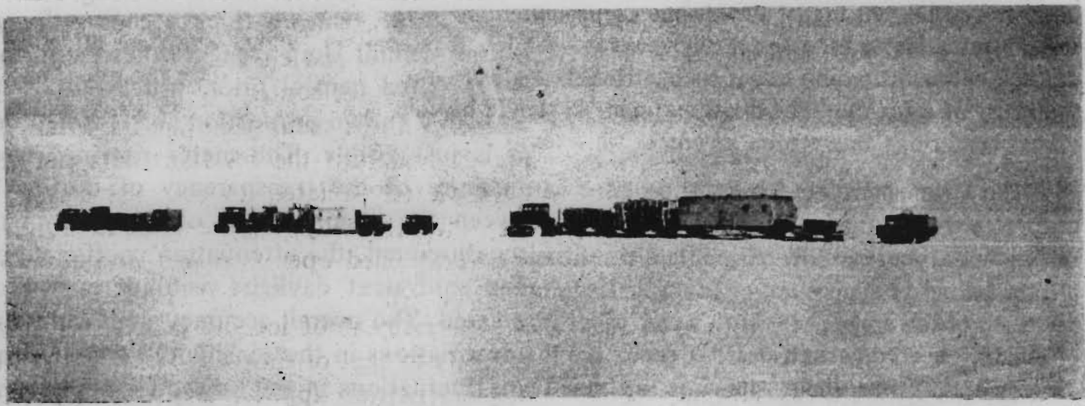
Measurement of ice fog is similar in most respects to that of droplet fog so that similar instrumentation applies. The size, shape, and structure of the ice crystals are determined by examination with both the optical and the electron microscopes, using replication techniques. Whiteout has not been subjected to quantitative measurements because of its limited occurrence and peculiar nature.

9-4.1 PREDICTION

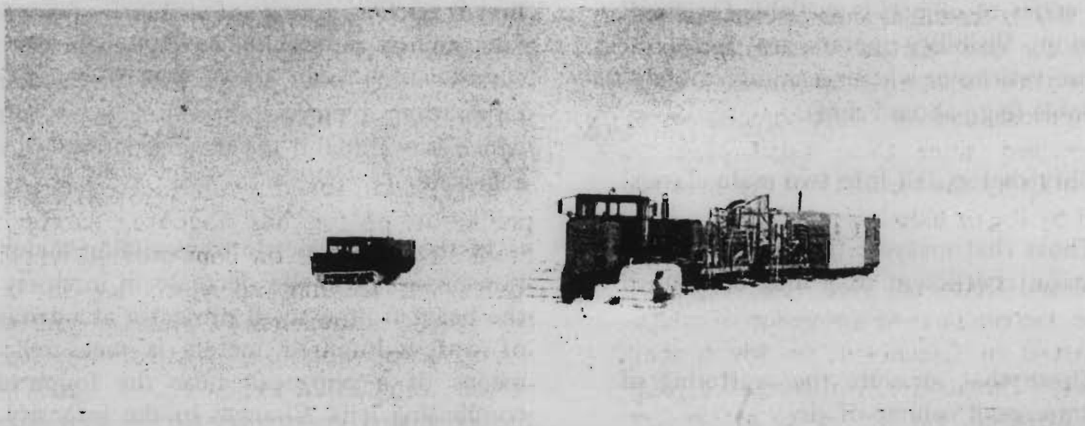
The search for direct indicators for the prediction of fog has not been successful. Prediction depends on conventional weather forecasting techniques, which are in turn based on measurements of pressure gradients, atmospheric moisture, temperature, wind velocity, and cloud and inversion data. Thus, the associated instrumentation is that found in weather stations. The same is true for predicting the duration of fog. In addition to normal meteorological information, data on visibility and both lateral and vertical extent



(A) Example of typically clear day. Note presence of horizon, high contrast of surface features, tractor swing elements, and all parts of the aircraft.



(B) Onset of whiteout with light diffusion and loss of shadow effects.



(C) Complete whiteout with no horizon and all surface features obliterated by full spatial diffusion of light.

Figure 9-15. Whiteout Development on the Greenland Ice Cap (Photos by R. W. Gerdel) of the fog are important. An important factor in any prediction is the experience of a forecaster with knowledge of the geographical influences on local weather patterns (Ref. 43).

9-4.2 VISIBILITY

Visibility measurements are frequently made by human observation of objects located at known distances from the observer. The objects chosen as markers should be black or nearly black, should appear against the horizon sky, and should be large enough to subtend an angle of 0.5 deg at the observer's eye. The most suitable objects for determining visibility at night are unfocused lamps of moderate intensity, at known distances; hills and mountains should be silhouetted against the sky. If no visibility meter is used, the luminous intensity of lamps used for visibility observations should be measured from time to time in the direction of the observation. Tables and instructions for preparing a nomogram for converting night visibility observations to the equivalent daylight visibility are available (Ref. 30).

Most visibility meters involve the measurement of atmospheric opacity or transmission and the adoption of certain assumptions in converting the measurement to visibility. There is no advantage, therefore, in using an instrument for daytime measurements if a suitable series of objects is available for direct observation. Visibility meters are useful for night observations or when no suitable objects are available (e.g., aboard ship).

Visibility meters fall into two main classes:

(1) Those that measure the attenuation or transmission coefficient of a long column of air

(2) Those that measure the scattering of light from a small volume of air.

Both classes include instruments in which the measurements are made by eye and those that use a photoelectric cell. The main disadvantage of the visual type is that considerable error may be introduced if the observer fails to allow sufficient time for his eyes to accommodate to darkness. Following is a brief description of the chief features of the main classes of visibility meters.

A number of telephotometers are available for daytime measurement of the attenuation coefficient. They compare the apparent brightness of a distant object with that of the sky background. These instruments may be useful for extrapolating beyond the most distant object, but they are not normally used for routine measurements because, as stated earlier, it is preferable to use visual observations.

A simple visual extinction meter for use with a distant lamp at night takes the form of a graduated neutral filter, which reduces the light in a known proportion and is varied until it is just visible. The meter reading gives a measure of the transparency of the air between the lamp and the observer; from this measurement, the attenuation coefficient and the equivalent daylight visibility can be calculated. The overall accuracy depends mainly on variations in the sensitivity of the eye and on fluctuations in the brightness of the lamp; the probable error is about 10 percent when the visibility is the same as the distance of the lamp, and increases in proportion to the visibility. The advantage of the instrument is that it enables a range of visibilities from 5 to 100 km to be covered with reasonable accuracy using only three well-spaced lamps rather than a more elaborate series of lamps which is essential if the same accuracy is to be achieved.

In the photoelectric transmission meter or transmissometer, the decrease in intensity of the beam from a small projector at a distance of a few hundred meters is measured by means of a photocell near the focus of a condensing lens. Changes in the intensity of the light source should be allowed for by means of a small auxiliary photocell placed at a negligible distance from the source, and the instrument should be standardized in terms of daylight visibility by using Koschmieder's theory. Periodic checks made soon after sunset on occasions when the daylight visibility is known to exceed about 15 km enable the relative sensitivity of the two photocells to be measured. Provided that the main photocell is well screened from extraneous light, the instrument can be used in weak daylight as well as at night. A transmissometer that uses a modulated light source can be operated in full daylight.

Although the attenuation of light is due both to scattering and to the effect of absorption by dust or smoke particles, the absorption effect is generally negligible so that the attenuation coefficient may be taken to be the same as the scatter coefficient. An instrument for measuring the latter can therefore be used to obtain the visibility. The measurement is most conveniently done by concentrating a beam of light on a small volume of air and determining, by photometric means, the proportion of light scattered. If it is completely screened, such an instrument can be used by day as well as by night. Since this method does not involve a long light path, it should be useful where no visible objects or lights are available, but it suffers from the disadvantage that only a very small sample of the air is used and may be unrepresentative of the outside air. This disadvantage can be overcome to some extent in a moving ship or aircraft by averaging a sufficient number of readings.

Wilkerson, Davis, and Simeroth (Ref. 44) have evaluated four instruments that employ scattering for the automatic detection of fog. These use various light sources emitting ultraviolet, visible, and infrared wavelengths and utilizing both backward and forward scattering modes.

9-4.3 DROPLET MEASUREMENT

Measurements of droplet (crystal) size, concentration, and liquid water content can be obtained through the use of photomicrography. A common procedure is to collect fog droplets on glass slides covered with a thin coating of oil, gelatin film (dyed and undyed), or other viscous material to retain them in place and to prevent them from merging to form larger droplets. The droplets are then photographed.

Droplet collection is frequently accomplished by the use of an impactor, which forces a measured amount of air with its fog droplets (50 to 100 ml per sample for conventional impactors) against a glass slide. Alternative techniques to collect droplets are to mount slides on a hand-operated sling or to attach film to the shaft of an anemometer. These methods normally require a calculation of the volume of sampled air containing fog droplets, based on exposure time and windspeeds. It is necessary to compute the collection efficiency of the slides in order to determine the actual droplet concentration because minute particles flow past the obstacle (slide) during collection without being captured (Ref. 15).

Photomicrography permits a determination of droplet size distribution (radius or diameter) based on magnification values. Concentration can be measured by a count of the particles. Corrections for collection efficiency must be made in both cases. Liquid water content can be computed from droplet size distribution and concentration by using Eq. 9-4 modified as follows:

$$W = \frac{4}{3}\pi\rho \sum_{i=1}^{n} \frac{N_i r_i^3}{E_i}, \text{ g m}^{-3} \quad (9\text{-}10)$$

where E_i is the collection efficiency for droplets of radius r_i.

Kumai (Ref. 45) describes a procedure in which fog droplets were collected on a gelatin reagent film containing colloidally dispersed red-silver dichromate. The diameter of a fog droplet in the atmosphere was estimated from the diameter of the droplet print on the gelatin film. The correlation between the droplet diameter and the print diameter was determined by comparing them with droplets of known diameter.

All of these methods and instruments have limitations. Smaller droplets may pass through the impactor, while droplets larger than the impactor orifice cannot pass through the orifice without changing size. Some difficulties are associated with the viscosity and thickness of the oil layers used to hold the droplets. Viscous oil can hold the larger droplets but smaller droplets cannot penetrate the oil layer deeply enough to prevent evaporation. Low viscosity oil cannot adequately retain the larger droplets, which penetrate so far into the oil that they spatter on the glass base.

Another limitation results from adiabatic expansion – the pressure drop through the orifice decreases the air temperature, thus producing changes in the size distribution as a result of the increase in supersaturation. Also, if the droplet concentration in the oil becomes too high, the droplets may stick together and form larger droplets, thus changing the size distribution. Droplets evaporate rapidly, even in oil, which presents particular problems in measuring small droplets (Ref. 46). (The impactor designed by Kumai and Francis, noted earlier (Ref. 15), was designed to eliminate this difficulty by instantly photographing the air samples drawn into the impactor.) Finally, theoretical collection efficiency values may differ considerably from actual collection efficiencies (Ref. 15).

A cloud droplet camera to make *in situ* photographs of air-suspended droplets is described by Itagaki (Ref. 46). The cloud droplet camera has many advantages. It is a direct observation; automatic measurements can be easily made; the effect of the apparatus on the droplets is negligible; ice crystals can be distinguished from droplets; and it provides a permanent record. Its primary limitation is its small sampling volume. While a single photograph of dense fog may be sufficient to make a droplet size distribution curve, more than 10 photographs may be required for less dense fog. Itagaki suggests that sample volume can possibly be increased by increasing the area of the field or by increasing the number of exposures per frame (Ref. 46). Some of these limitations have been overcome by using a Q-switched laser as a light source and a holographic recording technique. Ward reports successful testing of such an instrument for droplets in the 5- to 100-μm-diameter range (Ref. 47).

9-4.4 CHEMICAL COMPOSITION

Determination of the chemical composition of fog droplets or ice crystals requires chemical identification of the condensation nuclei around which the droplets or crystals are formed.

Methods for collecting nuclei include capture by impaction on a glass slide covered with a film of some sort, by adherence to a spider web, and by thermal precipitation (Ref. 45). Analysis of the samples is difficult. Commonly, nuclei are shadowed by chromium vapor in a vacuum chamber and examined under an electron microscope using a magnification of about 10,000.

9-4.5 VERTICAL DEPTH

The radiosonde with its humidity transducer is commonly used to determine the vertical thickness of clouds. Wright (Ref. 27) states that the radiosonde is relatively accurate for fogs with a thickness of 600 m or more, but questions its accuracy for more shallow fogs, such as radiation fogs, which are rarely more than 300 m thick. He devised an apparatus consisting of a photoresistor sensor to measure brightness, attached to a captive balloon and connected by wires to a recording instrument (ohmmeter) on the ground. Vertical thickness can also, of course, be measured by aircraft flights over the top of the fog deck.

9-5 OPERATIONAL CONSIDERATIONS

The primary effect of fog and whiteout is reduction in visibility. Since the secondary effects relating to humidity, ice particles, salt fog, pollutants, and water droplets are prime considerations of other chapters in this handbook, they are not considered here.

In the civilian sector, it has been estimated that fog closes the airports in the United States an average of 115 hr yr^{-1} and costs the commercial airlines an estimated $75 million because of disrupted schedules (Ref. 26). Fog has caused numerous collisions on highways involving as many as 100 vehicles in one incident with unenumerated but certainly large costs to the transportation industry as well as to the public. Similar effects on Army operations result from fog and whiteout.

Individual references to the effects of fog on air and ground mobility as well as other effects include the following:

(1) At Ft. Greely, Alaska, vehicular traffic virtually ceases during whiteouts. Artificial lighting is useless. During artillery tests, the firing position can be obscured by ice fog following firing of an artillery piece. Precautions include the positioning of all operating vehicles away from the test area to prevent ice fog and the use of blowers to dissipate the fog (Ref. 48).

(2) Another report from Ft. Greely notes that, in a 10-mph wind, ice fog greatly restricted the firing rate of a tank gunner and completely obscured tracer rounds. It also points out the hazards of whiteout to aircraft and the difficulties it presents in estimating distances (Ref. 49).

(3) A fog with a 100-ft visibility at 0°C (32°F) reduces the range of a pulsed X-band radar from 24 to 14 mi (Ref. 50).

(4) The diversion of a large military transport aircraft entails a direct cost of at least $1,000 with no accounting for disrupted passenger or cargo schedule costs (Ref. 51). Many military airports throughout the world are subjected to fog conditions that seriously restrict operations and cause the diversion of many aircraft. At Elmendorf AFB near Anchorage, Alaska, for example, 185 aircraft operations that would have been prevented by fog, were accomplished after the fog was dispersed (Ref. 52).

(5) During Project Lead Dog, in which the Greenland Ice Cap was traversed by Army vehicles, a 13-hr period of ice fog with 200-ft visibility reduced the vehicular speed but allowed operations to continue. Whiteout, however, prevented supply aircraft from flying because of pilot inability to estimate altitude above the snow surface (Ref. 53).

9-6 FOG DISSIPATION

Efforts toward protection from and control of the effects of fog are directed primarily to fog dissipation to improve local visibility. Although a considerable amount of work has gone into the development of fog dissipation techniques, results to date are limited. Most methods are relatively expensive, require specialized equipment, and are capable of clearing only small, local areas of fog. Fog clearance of local areas, particularly airport runways, is valuable but no existing system is capable of clearing large areas at low cost.

All fog dissipation techniques are based on three principles (Ref. 54):

(1) Replacing a large number of small droplets with fewer but much larger ones

(2) Evaporating the water droplets

(3) Withdrawing fog droplets from the atmosphere.

Small water droplets can be decreased in number by means of a transfer process or can be fused into larger, less numerous drops by coalescence processes. The transfer or transport of water vapor by condensation to soluble nuclei begins only if these nuclei in the liquid state have an equilibrium vapor pressure lower than the ambient vapor pressure. This is known as the solute effect. So long as this effect persists, the nuclei – now larger solution droplets – will compete favorably with the existing fog droplets, smaller and practically pure water, for the available water vapor until an equilibrium is reestablished, often at a slightly lower vapor pressure than before. As a result, the smaller droplets are evaporated, and the drop-size spectrum is shifted to a larger size range, thereby improving visibility, as noted in par. 9-2.2.5.2. Furthermore, these newer and larger droplets, being heavier, will fall through the fog under gravity, depending on the existing wind field, and trigger the coalescence process. In the case of supercooled droplets and ice crystals, the ice crystals have an equilibrium vapor pressure lower than that over the super-cooled droplets at a temperature at and below freezing. Then, instead of the coalescence process, the accretion or coagulation process comes into play among the crystals.

Procedures used to effect transfer processes are:

(1) *Seeding with ice crystals (supercooled fogs only).* At the temperature of the atmosphere, the vapor pressure over supercooled water droplets is greater than that over ice. If ice crystals are produced, they will develop at the expense of the water droplets. Ice crystals are commonly produced by a strong, local lowering of temperature: by vaporization of a liquid of low boiling point (Freon*, propane) or by sublimation (dry ice); or by crystallization of water on solid nuclei amorphous to ice (silver iodide).

(2) *Seeding with hygroscopic particles.* Hygroscopic particles lower the relative humidity of air by absorbing water vapor, and thus permit evaporation of fog droplets. They can be used dry or in aqueous solution in all droplet fogs regardless of temperature. A commonly used reagent is calcium chloride ($CaCl_2$); recent tests have shown that seeding with small sodium chloride (NaCl) particles will also dissipate warm fogs; some phosphates and urea have also been tested but with limited success (Ref. 55).

In coalescence processes, some droplets capture other droplets and grow to a larger size. Water drops of different sizes move with different fall speeds. Larger drops capture a fraction of smaller droplets contained in a column of air swept out in their fall. Procedures used to effect coalescence are:

(1) *Coalescence by gravity*. Creation of a vertical spray of water and dispersal of cold water droplets from a plane induce coalescence by gravity.

(2) *Coalescence by sonic or ultrasonic waves*. Sonic or ultrasonic waves agitate droplets and cause collisions between the small droplets oscillating at high amplitudes and the large droplets oscillating at lower amplitudes. The procedure is highly limited because of the enormous power requirements and the stresses it places on operating personnel and surroundings.

(3) *Coalescence by electrostatic capture.* Large electrically charged particles can capture fog droplets that have small, natural electric charges. Numerous studies and experiments have been conducted, but this method has not found practical application.

Fogs can also be dissipated by evaporation. For a droplet fog with a liquid water content of 0.5 g m^{-3}, a small temperature elevation of 2 deg C (3.6 deg F) is sufficient to evaporate the water droplets. Several procedures have been tested and used to produce the required temperature elevation:

(1) One of the first, the FIDO procedure (*F*og *I*nvestigation and *D*ispersal *O*peration), was used in Great Britain during World War II to clear runways. The area to be cleared of fog was surrounded with exhaust-gas burners fed under pressure through a network of pipes; however, the enormous amount of fuel required (estimated at 15,000 to 25,000 gal/landing) makes this procedure impractical in a peacetime economy.

(2) The U S Air Force has successfully demonstrated the use of jet engine exhausts to dissipate fog (Refs. 24, 51).

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*Freon is a trademark of E. I. du Pont de Nemours & Company for a group of fluorinated hydrocarbons.

(3) CRREL* tested the use of helicopter downwash to replace the fog layer with a volume of relatively dry warm air from above, thus reducing the relative humidity and promoting evaporation of the fog droplets (Ref. 56).

(4) Use of a CO_2 laser has been tested to increase the temperature of the air (Ref. 57).

(5) Monolayers of organic liquids have been spread over water with some success in order to prevent evaporation fogs from forming.

All five evaporative procedures are expensive and require special equipment. Dry ice and silver iodide seeding have been the most successful and the most feasible methods for fog dissipation, and are now in operation (Ref. 52).

Visibility in ice fogs cannot be improved by any of the given methods. Extensive investigations by CRREL and others (Refs. 10, 28, 29, 31) have indicated that the only solution appears to be to reduce the injection of water into the atmosphere. Various ways and means to accomplish this objective have been suggested, including the use of anthracite or bituminous coal (rather than the subbituminous grades used in Fairbanks), permitting cooling ponds to freeze over, eliminating low altitude sources of water vapor, and installing automobile exhaust-suppression devices. These may alleviate the problem but they are unlikely to solve it completely.

Visibility in whiteout can generally be improved only when either wet fog or low cloud overcast is the primary cause of reduced visibility. Investigations to improve whiteout visibility have consisted primarily of fog- and cloud-seeding experiments; however, success to date has been limited.

9-7 TESTING AND SIMULATION

Most tests related to improving visibility in fog attempt to determine the capability of various procedures, materials, and equipment to dissipate fog. The effects of fog on materials of construction, parts, components, and assemblies are not commonly tested; however, as noted earlier, the principal effects of fog are similar to those of rain, humidity, and salt fog. Therefore, testing of the effects of these environments (particularly salt fog and humidity) provides a basis for determining the capability of materials of construction, parts, components, and assemblies to withstand the effects of fog.

There are no known military test ranges for testing materials in fog. Much of the fog dissipation testing has been conducted in Greenland and Alaska, where fogs are prevalent, but some testing has also been done at air bases in Germany and on the U S west coast, where fogs are relatively frequent. Dissipation testing of ice fog by U S agencies has been exclusively conducted in the Fairbanks, Alaska, area, where this type of fog is a local phenomenon. Whiteout dissipation testing, which has consisted solely of fog dissipation tests, has been limited to the northern areas in Greenland and Alaska, where whiteouts occur.

Few types of equipment are designed solely to simulate fog for use in testing materials of construction, parts, components, and assemblies. The known fog chambers are given in Table 9-6 (Ref. 58).

Condensation of water vapor on materials can be accomplished readily in humidity test chambers, and this will meet most requirements for testing the effects of fog on materials of construction, parts, components, and assemblies.

9-8 SPECIFICATIONS

There are no known specifications for testing the effects of fog on materials of construction, parts, components, and assemblies. Fog is not included as an environment in MIL-STD-810, *Environmental Test Methods*, nor as an environmental condition

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*U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.

TABLE 9-6

FOG CHAMBERS

Location	Dimensions, ft	Environments
Rock Island Arsenal, Rock Island, Ill.	4 x 3 x 2	Fog
USA Mobility Equipment Research and Development Center (MERDC), Ft. Belvoir, Va.	4 x 3 x 2	Salt, fog
White Sands Missile Range, White Sands, N.Mex.	71 x 20-1/3 x 20-1/2	Temperature, rain, humidity, salt, fog
Naval Air Development Center, Johnsville, Pa.	6 x 6 x 8	Salt, wet fog
Naval Underwater Weapons Research and Engineering Station, Newport, R.I.	4 x 2-1/2 x 3	Salt, adaptable to fog

in MIL-STD-210, *Climatic Extremes for Military Equipment.* In AR 70-38 *Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions*, ice fog is included as an operational condition associated with the "cold" and "extreme cold" climatic categories. However, specifications related to protection against moisture and corrosion are discussed in Chap. 11, "Salt, Salt Fog, and Salt Water"; Chap. 4, "Humidity"; Chap. 2, "Terrain"; and Chap. 7, "Rain"; all in Part Two.

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CHAPTER 10

WIND

10-1 INTRODUCTION

Air in motion relative to the surface of the earth is called wind (Ref. 1). Differences in atmospheric pressure arising from unequal heating or cooling of the earth and its atmosphere are the primary driving forces of the wind on both local and global scales. Once the air is in motion, interaction with surface features – topography, buildings, trees, meadows, or ocean – becomes an important retarding factor near the ground, whereas the inertia of the air tends to maintain motion. Because the winds are observed from a rotating earth, an apparent force, called the Coriolis force, affects the wind.

Atmospheric winds transport vast quantities of heat and moisture, which ultimately affect the weather conditions distant from the airmass source regions. Strong winds accompanying hurricanes, severe thunderstorms, and other intense weather systems often damage structures, carry materials and objects over long distances, and constitute a safety hazard. Wind-driven tides constitute a water hazard for exposed equipment in coastal areas. Sand and dust raised and transported by the wind penetrate into and damage equipment (see Chap. 3 of Part Three of this handbook series). Snow and rain driven by the wind inhibit transportation for periods up to several days (see Chaps. 7 and 8 of this handbook). Evaporation rates normally increase as the ventilation (windspeed) increases, resulting in losses of exposed liquids and in increased windchill. Air pollutants, radioactive debris, and other trace materials are transported by the wind but, in contrast to most wind effects, they become more hazardous under low windspeed conditions.

The wind is a three-dimensional vector quantity. When described by its magnitude (speed) and its direction, the wind is properly called the wind velocity. In most cases, the horizontal component of the vector is much larger than the vertical component. References to "the wind" imply the horizontal velocity only, whereas "vertical velocity" is used to describe vertical motion of the air. The forces that act to modify the wind are also vector quantities. Vector quantities can be written in scalar form when a coordinate system is defined.

Since the earth is a spheroid, the most logical coordinate system would employ spherical coordinates if a global representation of the wind is desired. However, the measurements of wind are made in reference to local directions. Without introducing much error, the vector properties of the atmosphere can be written in local coordinates. The convention, called the tangent plane approximation, specified that x increases eastward, y increases northward, and z increases upward from a point. This approximation disregards the convergence of meridians toward the poles and the local curvature of the earth.

In the tangent plane coordinate system, a velocity vector is described by three components u, v, w in the x-, y-, z-directions, respectively. By convention, u is positive for air moving from west to east, v is positive for air moving from south to north, and w is positive when air is moving upward. The magnitude of the wind velocity (windspeed) V is given by

$$V = (u^2 + v^2 + w^2)^{1/2} \qquad (10\text{-}1)$$

The horizontal windspeed is given by

$$V_h = (u^2 + v^2)^{1/2} \qquad (10\text{-}2)$$

Windspeed is reported in units of length (distance) per unit time. By international convention it should be reported in units of meters per second (m s^{-1}) (Ref. 2). Windspeed may range from calm (no wind) to 150 m s^{-1} or more in tornadic storms. The maximum ground level windspeed, averaged over a 5-min period, ever observed was 84 m s^{-1} (188 mph) at Mt. Washington, N. H., on April 12, 1934 (Ref. 3). The peak wind gust recorded at the same time and place was 103.3 m s^{-1} (231 mph), which is also a world record.

By meteorological convention, the wind direction is reported as the direction from which the wind is blowing. North (along the positive y-axis) is defined as 0 or 360 deg and the wind direction angle increases in a clockwise manner about the compass points. Hence, air moving from east toward west is said to have a direction of 90 deg; from south to north, 180 deg; and from west to east, 270 deg.

When u and v are known, the formulas required to obtain the wind direction θ are given in Table 10-1. When the windspeed V and direction θ are known, u and v are given by

$$u = -V \sin\theta \qquad (10\text{-}3)$$

$$v = -V \cos\theta \qquad (10\text{-}4)$$

Both windspeed and direction may be variable over small distances and time periods. The windspeed is measured by an anemometer and the wind direction is indicated by a wind vane. Until recently, countries using the English system of units reported windspeeds in units of statute miles per hour (mph) or nautical miles per hour (kt). Current official practice in the United States is to record and report windspeeds in knots (kt) (Ref. 4) although mph is sometimes still used for the general public. For aviation, windspeeds aloft are commonly given in knots. The vertical windspeed and some horizontal windspeed measurements very near the ground may be reported in centimeters per second (cm s^{-1}). Table 10-2 gives the factors necessary to convert from one speed unit to another.

Although radian measure is the preferred unit for angular measure, wind directions at the surface are reported to the nearest 5 deg. Winds aloft are also reported to the nearest 5 deg although there is a greater uncertainty in that measure. The practice in the United States, prior to 1962, was to report wind direction by the appropriate direction of a 16-point compass, e.g., N, NNE, NE, ENE, E, etc.

TABLE 10-1

DETERMINATION OF WIND DIRECTION FROM VELOCITY COMPONENTS

Direction of components		Equation for direction θ
v	u	
+	+	θ = 180 deg + $\tan^{-1}(u/v)$
+	-	θ = 180 deg + $\tan^{-1}(u/v)$
-	+	θ = 360 deg + $\tan^{-1}(u/v)$
-	-	$\theta = \tan^{-1}(u/v)$

TABLE 10-2

CONVERSION FACTORS FOR WIND UNITS (Ref. 2)

	$m\ s^{-1}$	$cm\ s^{-1}$	$km\ hr^{-1}$	$ft\ s^{-1}$	$ft\ min^{-1}$	$mi\ hr^{-1}$	kt
Meter per second =	1	10^{2}	3.600	3.281	1.969×10^{2}	2.237	1.944
Centimeter per second =	10^{-2}	1	3.600×10^{-2}	3.281×10^{-2}	1.969	2.237×10^{-2}	1.944×10^{-2}
Kilometer per hour =	2.778×10^{-1}	2.778×10^{1}	1	9.113×10^{-1}	5.468×10^{1}	6.214×10^{-1}	5.400×10^{-1}
Feet per second =	3.048×10^{-1}	3.048×10^{1}	1.097	1	6.000×10^{1}	6.818×10^{-1}	5.925×10^{-1}
Feet per minute =	5.080×10^{-3}	5.080×10^{-1}	1.828×10^{-2}	1.667×10^{-2}	1	1.136×10^{-2}	9.875×10^{-3}
Mile per hour =	4.470×10^{-1}	4.470×10^{1}	1.609	1.467	8.803×10^{1}	1	8.689×10^{-1}
Nautical mile per hour, kt =	5.144×10^{-1}	5.144×10^{1}	1.852	1.688	1.013×10^{2}	1.151	1

10-2 ATMOSPHERIC MOTION

The motion of the atmosphere is described by application of Newton's equations of motion and by conservation of mass. The atmosphere reacts to the forces applied. Only three real forces act upon air: (1) the gravitational attraction on air by other bodies – principally the earth; (2) the pressure gradient forces, which tend to equalize the distribution of the air; and (3) the frictional forces caused by differential movement of the air – principally with respect to the earth. In addition, a correction must be applied to the equations of motion to account for the motion of the earth-bound coordinate system. Drag forces are a form of frictional force wherein the wind exerts a force on an object and is, in turn, affected by the reaction force. Instead of formulating equations relating these forces to the reaction forces, the analysis is customarily acccomplished in terms of accelerations (force per mass or time rate of change of velocity) of airmasses.

10-2.1 CORIOLIS ACCELERATION

Newton's laws of motion apply only to an "inertial coordinate system" – one that experiences no acceleration. An earth-bound observer or observation system is not an inertial system since the earth rotates about its axis and the sun, and the sun is accelerated with respect to the fixed stars. Consequently, the accelerations observed on the earth are different from those observed in an inertial system. The formulation of pressure and frictional accelerations are the same in both systems but additional apparent forces must be considered to describe acceleration of the gravitational and wind velocity fields as measured in the rotating system. The mathematical derivation of the relationship of the two coordinate systems is given in advanced physics (Ref. 5), or in meteorological texts (Refs. 6, 7). The correction factors applied to the laws of motion to accommodate them to the rotating coordinate system of the earth are known as the Coriolis acceleration.

The wind velocity measured in a rotating coordinate system undergoes changes in the horizontal and vertical directions due to motion with respect to the inertial system. When written in component form, the accelerations in the inertial system may be expressed by

$$a_x = a'_x + (uv/R_e)\tan\phi - uw/R_e + 2\,\Omega v\sin\phi - 2\,\Omega w\cos\phi \qquad (10\text{-}5)$$

$$a_y = a'_y - (u^2/R_e)\tan\phi - vw/R_e - 2\,\Omega u\sin\phi \qquad (10\text{-}6)$$

$$a_z = a'_z + (u^2 + v^2)/R_e + 2\,\Omega u\cos\phi \qquad (10\text{-}7)$$

where

a_x, a_y, a_z = accelerations in the inertial system, m s^{-2}

a'_x, a'_y, a'_z = accelerations due to pressure, friction, and gravitation in the rotating system, m s^{-2}

ϕ = geographic latitude, rad

R_e = mean radius of the earth, $\approx 6.4 \times 10^6$ m

Ω = angular velocity of the earth, 0.729×10^{-4} rad s^{-1}

u, v, w = windspeeds measured in the rotating coordinate system, m s^{-1}

These equations apply to all motions relative to a rotating earth, including winds, clouds, rockets, missiles, satellites, and aircraft. As applied to atmospheric winds, the terms involving w are normally much less than those involving u and v. Except in polar latitudes and/or at high windspeeds, the remaining terms involving R_e are also small. The last term in Eq. 10-7 is small relative to the force of gravity. In meteorological applications, the only significant correction terms are those involving $f = 2\Omega \sin\phi$. The equations thus become:

$$a_x = a'_x + fv \tag{10-8}$$

$$a_y = a'_y - fu \tag{10-9}$$

$$a_z = a'_z \tag{10-10}$$

By convention, Ω is always a positive quantity and ϕ is positive in the Northern Hemisphere and negative in the Southern Hemisphere. Thus, in the Northern Hemisphere, a northward motion of the air relative to the earth produces an apparent acceleration to the east and a southward (negative) acceleration is given to air moving eastward. In the Southern Hemisphere, northward motion is apparently deflected to the west (negative x-direction) and eastward motion is apparently deflected to the north (positive y-direction). Thus, the wind is apparently accelerated to the right of its direction in the Northern Hemisphere and to the left of its direction in the Southern Hemisphere.

This apparent acceleration is called the Coriolis acceleration and depends upon the windspeed and the latitude (the maximum magnitude of f is $1.458 \times 10^{-4} s^{-1}$ at the poles and the minimum is zero at the Equator). However, since the acceleration is perpendicular to the velocity vector, no work is done on air, i.e., the energy of the air is unchanged by the Coriolis acceleration, although the direction of the motion is changed.

10-2.2 PRESSURE GRADIENT ACCELERATION

Pressure is defined as force per unit area but can be equivalently expressed as energy per unit volume. Thus, a difference in atmospheric pressure between two points means that an energy difference also exists. Natural processes tend to eliminate energy differences by some transfer mechanism. In the atmosphere, the mechanism is predominantly by the motion of the air, i.e., the wind. The rate of change of energy with distance is a force. If ΔP is the pressure difference between the two sides of a small cylindrical volume of air, then the force exerted on that air is given by

$$F = V\left(\frac{\Delta P}{\Delta S}\right), \text{N} \tag{10-11}$$

where

F = force exerted on the air within the volume, N

V = volume of the air, m^3

ΔP = pressure difference between the two sides of the volume, N m^{-2}

ΔS = distance between the sides, m

The force tends to move the air from high pressure toward low pressure. As ΔS becomes smaller, $\Delta P/\Delta S$ can be expressed as $\partial P/\partial S$, which is the magnitude of the pressure gradient. By mathematical convention, a gradient is a vector quantity, with its direction pointing from low values toward high values. Thus, the direction of the force is opposite to the pressure gradient and

$$F = -V\left(\frac{\partial P}{\partial S}\right), \text{N} \tag{10-12}$$

where S increases from low toward high pressure. The pressure gradient acceleration is therefore

$$a = -\frac{1}{\rho}\left(\frac{\partial P}{\partial S}\right), \text{m s}^{-2} \tag{10-13}$$

where

a = acceleration of air resulting from pressure differentials, m s^{-2}

ρ = atmospheric density, kg m^{-3}

10-2.3 FRICTIONAL ACCELERATION

The effect of frictional forces in the atmosphere is to reduce the general flow of the air. The effect is found principally near the surface of the earth where momentum is transferred from the air to the earth. Surface friction is the main sink for the mechanical energy of the atmosphere. If all of the energy sources of the atmosphere (predominantly the sun) were cut off, it is estimated that the atmosphere would lose almost all of its kinetic energy within 5 days (Ref. 8). Surface friction of the air over the oceans is partly responsible for the ocean circulation patterns, generates storm tides, and makes the ocean surface choppy. Friction induces gustiness and turbulence in the wind, reduces the wind-speeds near the surface of the earth, and is the controlling factor in the diffusion of pollutants in the atmosphere. In turn, the magnitude of frictional acceleration is partially determined by the stability of the atmosphere.

Representation of atmospheric frictional forces in the equations of motion takes many forms in theoretical and empirical analyses. In practice, theoretical models must be simplified in order to obtain solutions. Definitive discussions of the theories of turbulence and friction are available in a number of texts (Refs. 9-11).

Frictional forces result from normal and tangential stresses on each volume of air. The gradient of the stresses is proportional to the force. Atmospheric friction is characterized by the turbulence induced by the friction. The turbulence appears as random or chaotic fluctuations about the average properties of the air, such as the instantaneous speed or direction fluctuations recorded by an anemometer or a wind vane. The turbulence is described by the statistical properties of the observed motion and is related to the stresses on the air volumes.

If u is the instantaneous west windspeed at a point (x,y,z) and time t, its average value $\overline{u}$ (x,y,z) during a sampling period T is given by

$$\overline{u}(x,y,z) = \frac{1}{T}\int_{t - T/2}^{t + T/2} u(x,y,z,t)\,dt \qquad (10\text{-}14)$$

At any given instant during the sampling period, u may be written as

$$u(x,y,z,t) = \overline{u}(x,y,z) + u'(x,y,z,t) \qquad (10\text{-}15)$$

where u' is the instantaneous deviation of u from its mean value. The average value of u' over the sampling period is zero, but the mean square deviation or variance of u', written $\overline{(u')^2}$, is not normally zero, i.e.,

$$\overline{(u')^2} = \frac{1}{T}\int_{t - T/2}^{t + T/2} [u'(x,y,z,t)]^2\,dt \neq 0 \qquad (10\text{-}16)$$

The standard deviation of u, written σ_u, is equal to the square root of the variance of u:

$$\sigma_u = \left(\overline{(u')^2}\right)^{1/2} \qquad (10\text{-}17)$$

Similar representations of the other wind components may be made as follows:

$$\left.\begin{aligned} v &= \overline{v} + v' \\ w &= \overline{w} + w' \end{aligned}\right\} \qquad (10\text{-}18)$$

$$\left.\begin{aligned} \overline{(v')^2} &= (\sigma_v)^2 \neq 0 \\ \overline{(w')^2} &= (\sigma_w)^2 \neq 0 \end{aligned}\right\} \qquad (10\text{-}19)$$

The intensities of turbulence in the x-, y-, and z-directions i_x, i_y, and i_z are defined by the relations (Ref. 12):

$$\left.\begin{aligned} i_x &= \sigma_u/\overline{V} \\ i_y &= \sigma_v/\overline{V} \\ i_z &= \sigma_w/\overline{V} \end{aligned}\right\} \qquad (10\text{-}20)$$

where $\overline{V}$ = mean windspeed = $(\overline{u}^2 + \overline{v}^2 + \overline{w}^2)^{1/2}$, m s^{-1}.

When the mean wind is in the x-direction, for most conditions below 30-m altitude, the ratio $i_x : i_y : i_z = 1 : 1.16 : 0.75$ is approximately correct (Ref. 6). This indicates that the turbulence is anisotropic.

The gustiness g of the wind in each direction is defined as

$$\left.\begin{aligned} g_x &= \overline{|u'|}/\overline{V} \\ g_y &= \overline{|v'|}/\overline{V} \\ g_z &= \overline{|w'|}/\overline{V} \end{aligned}\right\} \qquad (10\text{-}21)$$

where, for any quantity u', $|u'|$ indicates its absolute value. The gustiness is different from the intensity of turbulence (Ref. 1).

Another parameter of the wind fluctuation that has found wide use in diffusion estimates is the standard deviation of the azimuthal wind direction angle σ_θ. It is related to the intensity of turbulence in the cross wind direction, i.e., when the x-direction is chosen along the mean wind direction, it is given by

$$\sigma_\theta^2 = \frac{\overline{(v')^2}}{\bar{u}^2} = \left(\sigma_v/\bar{u}\right)^2 \qquad (10\text{-}22)$$

when v' is the windspeed in the direction perpendicular to the mean wind direction and in the horizon plane (Ref. 12). The standard deviation of the wind direction fluctuations in the vertical σ_θ is similarly defined by

$$\sigma_\theta^2 = \frac{\overline{(w')^2}}{\bar{u}^2} = \left(\sigma_w/\bar{u}\right)^2 \qquad (10\text{-}23)$$

when $\bar{u}$ is the mean horizontal windspeed.

The covariance of the horizontal, velocity fluctuations, e.g.,

$$\overline{u'v'} = \frac{1}{T}\int_{t\,-\,T/2}^{t\,+\,T/2} [u'(x,y,z,t)v'(x,y,z,t)]\,dt \qquad (10\text{-}24)$$

are important statistical parameters of the turbulence and hence the friction. Integrations similar to Eq. 10-24 define the other covariances $\overline{u'w'}$ and $\overline{v'w'}$, which are also important. These covariances are symmetrical so that

$$\left.\begin{aligned} &\overline{u'v'} = \overline{v'u'} \\ &\overline{u'w'} = \overline{w'u'} \\ \text{and}\quad &\overline{v'w'} = \overline{w'v'}. \end{aligned}\right\} \qquad (10\text{-}25)$$

Expressing the velocity components as in Eq. 10-15 and then averaging the equations of motion for an incompressible fluid yields the frictional forces per unit mass in the form:

$$F_x = \frac{1}{\rho}\left\{\frac{\partial}{\partial x}\left[-\rho\overline{(u')^2}\right] + \frac{\partial}{\partial y}\left(-\rho\overline{u'v'}\right) + \frac{\partial}{\partial z}\left(-\rho\overline{u'w'}\right)\right\} \qquad (10\text{-}26a)$$

$$F_y = \frac{1}{\rho}\left\{\frac{\partial}{\partial x}\left(-\rho\overline{u'v'}\right) + \frac{\partial}{\partial y}\left[-\rho\overline{(v')^2}\right] + \frac{\partial}{\partial z}\left(-\rho\overline{v'w'}\right)\right\} \qquad (10\text{-}26b)$$

$$F_z = \frac{1}{\rho}\left\{\frac{\partial}{\partial x}\left(-\rho\overline{u'w'}\right) + \frac{\partial}{\partial y}\left(-\rho\overline{v'w'}\right) + \frac{\partial}{\partial z} + \left[-\rho\overline{(w')^2}\right]\right\} \qquad (10\text{-}26c)$$

In these equations, the variance and covariance of the velocity components appear as the normal and tangential stresses, respectively, on a volume of air. The terms in parentheses are called the turbulent stresses or the Reynolds stresses and are interpreted as the transport of momentum across a surface in the air. Often, the Reynolds stresses are written as τ'_{xx}, τ'_{xy}, τ'_{xz}, etc.

Although the friction may be expressed by Eqs. 10-26, the magnitude of the force is

TABLE 10-3

VALUES OF HORIZONTAL EDDY VISCOSITIES AT VARIOUS SCALES (Ref. 12)

Scale, cm	K, cm^2 s^{-1}	Source of data
5×10^{-2}	1.7×10^{-1}	Molecular diffusion
1.5×10^{3}	3.2×10^{3}	Low-level wind shear
1.4×10^{4}	1.2×10^{5}	Low-level wind shear
5×10^{4}	6×10^{4}	Pilot balloons, 100 to 800 m
2×10^{6}	1×10^{8}	Manned and unmanned balloons
5×10^{6}	5×10^{8}	Volcanic ash
1×10^{8}	1×10^{11}	Cyclonic storms

difficult to obtain, since at least two points in each direction are required to obtain the indicated derivatives. Other representations of frictional forces have been developed to express the frictional force in terms of the mean motion, rather than the turbulent motion. These include the exchange coefficient hypothesis and the mixing length hypothesis.

10-2.3.1 EXCHANGE COEFFICIENTS

The exchange coefficient hypothesis assumes that the Reynolds stress term can be expressed as the product of an exchange coefficient, sometimes called the Austauch coefficient, and the gradient of the mean motion, in a manner analogous to the viscous forces. If A is the exchange coefficient then

$$\left.\begin{aligned} \tau'_{xx} &= A_x \frac{\partial \bar{u}}{\partial x} \\ \tau'_{yx} &= A_y \frac{\partial \bar{u}}{\partial x} \\ \tau'_{zx} &= A_z \frac{\partial \bar{u}}{\partial x} \end{aligned}\right\} \qquad (10\text{-}27)$$

and similarly for the other Reynolds stresses. The subscript on A indicates the exchange coefficient for the particular direction. A_x, A_y, A_z have dimensions of mass per time per length.

The eddy viscosity K is defined as (Ref. 12)

$$K = A/\rho, \text{ m}^2 \text{ sec}^{-1} \qquad (10\text{-}28)$$

For each component, K is related to the velocity variance or covariance by

$$\left.\begin{aligned} K_x &= -\overline{(u')^2} \Big/ \frac{\partial \bar{u}}{\partial x} \\ K_y &= -\overline{(u'v')} \Big/ \frac{\partial \bar{u}}{\partial y} \\ K_z &= -\overline{(u'w')} \Big/ \frac{\partial \bar{u}}{\partial z} \end{aligned}\right\} \qquad (10\text{-}29)$$

Although K_x, K_y and K_z are related to the velocity variance and covariance at a point and vary within the atmosphere, they are often assumed to be (in order of decreasing validity) variable only in the vertical, or constant, or equal. Within the atmosphere, K takes on values ranging from 10^{-1} $m^2 s^{-1}$ to 10^7 $m^2 s^{-1}$ or greater, depending upon the scales of motion considered. Table 10-3 gives typical values of K for various scales of motion.

When the eddy exchange hypothesis is used, the frictional components become

$$\left.\begin{aligned}
F_x &= \frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(A_x \frac{\partial \bar{u}}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_y \frac{\partial \bar{u}}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_z \frac{\partial \bar{u}}{\partial z}\right)\right] \\
F_y &= \frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(A_x \frac{\partial \bar{v}}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_y \frac{\partial \bar{v}}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_z \frac{\partial \bar{v}}{\partial z}\right)\right] \\
F_z &= \frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(A_x \frac{\partial \bar{w}}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_y \frac{\partial \bar{w}}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_z \frac{\partial \bar{w}}{\partial z}\right)\right]
\end{aligned}\right\} \qquad (10\text{-}30)$$

10-2.3.2 MIXING LENGTHS

The mixing length hypothesis assumes that, because of the turbulent motion, a small discrete air parcel breaks away from its original altitude z and is transported to a new level $z + \ell$, where the volume mixes with the mean flow. The absorption of the parcel induces a fluctuation of velocity u' where

$$u' = \bar{u}(z + \ell) - \bar{u}(z) \approx \ell \frac{\partial \bar{u}}{\partial z} \qquad (10\text{-}31)$$

A similar argument defines v' and w', although the value of ℓ may differ numerically in the different directions. The mixing length hypothesis is that the quantity ℓ is a unique length that characterizes the local intensity of the turbulent motion. This length is sometimes called the eddy size.

The relationship of the normal and tangential Reynolds stresses in the mixing length hypothesis is given by

$$\left.\begin{aligned}
\tau'_{xx} &= \rho \ell^2 \left(\frac{\partial \bar{u}}{\partial x}\right) \cdot \left|\frac{\partial \bar{u}}{\partial x}\right| \\
\tau'_{zx} &= -\rho \ell^2 \left(\frac{\partial \bar{u}}{\partial z}\right) \cdot \left|\frac{\partial \bar{u}}{\partial z}\right|
\end{aligned}\right\} \qquad (10\text{-}32)$$

where $|\partial \bar{u}/\partial x|$ and $|\partial \bar{u}/\partial z|$ are the absolute values of the indicated gradients. The gradient terms are separated to allow τ to change sign as the sign of the gradient changes.

The relationship between K and ℓ is obtained through the Reynolds stresses. In the case of K_z and ℓ

$$K_z = -\overline{(u'w')} \Big/ \frac{d\bar{u}}{dz} = \ell^2 \frac{d\bar{u}}{dz} \qquad (10\text{-}33)$$

10-2.3.3 DRAG FORCES

In aerodynamics, the normal force exerted on a body moving relative to the air is proportional to the kinetic energy per unit volume and is given by

$$F_D = C_D \, (\rho V^2 A/2), \text{ N} \qquad (10\text{-}34)$$

where

F_D = drag force, N

C_D = factor of proportionality, called the drag coefficient, dimensionless

V = undisturbed relative velocity, m s^{-1}

ρ = air density, kg m^{-3}

A = cross-sectional area of the body perpendicular to the air flow, m^2

The drag coefficient varies for different objects and windspeeds because of differing dynamic shapes. Usually, it is determined by measurements in a wind tunnel employing scale models of the body. C_D is dependent upon the geometry of the body and the Reynolds number, Vd/ν, of the flow, where d is a characteristic length, such as the diameter, of the body and ν is the kinematic viscosity (Ref. 13). This representation of the normal force on a building, aircraft, or surface structure indicates that the force is proportional to the square of the windspeed.

In addition to the static pressure, a dynamic oscillatory force acts upon the buildings. As the air impinges upon the face of the building, a reduction in pressure occurs on the leeward side of the structure. Vortices or eddies develop as the air moves around the building in an attempt to equalize the pressure. The eddies move downstream with the mean flow so the wind force against the leeward face pulsates as one eddy replaces another.

10-3 WIND DISTRIBUTION

The relative importance of the Coriolis force, pressure gradient force, and frictional forces delineate three categories for examining the wind distributions in the vertical:

(1) The "constant stress" layer extending to several tens of meters above the surface of the earth where pressure gradient and frictional forces dominate

(2) The "planetary boundary layer" extending upward to about 1 km, where all three forces are about equal

(3) The "free" atmosphere above 1 km where frictional forces are negligible.

The horizontal scale of motion, i.e., the wavelength of disturbances in the wind field, also delineates types of wind circulation effects. Global scale systems have wavelengths on the order of the radius of the earth, and friction contributes only in a minor manner to changing these patterns. Synoptic scale wind systems, on the order of 1,000 km, are the wind-pressure systems displayed on a weather map. Friction caused by mountain ranges and the like become important in describing this type of flow.

Mesoscale systems include the broad intermediate range of wind disturbance patterns from hurricanes and thunderstorms to tornadoes. Surface frictional effects and local heating and cooling differences become important to the development, maintenance, and dissipation of the circulation, although the circulation may exist on and out of the planetary boundary layer.

Microscale motion is normally confined to the planetary boundary layer and dissipates energy from larger scale motions. Evaporation, heat, and momentum transfer on scales of 100 m or less are included in microscale phenomena. All scales are present in each wind observation but may become apparent only if the data density in time or space is sufficiently large.

10-3.1 VERTICAL DISTRIBUTION

The three regimes of winds in the vertical – surface layer, planetary boundary layer, and free atmosphere – are each important in the consideration of materiel effects and each is considered in the paragraphs that follow.

10-3.1.1 THE SURFACE LAYER

Atmospheric motions near the surface of the earth are changing rapidly enough that the effects of earth rotation are negligible. Hence, the mean motion is described in terms of pressure gradient forces and frictional forces. Since the geographic orientation of the wind is important only in describing the Coriolis acceleration, the direction of the mean windspeed is taken as the x-direction and the mean windspeed is given the value $\bar{u}$. Within the first kilometer of the surface of the earth, the friction forces due to the vertical shear of the horizontal wind are much larger than other frictional terms. Thus, the equation of motion appropriate for the near surface layer is

$$\frac{d\bar{u}}{dt} = -\frac{1}{\rho}\frac{\partial\bar{P}}{\partial x} + \frac{1}{\rho}\frac{\partial\tau}{\partial z} \qquad (10\text{-}35)$$

wherein the first term, $-1/\rho\ \partial\bar{P}/\partial x$, is the appropriate term from Eq. 10-13 for the pressure gradient force and the second term, equal to $\partial/\partial z\ (-\rho\overline{u'w'})$, is the frictional force associated with vertical shear as given in the last term for F_x in Eq. 10-26a. The subscripts are omitted for this restricted treatment. For the case of an unaccelerated mean wind, the pressure gradient forces must balance the frictional forces, viz.,

$$\frac{\partial\bar{P}}{\partial x} = \frac{\partial\tau}{\partial z} \qquad (10\text{-}36)$$

Integrating with respect to z and assuming the pressure gradient to be constant over the depth of integration gives for the turbulent stress τ

$$\tau = \tau_0 + \left(\frac{\partial\bar{P}}{\partial x}\right)z \qquad (10\text{-}37)$$

The downstream pressure gradient is generally small so that for $z < 35$ m, the stress reduces to

$$\tau \approx \tau_0 \qquad (10\text{-}38)$$

Thus, the earth-air interface is characterized by a nearly constant stress. The constant stress assumption is valid to within ± 10 percent.

From the mixing length theory (Eq. 10-32), τ may be given as

$$\tau = \tau_0 = \rho\ell^2 \frac{\partial\bar{u}}{\partial z}\left|\frac{\partial\bar{u}}{\partial z}\right| \qquad (10\text{-}39)$$

Defining the friction velocity u_* as

$$u_*^2 = \left|\frac{\tau_0}{\rho}\right| \qquad (10\text{-}40)$$

gives

$$u_* = \ell\frac{\partial\bar{u}}{\partial z} \qquad (10\text{-}41)$$

where ℓ is the mixing length. It is generally assumed and experimentally confirmed that ℓ increases linearly with altitude z so that

$$\ell = kz \qquad (10\text{-}42)$$

where $k = 0.4$ is von Kármán's constant (dimensionless).

Substitution of Eq. 10-42 into Eq. 10-41 gives

$$\frac{1}{u_*}\frac{\partial\bar{u}}{\partial z} = \frac{1}{kz} \qquad (10\text{-}43)$$

Integration with respect to z gives

$$\bar{u}\,(z) = \frac{u_*}{k}\ln z + \text{constant} \qquad (10\text{-}44)$$

The integration constant is usually formed to introduce the effect of surface roughness by requiring $\bar{u}\,(z_0) = 0$.

The mean velocity in the constant stress layer is given by the logarithmic wind profile equation

$$\bar{u}\,(z) = (u_*/k)\ln(z/z_0) \qquad (10\text{-}45)$$

where z_0 is called the roughness length and varies with the type of surface as shown in Table 10-4. Below z_0, $\bar{u}$ is not defined.

Sometimes z_0 is chosen so that $\bar{u}\,(0) = 0$. In that case the wind profile is given by

$$\bar{u}\,(z) = (u_*/k)\ln[(z + z_0)/z_0] \qquad (10\text{-}46)$$

TABLE 10-4

TYPICAL VALUES OF PARAMETERS GOVERNING THE LOGARITHMIC WIND PROFILE NEAR THE SURFACE OF THE EARTH (Ref. 12)

Type of surface	z_0, cm	u_*, m s^{-1} †
Smooth mud flats; ice	0.001	0.16
Smooth snow	0.005	0.17
Smooth sea	0.02	0.21
Level desert	0.03	0.22
Snow surface; lawn to 1 cm high	0.1	0.27
Lawn, grass to 5 cm	1-2	0.43
Lawn, grass to 60 cm	4-9	0.60
Fully grown root crops	14	1.75

† For $\bar{u}(2\text{m}) = 5$ m s^{-1}

Normally, z is much greater than z_0 and Eqs. 10-45 and 10-46 are equivalent.

Other equations applicable to the constant stress layer are

$$\bar{u}(z) = (u_*/k)\ln(z/z_0 + \alpha z/L) \quad (10\text{-}47)$$

where α is a dimensionless factor and

$$L = -\left\{u_*^3/[k(g/T_a)]\right\}/[H/\rho c_p] \quad (10\text{-}48)$$

where

g = gravitational acceleration, m s^{-2}

u_* = friction velocity, m s^{-1}

T_a = mean air temperature, K

k = von Kármán's constant, dimensionless

H = surface heat flux, W m^{-2}

ρ = air density, g m^{-3}

c_p = specific heat of air at constant pressure, J g^{-1} K^{-1}

L = Monin-Obukhov length, m

This profile, through the z/L term, includes the effect of buoyancy (atmospheric stability) upon the eddy transfer properties.

For many applications it is convenient to express the mean windspeed at a height z in terms of a measurement of $\bar{u}$ at a level z_1 in the form

$$\bar{u}(z) = \bar{u}(z_1)(z/z_1)^{1/n} \quad (10\text{-}49)$$

where n is a positive number. Typical values for n, dependent upon surface conditions when z_1 = 30 m are given in Table 10-5. The column headed Z_g in the table is the level above which friction with the surface of the earth becomes negligible, i.e., the top of the planetary boundary layer. It is discussed in par. 10-3.1.2. Fig. 10-1 shows the relation between the coefficient $1/n$ and Z_0, the surface roughness lengths, as well as Z_g.

TABLE 10-5

POWER LAW AND GRADIENT WIND LEVELS (Ref. 14)

Terrain	n	Z_g, ft
Level or slightly rolling land with some obstructions, e.g., farm land with scattered trees and buildings and airports.	7	950
Rolling or level country broken by numerous obstructions of various sizes, e.g., suburbs where lots are half acre or more.	5	1,150
Broken surface with large obstructions, e.g., near suburbs with one-fourth acre or less lots and outskirts of large cities	3	1,500
Large obstructions, e.g., center of large city.	2	1,800

10-3.1.2 PLANETARY BOUNDARY LAYER

Above the constant stress layer, the influence of friction normally decreases with altitude and experimental evidence shows that the mixing lengths and the Austauch coefficients decrease with altitude. When a steady unaccelerated flow exists – i.e., when the pressure gradient, Coriolis, and frictional forces are in balance – the equations of the average horizontal motion become

$$\left.\begin{aligned} &-\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x} + f\overline{v} + \frac{1}{\rho}\frac{\partial \tau_{xz}}{\partial z} = 0 \\ &\text{and} \\ &-\frac{1}{\rho}\frac{\partial \overline{P}}{\partial y} - f\overline{u} + \frac{1}{\rho}\frac{\partial \tau_{yz}}{\partial z} = 0 \end{aligned}\right\} \qquad (10\text{-}50)$$

The profiles of $\overline{u}$ and $\overline{v}$ are obtained by assuming that

$$\frac{1}{\rho}\frac{\partial}{\partial z}(\tau_{xz}) = K\frac{\partial^2 \overline{u}}{\partial z^2} \qquad (10\text{-}51a)$$

$$\frac{1}{\rho}\frac{\partial}{\partial z}(\tau_{yz}) = K\frac{\partial^2 \overline{v}}{\partial z^2} \qquad (10\text{-}51b)$$

$$-\frac{1}{\rho}\frac{\partial \overline{P}}{\partial y} = f\overline{v}_g \qquad (10\text{-}51c)$$

$$-\frac{1}{\rho}\frac{\partial \overline{P}}{\partial y} = f\overline{u}_g \qquad (10\text{-}51d)$$

where $\overline{u}_g$ and $\overline{v}_g$ are the "geostrophic wind components" (see par. 10-3.1.3).

At some altitude, the effect of friction becomes negligible and the wind becomes geostrophic. Choosing the x-direction parallel to the isobars at that level, i.e., $\overline{u} = \overline{u}_g = [-1/(\rho f)]\ \partial P/\partial y$ at the top of the friction layer, the solutions to Eq. 10-50 are

$$\left.\begin{aligned} &\overline{u}(z) = \overline{u}_g(1 - e^{az}\cos az) \\ &\text{and} \\ &\overline{v}(z) = \overline{u}_g(e^{az}\sin az) \end{aligned}\right\} \qquad (10\text{-}52)$$

where $a^2 = f/(2k)$.

This solution, for a constant value of K, is known as the Ekman spiral and is shown in Fig. 10-2. At any altitude z, the angle between the actual wind vector $\vec{V}$ and the vector $(\vec{V} - \overline{u}_g)$ remains constant. The figure also shows that the effect of friction is to turn

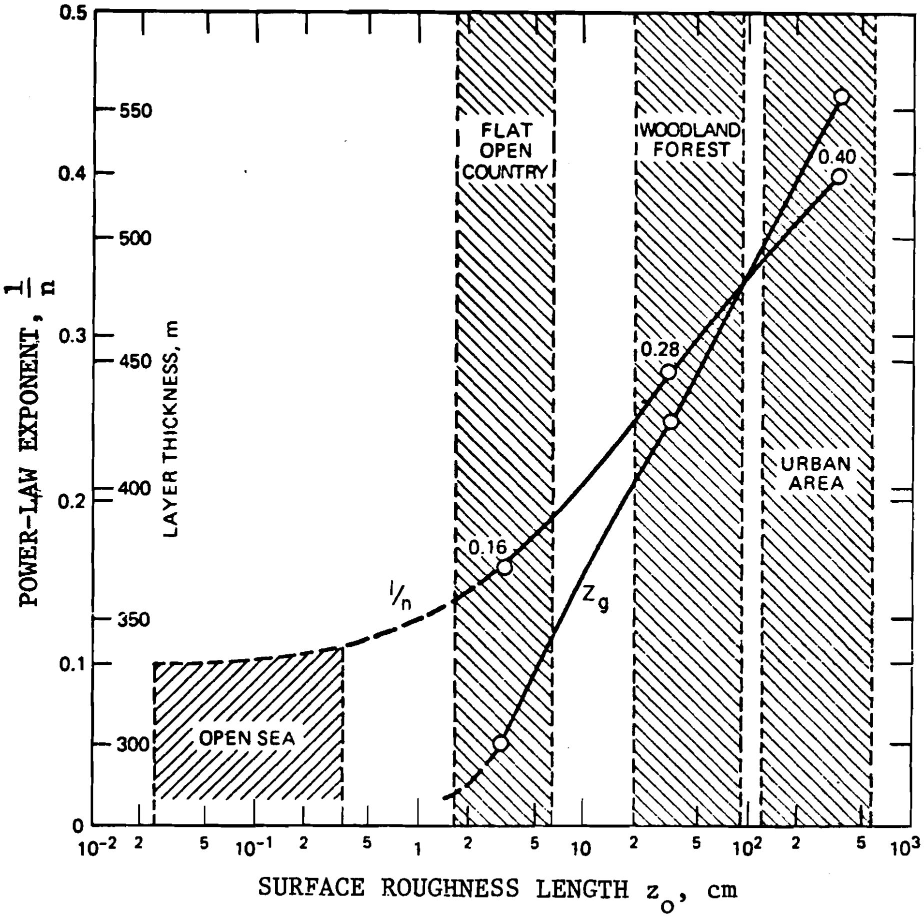

Figure 10-1. Boundary Layer Properties as Functions of Terrain (Ref. 15)

the wind so that it blows across the isobars toward low pressure, near the surface. The cross-isobar flow decreases with altitude, until V first becomes zero, i.e., when $az = \pi$. That altitude defines the top of the planetary boundary layer or the gradient wind level, above which friction with the surface of the earth becomes negligible. Taking f as 10^{-4} s^{-1} (latitude 43 deg N. and K as 1 m^2 s^{-1} gives the gradient wind level, $Z_g \approx 450$ m ($\approx$1475 ft).

10-3.1.3 FREE ATMOSPHERE AND THE JET STREAM

In the absence of frictional forces, the equations of horizontal motion become

$$\left.\begin{aligned} \frac{du}{dt} &= -\frac{1}{\rho}\frac{\partial P}{\partial x} + fv \\ \frac{dv}{dt} &= -\frac{1}{\rho}\frac{\partial P}{\partial y} - fu \end{aligned}\right\} \qquad (10\text{-}53)$$

where in each equation the acceleration is equated to the sum of the pressure gradient and Coriolis accelerations.

For the case of unaccelerated flow, the left side of each of the equations became zero, leaving the windspeed components proportional to the pressure gradient acceleration and the latitude of the observations. The wind components satisfying these conditions are

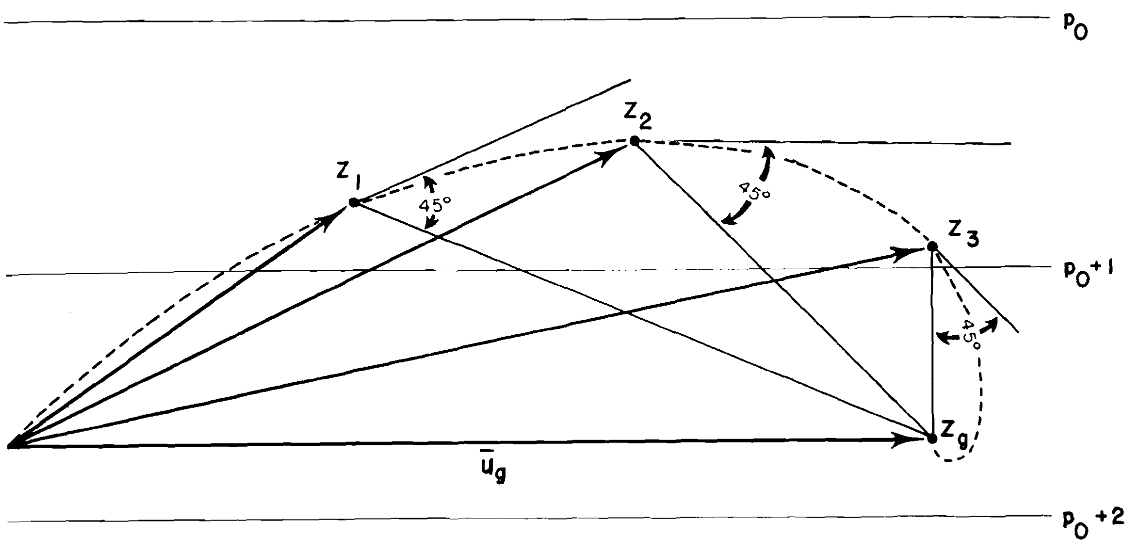

Figure 10-2. The Ekman Spiral Showing Wind Distribution in the Planetary Boundary Layer (Ref. 12)

called the geostrophic wind components and are written as u_g and v_g. They are given by

$$u_g = -\frac{1}{\rho f}\frac{\partial P}{\partial y}$$

and (10-54)

$$v_g = \frac{1}{\rho f}\frac{\partial P}{\partial x}$$

The total geostrophic wind speed V_g is given by

$$V_g = \left(u_g^2 + v_g^2\right)^{1/2} \tag{10-55}$$

and the direction is parallel to the isobars (lines of constant pressure). V_g may also be expressed as

$$V_g = -\frac{1}{\rho f}\frac{\partial P}{\partial s} \tag{10-56}$$

where s is perpendicular to the isobars.

The geostrophic condition is a first approximation to the actual wind in the free, frictionless atmosphere, and is approximately satisfied at latitudes poleward of the tropics. In tropical latitudes, as f goes to zero, the relationship between observed winds and geostrophic winds, computed from the pressure gradient, is generally poor.

Even in midlatitudes, the relationship is only approximately satisfied at any given instant or position because the pressure forces change as the parcel of air moves and because the latitude of the parcel changes. In long-term averages of pressure and wind distributions, the winds tend to be geostrophic.

The horizontal accelerations that a parcel will experience can be obtained by eliminating the pressure gradient forces between Eq. 10-53 and Eq. 10-54 to give

$$\left.\begin{aligned}\frac{du}{dt} &= f(v - v_g)\\ \frac{dv}{dt} &= f(u_g - u)\end{aligned}\right\} \tag{10-57}$$

The components $(u_g - u)$ and $(v_g - v)$ are called the ageostrophic wind components u_{ga} and v_{ga}. The horizontal accelerations are proportional to the ageostrophic wind components. The magnitude of the net accelerations may be within

$$\frac{dv}{dt} = f(V - V_g) \qquad (10\text{-}58)$$

When a particle of air moves in a curved path, the acceleration is proportional to the square of the windspeed and inversely proportional to the radius of curvature R. Thus, for motion in a curved path, the magnitude of the net acceleration is given by the gradient wind equation

$$\frac{dV}{dt} = \frac{V^2}{R} = f(V - V_g) \qquad (10\text{-}59)$$

The radius of curvature is considered positive for cyclonic motion and negative for anticyclonic motion. It is small when the wind changes direction quickly and is infinite for straight line flow.

The actual wind is greater than the geostrophic value in anticyclonic flow and less than the geostrophic value in cyclonic flow. The differences increase as the radius of curvature decreases.

With the absence of frictional force above the planetary boundary layer, the seasonal or monthly windspeed vector at a given altitude becomes approximately equal to the geostrophic wind determined from the mean pressure gradient. Generally, average winds tend to become more westerly with altitude and to develop a maximum speed near a 200-mb altitude. Maximal westerly windspeeds occur in the midlatitudes, migrating poleward in the summer season and equatorward with stronger winds in the winter season as shown in Fig. 10-3. The tropical latitudes exhibit a general decrease in windspeed with altitude in the lower part of the atmosphere, then an increase but primarily in an easterly direction. Note in Fig. 10-3 that altitude is given in terms of atmospheric pressure.

The wind distribution as a function of altitude at a given position and time may differ substantially from the mean profiles inferred from Fig. 10-3, because of ageostrophic and local atmospheric structure effects. Yet, to a first approximation the vertical wind shear $\partial V/\partial z$ may be expressed as the vertical shear of the geostrophic wind. That relationship, known as the thermal wind equation is, in component form,

$$\left.\begin{aligned} \frac{\partial u_g}{\partial z} &= \frac{g}{fT} \cdot \frac{\partial T}{\partial y} \\ \frac{\partial v_g}{\partial z} &= -\frac{g}{fT} \cdot \frac{\partial T}{\partial x} \end{aligned}\right\} \qquad (10\text{-}60)$$

where the horizontal derivatives are taken along the pressure surface and

T = temperature, K

g = gravitational acceleration, m s^{-2}.

These equations indicate that the geostrophic windspeed increases most rapidly with altitude (decreasing pressure) when the temperature gradient is large; when the temperature is low (as would be the case at higher altitudes); and toward the tropics, where f is small. The principal controlling variable is the horizontal temperature gradient. In the troposphere*, the temperature generally decreases poleward; hence $\partial u_g/\partial z$ is usually larger than $\partial v_g/\partial z$, and the winds tend to become more westerly with increasing altitude. Especially in the winter hemisphere, the isotherms on a pressure surface may exhibit a wavelike pattern rather than a simple poleward decrease. In such conditions, $\partial v_g/\partial z$ and the wind direction may not change, although the windspeed increases with altitude.

The change of the wind velocity with height and its relationship to the average

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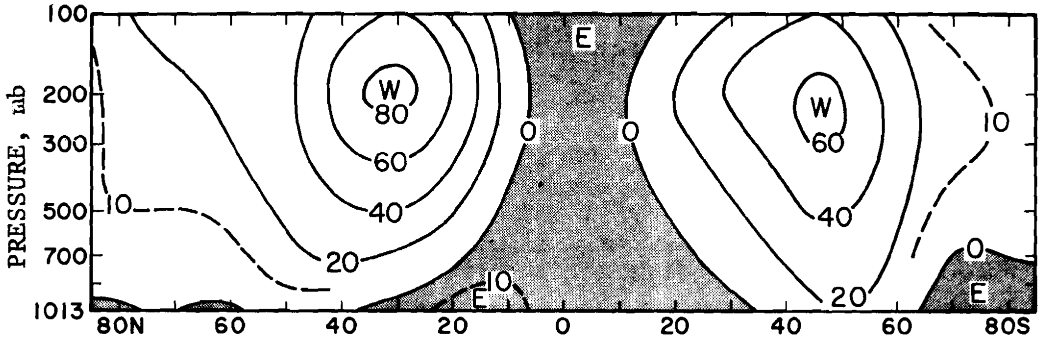
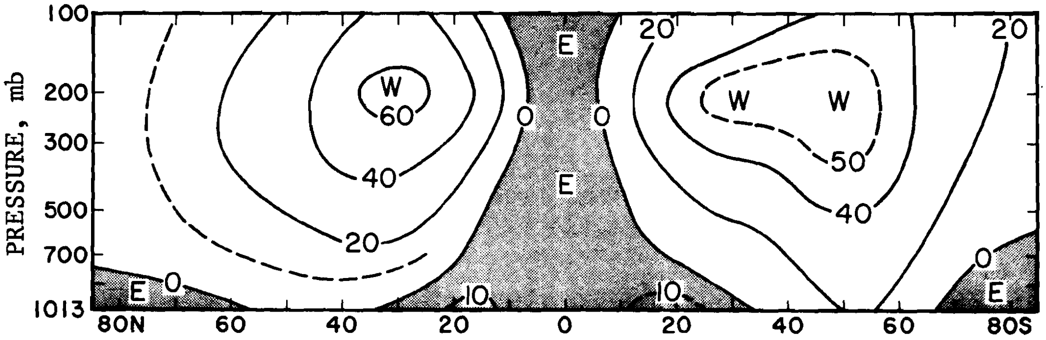
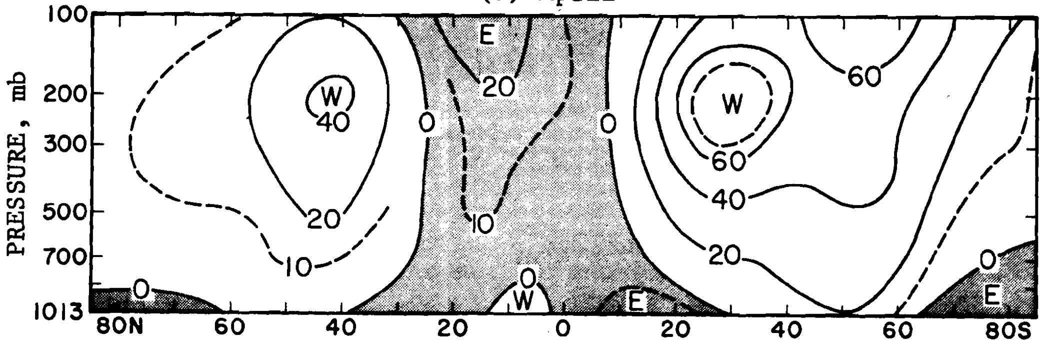
*The troposphere is the name given to the portion of the atmosphere in which the temperature decreases with altitude at a nominal rate of 6.5 K km^{-1}. The tropopause is the name given to the altitude(s) at which the temperature ceases to decrease at that rate, and decreases more slowly ($\approx$1.0 K km^{-1}), remains constant, or increases with altitude. The altitude of the tropopause varies with season and latitude, being as low as 8 km in the polar winter and as high as 15 km in the tropical summer. The stratosphere lies above the tropopause.



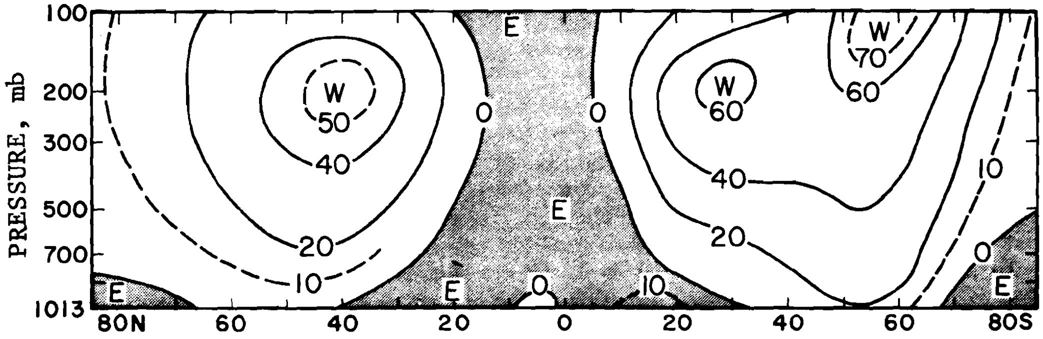
(A) January



(B) April

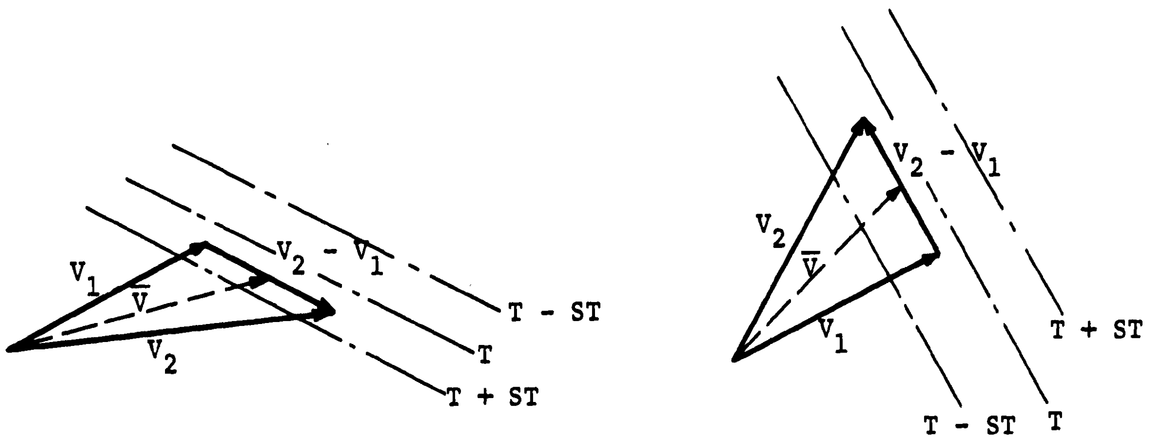


(C) July



(D) October

Figure 10-3. Mean Zonal Windspeed (kt) for the Midseason Months (areas of easterly wind are shaded and westerly wind unshaded) (Ref. 16)



(A) Veering (B) Backing

Figure 10-4. Schematic Representation of the Relative Wind Direction Change With Height and Mean Temperature Distribution (See text for definition of terms and discussion.)

temperature gradient between the altitudes is shown in Fig. 10-4. The vector V represents the wind velocity at the lower altitude; $V_2 - V_1$, the shear vector; $\bar{V}$, the vector average wind through the layer; and δT is the positive temperature increment. In Fig. 10-4(A), windspeed increases with altitude and the direction increases (becomes more westerly). The shear vector lies parallel to the isotherms with the warm air to the right of the vector. The $\bar{V}$ for the layer is directed from warm toward cold temperatures, indicating that warmer air is replacing cooler air; this is called warm air advection. The wind direction is said to be veering with altitude (turning counter to the direction of earth rotation). In Fig. 10-4(B), warmer temperatures again lie to the right of the shear vector, but $\bar{V}$ is directed from cold to warm temperatures; i.e., cold air advection is occurring. The wind direction is said to be backing with altitude (turning in the direction of earth rotation).

Above the tropopause, the horizontal temperature gradient changes sign and windspeeds decrease with altitude in the lower stratosphere. However, an altitude of maximum windspeed is found at or just below the tropopause.

Above the positions where the vertically average horizontal temperature gradient is greatest, a maximum in the horizontal windspeed is found. The axis of the maximum wind is called the jet stream. A vertical profile of windspeed through a jet stream (see Fig. 10-5) shows a rapid increase of speed below the maximum, but a more rapid decrease above the jet stream (Ref. 17). This pattern of vertical shear is common; the magnitude of the shear increases with the maximum windspeed as shown in Fig. 10-6.

The idealized model of the jet stream shown in Fig. 10-7 depicts the variation of windspeed and temperature with altitude perpendicular to the jet core. To the north of the axis, windspeed decreases more rapidly than to the south. A comparison of the horizontal profiles across the jet stream core at various positions in the jet for various classes of flow is shown in Fig. 10-8. The greatest horizontal and vertical shear appears to the north and slightly above the jet stream core, enhancing the possibility of the occurrence of the shear-induced turbulence aloft. Recent evidence indicates that clear air turbulence (CAT) is most likely to occur near the boundaries of the jet front shown in Fig.

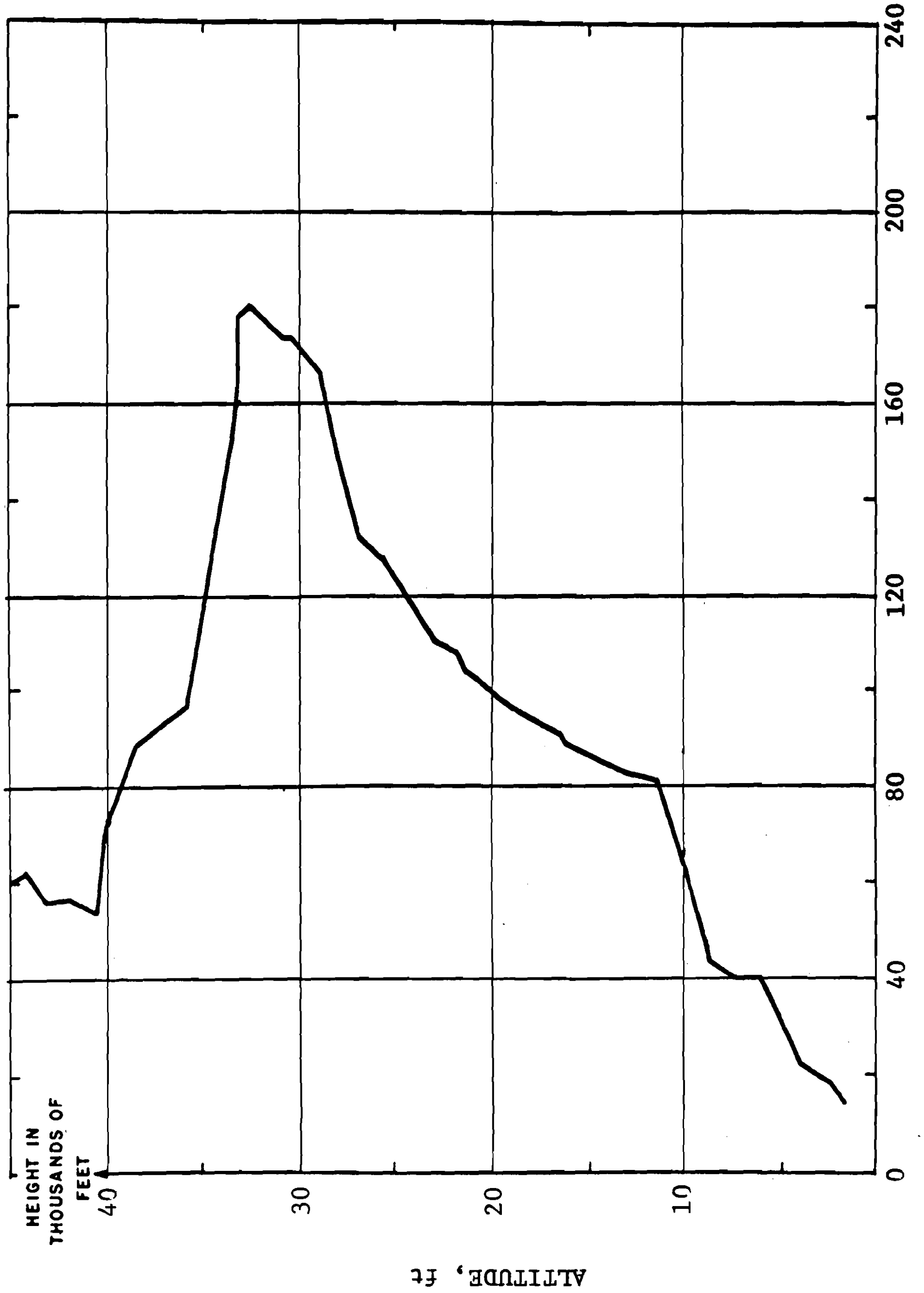


Figure 10-5. Typical Profile of Windspeed in a Jet Stream (Ref. 17)

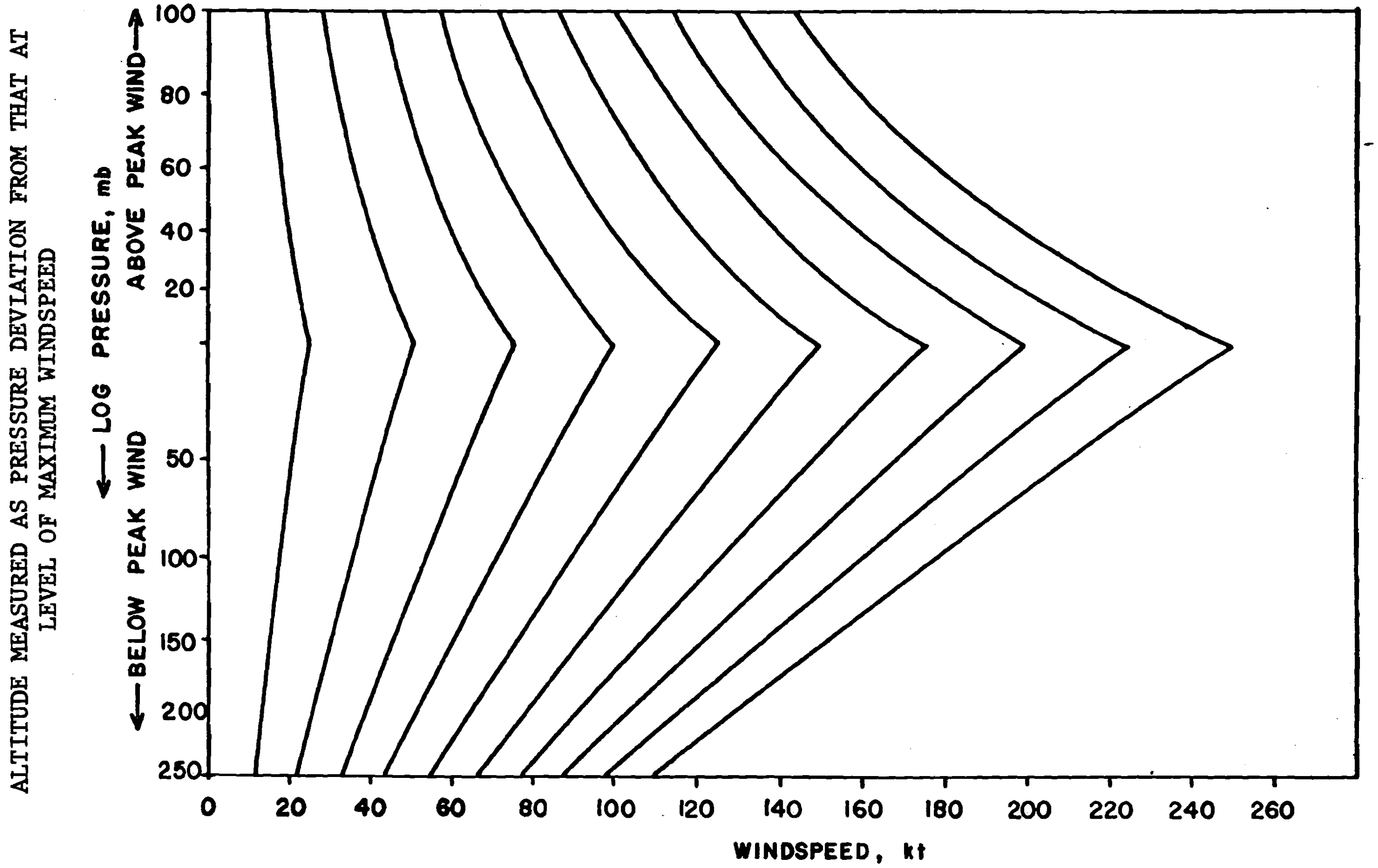


Figure 10-6. Average Profiles of Windspeeds Relative to the Maximum Windspeed (Curves are for maximum speeds at 25-kt intervals) (Ref. 17)

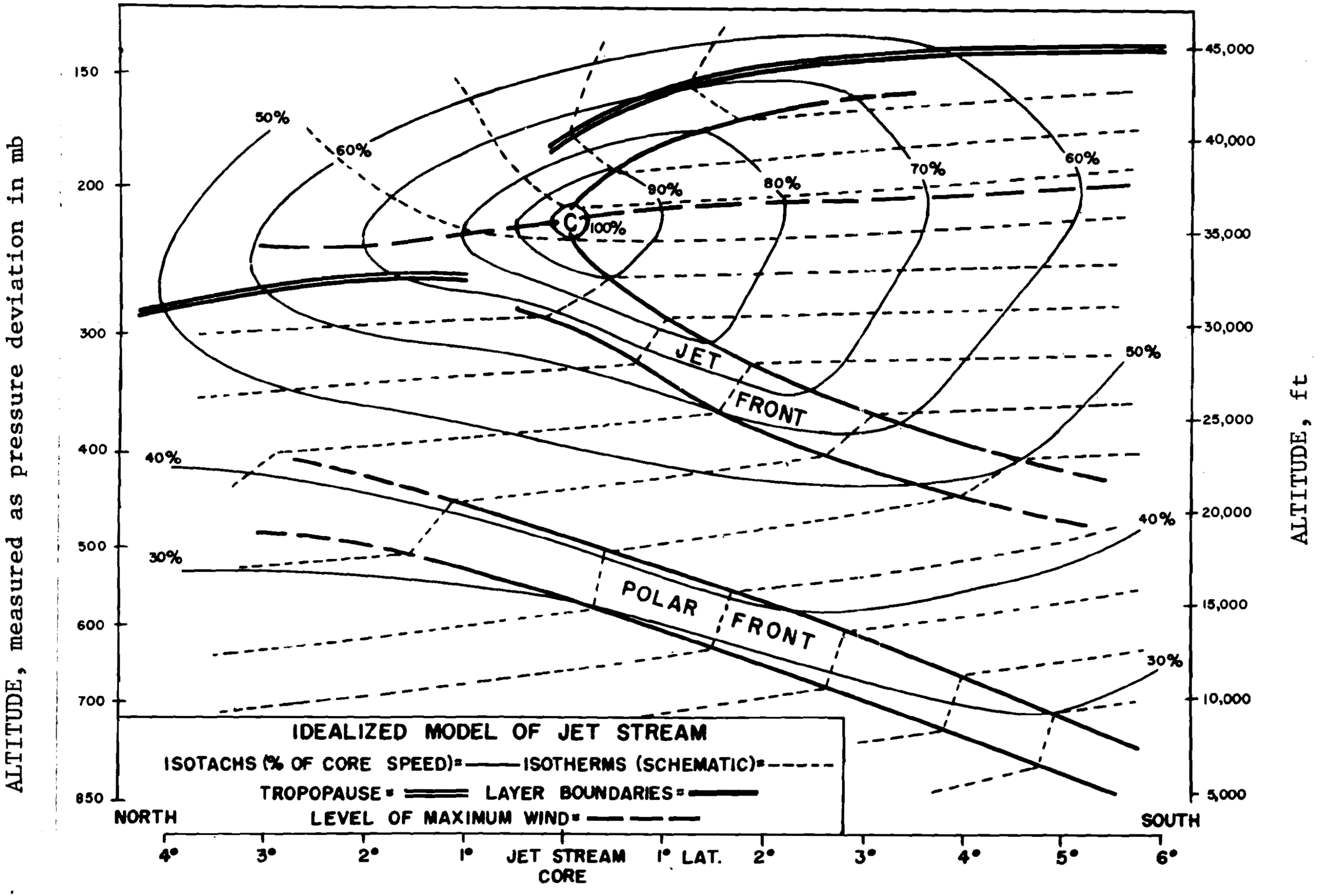


Figure 10-7. Average Structure of the Jet Stream in a Cross Section Perpendicular to the Flow (Ref. 17)

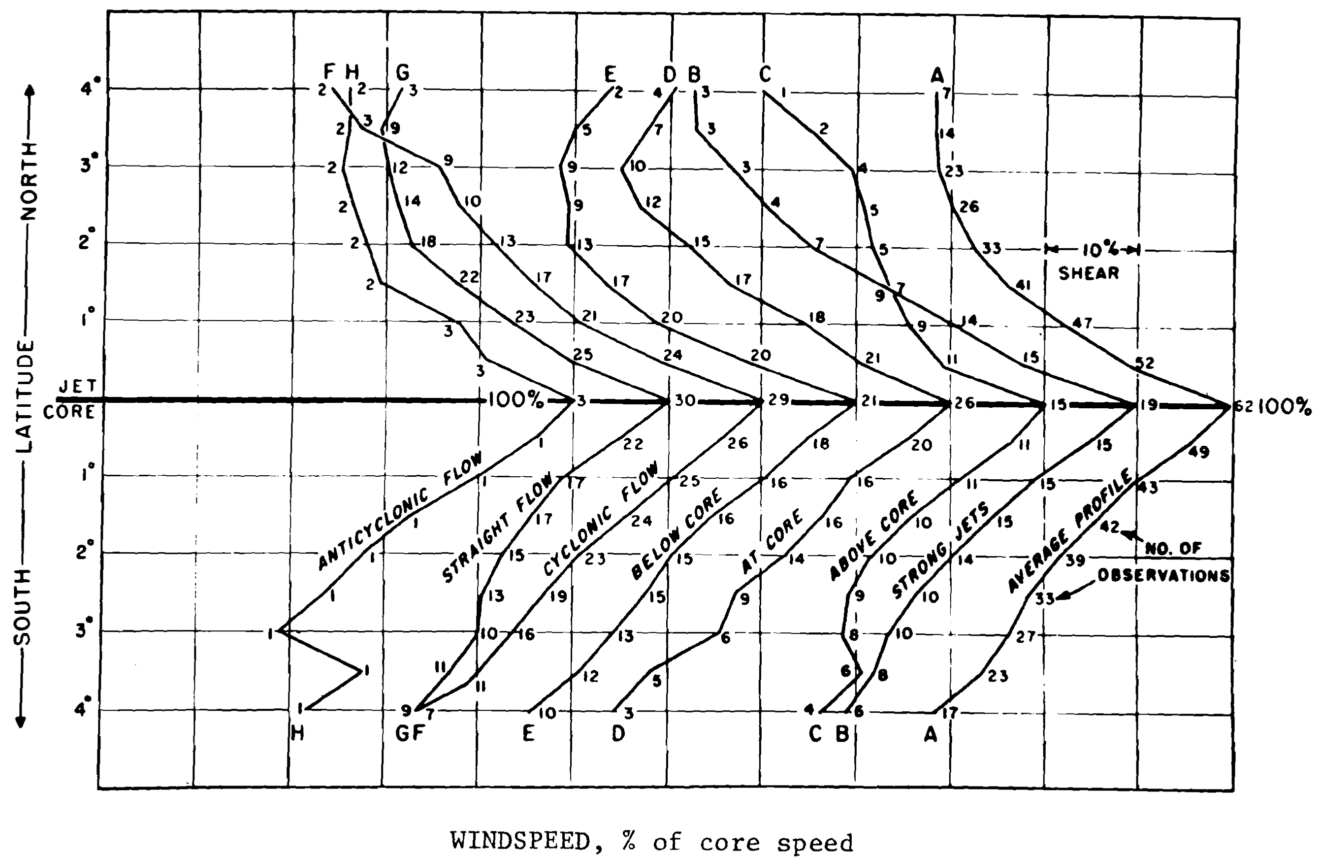


Figure 10-8. Average Windspeed Profiles Across Jet Stream for Various Horizontal Profile Classes (Windspeeds are expressed in percent of the maximum speed with each horizontal division being 10 percent. There is no significance to the spacing between the curves.) (Ref. 17)

10-7 where a change of atmospheric stability and sufficient wind shear occur (Ref. 18).

Multiple jet streams exist in a hemisphere at one time, each with a different maximum windspeed and altitude. The summer hemisphere has a weak westerly jet stream near 50 deg latitude with windspeeds less than 40 m s^{-1} (80 kt). In the Northern Hemisphere summer, over Africa and Asia, an easterly jet stream lies near latitude 10 deg N. and 13 km altitude (Fig. 10-9), which accounts for the increase of tropical high altitude east winds shown in Fig. 10-3. No comparable jet is found in the Southern Hemisphere. In the winter hemisphere, two jet streams, the polar jet and the subtropical jet, prevail, with lesser jets poleward of the polar jet.

The polar jet stream migrates with the surface fronts, ascending in altitude as it moves southward and descending in the north-bound portion. Maximum windspeeds are usually in the southward and northward moving portions exceeding 75 m s^{-1}.

The subtropical jet stream (Fig. 10-10) maintains nearly constant position relative to the earth and is at a higher mean altitude than the polar jet. Maximum winds are found in its northernmost extent, but windspeeds are steadier than in the polar jet stream.

The areas of influence of these two jet streams in the Northern Hemisphere winter are shown in Fig. 10-11. Exceptionally strong winds (greater than 100 m s^{-1}) occur with the confluence of the two jet streams over Japan, the United States, and the Eastern Mediterranean.

10-3.2 HORIZONTAL DISTRIBUTION

For horizontal motion scales larger than 1,000-km wavelength, the wind distributions in the atmosphere are approximately geostrophic; i.e., the wind is parallel to the isobars, proportional to the pressure gradient, and inversely proportional to the Coriolis parameter and the air density. In the Northern Hemisphere, the winds turn in a counterclockwise manner about a low pressure center or area and in a clockwise manner about a high pressure center or area. The inverse is true in the Southern Hemisphere.

The principal high pressure regions near the surface of the earth are located over oceanic areas near 30 deg latitude (the subtropical high pressure cells) and in the polar regions. A low pressure band, the equatorial trough or doldrums, extends about the earth near the Equator and another lies near 60 deg latitude. These pressure features migrate with the seasons, varying in intensity, and are further influenced by the landmasses. The resulting generalized windflow pattern is for light and variable winds to flow in the equatorial trough area, easterly winds are found equatorward of the subtropical high pressure cells, light and variable winds are within that cell, and westerly winds blow poleward of the cell. Poleward of the higher latitude low pressure trough, the winds become easterly again. Near the surface of the earth, the balance of geostrophic forces and frictional forces tends to make the wind blow outward from the high pressure regions and inward toward the low pressure regions.

Superimposed upon the mean pressure distribution are the migrating high and low pressure systems, principally of the midlatitudes. These systems bring the changes of weather, but the sense of the circulation about the centers remains the same.

Aloft, the pressure patterns lose their cellular characteristics and appear in a wavelike pattern of ridges and troughs about each hemisphere. The windspeeds increase with altitude to the tropopause and decrease above it. These transient systems and seasonal changes cause the winds at a position to vary. Tabulations and charts of the mean wind and its variability at various altitudes are found in many publications (Refs. 20-22).

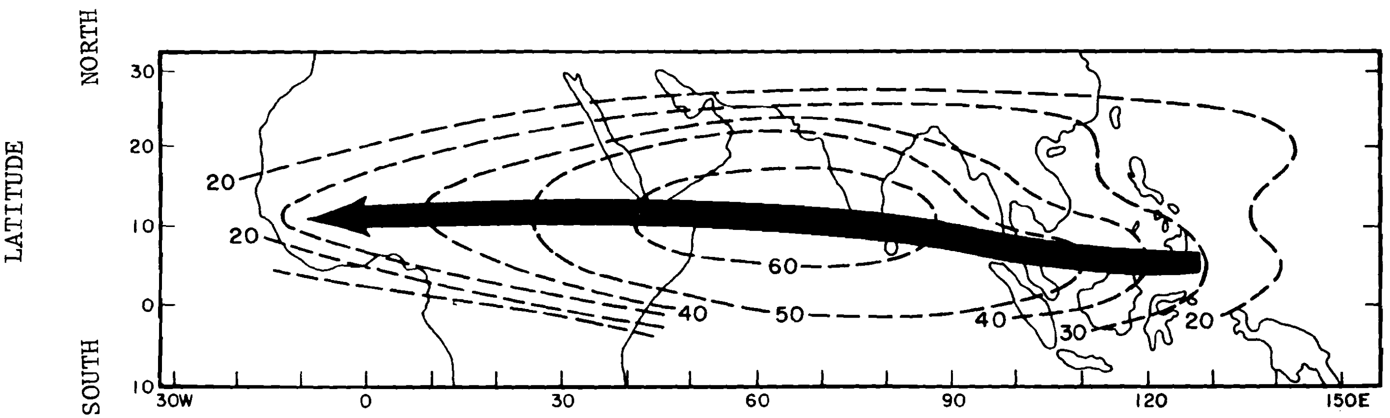


Figure 10-9. The Tropical Easterly Jet Over the Eastern Hemisphere (Illustrated by the resultant windspeeds at 150 mb during July-August) (Ref. 16)

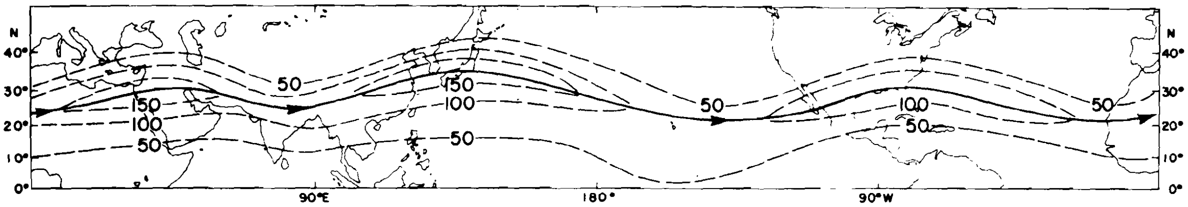


Figure 10-10. Mean Subtropical Jet Stream for Winter 1955-1956 (Solid line shows mean position of jet stream core and dashed lines are isotachs in knots) (Ref. 16)

10-4 WIND SYSTEMS

Windflow patterns that have the most immediate effects on materiel and personnel include cyclones, thunderstorms, tornadoes, sea breezes, urban heat island circulation, and mountain-valley winds. These are discussed in the subparagraphs that follow. Most extreme anomalies in winds are associated with these wind systems rather than the large circulating patterns.

10-4.1 TROPICAL CYCLONES

Cyclone is the term applied to all air circulation patterns that, when viewed from

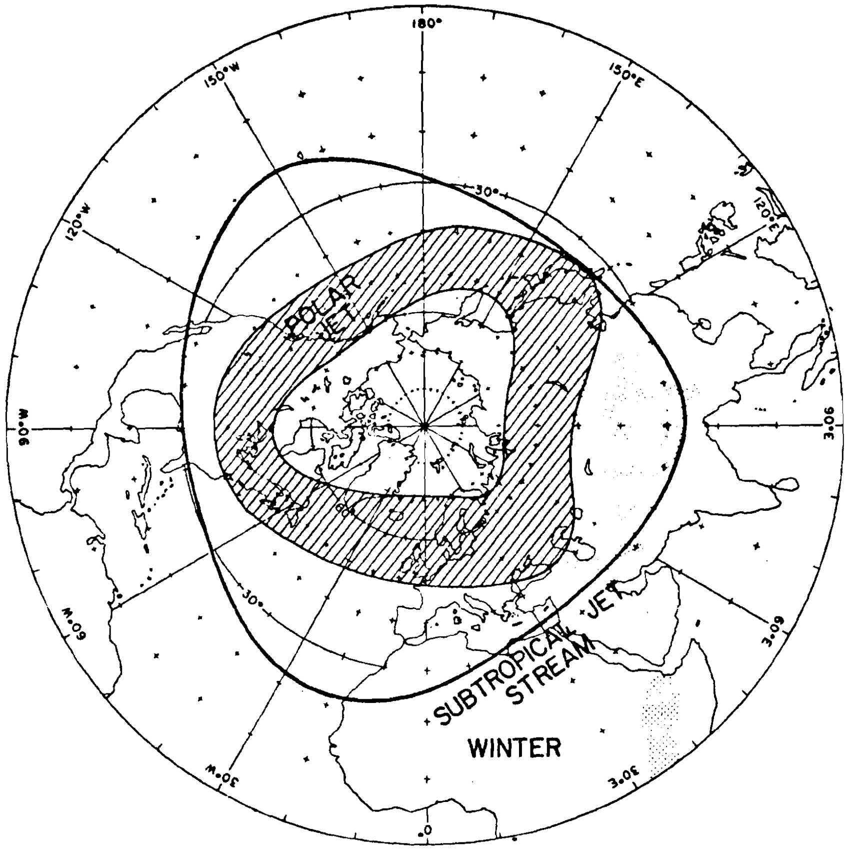


Figure 10-11. Mean Axis of Subtropical Jet Stream During Winter, and Area (Shaded) of Principal Activity of Polar-front Jet Stream (Ref. 19)

above, rotate about the local vertical so that, in the Northern Hemisphere, the circulation is counterclockwise, in the Southern Hemisphere, clockwise. The United States meteorological services define the following three classifications of tropical cyclones (Ref. 16):

(1) *Tropical depression*. A weak cyclone with a definite closed surface circulation, with highest sustained windspeeds, averaged over a 1-min period or longer, of less than 34 kt.

(2) *Tropical storm*. A tropical cyclone with closed isobars and highest sustained windspeed of 34 to 63 kt, inclusive.

(3) *Hurricane or typhoon*. A tropical cyclone with highest sustained windspeeds of 64 kt or more. The term typhoon applies to storms of this type west of 180 deg longitude, and hurricane applies to those east of that longitude.

Other names, some of local origin, are given to these storms and the classification by windspeed varies with other meteorological services.

As the name implies, these wind systems originate in the tropical regions of the world, primarily over oceanic areas, and principally in the summer to early autumn season. The origin and development of the tropical cyclone is a complex phenomenon, but preferred areas of development exhibit sea surface temperatures in excess of 26°C, are more than 300 km from the equator, and have weak vertical wind shear through a large region of the troposphere (Refs. 19,22). Development regions for these storms are shown in Fig. 10-12, and the monthly frequencies of occurrence in each development region are shown in Fig. 10-13. The cold water currents to the west of South America and Africa prevent tropical cyclone formation in the eastern South Pacific and South Atlantic.

Storm tracks are normally from east to west in the beginning stages of development but begin to turn poleward on the western edge of the subtropical high pressure cell. The storms normally move at speeds of 8 to 15 kt, but significant departures are recorded.

Tropical depressions begin as a mass of clouds 200 km or so in diameter. As the storm grows from a depression, it becomes more organized; the low level wind field becomes more circular and develops a small eye with calm winds and low pressure. As the hurricane develops, the eye becomes more pronounced and the central pressure decreases. A wall of giant cumulonimbus clouds surrounds the eye for a distance of 8 to 16 km. Inside the wall, winds rapidly increase to hurricane or greater intensity, persisting from 15 to 80 km farther outward and are accompanied by intense rainfall. The strongest winds are found in the quadrant to the right of the direction of propagation (in the Northern Hemisphere). Windspeeds slowly diminish toward the outer limits of the storm, which may be 400 to 500 km away from the eye as shown in Fig. 10-14. Estimates of the maximum sustained winds to be encountered in a tropical cyclone are possible if the pressure and latitude are known using Fig. 10-15.

The potential for damage to structures must not be underestimated. Windspeed and water combined in a hurricane produce disasterous effects. At a windspeed of 50 m s^{-1} ($\approx$ 100 kt), the wind pressure is sufficient to damage many structures. Windborne debris may injure personnel or damage other structures. The hurricane also causes abnormally high tides and wave action, which may inundate coastal regions with corrosive salt water and undermine the foundations of structures. Salt spray may be carried many miles inland to deposit and corrode exposed material.

When the eye of the storm moves over a location, winds rapidly diminish but in a short time suddenly increase from the opposite direction, creating further stress on structures. As a storm moves inland, the moisture supply

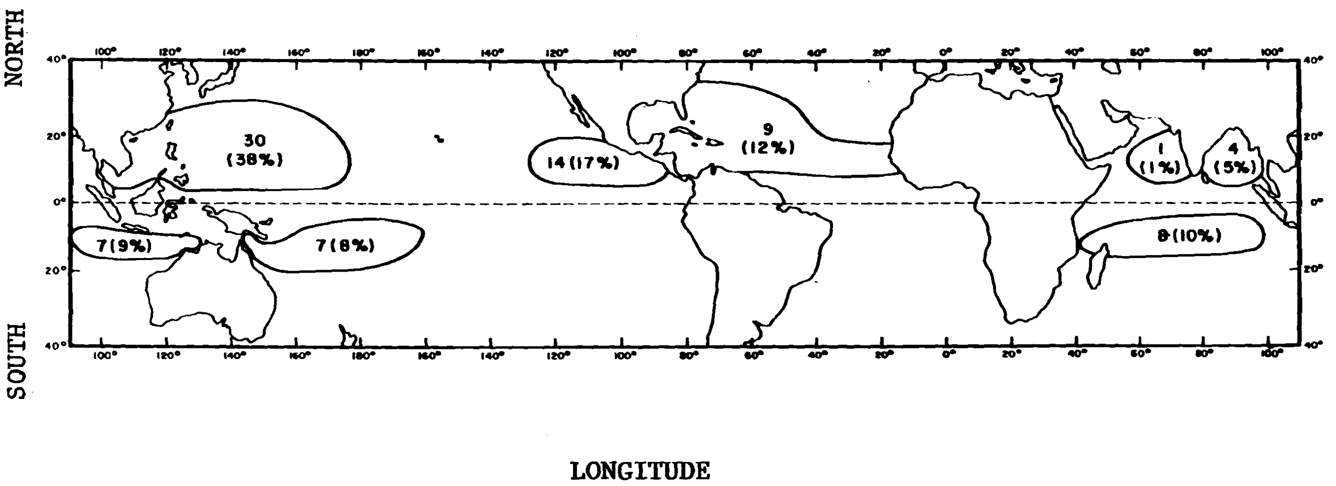


Figure 10-12. Average Annual Number (and Percent of Global Total) of Tropical Cyclones of Tropical-storm or Greater Intensity in Each Development Area (Ref. 16)

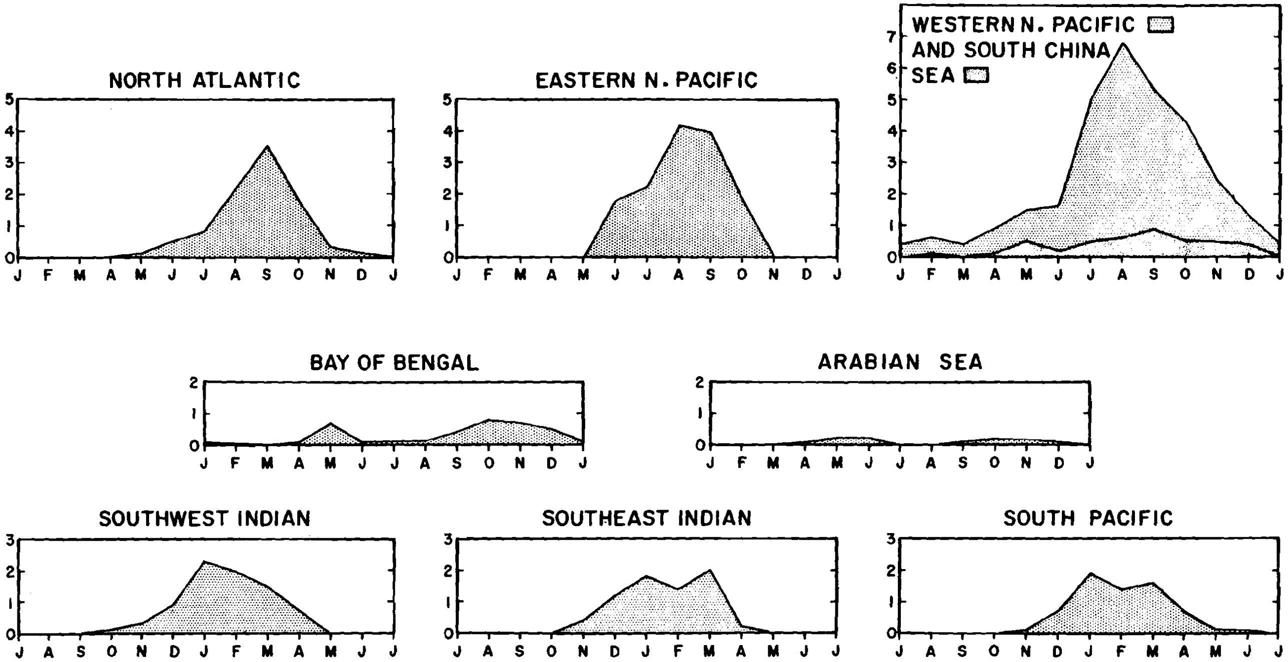


Figure 10-13. Average Monthly Frequency of Tropical Cyclones of Tropical-storm or Greater Intensity in Each Development Area (Abscissas start with January in Northern Hemisphere areas and July in Southern Hemisphere areas) (Ref. 16)

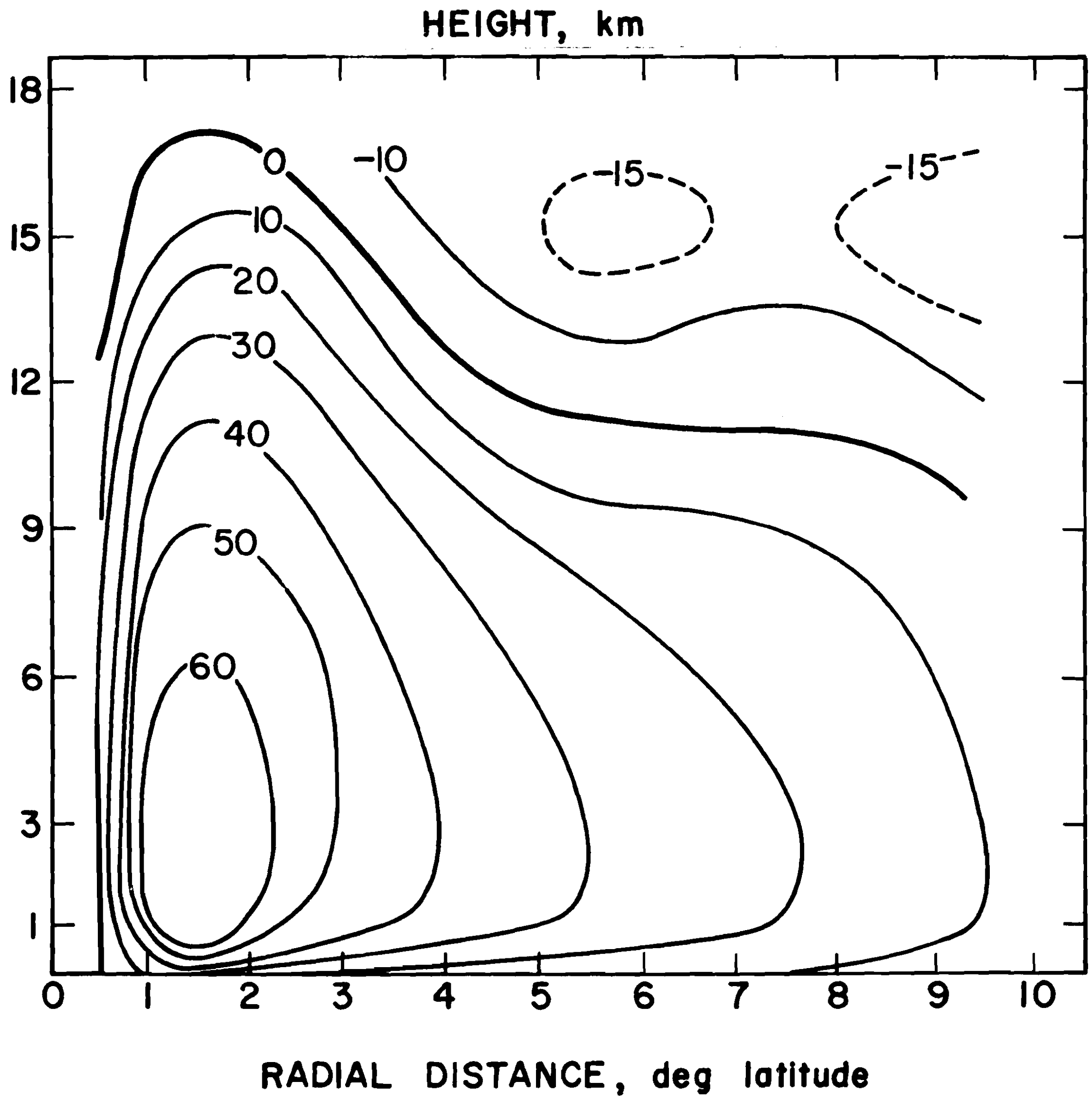


Figure 10-14. Vertical Radial Cross Section of the Mean Tangential Velocity (kt) in 14 Pacific Typhoons (Positive values denote cyclonic and negative values anticyclonic circulation) (Ref. 16)

necessary for its maintenance is decreased and increased friction diminishes the windspeed. However, the precipitation continues with increased possibilities of flooding. Tornadoes have also occurred with hurricane passage. Most of these occur in the right front quadrant of the storm as shown on Fig. 10-16.

10-4.2 THUNDERSTORMS

A thunderstorm is a local storm, invariably produced by a cumulonimbus cloud, always accompanied by lightning and thunder, and usually associated with strong gusts of wind, heavy rain, and sometimes hail (Ref. 1). They occur in all latitudes but more frequently over land than over water. The average annual number of days with thunderstorms is shown in Fig. 10-17.

Thunderstorms may occur as the individual cloud cells grow as a result of very local airmass instability or they may occur in a systematic manner, often in lines as a result of a larger scale instability associated with the

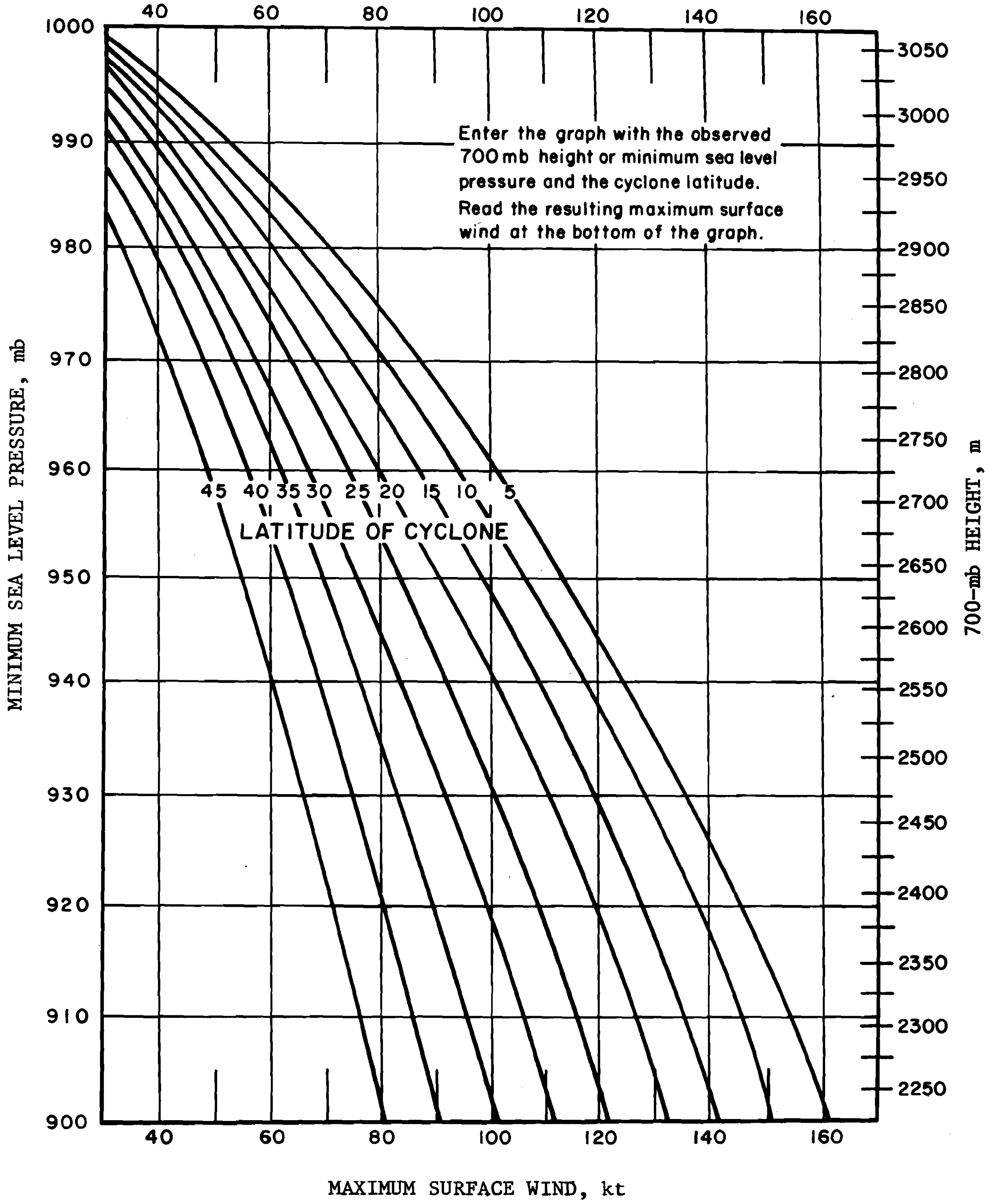


Figure 10-15. Graph for Determining Maximum Sustained Surface-wind Speeds in Tropical Cyclones From Reconnaissance Data at 700 mb or the Minimum Sea Level Pressure in the Storm (Ref. 16)

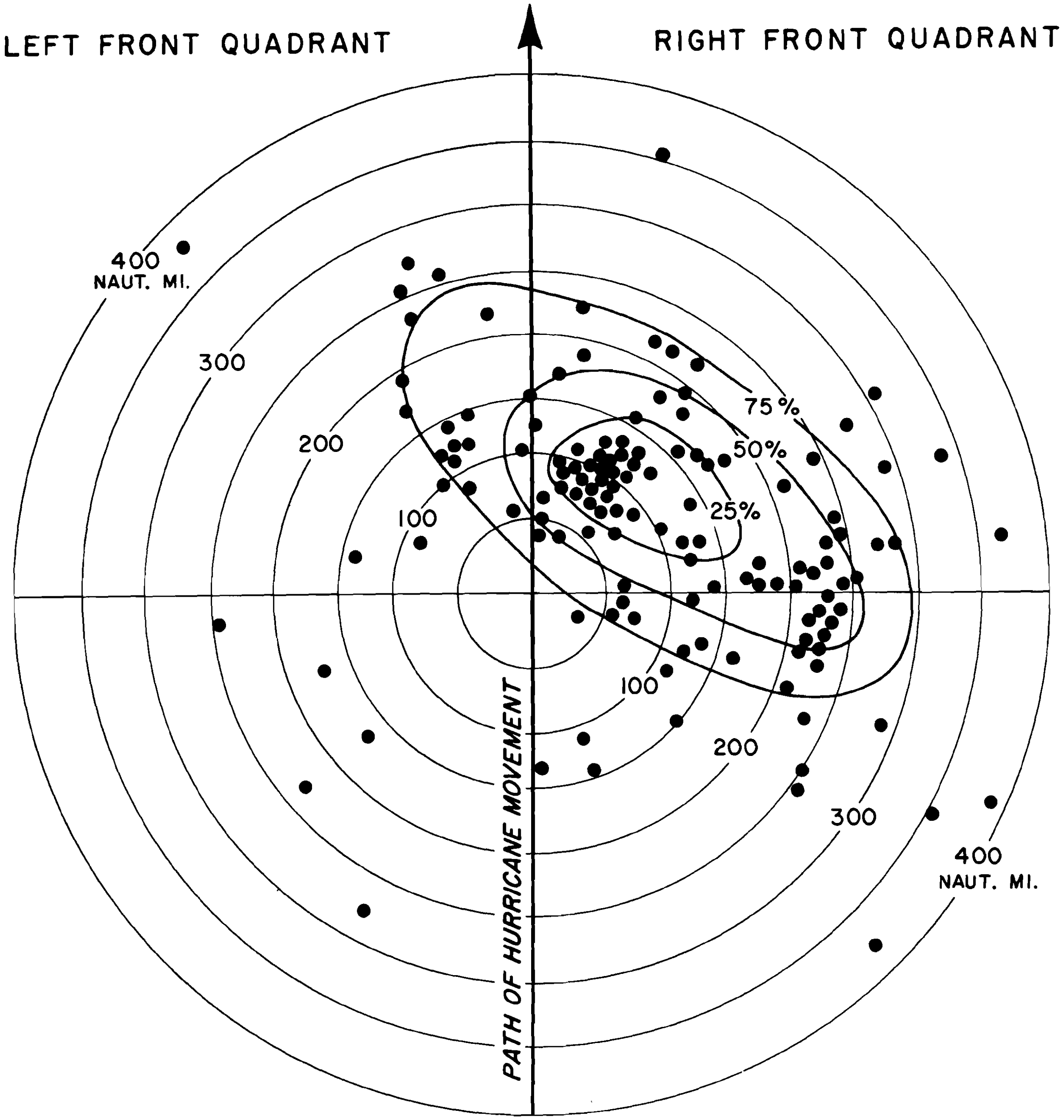


Figure 10-16. Hurricane Tornadoes Over the United States During 1955-1964, Located With Reference to Center and Direction of Movement of the Hurricanes (Isolines are drawn enclosing 25%, 50%, and 75% of the cases) (Ref. 16)

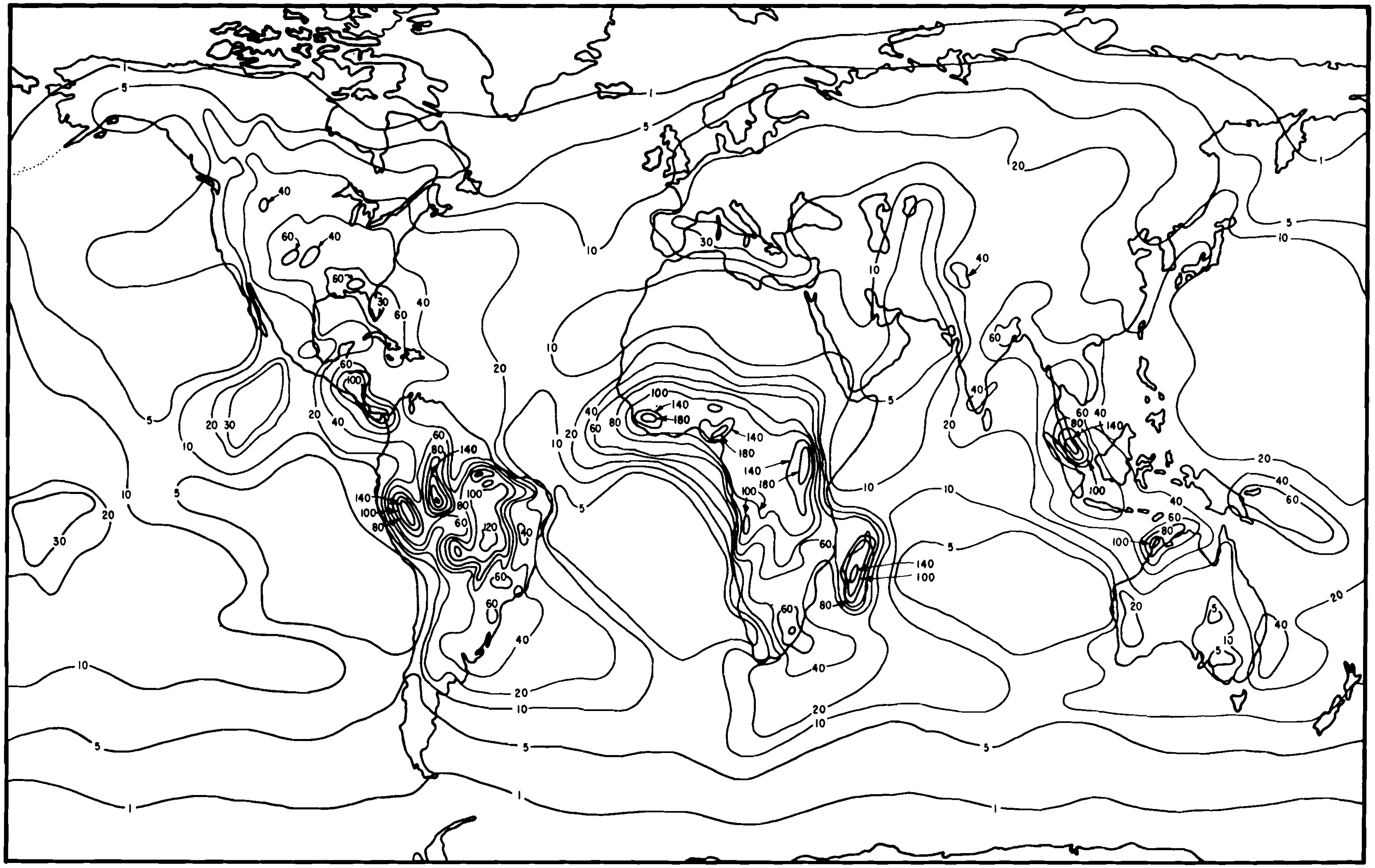


Figure 10-17. Mean Annual Number of Thunderstorm Days Over the Globe (Ref. 16)

boundary between contrasting airmasses. Others may be produced by orographic lifting. The lifetime of an individual thunderstorm-producing cloud is on the order of 1 to 2 hr, although some have been observed for longer periods. The thunderstorm line, or squall line, persists for longer periods through the generation of new cells ahead and to the right rear flank of the line as the line propagates. The individual cell, alone or in the squall line, is approximately 10 mi in diameter and extends vertically to the tropopause or even higher. Observations with radar indicate that some thunderstorm clouds attain a 23-km altitude in the Great Plains of the United States.

The life cycle of the thunderstorm has been divided into three stages (Ref. 23). The cumulus or growth stage is characterized by updrafts (20 m s^{-1} or less) within the cloud, and weak downdrafts about the periphery of the cloud. Liquid water drops are present throughout the cloud, some being supercooled, but surface precipitation is absent.

The mature stage begins with the organization of a downdraft within the cloud, coexisting with the updraft, and the onset of the rain at the ground. The updraft speeds may exceed 30 m s^{-1} and the downdraft, 15 m s^{-1}. This strong shear produces turbulence and vertical acceleration in excess of ± 3 G (Ref. 24). Supercooled waterdrops and ice crystals coexist above the freezing level. The intense precipitation may cause erosion of the skin of an aircraft, while hail, which may be present, can penetrate the skin. A precipitation-cooled downrush of air spreads out along the ground in advance of the approaching storm creating an abrupt shift and increase of surface winds and a rapid pressure rise. A highly turbulent roll cloud or lenslike cloud may accompany the wind shift. The dissipating or anvil stage of the thunderstorm features a weak downdraft through most of the cloud, light rain at the surface, and water, principally in the form of ice crystals, in the cloud. Surface winds diminish and turbulence is minimal.

The air circulation within the mature stage is quite complex. Fig. 10-18 schematically depicts the airflow relative to a mature, severe thunderstorm of the Great Plains. In the figure, the storm is moving from left to right, with cyclonic rotation. Upper level winds (10- to 12-km altitude) from the upper left divide and flow about the cell, with minimal entrainment. Middle level air ($\approx$ 6-km altitude) also divides but is partially entrained as it acquires cyclonic rotation. Precipitation, falling from the updraft, induces a moist downdraft of this air, eventually producing the gust front of the surface. The warm moist low level air ($\approx$ 2-km altitude) flows in from the right front flank, overriding the gust front, ascends through the depth of the cloud, releasing heat to perpetuate the cloud and moisture for precipitation, and exists the cloud after turning in the direction of the upper level winds.

The strong surface winds accompany the outflow of the cumulonimbus (thunderstorm) clouds and raise sand and dust to as much as 1 to 2 km above the earth in an almost "solid" wall. In the area adjacent to the Red Sea, these storms are known as haboobs. The average haboob moves at a speed of 30 kt and lasts for 3 hr, although some have persisted for over 6 hr. During passage the temperature drops and the relative humidity increases. In the Sudan, haboobs occur an average of 24 times per year. Similar phenomena, although not as persistent, occur in the desert Southwest and in the arid plains of the United States (Ref. 26).

10-4.3 TORNADOES

A tornado (sometimes called a cyclone or twister) is the most destructive of all atmospheric wind phenomena. It is characterized by a violent, rapidly turning column of air attached to a cumulonimbus cloud. Windspeeds are estimated as high as 150 m s^{-1}, but direct measurements are lacking. At the ground, the average diameter increases somewhat with altitude. Within the funnel, the atmospheric pressure is estimated to

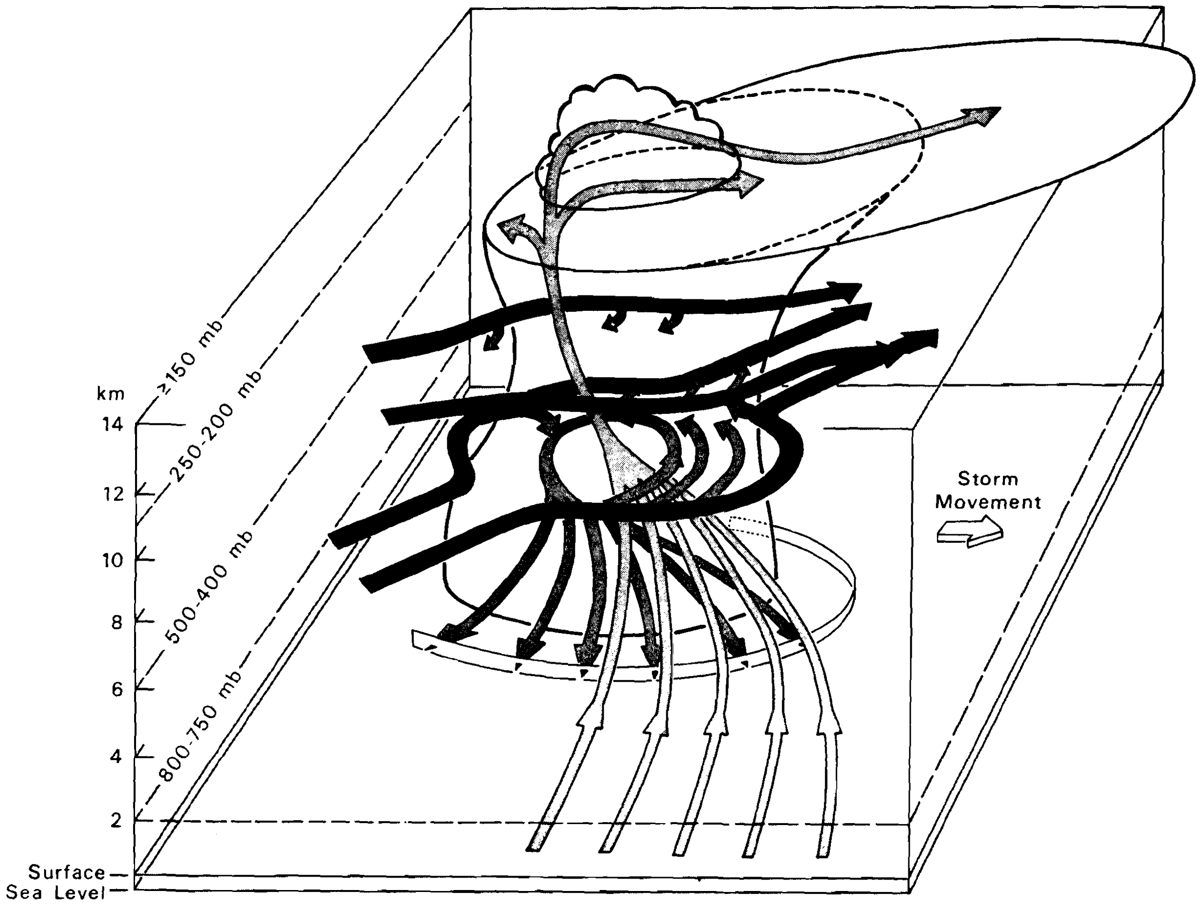
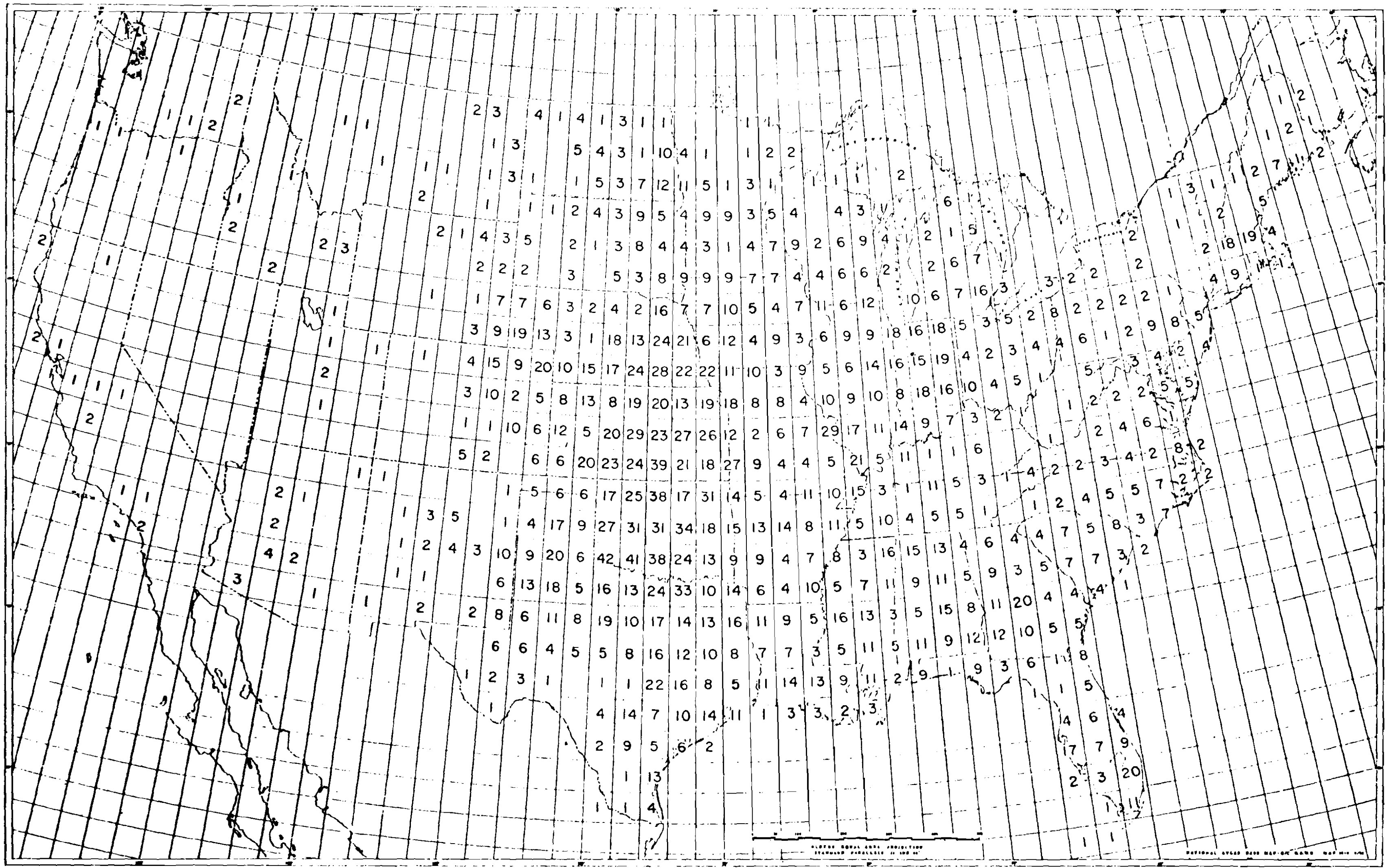


Figure 10-18. Wind Patterns in a Thunderstorm (Ref. 25)

decrease 100 mb (Ref. 1). Dust and debris are entrained in the column, making it visible in the daytime, while accompanying lightning illuminates it at night. Observers describe the approach of a tornado as sounding like an approaching freight train.

Tornadoes may occur in all land areas (even Alaska) and at any time of day or night. Most tornadoes in the United States and Australia occur between 4:00 and 7:00 p.m. Fig. 10-19 shows the distribution of tornadoes in the United States for a 5-yr period. Normally, one tornado is found with a single parent cloud but as many as six have been seen from one parent cloud. The tornado path appears to move with the average speed of the parent cloud (25- to 40-mph average) but tracing a cycloid along the ground. Usually the tornado moves from the south-west. The tornado path length is usually 10 to 40 mi, averaging 13 mi. Table 10-6 summarizes tornado properties. In some instances the tornado seems to skip along the ground, leaving buildings in its path unaffected (Ref. 29). However, Reynolds suggests that the lack of damage may be due to better construction of the skipped buildings, e.g., roofs firmly attached to the frame and the frame to the foundation (Ref. 30).

Tornado damage is caused by both excessive winds and rapid pressure change. The wind creates an excess pressure on the windward wall, a pressure deficit on the leeward wall, and an upward pressure force on the roof of a structure. The rapid ambient pressure change causes an outward force on



BASED ON FIRST POINT OF CONTACT WITH GROUND OF 4,126 TORNADOES.

Figure 10-19. Tornado Occurrence in the United States – 1953-1959 (in 1-deg squares) (Ref. 27)

TABLE 10-6

TORNADO PHYSICAL PARAMETERS* (Ref. 28)

Characteristic	Reported range	Typical range	Weighted average
Maximum rotational velocity, km hr^{-1}	160-800	320-640	480
Maximum updraft velocity, km hr^{-1}	32-320	80-240	160
Core travelling velocity, km hr^{-1}	0-100	32-64	48
Core pressure drop, atm	0.02-0.2	0.05-0.1	0.075
Damage width†, m	15-1500	30-300	180
Lifetime	few minutes to few hours	15-60 min	20 min
Damage range	almost zero to few hundred km	1.6-80 km	16 km
Visual height L below cloud base, m	150-3000	300-1500	900
Number of concurrent tornadoes	one or more (up to six observed)	one	one
Circulation, $m^2 s^{-1}$	$(0.1\text{-}10)\mathrm{X}10^4$	$(1\text{-}5)\mathrm{X}10^4$	$3\mathrm{X}10^5$
Sense of rotation in Northern Hemisphere	usually cyclonic but some anticyclonic	cyclonic	cyclonic
Tilting angle near ground‡	5-40 deg	10-30 deg	15 deg

*This information is collected from many sources and from private communications. N.B. Ward particularly should be mentioned.

†Damage width is estimated roughly about twice the visual core diameter D and is about one-half of the visual funnel diameter.

‡The tornado vortex column is usually tilted to the right for cyclonic rotation and to the left for anticyclonic rotation. At birth, the tilting angle is small and at the dissipating stage the tilting angle becomes large.

TABLE 10-7

PRESSURES (psf) ON EXTERIOR OF HOUSES DURING TORNADIC WINDS (Ref. 30)

	No windows broken		Windward windows broken	
	Windspeed, mph		Windspeed, mph	
Position	150	200	150	200
Leeward wall (outward)	45	85	100	180
Roof (upward)	55	95	135	240
Windward wall (inward)	65	120	65	120

the walls and roof. Assuming that tornado translation speed is 40 mph, that the windspeed increased to its maximum speed in a distance of 1/8 mi, and that the wind pressure is approximately given by

$$P = 0.003\ V_m,\ \mathrm{lb\ ft^{-2}} \qquad (10\text{-}61)$$

where

P = wind pressure, lb $\mathrm{ft^{-2}}$

V_m = maximum windspeed, mph

Reynolds derives Table 10-7. Although those numbers are only approximate, the reason that some buildings appear to explode when struck by a tornado is evident. Flying debris also may cause severe damage to otherwise unaffected material. Tornado safety precautions recommend that some windows in a structure be left open to let the air escape but that occupants stay away from windows. Buildings with large unsupported roof spans should be avoided (Ref. 31).

Thom (Ref. 32) estimates that the probability p of the occurrence of a tornado at a specific point is given by

$$p = \frac{2.8209}{A}\bar{t} \qquad (10\text{-}62)$$

where

$\bar{t}$ = mean number of tornadoes per year in the 1-deg square (Fig. 10-19) where the point is located

A = area of the square, $\mathrm{m^2}$

The mean recurrence interval R for a tornado striking the point is

$$R = 1.0/p \qquad (10\text{-}63)$$

10-4.4 SEA BREEZES

The temperature of a land surface increases and decreases at a faster rate than an adjacent water surface. The temperature differential induces the land-sea breeze circulation illustrated in Fig. 10-20. During the day, the solar radiation increases the land temperature, which causes the air to rise and to be replaced by cooler air from near the water surface. Showers and thunderstorms may develop over 30 to 40 mi inland during the afternoon. At night, the land cools at a faster rate, becoming colder than the water surface so that a land-to-sea circulation is established at the surface.

This circulation is most noticeable on days when the large-scale circulation pattern is weak and the land-sea temperature differences are well defined. Since the windspeeds are not excessive (except perhaps with thunderstorms), the circulation presents no real

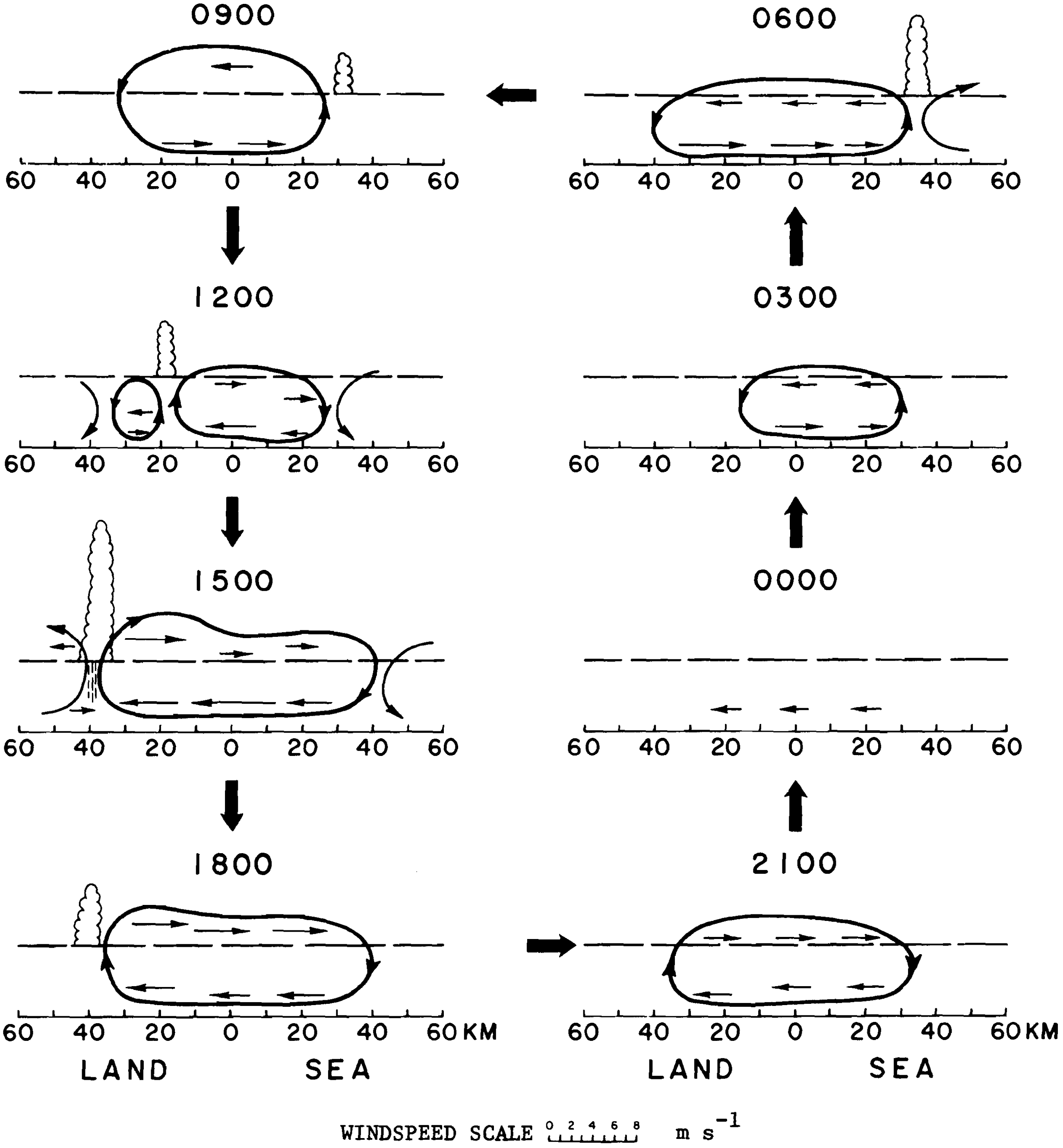


Figure 10-20. Schematic Representation of the Land-Sea Breeze System (Arrow lengths are proportional to windspeed) (Ref. 16)

hazard from high winds. Atmospheric diffusion estimates in coastal areas should consider the effect of this quasi-closed circulation. When large-scale circulations are strong, the land-sea breeze circulation may be unidentifiable.

10-4.5 URBAN HEAT ISLAND

The central portion of a city accumulates heat during the daytime hours. During the night, outlying areas cool more rapidly, establishing a thermal contrast similar to the land-sea contrast. During the night, a toroidal circulation towards the inner city is established along the ground with a return flow toward the suburbs aloft. The circulation reaches its maximum intensity near sunrise, by mid to late morning the urban-suburban temperature difference is relatively small and the circulation becomes quite weak. The effect of the urban heat island circulation to a first approximation is additive to the larger-scale circulation; hence, it is more predominant where the large-scale circulation is weak.

10-4.6 MOUNTAIN WIND SYSTEMS

The introduction of topographic features significantly affects the normal distribution of winds and the type of wind system encountered. Large mountain barriers such as the Himalayan and Rocky Mountains play a large role in determining the position of the semipermanent high altitude airflow pattern. To the lee side of a major mountain chain, surface low pressure systems are induced. In the central plains of the United States, these systems produce many of the major snowstorms.

A more localized phenomenon, known as mountain lee wave, is also produced by the airflow over mountain ridges. The air is forced over the ridge and oscillates as it moves downstream, with a slowly damped amplitude. The trajectory of two constant volume balloons in the lee of the Rocky Mountains is shown in Fig. 10-21. These oscillations extend from near the ground well into the stratosphere and often establish a standing wave pattern to the air trajectories. Aircraft may encounter moderate or severe turbulence at all flight levels in association with these waves. The presence of the standing lee wave is often identified by the lens-shaped clouds of Fig. 10-22 above and leeward of the ridge line. Near the ground a very turbulent cloud may be visible if sufficient moisture is available.

A foehn is a warm, dry wind that occurs on the lee slopes of mountain ranges (Ref. 1). The warmth and dryness are due to the adiabatic compression of the air as it descends from a high altitude. The phenomenon is also known as a chinook on the eastern slope of the Rocky Mountains, as the Santa Ana winds in Southern California, and by various other names, usually of local origin, elsewhere. These winds are often associated with lee waves although the cloud formations are not necessarily present. Surface windspeed is variable depending on topography but may exceed 30 m s^{-1} in gusts. Windspeeds aloft may be even higher and more variable.

The foehn is most frequent in the wintertime. It produces a rapid rise in temperature, 10 to 20 deg C in a period of 15 min or less, causing snow or ice, if present, to melt or evaporate. However, the Santa Ana winds are prevalent in the late summer and early fall. Air from the inland, hot, dry desert areas descends, warming or causing a "heat wave". These winds create a fire hazard by their drying action. Even after the temperature rises cease, the high winds may persist for days.

Windspeeds in the Rocky Mountains of Colorado and Wyoming have frequently exceeded 60 mph causing excessive damage. The anemometer trace of Fig. 10-23 shows windspeed varying from 10 to 120 mph in less than a minute.

As air moves at an angle to the axis of a system of ridges and valleys, the flow may

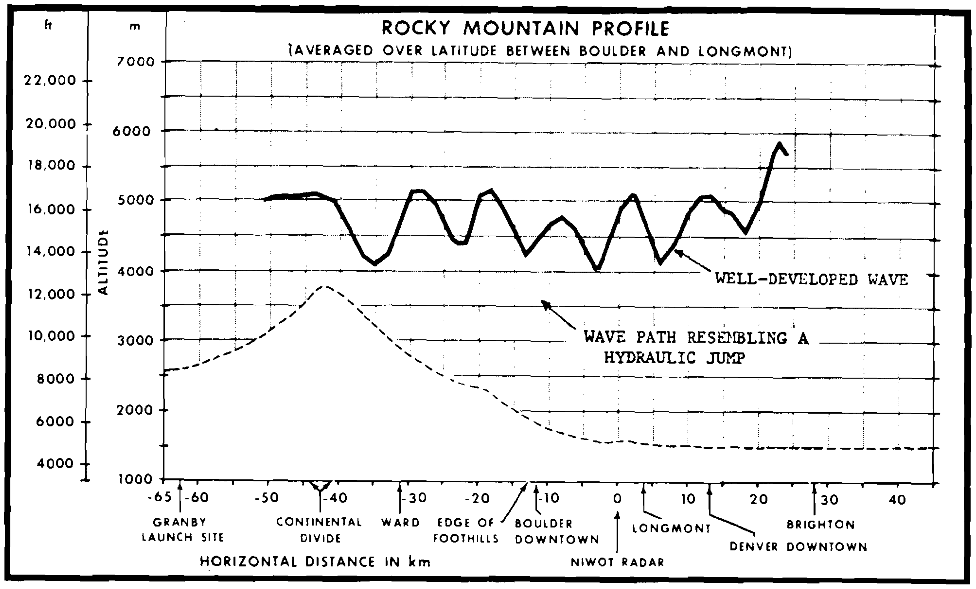


Figure 10-21. Balloon Tracings Showing the Effect of Mountains on Overland Winds (Ref. 33)

become separated into two parts, one continuing to flow over the ridge, another channeled along the valley (Fig. 10-24). The large-scale windflow interpreted from the pressure distribution even with allowance for usual frictional effects will not describe this type of flow.

Especially at nighttime, cool air, being more dense, descends into the valleys, draining from the ridges, establishing a cool pool of air, which travels down the valley, i.e., toward lower elevation and a temperature inversion – cool air underlying warmer air – in the valley. The windspeed encountered in this situation depends upon the elevation change, the drainage area, the inversion depth, and the cross-sectional area across the valley.

The depth of the cool air increases during the night. In some instances such as shown in Fig. 10-24(B), the depth of the cool air may reach the altitude of a pass, permitting the air to spill out of the valley. If the pass is narrow, high windspeed may occur in the pass.

With the onset of solar heating in the valley, the cool pool of air is warmed, and eventually, the inversion is dissipated. One side of the valley, being inclined to the horizontal, receives more direct solar heating than a level surface. The air adjacent to the sunlit side is warmed more rapidly and begins to rise. At higher elevations up the valley, the heating rate is even greater and an up-valley circulation is induced.

Along the coasts of ice-covered plateaus, such as Greenland and Antarctica, drainage winds through fjords may exceed 90 kt during cyclonic storms (Ref. 36). These strong winds are principally found where interior regions are drained or channeled through a narrow valley.

10-4.7 ATMOSPHERIC DISPERSION

When material is injected into the atmosphere and becomes airborne, it is transported and diffused through a larger volume, diluting the initial concentration. If the material can produce deleterious effects, it is important to determine its concentration that would be received at one or more points downwind from its source.

Figure 10-22. Linear Arrays of Lenslike Clouds, Often Layered or Stratified, Marking the Crests of Standing Waves Produced by Mountains (Ref. 34)

Among the many factors that influence the measured or calculated concentration at a given point, are:

(1) *Source characteristics*. Duration, configuration (point, line, area, volume), elevation, and the amount of material released

(2) *Atmospheric characteristics*. Windspeed and direction, amount of turbulence, and temperature distribution with altitude

(3) *Type of material*. Conservative or nonconservative properties, and interaction with other materials in the air

(4) *Removal processes*. Washout by precipitation, decay enroute, and gravitational settling.

Of these four factors, the atmospheric characteristics are among the most difficult to quantify, and they have the greatest effect upon the concentration of material received at a point, once the source characteristics are known. The horizontal wind transports the material and, in conjunction with the wind direction, determines the path taken. Atmospheric turbulence diffuses the material vertically and horizontally perpendicular to the path taken. The methods of describing the diffusion coincide with those that attempt to describe the frictional forces in the atmosphere: statistical theories of turbulence, the similarity theory, and the gradient transfer theories. Each of these methods is surveyed in Refs. 16 and 37 among many others.

The most frequently used model for computing the concentration occurring at a point for a given source is the Gaussian diffusion model, which arises from the eddy transfer method. A major assumption is that the material is transported with the mean wind and that in any cross section across the plume or puff, the concentration is distributed as the normal curve of error or Gaussian distribution, e.g., as

$$\exp\left[-\frac{r^2}{2\sigma_r^2}\right]$$

where

r = distance from the maximum concentration, m

σ_r = standard deviation measured in the r-direction, m

The standard deviations in the x-, y-, and z-directions are independent of each other but are dependent upon the time elapsed since the material was released into the atmosphere t, the averaging period T used to determine them, and upon the stability of the atmosphere.

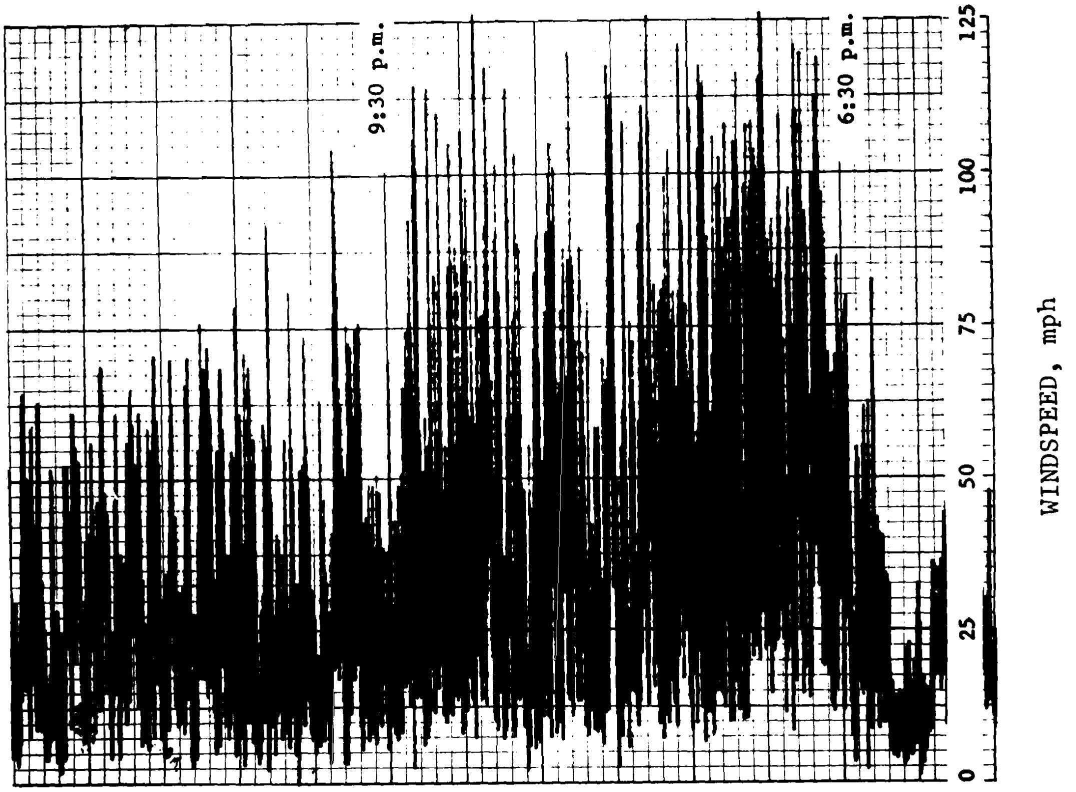


Figure 10-23. Anemometer Trace of the Foehn Wind in Boulder, Colo. (7 Jan 69 with instrument on roof of National Center for Atmospheric Research) (Ref. 35)

For an instantaneous point source of Q grams released at the origin of a coordinate system at time zero, the concentration χ (g m^{-3}) observed at a point x, y, z after the cloud has traveled at a speed $\bar{u}$ for a time t, diffusing in all directions independently, is given by (Ref. 12):

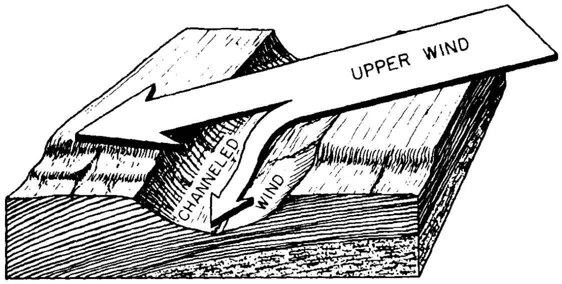
$$\chi(x,y,z,t) = \frac{Q}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} \times \exp\left\{-\left[\frac{(x-\bar{u}t)^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2}\right]\right\} \qquad (10\text{-}64)$$

Here, σ_x, σ_y, and σ_z are instantaneous values at the time of measurement. By superimposing the effect of one instantaneous release after another, so that the source becomes a continuous point source, emitting Q' grams per unit time, and by neglecting the diffusion in the line of travel (e.g., σ_x), the time average concentration $\bar{\chi}$ at x, y, z is given by (Ref. 12):

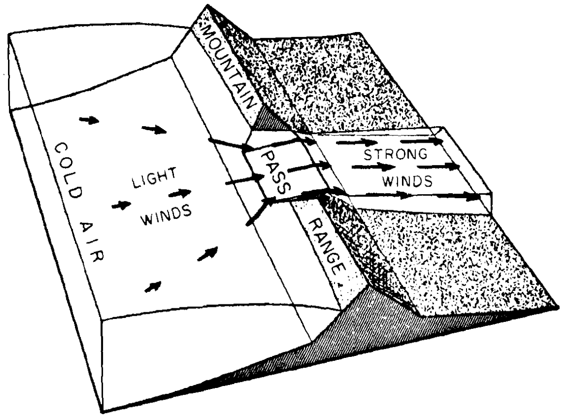
$$\bar{\chi}(x,y,z) = \frac{Q'}{2\pi\sigma_y\sigma_z\bar{u}} \times \exp\left[-\left\{\frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2}\right\}\right] \qquad (10\text{-}65)$$

In this equation, σ_y and σ_z become dependent upon the distance x from the origin rather than the time that the cloud passed over the point, while also remaining dependent upon the atmospheric stability. The dependence of σ_y and σ_z upon x depends upon the averaging time as illustrated in Fig. 10-25.

Eq. 10-65 holds for large averaging times and for homogeneous, nonvarying conditions.



(A) Channeling of the wind by a valley



(B) The effect of a mountain pass

Figure 10-24. Distortions of Windflow by Topographic Obstacles (Ref. 16)

These conditions are rarely met in the real atmosphere, but diffusion experiments (Chap. 4, Ref. 12) have shown that Eq. 10-65 is applicable in many cases, especially over flat terrain. In nonhomogeneous terrain with local wind circulations and varying atmospheric stability regions, the equation is likely to give erroneous estimates.

From the measurements of numerous field studies, it is possible to estimate the dependence of σ_y and σ_z in terms of distance downwind of the source and in terms of the atmospheric stability or prevailing weather conditions. Six categories of stability (A through F) have been suggested by Pasquill (Ref. 38). Values of σ_y and σ_z appropriate to each category are shown in Figs. 10-26 and 10-27, respectively. Table 10-8 defines the categories and relates them to the prevailing sky conditions and windspeed. The stability categories are also related to σ_θ, the standard deviation of the horizontal wind direction, as shown in Table 10-9. Markee (Ref. 39) suggests that σ_θ is related to the wind direction range R, by

$$\sigma_\theta = R/6.0 \qquad (10\text{-}66)$$

Refs. 9, 12, and 40 give formulas for estimating concentrations and dosages for differing source conditions based upon the Gaussian model.

10-5 WIND MEASUREMENTS

Wind is measured by its effects. The motion of trees or flags, the drift of smoke plumes, balloon trajectories, and the angle at which precipitation falls are only a few of the empirical techniques for estimating the windspeed and/or wind direction. Instruments used to measure the windspeed near the ground are called anemometers while wind vanes are used to indicate the wind direction. Aloft, since anemometers are impractical, the drift of balloons or other objects with the wind are measured to determine the wind velocities.

10-5.1 WINDSPEED*

Because the measurement of windspeed is of prime interest to both meteorologists and others, a large variety of anemometers have been developed. These types are listed in Table 10-10 and are described in the subparagraphs that follow.

10-5.1.1 ROTATION ANEMOMETERS

The most commonly used windspeed measurement system is the cup anemometer revolving about a vertical shaft. High-quality

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*This paragraph is adapted from a similar discussion of anemometers in *Meteorology and Atomic Energy 1968* (Ref. 12).

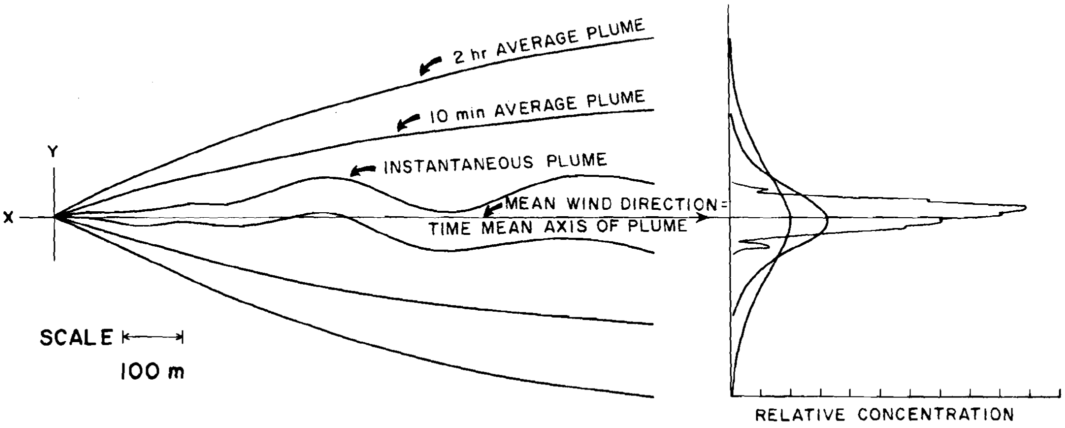


Figure 10-25. Schematic Diagram of a Smoke Plume (Instantaneous and Time-averaged) With the Projected Distributions of the Concentration for Each of the Plume Types (Ref. 12)

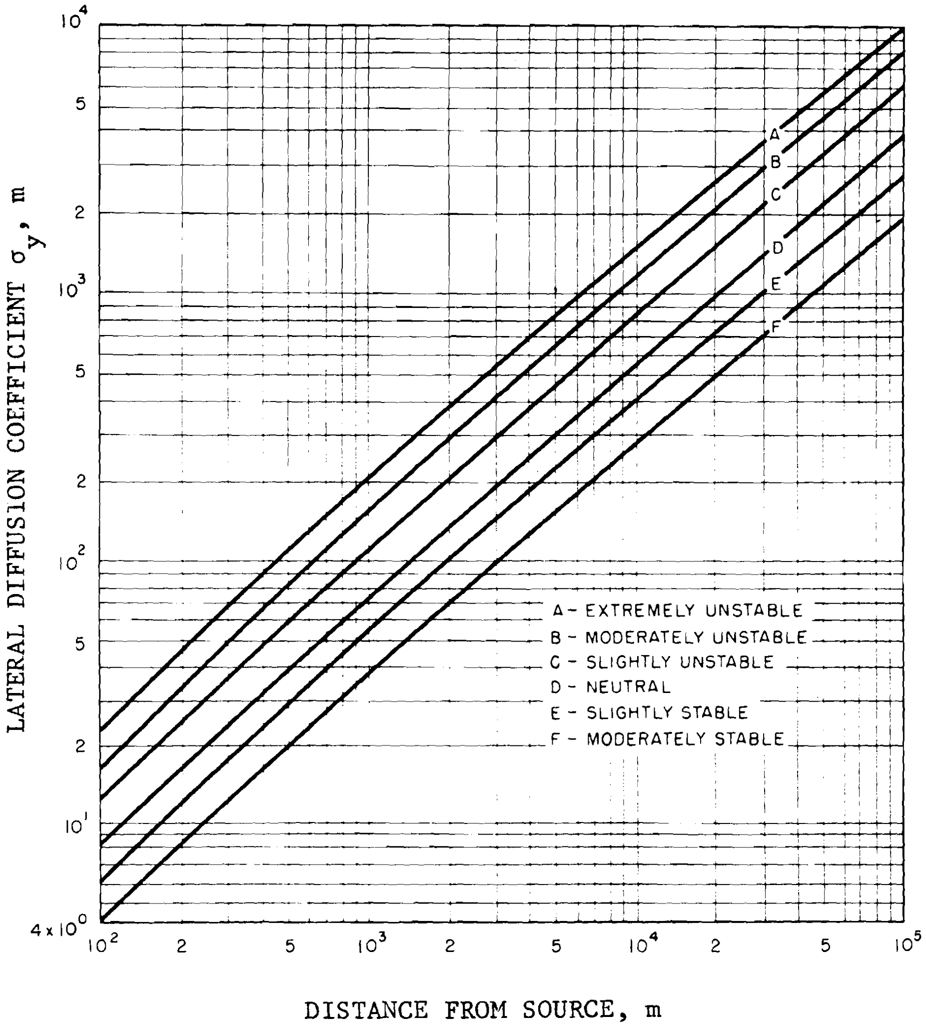


Figure 10-26. Lateral Diffusion σ_y vs Downwind Distance From Source for Pasquill's Turbulence Types (Ref. 12)

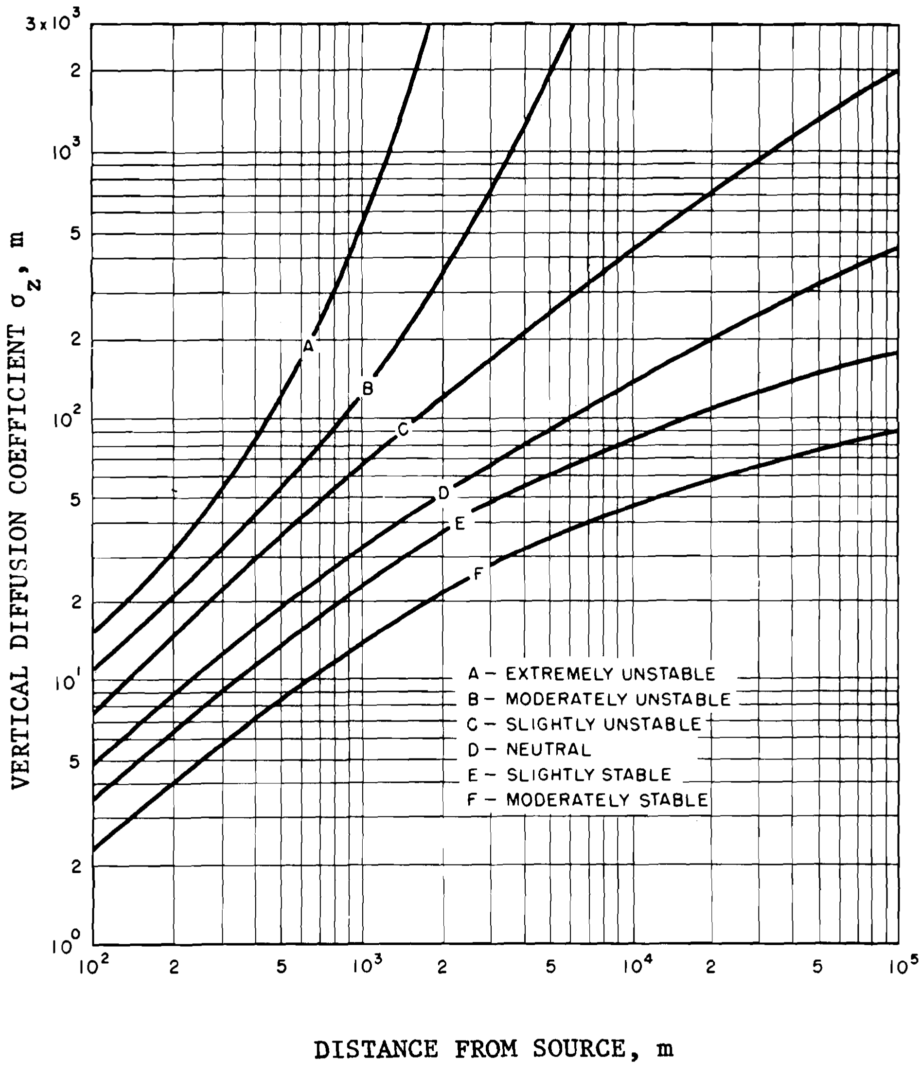


Figure 10-27. Vertical Diffusion σ_z vs Downwind Distance From Source for Pasquill's Turbulence Types (Ref. 12)

instruments are durable and accurate, and give years of reliable service with little maintenance. Cup anemometers usually employ a cup wheel with a diameter of 38 to 45 cm measured at the center of the cups, and utilize conical cups about 10 cm in diameter with beaded edges. At windspeeds between 1 and 30 m s^{-1}, the rate of rotation of the cups is linearly dependent on windspeed.

For accurate wind measurements at low speeds and for more sensitivity (more rapid response to fluctuations in windspeed), small three-cup anemometers have been developed. These have a cup-wheel diameter of about 15 cm and a cup diameter of 5 cm. The cups are made of either plastic or thin aluminum. The moment of inertia of such anemometers is appreciably smaller than that of the standard type. These instruments minimize friction losses with miniature ball bearings and usually employ a light beam-photocell arrangement for counting the revolutions. Several standard lightweight cup anemometers are shown in Fig. 10-28.

During steady rotation of a cup anemometer, the speed of the wind is from two to

TABLE 10-8

RELATION OF TURBULENCE TYPES TO WEATHER CONDITIONS

Surface windspeed, m s^{-1}	Daytime insolation			Nighttime conditions	
	Strong	Moderate	Slight	Thin overcast or $\geq$ 4/8 cloudiness*	$\leq$ 3/8 cloudiness
< 2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
> 6	C	D	D	D	D

A Extremely unstable conditions
B Moderately unstable conditions
C Slightly unstable conditions
D Neutral conditions (applicable to heavy overcast, day or night)
E Slightly stable conditions
F Moderately stable conditions

*The degree of cloudiness is defined as the fraction of the sky above the local apparent horizon that is covered with clouds.

TABLE 10-9

PASQUILL STABILITY CATEGORIES (Ref. 12)

Category	Description	Standard deviation of the horizontal wind direction σ_θ, deg
A	Extremely unstable	25.0
B	Moderately unstable	20.0
C	Slightly unstable	15.0
D	Neutral	10.0
E	Slightly stable	5.0
F	Moderately stable	2.5

TABLE 10-10

ANEMOMETER TYPES (Ref. 41)

Type	Variations
Rotation	Cup Propeller or windmill
Thermal	Hot-wire Heated thermometer Heated thermocouple
Bridled cup	
Pressure tube	
Pressure plate	Free swinging Constrained
Sonic	

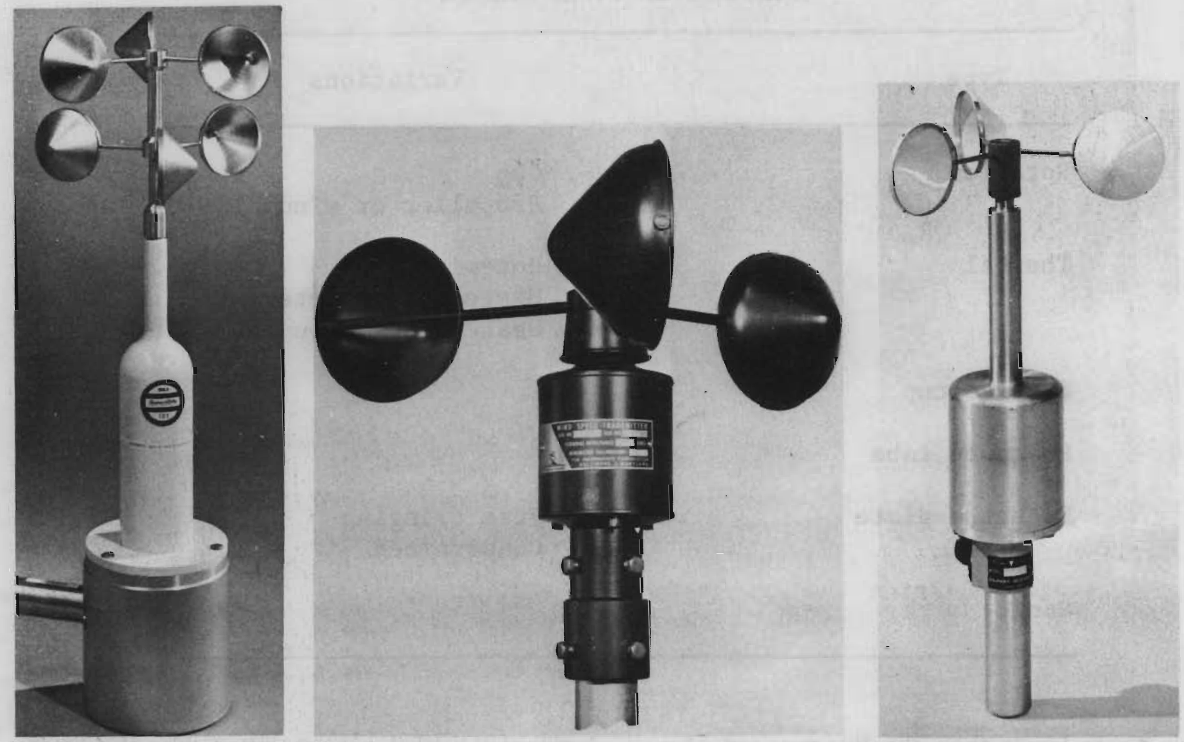
three times larger than the linear speed of a point on the center of a cup as determined by such factors as the arm length, cup diameter, and moment of inertia of the system.

The second most commonly used windspeed measuring system is that in which a propeller or windmill revolves about a pivoted horizontal shaft that is oriented by vanes into the wind. Several propeller-type anemometers are shown in Fig. 10-29 with the more usual type shown in Fig. 10-29(A). Between speeds of 1 and 45 m s^{-1}, the rate of rotation of the propeller in these anemometers is linearly proportional to the windspeed. An example of a light, responsive propeller-type anemometer is shown in Fig. 10-29(B), and a sensor for measuring the vertical component of the wind is shown in Fig. 10-29(C). This vertical velocity sensor consists of a three-blade propeller mounted on a vertical shaft and also indicates whether the wind is directed upward or downward.

The transducer that converts anemometer rotational speed to a recordable electrical signal is called a transmitter. For this, many anemometers use a small permanent-field direct-current generator that is connected electrically to a recorder. The output of the generator is linearly proportional to the turning rate of the cup wheel or propeller and, therefore, windspeed. Although these transmitters have low friction, it is enough to cause the starting speed to lie in the range of 1 to 2 m s^{-1}. A continuous trace of windspeed is obtained.

Some anemometers use alternating-current generators instead of direct-current generators to avoid using the brushes and commutator. This reduces friction and lessens maintenance requirements.

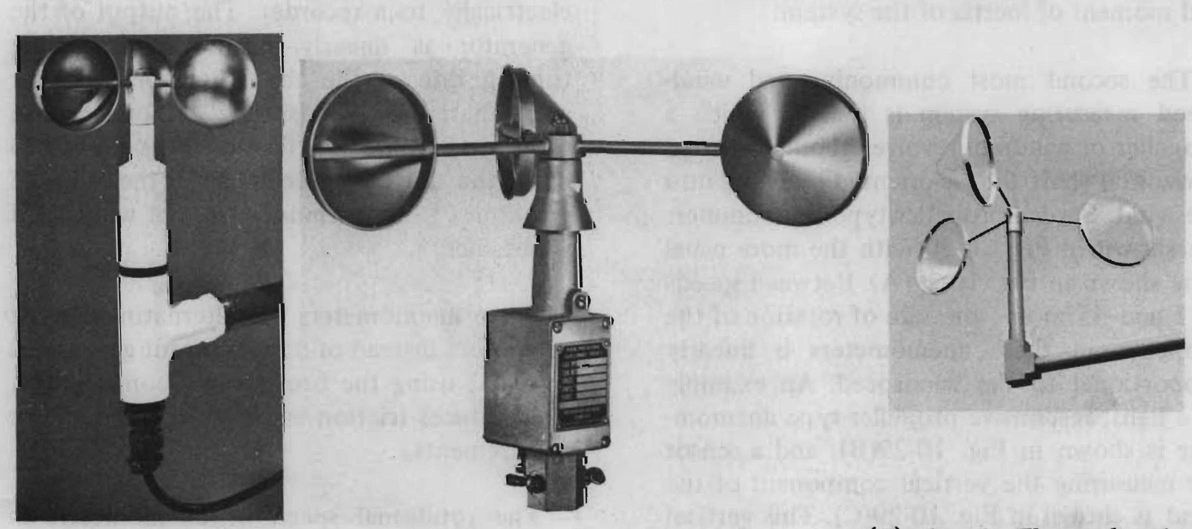
The rotational speed of anemometers is also obtained by use of switches or relays. Three general types of transmitters are in this category: mechanical contacts similar to telephone relays, light interrupters, and magnet-actuated switches. In instruments of the mechanical-contact type, a rotating shaft is coupled through one or more gears to an



(A) Beckman and Whitley, Inc.

(B) Belfort Instrument Co.

(C) Climet Instruments, Inc.

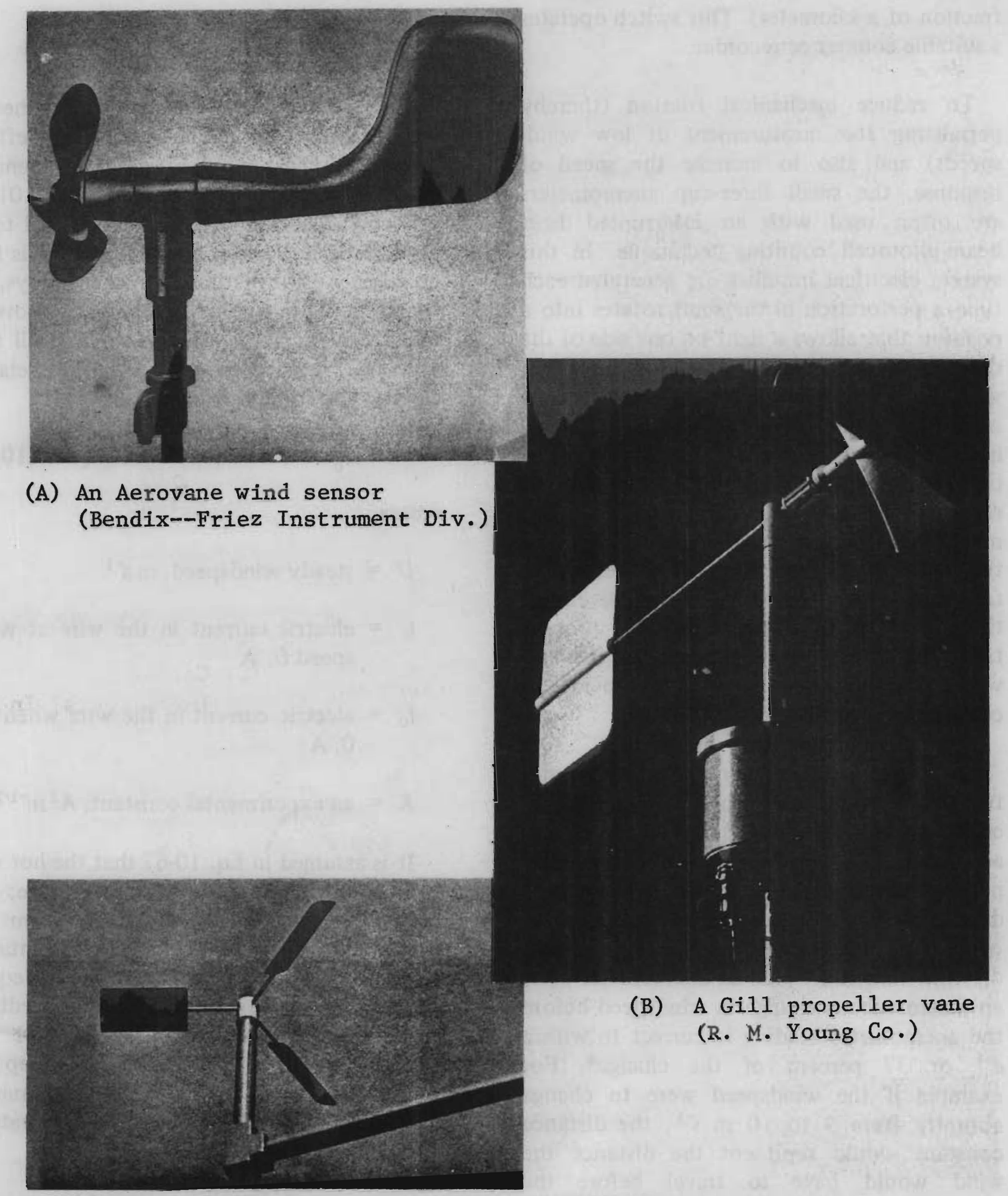


(D) R. M. Young Co.

(E) Belfort Instrument Co.

(F) C. W. Thornthwaite Assoc.

Figure 10-28. Cup-type Anemometers (Ref. 12)



(A) An Aerovane wind sensor (Bendix--Friez Instrument Div.)

(B) A Gill propeller vane (R. M. Young Co.)

(C) A vertical velocity propeller sensor (C. W. Thornthwaite Assoc.)

Figure 10-29. Propeller-type Wind Sensors (Ref. 12) eccentric cam that opens and closes a mechanical switch after the passage of a predetermined amount of wind (e.g., a fraction of a kilometer). This switch operates a suitable counter or recorder.

To reduce mechanical friction (thereby permitting the measurement of low windspeeds) and also to increase the speed of response, the small three-cup anemometers are often used with an interrupted light beam-photocell counting technique. In this system electrical impulses are generated each time a perforation in the shaft rotates into a position that allows a light on one side of the shaft to shine on a photocell on the other side. The shaft can be drilled with one or many such holes. When only a few electrical impulses are generated for each rotation of the shaft-cup wheel assembly, counters or recorders are usually used for totaling. When many pulses originate with each revolution of the shaft, i.e., six or more, it is convenient to feed them to a frequency-measuring circuit that gives a voltage output directly proportional to the speed of rotation of the cup wheel. Recording this voltage provides a continuous record of the windspeed.

Owing to the moment of inertia and friction, a rotation anemometer has appreciable lag; i.e., variations in windspeed are attenuated for frequencies greater than 1 Hz per several seconds. Lag characteristics can be described by a length called the distance constant. The distance constant is the length of wind that must pass an anemometer after an instantaneous change in windspeed before the anemometer reading is correct to within e^{-1} or 37 percent of the change*. For example if the windspeed were to change abruptly from 9 to 10 m s^{-1}, the distance constant would represent the distance the wind would have to travel before the anemometer indicates a value of 9.63 m s^{-1}, i.e., 63 percent of the change. For any anemometer the distance constant is independent of the windspeed. Values of the distance constant range from about 0.7 to 8.0 m for commercially available anemometers (Table 10-11).

10-5.1.2 THERMAL ANEMOMETERS

The speed of air moving over a fine heated wire can be measured by the cooling effects produced. The hot wire used as an anemometer may range from 0.003 to about 0.01 cm in diameter and may be from about 0.1 to 10 cm in length. Various types of materials may be used, e.g., platinum, nickel alloys, or tungsten. The wire may be heated over a range of from several hundred to well over 1,000°C. An approximate equation relating electric current and wind velocity is

$$i^2 = i_0^2 + KU^{1/2}, \text{A} \qquad (10\text{-}67)$$

where

U = steady windspeed, m s^{-1}

i = electric current in the wire at windspeed U, A

i_0 = electric current in the wire when U = 0, A

K = an experimental constant, $\text{A}^2\,\text{m}^{-1/2}\,\text{s}^{1/2}$

It is assumed in Eq. 10-67 that the hot wire is maintained at constant temperature; i.e., current is added or subtracted from the circuit as the windspeed varies to maintain a Kelvin bridge in balance. Electronic equipment has been developed that uses feedback amplifiers to automatically control the temperature of the hot wire and keep the bridge in balance. Hot-wire anemometers capable of measuring rapid wind fluctuations are commercially available.

With a hot-wire anemometer, important variables of windspeed – such as the root-mean-square velocity or the correlation coefficient between two anemometers placed at different positions, or even lag correlations – can be derived. Furthermore, with

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*Here e is the base of natural or Napierian logarithms.

TABLE 10-11

ANEMOMETER DISTANCE CONSTANTS (Ref. 12)

Manufacturer and instrument	Model	Distance constant, m
Beckman & Whitley, Inc.:		
3 cup	Series 50	1.22
Staggered 6	Series 50	0.98
Bendix--Friez Instrument Division:		
Aerovane (3-blade prop.)	Model 120	4.6
Aerovane (6-blade prop.)		5.8
Climet Instruments Inc.:		
3 cup		1.0-1.5
4-blade prop.		0.45
Electric Speed Indicator Co.:		
3 cup	Type F-420C	7.9
R. M. Young Company:		
Gill anemometer, 3 cup		0.73
Belfort Instrument Co.:		
3 cup	Type M	6.4
Meteorology Research, Inc.:		
Velocity Vane	1057	1.7-1.8
C. W. Thornthwaite Associates:		
3 cup		1.07

suitable electronic circuiting, wind turbulence spectra can be obtained automatically.

Another type of thermal anemometer allows the temperature of the hot wire, and thus its resistance, to vary, and the output voltage is read on a Wheatstone or a Kelvin bridge. This instrument is calibrated to relate windspeed with bridge imbalance to give windspeed fluctuations. This technique is not used as frequently as is the constant-temperature technique. Although this technique is referred to as the constant-current technique, the current is not really constant.

In the Kata thermometer (Ref. 41), the time required for an exposed heated thermometer to decrease its indicated temperature through a defined range, from 38° to 35°C, is related to windspeed. This instrument is employed for measuring very low windspeeds with fair accuracy.

Another technique for measuring windspeed utilizes three thermocouples in a T-formation, as shown in Fig. 10-30. The thermocouple junctions *A* and *B* form the probe and face into the wind. Junction *C* acts as a temperature-compensating junction. The thermocouples are made of fine constantan-chromel P wires. Thermocouples *A* and *B* are heated by alternating current provided by a transformer; thermocouple *C* is unheated. The millivoltmeter *V* measures only direct current because the transformer is center tapped and the resistances of the heated thermocouples are equal.

Although hot-wire and thermocouple techniques can be extremely useful for turbulence

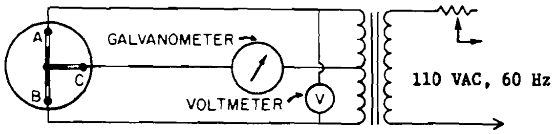


Figure 10-30. Schematic Drawing of a Heated-thermocouple Anemometer (Thermocouple junctions are labeled A, B, and C.) (Ref. 12)

studies both in wind tunnels and in the atmosphere, they are not usually used in operational wind studies because the instruments have the following disadvantages:

(1) Deposits of dust and dirt necessitate frequent cleaning and recalibration.

(2) Zero shifts in the bridge can cause appreciable errors.

(3) Rain or snow can cause very large errors.

10-5.1.3 OTHER ANEMOMETERS

If a rotation-type anemometer is prevented from rotating, it develops a torque proportional to the square of the windspeed. Therefore, a measurement of this torque provides a measure of the windspeed. An instrument based on this principle is called a bridled-cup anemometer. Because of its insensitivity and inaccuracy at low speeds, as well as its distorted recording of gust speeds, it is no longer manufactured and is used rarely.

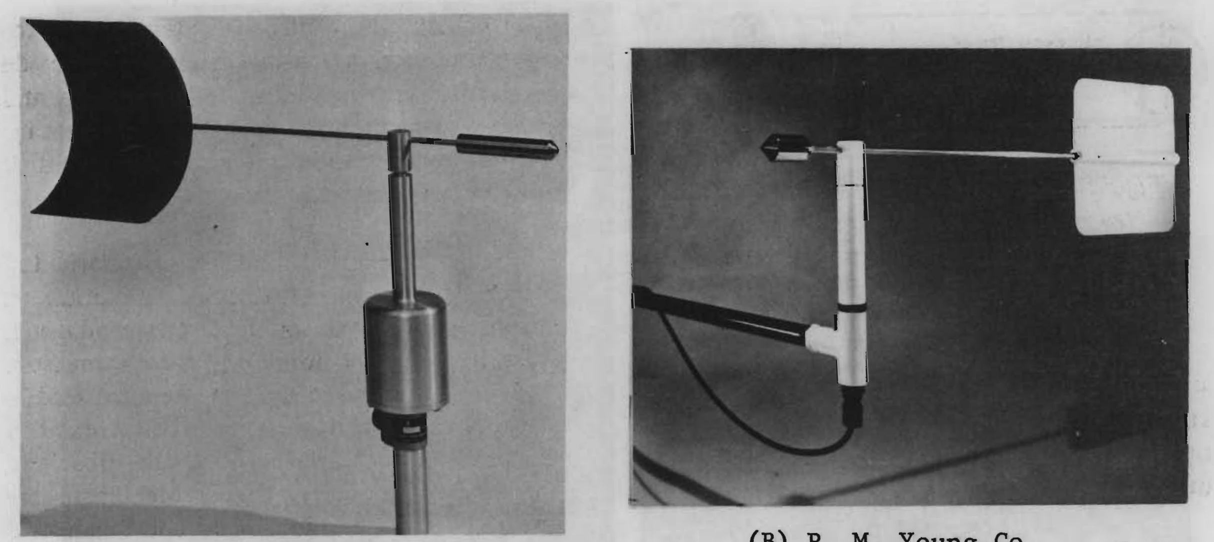
The pressure-tube anemometer based on Bernoulli's principle is another rarely used instrument. Static and dynamic pressure holes lead to a float manometer that measures the pressure difference and transforms this difference into a linear displacement recorded on a chart wound about a clock-driven drum. Although the pressure difference is proportional to the square of the windspeed, the float manometer arrangement is designed to provide a linear relation between pen displacement and windspeed. Standard electrical transducers are also available to provide windspeed readings based on the static and dynamic pressure difference. A disadvantage of the pressure-tube anemometer is that it must be oriented with respect to the wind.

The force exerted upon a plate oriented perpendicularly to the wind direction is proportional to the square of the windspeed. Pressure-plate anemometers, which measure this force, have been used for detailed studies of the wind. Although such instruments offer the potential of high-frequency response and conceptual simplicity, they suffer from the difficulties of a nonlinear drag coefficient and the necessity for orientation into the wind.

Sonic anemometers, which are used exclusively as research instruments, operate on the principle that the velocity of a sound is equal to the velocity of the sound in still air plus the velocity of the air. The speed of sound is dependent upon the air temperature, which also must be measured. The instrument is extremely sensitive and has no moving parts. In normal installations, the sensor is fixed in space so that it measures only one component of the wind. Three instruments, placed mutually perpendicular, are required to determine the total wind vector.

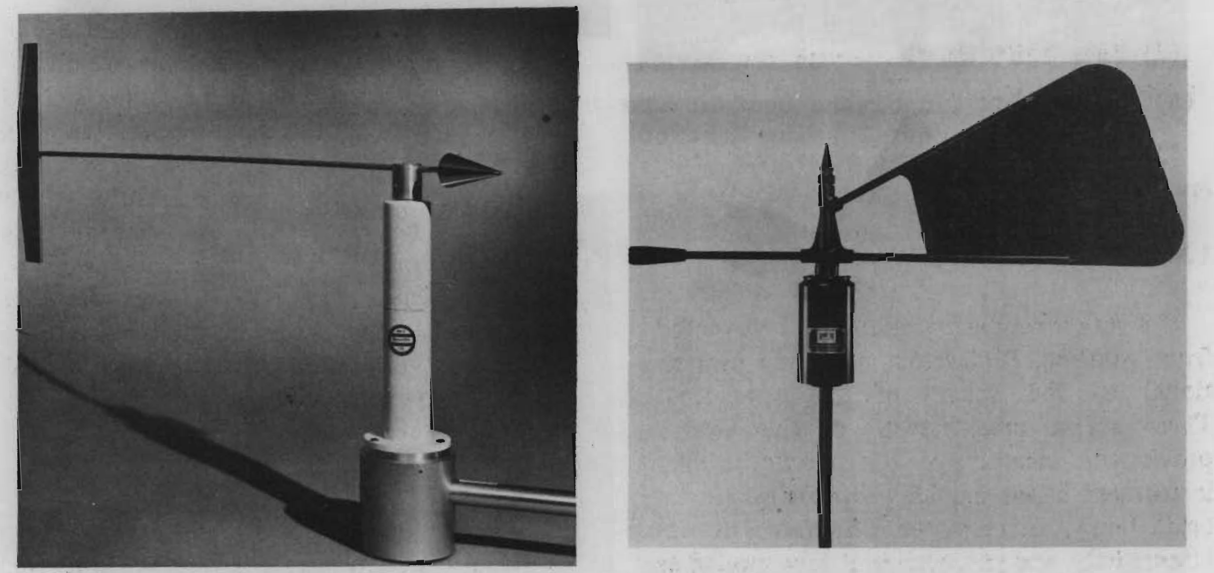
10-5.2 WIND DIRECTION

Wind vanes can take many different forms, from the very ornate often seen on farmhouses to the relatively simple flat plate. Flat plate vanes are easy to construct and provide reliable data. For increased torque at low windspeeds, splayed vanes, i.e., two vanes joined at their forward vertical edge and spreading out at an angle up to 20 deg, have been used but the overall performance of the splayed vane is not superior to that of a single vane. Some manufacturers use an airfoil as a vane. Up to 15 percent more torque is produced by airfoils over vanes with the same physical dimensions but – because of the added mass and, therefore, the increased moment of inertia of the airfoil – the



(A) Climet Instruments, Inc.

(B) R. M. Young Co.



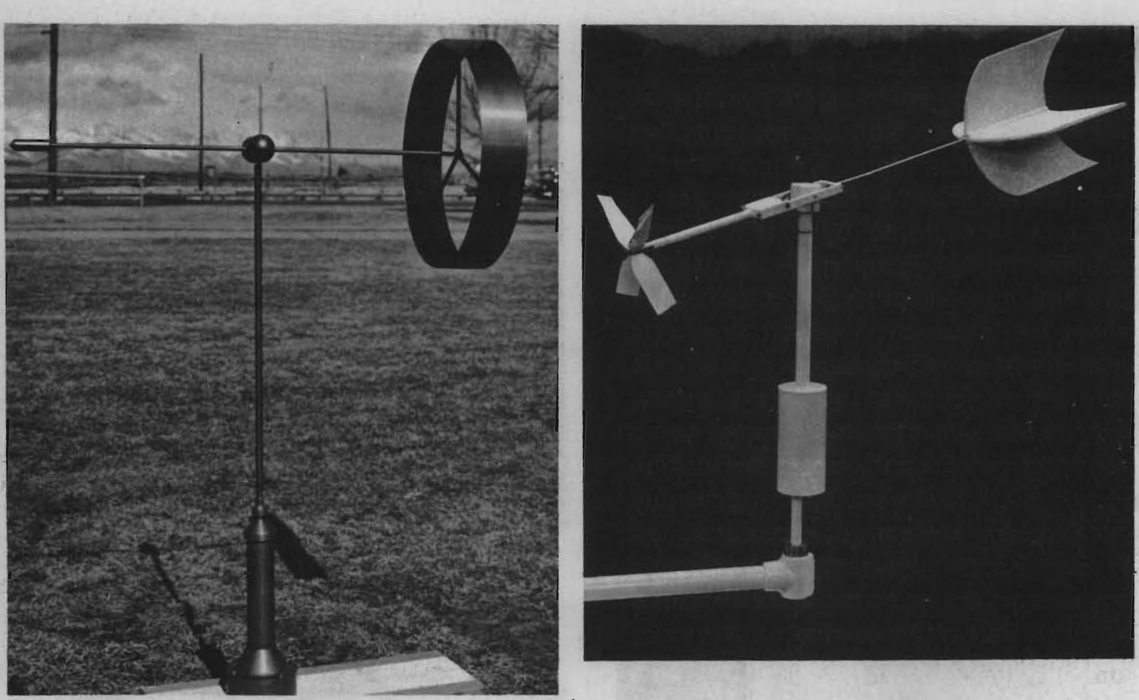
(C) Beckman and Whitley, Inc.

(D) Belfort Instrument Co.

Figure 10-31. Wind Vane Forms (Ref. 12)

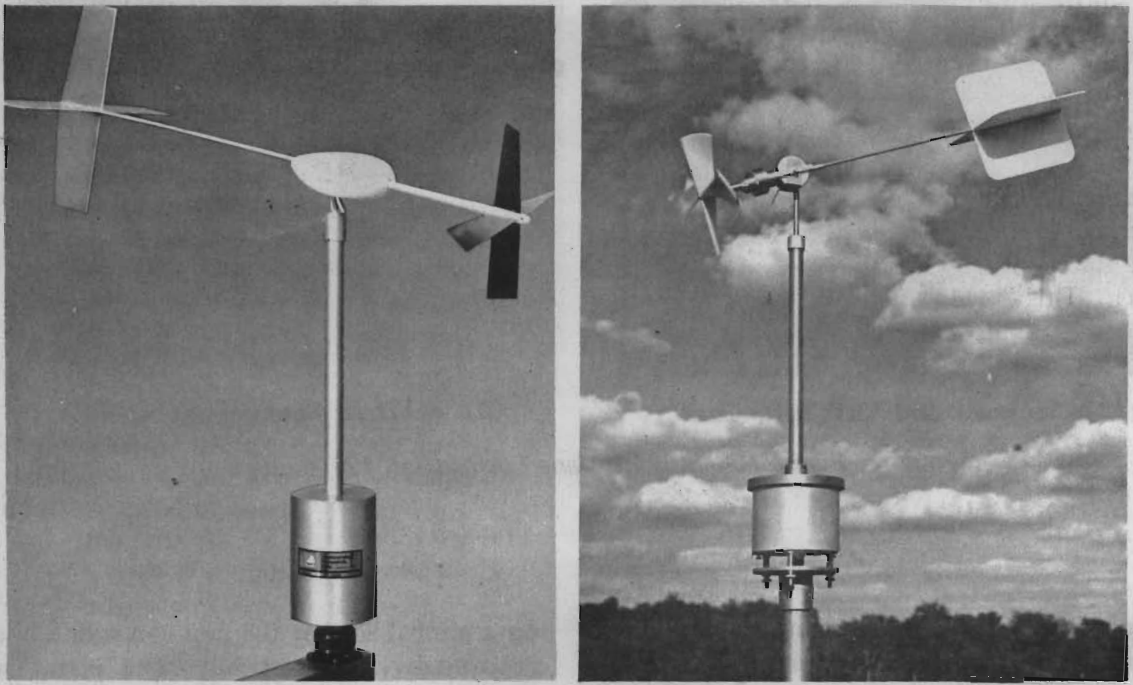
improved torque is offset by poorer dynamic performance. Various wind vane forms are shown in Fig. 10-31.

The vertical and horizontal components of wind direction can be determined by means of a bivane. The bivane can take either of two forms. The first arrangement consists of two plates perpendicular to each other mounted on a gimbal so that the unit can rotate both horizontally and vertically. The plates are constructed of thin aluminum or expanded polystyrene. The second type consists of an annular fin, either an airfoil or a flat sheet of metal, with a similar gimbal arrangement. Various bivanes are shown in Fig. 10-32. Both of these types of bivanes as well as bivanes with a propeller mounted on the shaft are



(A) An annular fin bivane used at the National Reactor Testing Station

(B) The Axiometer Sensor by Climet Instruments, Inc.



(C) The Vector Vane by Meteorology Research, Inc.

(D) The Gill Anemometer Bivane by R. M. Young Co.

Figure 10-32. Bidirectional-vane (Bivane) Sensors (Ref. 12) available commercially. The output from such an instrument can be used to determine all three components of the total wind vector.

Perhaps the most trouble-free and reliable technique for recording the angular position of a vane is one that utilizes a synchro-motor system. The vane is coupled to the shaft of a synchro transmitter, which can be located 100 m or more away from but is connected electrically to a synchro receiver. The shaft of the synchro receiver reproduces the rotation of the shaft of the synchro transmitter and thereby locates the vane position. The shaft of the synchro receiver can operate the pointer of a wind-direction-indicating dial or it can drive the pen of a strip-chart recorder.

A less costly method of recording the position of a wind vane utilizes a potentiometer and recording voltmeter. The potentiometer contact is coupled to the vane shaft and a constant voltage applied to the potentiometer; thus, any angular position of the vane corresponds to a specific voltage that can be used to drive a calibrated recorder. One disadvantage in this method is the voltage discontinuity that occurs when the contact moves across the gap in the potentiometer. If the wind direction oscillates about a position corresponding to this gap, the recorder pen has a full-scale oscillation, giving a confusing record. This can be avoided by using a double-contact potentiometer and simple switching circuits. Another disadvantage of the potentiometer system is the wear produced as the contact moves along the wires. Its advantage is a low moment of inertia of the potentiometer system compared to that of the synchro-motor system.

A third type of transmitter is the commutator system in which the vane is coupled to a unit that has two electrical contactors or brushes, spaced about 22.5 deg apart, making contact with one or two of eight 45-deg conducting sectors. Each of the sectors corresponds to 45 deg of wind direction, i.e., one point of an eight-point compass. When both brushes make contact in one sector, the direction corresponds to one of the eight compass points; e.g., north, northeast, or east. When the brushes contact two of the sectors, the direction corresponds to an intermediate direction, such as north-northeast, east-northeast, or east-southeast. Thus, wind direction to 16 points is obtained. This system can be used to energize lamps for visual reading or to operate electromagnetic relays that drive recorder pens. Similar systems can be used for dividing the compass into any additional number of sectors.

A parameter similar to the distance constant of an anemometer can be applied to a vane. Although the definition is not universally accepted, the distance constant for a wind vane has been defined as the length of wind passing the vane after a step change in direction before the vane deflects 50 percent of the angle to the new direction.

10-5.3 UPPER AIR MEASUREMENTS

Wind velocities away from the surface of the earth are measured using the trajectory of a lightweight material suspended within the air. The hypothesis is that the material moves with the speed of the wind. By observing two positions along the trajectory, the average velocity vector between these points can be estimated. The accuracy of the measurements depends upon the material and observing system used.

The most common tracer (material) for upper wind measurements is helium-filled balloons, which may be designed to ascend through the atmosphere or to maintain a constant level. The size and shape of the balloon determine its response to the wind and partially govern the accuracy of the wind measurements. Instrument packages may be attached to the balloon to measure atmospheric variables or to aid in tracking the balloon.

The aerodynamics of guided and unguided missiles in the atmosphere are affected by the wind. If the missile is carefully tracked, variance due to the wind can be filtered from the data to give an estimate of the vertical wind profile. Smoke or exhaust trails from rockets and trails of chemiluminescent materials ejected from a rocket may be photographically tracked to estimate wind and wind turbulence properties.

A succession of pictures made from geostationary satellites may be used to estimate the wind by the motion of identifiable cloud elements. However, the trajectory of a cloud is not necessarily that of the wind.

Doppler radar units are used in specialized research to determine the windspeed in a direction along the radar beam axis. With two units examining the same volume of air, the three-dimensional velocity of the air can be determined (Ref. 42).

10-5.3.1 TYPES OF BALLOONS

Pilot balloons or pibals are small (1-m diameter), lightweight (100 g) spherical balloons used to obtain the wind profile-wind velocity as a function of height (Ref. 41). Generally, they are made of neoprene and carry no instruments. Some may have a battery-operated lamp attached during nighttime releases or a weighted reflector to assist in radar tracking. The balloon is inflated with helium until a prescribed free lift is obtained. The free lift (usually expressed in grams) is the total buoyant force of the balloon less the weight of the balloon and any payload, and remains nearly constant throughout the flight. Upon release, the balloon initially accelerates but the vertical drag force (air resistance) quickly equalizes the buoyance so that the balloon ascends at a nearly constant rate. The balloon is observed continuously until it bursts, passes through a cloud layer, or otherwise cannot be located.

Pilot balloons are subject to self-induced horizontal oscillation during the ascent. This may affect the computed wind velocities. Another source of error is the inertia of the balloon, which limits its ability to respond to sudden changes in the wind. To minimize those errors, Scoggins (Ref. 43) developed a 2-m diameter balloon called the Jimsphere, which is roughened with 398 cones of 7.5-cm height on the surface. The Jimsphere is more responsive to the wind.

Radiosonde balloons are larger ($\approx$ 2-m diameter on the ground), are heavier (600 or 1,200 g) with a greater payload capability, and have greater altitude capability (100,000 ft) than do pilot balloons. An instrument package – the radiosonde contains sensors to measure air temperature, pressure, and humidity and includes a radio transmitter – is attached to the balloon so that the ascent rate (≈ 300 m min^{-1}) is comparable to that of the pibal. In its simplest form, the radiosonde transmits a modulated signal for each of the three sensors.

Wind velocity at a given altitude can be determined using constant level balloons. Unlike the pilot or radiosonde balloons, these maintain a constant volume. When inflated with helium to pressures in excess of atmospheric pressure, the balloon rises until the interior density equals the atmospheric density. Since the altitude of a given atmospheric density surface is subject to time and space changes, the "constant level" is a slight misnomer. For high altitudes, these balloons are usually spherical, but at altitudes below 3 km a tetrahedral-shaped balloon called a tetroon is often used. The low altitude balloons are tracked by conventional methods but the flight duration and altitude of the high level balloons require other means, such as earth satellites or multiple ground tracking stations.

10-5.3.2 BALLOON TRACKING SYSTEMS

The most elementary method of tracking a balloon is the single theodolite method (Ref. 41). A theodolite is essentially a surveyor's transit. The ascent of the balloon is continuously traced, and azimuth and elevation angles are recorded at least once each minute. Thus, assuming a constant rate of ascent, the elevation z of the balloon at any time is known. The horizontal range of the balloon is the product of the elevation and the cotangent of the elevation angle. A continuous record of the horizontal range allows the calculation of the horizontal trajectory of the balloon and thus windspeed and direction.

Significant errors arise from small errors in the measured elevation angle when the angle is small and its cotangent is varying rapidly. High wind conditions usually accompany those cases.

Some improvement in accuracy is achieved by the double theodolite (Ref. 41). This allows calculation of the horizontal trajectory of the balloon using only the azimuthal angles but requires simultaneous measurements.

It is more convenient and accurate to coat a balloon with a reflective surface or attach a reflector (weighted slightly to prevent free oscillation) and follow the flight using a tracking radar. Azimuth and elevation are obtained much more frequently with theodolites, and the radar provides the slant range of the balloon.

Radiosonde balloons are also tracked by high gain, highly directional tracking systems using the radio transmitter as a source.

A radiosonde package has recently become operational in which either LORAN or OMEGA navigation systems are used to continually locate the geographic position of the balloon, and a radio transmitter telemeters the information to a ground tracking station. The position record provides estimates of wind velocities with an error of ± 0.1 m s^{-1} in speed and ± 1 deg in direction. This system appears superior to other tracking techniques and eliminates the need for highly directional antennas on stable platforms.

10-5.4 WIND REPORTING AND DISPLAY

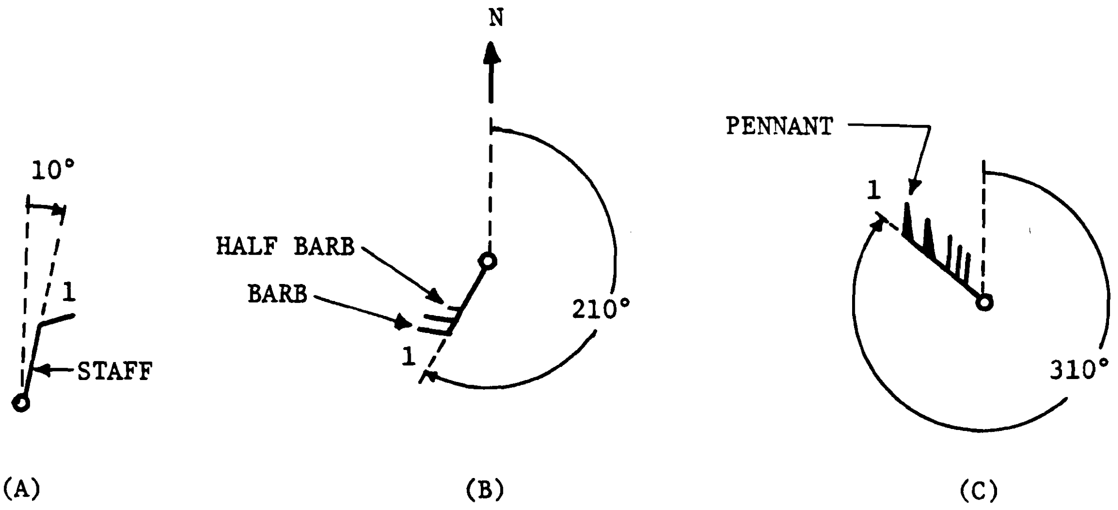
Throughout the world, surface wind observations are made and recorded at primary observation points at least every 6 hr, usually every 3 hr; and at first-order stations in North America, hourly. When required by specified criteria, wind observations may be made more frequently. Upper air radiosonde observations are routinely taken as close as practical to 0000 and 1200 hours GMT at designated stations. Pilot balloon observations with either manual or radar tracking are taken near 0600 and 1800 hours GMT. One purpose of these observations is to determine the pattern of the wind in the horizontal and the vertical. The information gained aids in the diagnosis of current and future weather systems, and the short-term planning of airborne operations.

Windspeeds are reported starting at an altitude of 500 ft, then at 1,000 ft, and in 1,000-ft increments to 10,000 ft, then in 2,000-ft increments to 20,000 ft, and then in 5,000-ft increments at higher altitudes. Radiosonde reports give winds at the mandatory pressure surfaces. These data are encoded and transmitted via teletype circuits and/or radio communications. Historical data for the designated upper air observing stations are available through the National Climatic Center, Asheville, N.C.

The horizontal distribution of winds is shown in either of two ways. Outside of the tropics, the winds of a particular altitude are normally plotted on a map (often with other data appropriate for that altitude) using the system of pennants, barbs, and staffs shown in Fig. 10-33.

The staff is the line drawn from the station in the direction from which the wind blows. The number at the end of the staff indicates the tens of degrees, with the hundreds of degrees understood; e.g., the 1 in Fig. 10-33(A) indicates that the wind is from 010 deg, whereas the 1 on Fig. 10-33 (B) indicates 210 deg, and in Fig. 10-33(C) it indicates 310 deg.

The full barb (Fig. 10-33(A)) indicates a speed of 10 kt. Each additional barb indicates an additional 10 kt, and a half-barb indicates 5 kt. Fig. 10-33(B) thus indicates a wind from 210 deg at 25 kt. Each pennant on the staff indicates 50 kt. Thus, Fig. 10-33(C) indicates



The pennants and barbs point in the direction of low pressure.

Figure 10-33. Staff, Barb, and Pennant Representation of the Wind

a 130 kt windspeed. The pennants and barbs point in the direction of low pressure. Calm winds are indicated by a circle circumscribing the station circle.

In tropical regions, since the relationship of wind and pressure is weak and observations are normally farther apart, a streamline-isotach analysis is most frequently used. A streamline is a line drawn tangent to the velocity vector at every point. They are drawn subjectively to display the general flow pattern of the winds such as shown in Fig. 10-34. In an isotach analysis, isolines of equal windspeed are superimposed upon the streamline pattern. Often, the streamlines converge along an asymptote in high windspeed areas and diverge in low windspeed areas. However, the spacing between streamlines does not necessarily indicate the windspeeds. The velocity vector is implied but not explicitly stated by this representation, but the method is useful in displaying the kinematic properties of the wind field. If the streamline pattern did not change with time, the streamlines would become trajectories, i.e., the paths that parcels of air follow.

The isogon-isotach analysis is less commonly used. In addition to the isotachs, the isogons-isolines of equal wind direction may be analyzed, usually at 30-deg intervals. Fig. 10-35 is an example of this analysis technique. The wind velocity vector is explicitly given (subject to interpolation) at any point in the analysis.

A wind rose is a graphical display in polar coordinates of the frequency of occurrence of the wind in a given sector, such as shown in Fig. 10-36. The length of each radius is proportional to the frequency of occurrence of the wind from a given sector. A sector may be 45 deg in width, giving an 8-point rose, 22.5 deg in width giving a 16-point rose, or 10 deg in width giving a 36-point rose, depending upon the original data format and the resolution desired. Normally, a 16-point rose is used. The frequency of occurrence of calm winds, which have no direction, is indicated in the center of the diagram.

The radials may be further subdivided according to the frequency of occurrence of windspeed categories within each sector such as shown in Fig. 10-37. In other cases the average windspeed for a given sector may be indicated.

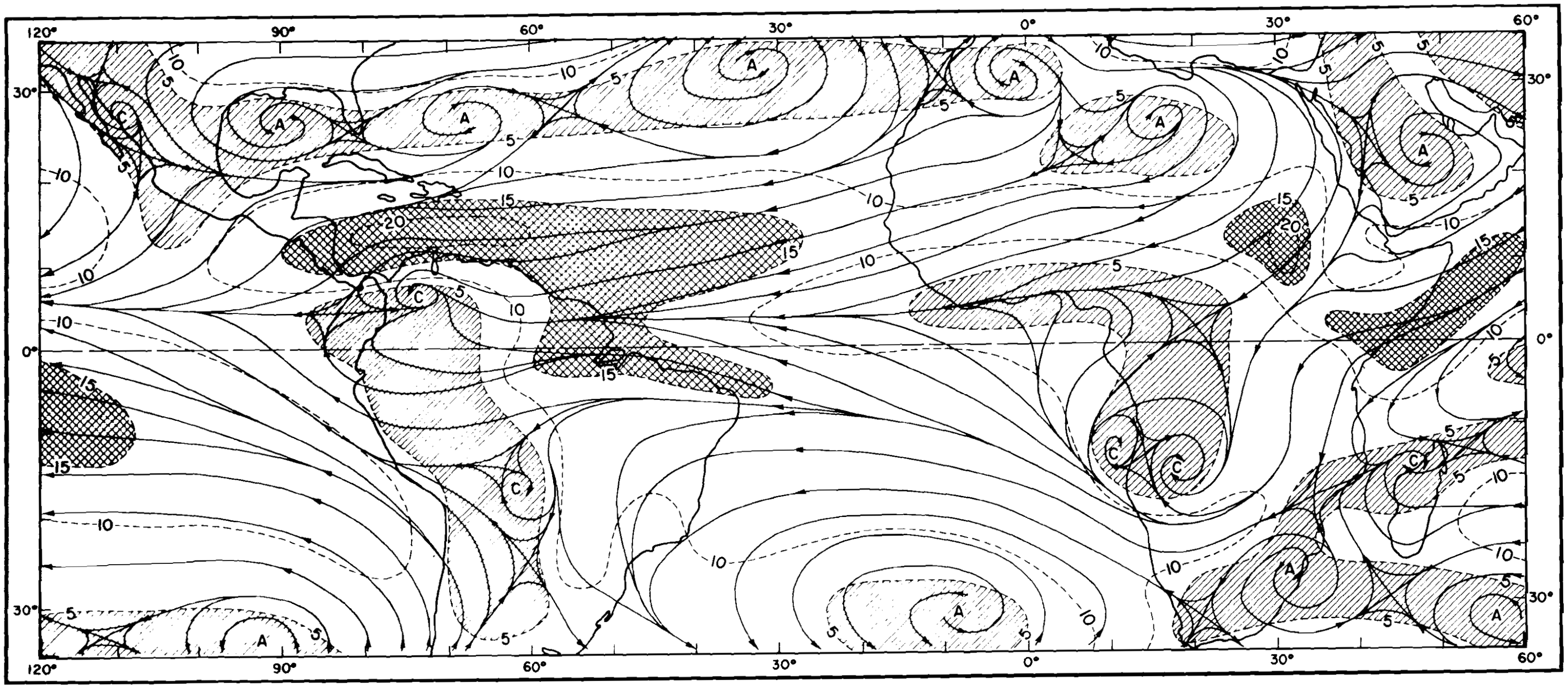


Figure 10-34. Streamline-Isotach Representation of the Wind (Ref. 16)

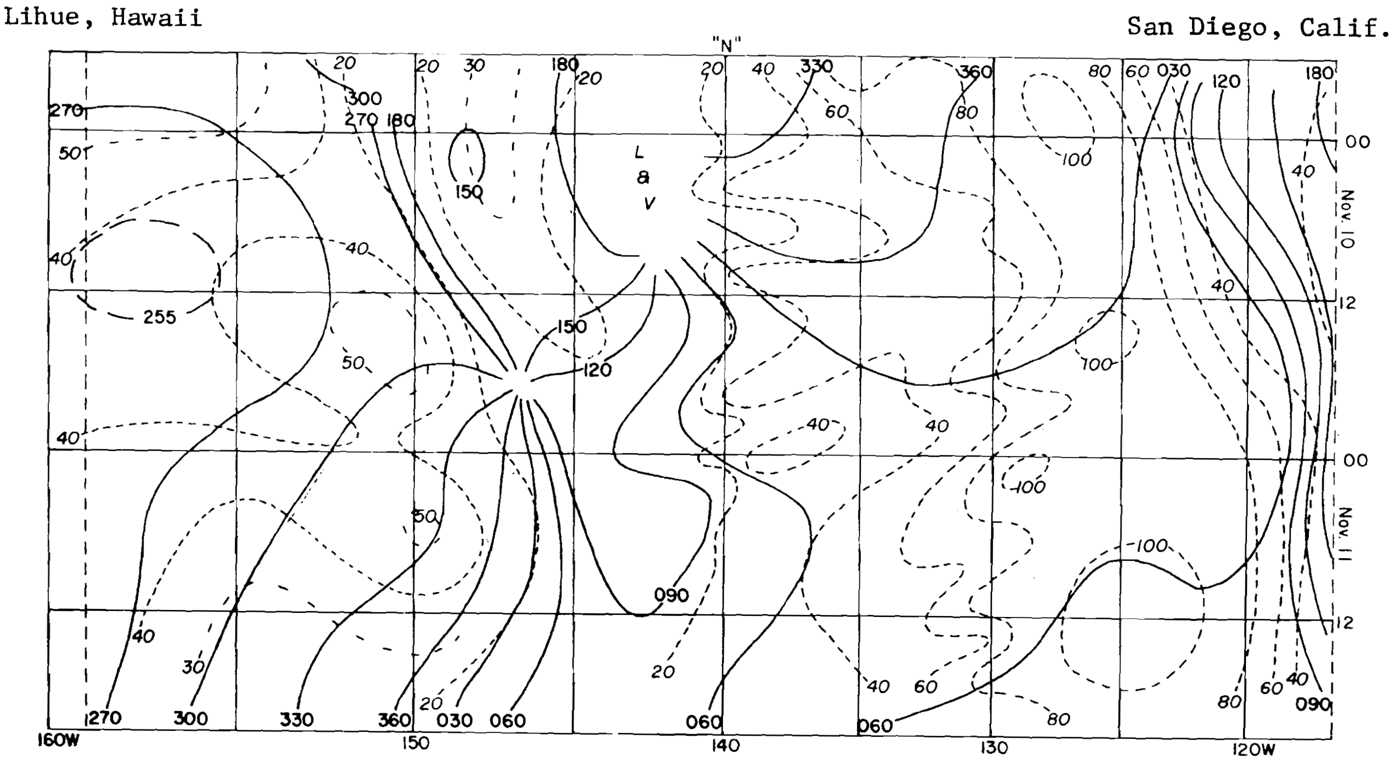


Figure 10-35. Isogon (solid lines)-Isotach (dashed line) Analysis of Wind Velocity at the 250-mb Level as a Function of Time and Space Between Lihue, Hawaii, and San Diego, Calif. (Ref. 44)

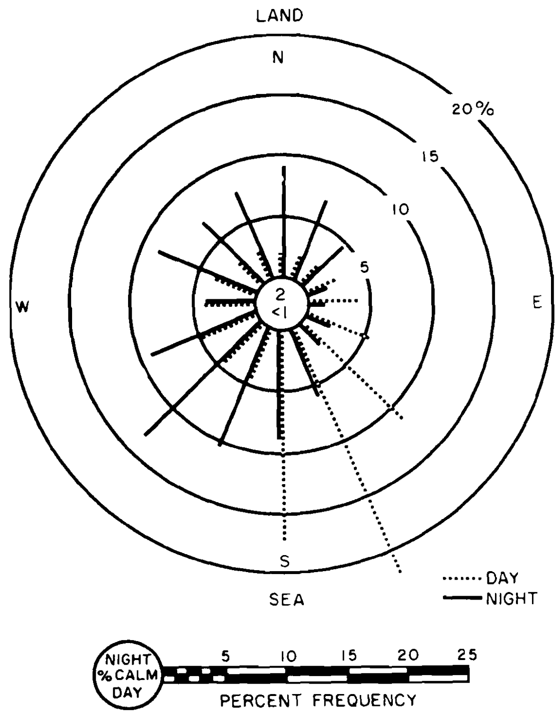


Figure 10-36. A Day-Night Wind Rose Showing, in This Case, the Diurnal Effect of the Sea Breeze (Ref. 12)

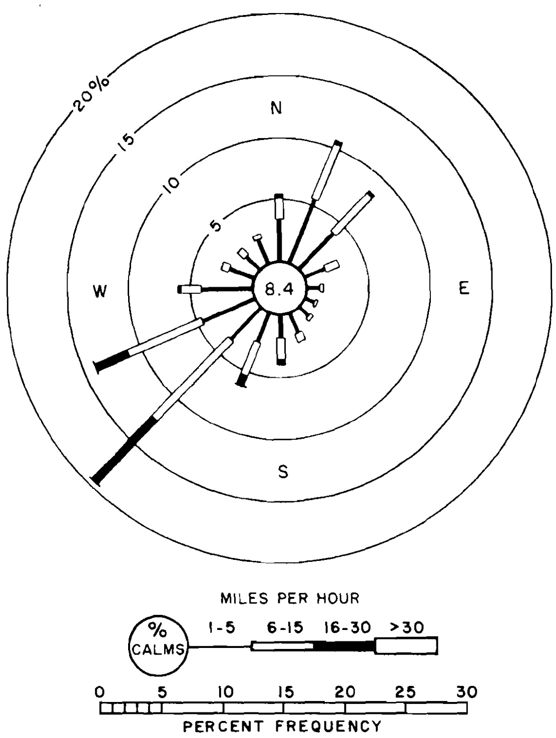


Figure 10-37. A Typical Wind Rose With Windspeed Information (Ref. 12)

Wind roses may be for mean annual, mean seasonal, or mean monthly frequencies of occurrence. Caution must be taken to see that an adequate data base – e.g., total number of observations – exists before accepting the indicated distribution as fact.

For long-term estimates of atmospheric dispersion properties of the air, wind roses may be further subdivided by the joint frequency of occurrence of windspeed, wind direction, and atmosphere stability. A pollution wind rose shows the joint frequency of occurrence of wind direction, measured pollution concentrations, and perhaps windspeed.

10-6 EFFECTS OF WIND

In most regions of the earth, the effects of normal winds on materiel are not important. Wind forces, windborne dust and debris, cooling effects, and enhanced evaporation rates are well-recognized, often beneficial, derivatives of air movement. Thus, in considering the detrimental effects of wind on materiel, attention is focused on either the infrequently occurring extreme winds or those few regions of the earth, e.g., mountain peaks or topographic abnormalities, wherein high wind velocities are frequent. Design engineers often neglect the effects of low probability extreme winds; therefore, when wind velocities exceed their normal range, widespread destruction often occurs.

The effects of wind may be subdivided into a number of categories. These are enumerated and described briefly in this paragraph; however, any one of them constitutes a comprehensive subject area within itself for which much more voluminous information could be assembled.

TABLE 10-12

EFFECTS OF EXTREME WINDS

1. Damage to buildings, bridges, and other structures
2. Flooding by wind-driven water
3. Outages of power distribution and communication systems
4. Hazards to aircraft causing damage and loss of life as well as limiting operations
5. Interference with ground vehicle operations causing accidents
6. Injuries and damage by wind-blown objects
7. Damage to vegetation and terrain
8. Restriction of visibility

10-6.1 EFFECT CATEGORIES

The eight categories into which the effects of wind are separated in this paragraph are listed in Table 10-12.

10-6.1.1 STRUCTURAL DAMAGE

Structural damage constitutes perhaps the most important of all wind effects. The literature of civil engineering since the early 1800's contains many references to structural failures caused by wind (Ref. 45). Among the more dramatic of these are the failures of large suspension bridges (e.g., the Tacoma Narrows Bridge in 1940) caused by wind-induced oscillations. Other types of bridges have been overturned by wind and many large buildings have been damaged, particularly in the construction stages when engineers may be lax (or willing to accept the low probability risk of extreme wind). Bridges and large buildings, however, constitute only the more newsworthy of wind-induced structural failures. In most regions, on several occasions during a year, winds become sufficiently strong to destroy some structures. Among the more vulnerable of such structures are those temporary buildings often associated with military operations.

10-6.1.2 FLOODING

Wind-driven water can constitute a greater damaging force than the wind itself. Widespread damage with large economic losses are not uncommon occurrences in low lying coastal regions when tides, driven by hurricanes or other cyclonic storms, inundate large areas. Military operations, which often are centered in coastal regions, can be particularly susceptible to damage of this type.

10-6.1.3 POWER AND COMMUNICATION OUTAGES

Tornadoes, hurricanes, and other high winds cause outages of power distribution and communication systems that depend on suspended wires. Wind factors are taken into account in the design of such systems, but the swinging and oscillations of wires, particularly when loaded with ice, can produce arcing and breakages. In addition, wind-blown debris and broken tree branches damage suspended wires, and wind-driven rain, dust, or salt water disrupt the operation of accessory equipment.

10-6.1.4 HAZARDS TO AIRCRAFT

The hazards to aircraft operations of extreme winds are well documented. Recent attention has been given to high altitude winds such as clear air turbulence (CAT), but equal if not greater hazards are associated with high winds at low levels during landing and takeoff operations. Slow and low flying aircraft – particularly helicopters – are difficult to operate in extreme wind conditions and frequently are damaged by wind while parked on the ground.

10-6.1.5 INTERFERENCE WITH GROUND MOBILITY

While the effects of wind on air mobility are immediately obvious, effects on ground mobility vehicles are also important. Instabilities in ground vehicles moving at high speeds are not uncommon and often result in vehicle accidents. Among the various classes of military vehicles, only the lightest of these would be affected significantly by wind. For the transport of oversized loads on highways and for light vehicles, the possibility of loss of control and/or overturning of the vehicle must be considered when extreme wind conditions are encountered.

10-6.1.6 INJURIES AND DAMAGE

Wind-blown material at times constitutes a real threat to materiel as well as to personnel. In an unusual wind-storm at Thule Air Force Base in Greenland in March of 1972, it was reported that rocks and chunks of ice the size of baseballs or larger were picked up by the wind and bombarded all exposed materiel (Ref. 46). Windows of buildings were broken allowing the wind to invade structures, which increased the susceptibility of the structure to wind damage. Tornadoes and hurricanes entrain large items such as roofs of buildings creating extreme hazards for personnel and other materiel. More common is the airborne sand and dust associated with high wind conditions. Wind-blown sand and dust penetrate, erode, and damage the surface coatings of all exposed materiel.

10-6.1.7 DAMAGE TO VEGETATION AND TERRAIN

The damage of natural vegetation by wind is not a direct hazard to military materiel but can have significant impact upon operations. Destruction of ground vegetation and trees is a common occurrence in hurricanes and similar severe storms. Downed trees block roads, damage structures, and can destroy communication lines. Destroyed vegetation working in synergism with other environmental factors such as rain can decrease ground mobility and produce earth movements that block highways or produce other damaging effects. Wind is one of the primary factors in shaping the terrain; extreme winds may change it rapidly.

10-6.1.8 RESTRICTION OF VISIBILITY

Associated with wind-blown material is a decrease in visibility. Decreased visibility also results from wind-driven rain and snow and, in desert regions of the earth, from 10 to 50 sandstorms per year are reported in which the visibility is reduced to a few meters. Even in the absence of precipitation, wind-driven snow in the cold and extreme cold regions of the earth severely restrict visibility, thereby impeding both ground and air transportation.

Blowing and drifting snow is, in many respects, much more important than snow alone. The movement of snow by wind degrades visibility, causes drifts that impede traffic, and may exert extra loads on structures because of the increased weight of the drifted snow. However, the wind may also help keep some surfaces from becoming overloaded and free some surfaces from snow, thereby enhancing trafficability. Chap. 8 of this handbook explores these effects more fully.

10-6.2 SYNERGISTIC EFFECTS OF WIND AND TEMPERATURE

The synergistic effects of wind and temperature are important. The natural evaporative cooling of the human body is augmented by the ventilation provided by the wind. In conditions of warm temperature and a moderate wind, this process may make a person more comfortable. At low temperatures, however, this enhanced cooling causes discomfort, reduces stamina, and sometimes produces injury by freezing exposed skin. Windchill is a measure of relative cooling of the body when exposed to various conditions of wind and temperature. The Siple-Passel formula for windchill is (Ref. 47)

$$K_0 = (10\sqrt{V} + 10.45 - V) \times (306 - T) \qquad (10\text{-}68)$$

where

K_0 = rate of heat loss, kg cal $\mathrm{hr}^{-1}\,\mathrm{m}^{-2}$

V = windspeed, $\mathrm{m \cdot s}^{-1}$

T = air temperature, K

The nomogram of Fig. 10-38 shows the cooling rate as a function of wind and temperature; however, all of the ways by which heat loss or gain may occur at the body surface are not taken into account. Allowance must be made for the type of clothing worn, the atmospheric humidity, and the solar radiation. A nomogram for predicting probability of occurrence of windchill is shown in Fig. 10-39.

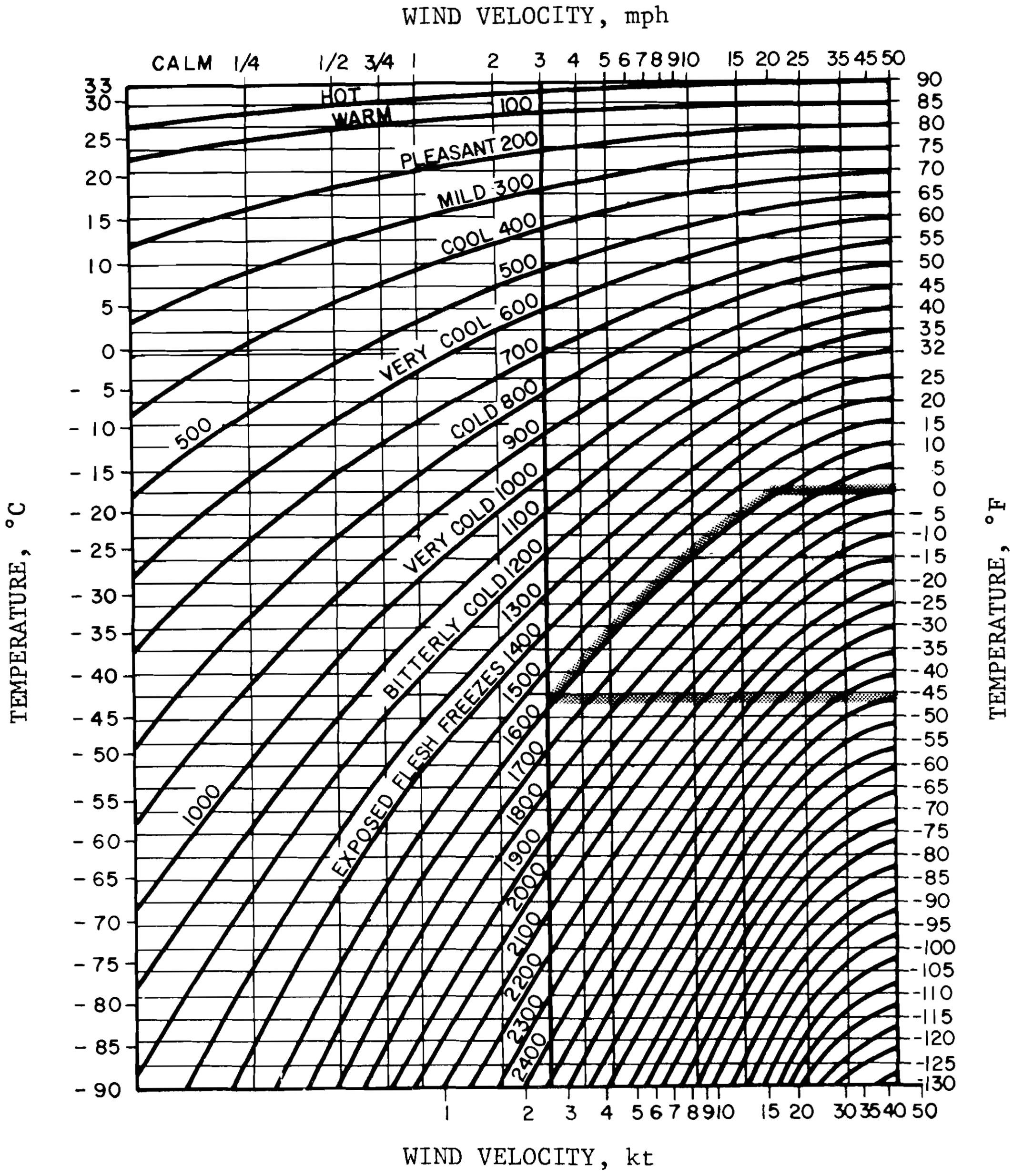
10-6.3 EVAPORATION OF LIQUIDS

Evaporation rates of liquids are also materially affected by wind. Evaporation is the transfer of a liquid material to its vapor state across the liquid interface and is measured by the mass transferred. The evaporation rate, the mass transferred per unit time, depends upon the substance and the gradient of the vapor pressure across the interface. The change of state from liquid to vapor requires that energy be added to the vapor; hence, a net cooling of the liquid and heating of the air results, the magnitude of the heat being equal to the product of latent heat of vaporization and the amount of mass transferred. Wind across the surface increases the ventilation of the vapor, transferring it upward by turbulence rather than by molecular processes, thereby maintaining a large vapor gradient across the interface and increasing the evaporation rate over what it would be in the absence of wind.

10-7 DESIGN

Countermeasures against the detrimental effects of wind on materiel are included in the design of many items. For example, the design and use of guns provide for windage corrections, surface finishes on vehicles are chosen to resist the erosive effects of wind, and seals are provided for various items of materiel as well as for structures in order to prevent wind penetration. Such practices are inherent in good design and are too voluminous to enumerate in this discussion. Attention is focused instead on the occurrence of extreme winds that cause damage or malfunction of materiel.

The economic costs of designing so as to avoid the detrimental effects of normal winds are large but, because they are spread throughout many areas, these costs cannot be estimated accurately. The costs involved in designing for winds of increasing severity and decreasing probability rapidly escalate. In order to apply engineering judgment in a rational manner to the design of materiel, the design engineer must have information on the probability of occurrence of severe winds. With such information, the design engineer can weigh the relationship between the risk of wind damage, the useful life of the materiel item, the cost of increased protection, and the risk that is acceptable to the user. For example, if the life expectancy of a materiel item is short, then it is unrealistic to design it



To obtain equivalent windchill temperature, select current temperature value (F°) at right side of curve; move horizontally to the left to a point vertically below the current wind velocity (mph); follow to the left and downward to the nearest parallel line until you intersect the 3-mph vertical line; go back horizontally to the right and read off the equivalent windchill temperature.

Example: At 0°F, with a 20-mph wind, the equivalent windchill temperature would be -46°F. Curves based upon Paul Siple's index as published in Quartermaster Research and Engineering Command, USA Technical Report EP-82, "Windchill in the Northern Hemisphere", Falkewaki and Hastings, February 1958.

Figure 10-38. Windchill Index (Ref. 48)

EXPLANATION ON USE OF CHART

BY A SIMPLE TECHNIQUE, IT IS POSSIBLE TO ESTIMATE THE PROBABILITY OF A SPECIFIED LEVEL OF WINDCHILL. DATA REQUIRED (MEAN MONTHLY AIR TEMPERATURE AND WINDSPEED) ARE ENTERED IN THE SIPLE WINDCHILL NOMOGRAM AT THE LEFT AND A WINDCHILL INDEX OBTAINED. THIS INDEX IS TRANSFERRED TO THE PREDICTION CHART AT THE RIGHT AND FOLLOWED TO THE PREDETERMINED LEVEL DESIRED (READ ON ACTUAL WINDCHILL SCALE AT THE EXTREME RIGHT). PERCENTAGE FREQUENCY CAN BE READ ON THE PROBABILITY SCALE AT EITHER TOP OR BOTTOM OF THE PREDICITION CHART.

EXAMPLE: AT FORT CHURCHILL, JANUARY MEAN TEMPERATURE (-18°F) AND WINDSPEED (14.9 mph) ENTERED IN THE NOMOGRAPH AT THE LEFT GIVE AN 1,800 WINDCHILL INDEX. THIS 1,800 INDEX INTERSECTS THE 1,400 ACTUAL WINDCHILL (CONDITION AT WHICH EXPOSED FLESH FREEZES) AT 72 PERCENT ON THE UPPER SCALE OR 28 PERCENT ON THE LOWER SCALE, INDICATING THAT DANGER OF FREEZING IS A PROBABILITY 72 PERCENT OF THE TIME AT CHURCHILL DURING JANUARY. SAFETY FROM FREEZING IS A PROBABILITY 28 PERCENT OF THE TIME. THE POSSIBILITY OF THE SITUATION BECOMING DANGEROUS FOR TRAVEL OR LIVING IN TEMPORARY SHELTERS (2,000 ACTUAL WINDCHILL) IS A PROBABILITY 16 PERCENT OF THE TIME.

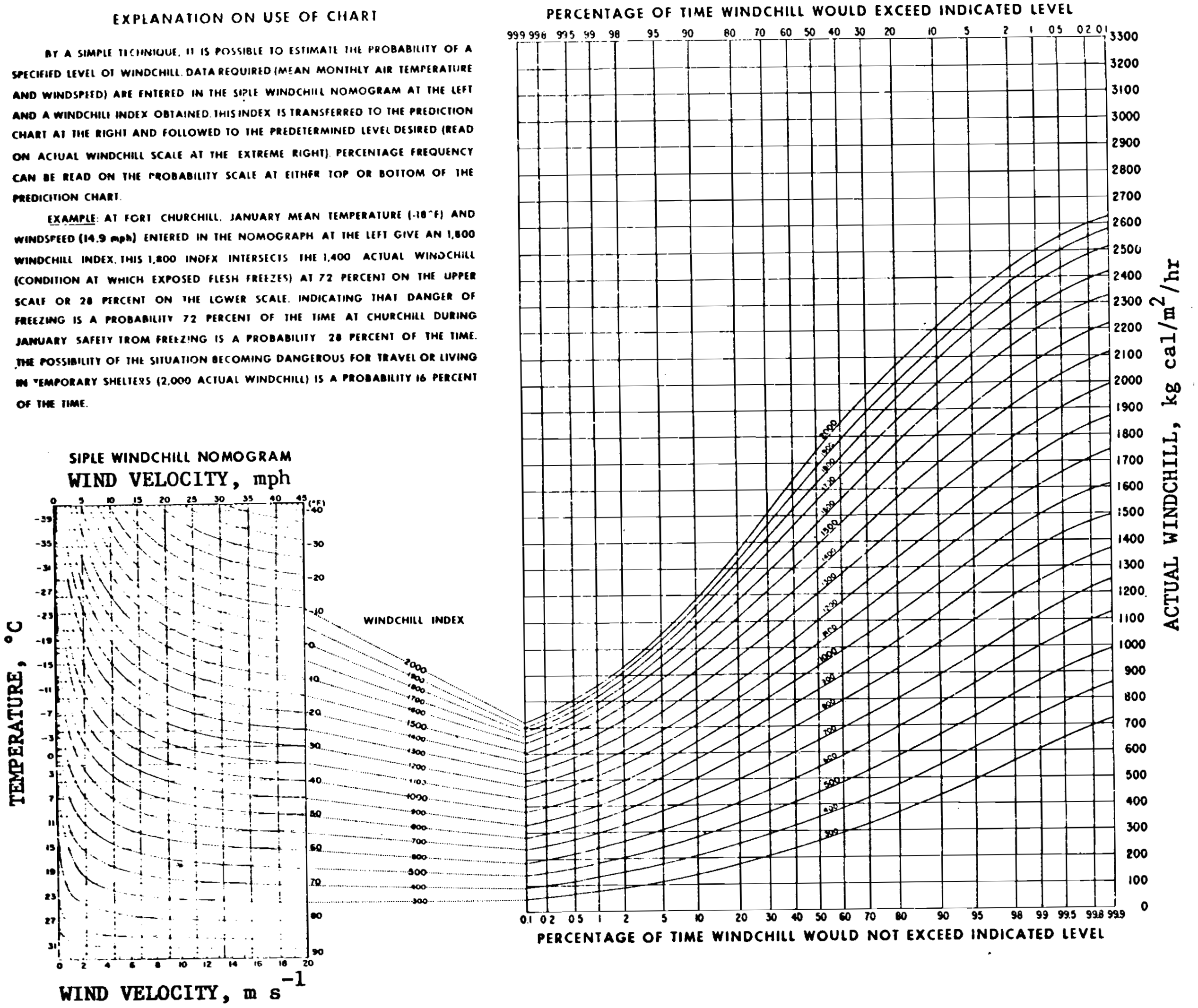


Figure 10-39. Windchill Prediction Chart (Ref. 49)

to survive a windspeed that occurs only once in 100 yr. Similarly, if the cost of protection is doubled for less than a doubled survival period, then it may be more cost-effective to accept the risk and replace the item when necessary.

Severe wind occurrence probabilities are not available for many regions of the earth. When they are available, they are based on analyses of existing climatological data. For the United States, Thom has estimated the probability of occurrence of extreme winds, taking into account all weather systems except tornadoes (Ref. 14). These probabilities are given in terms of the recurrence intervals of extreme wind velocities. Fig. 10-40 gives these data for recurrence intervals of 2, 10, 50, and 100 yr. The data from which these maps were compiled were selected from stations where the terrain was relatively uniform for at least 25 mi in all directions. All data are normalized to the 30-ft elevation by use of the 1/7 power law ($n = 7$ in Eq. 10-49). The extreme windspeed for other altitudes or for different wind profiles may be computed from the data given and Eq. 10-49. In complex terrain, extreme windspeeds vary greatly with exposure, requiring caution in the application of the data given in Fig. 10-40.

When extreme windspeed data are required for a particular site on which a building, antenna installation, or other structure is to be erected, data on extreme windspeeds at that site are preferred. Since it is the low-probability-of-occurrence winds that are most important, it is often necessary to extrapolate either from regional climatological data or from specific climatological data from a nearby weather station.

When designing a structure to withstand wind damage for a certain period of time, it is necessary to use a relation such as

$$P_n = 1 - [F(u)]^n \qquad (10\text{-}69)$$

where

n = time interval, yr

u = extreme windspeed, mph

$F(u)$ = probability that windspeed u will not be exceeded in 1 yr, dimensionless

$[F(u)]^n$ = probability that windspeed u will not be exceeded in n yr, dimensionless

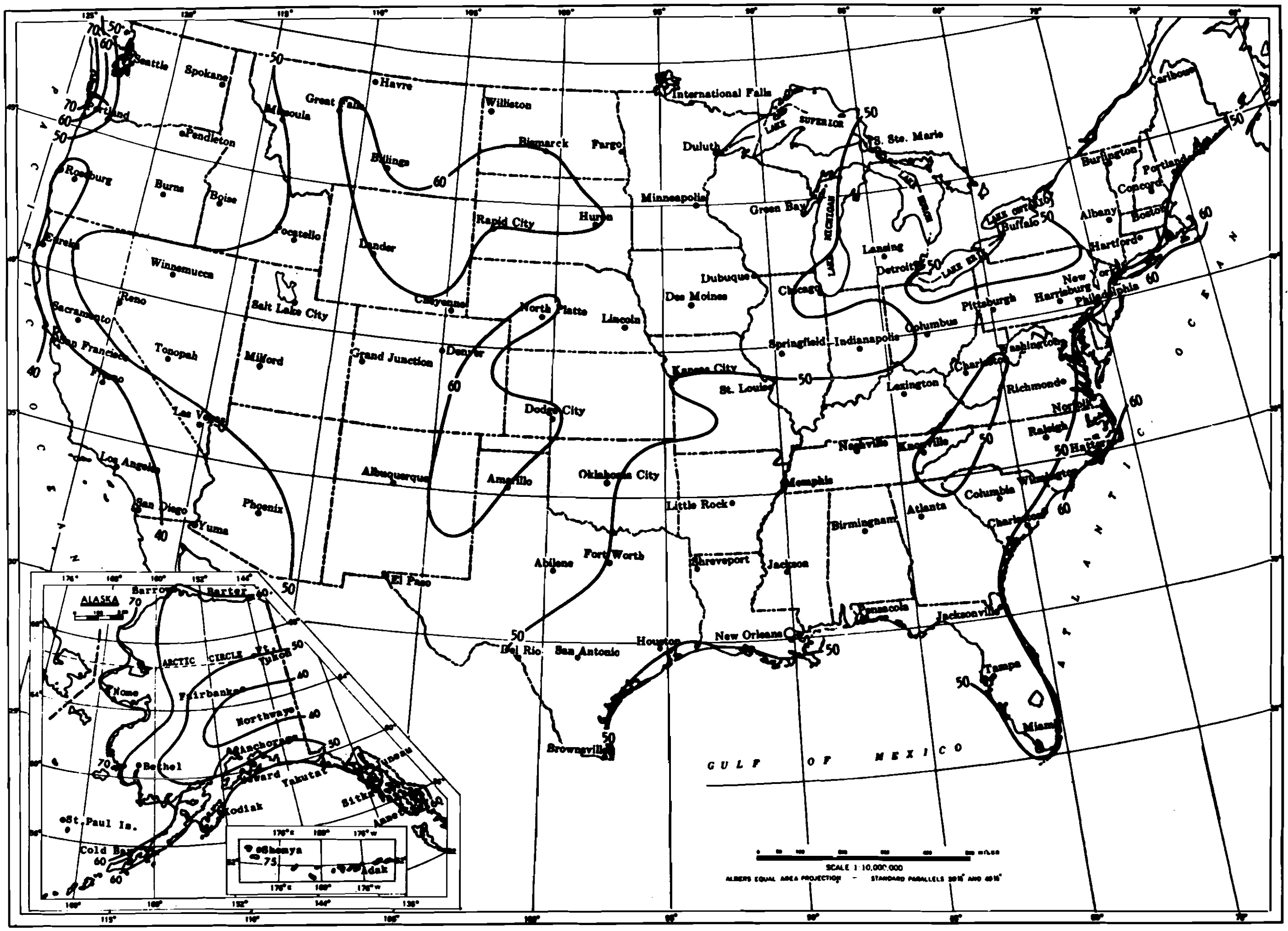
P_n = probability of at least one wind occurring with a speed u in n years, dimensionless.

Since P_n and n are chosen by the designer, it is preferable to solve Eq. 10-69 for $F(u)$, obtaining

$$F(u) = (1 - P_n)^{1/n} \qquad (10\text{-}70)$$

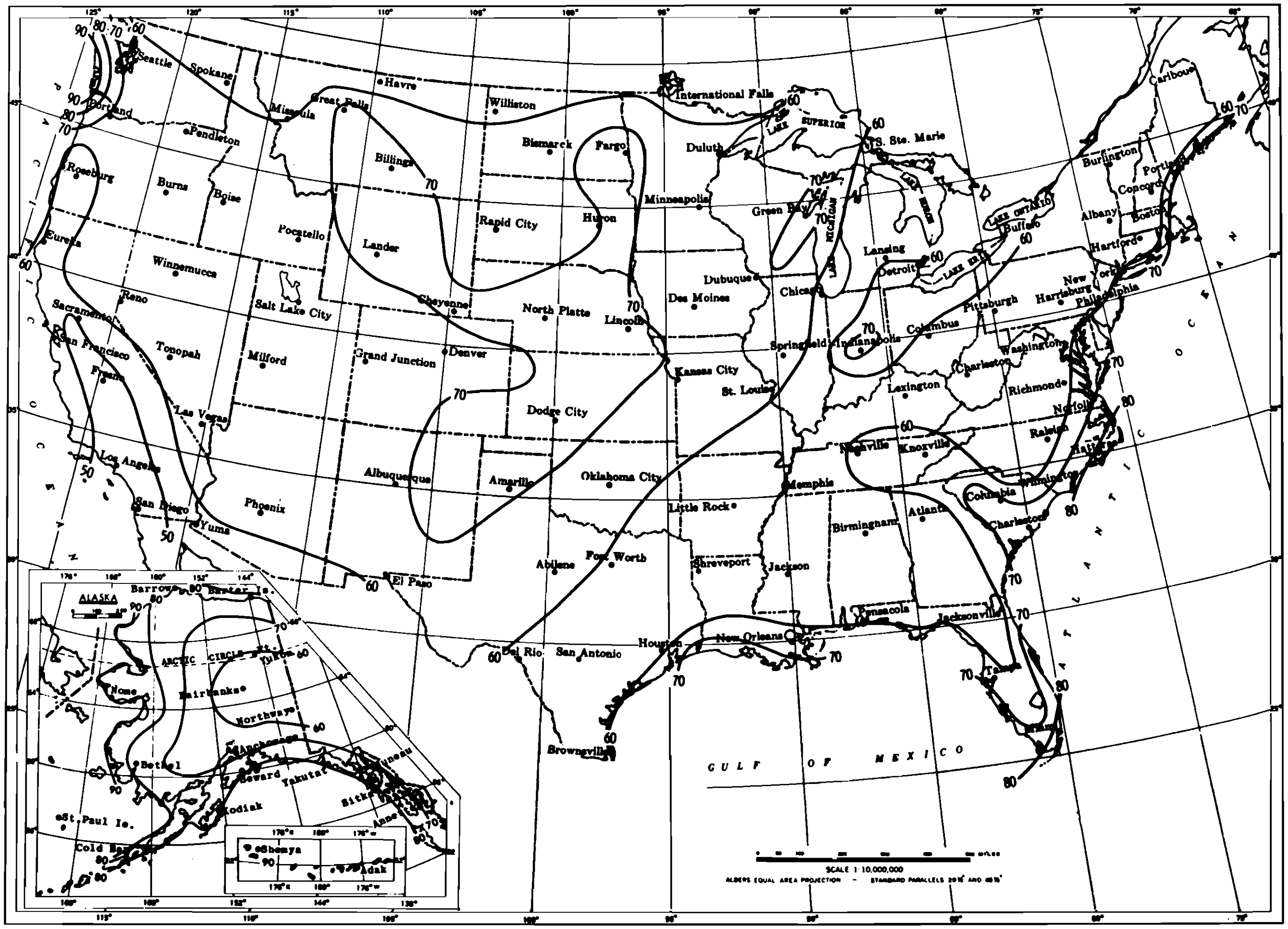
This gives the required occurrence probability. If, for example, $n = 3$ yr and a 5 percent chance of the wind exceeding u ($P_3 = 0.05$) is acceptable, then $F(u) = 0.983$. To determine the wind velocity at a specified location where $F(u)$ has this value, climatological data are required wherein $F(u)$ and u are related. Such data are sometimes available; when they are not, they may be derived from data such as given in Fig. 10-40. For example, the data in Fig. 10-40(A) are for a recurrence interval of 2 yr, corresponding to $F(u) = 0.5$ since the recurrence interval is the reciprocal of $1 - F(u)$. Using the data from all four maps in Fig. 10-40, four data points may be obtained for a plot of $F(u)$ versus u. Extreme probability graph paper is normally used as illustrated in Fig. 10-41. For the site plotted – Washington, D.C. – the windspeed for $F(u) = 0.983$ is approximately 75 mph.

Particularly for long recurrence intervals, the estimates of extreme wind probability are statistically rather than observationally derived. Hence, confidence intervals to reflect the variability of observation from estimates should be placed upon the probability estimates. Table 10-13 gives the upper and



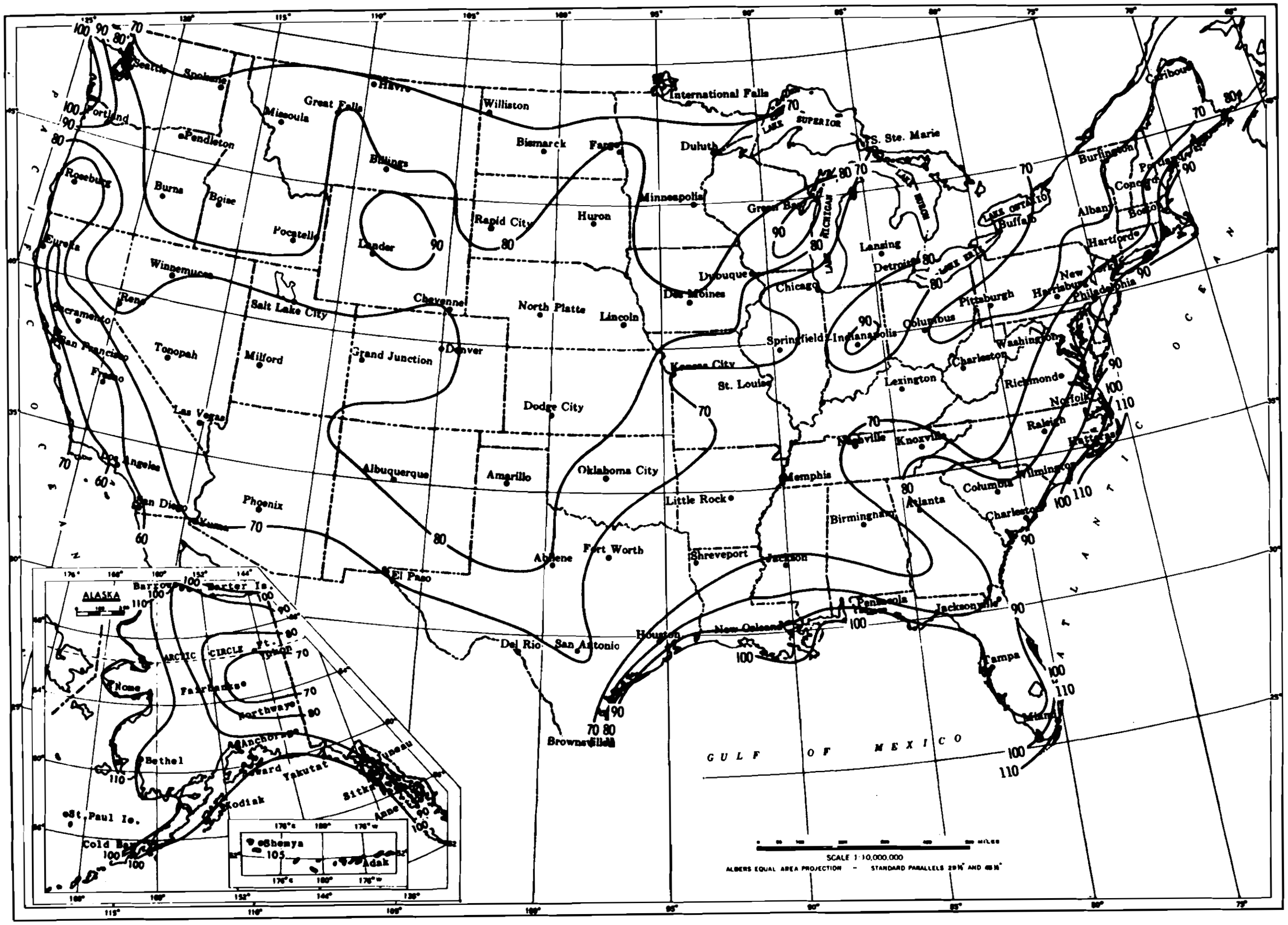
(A) 2-yr mean occurrence interval, isotach 0.50 quantiles, in mph

Figure 10-40. Distribution of Extreme Winds in the United States (Ref. 14)



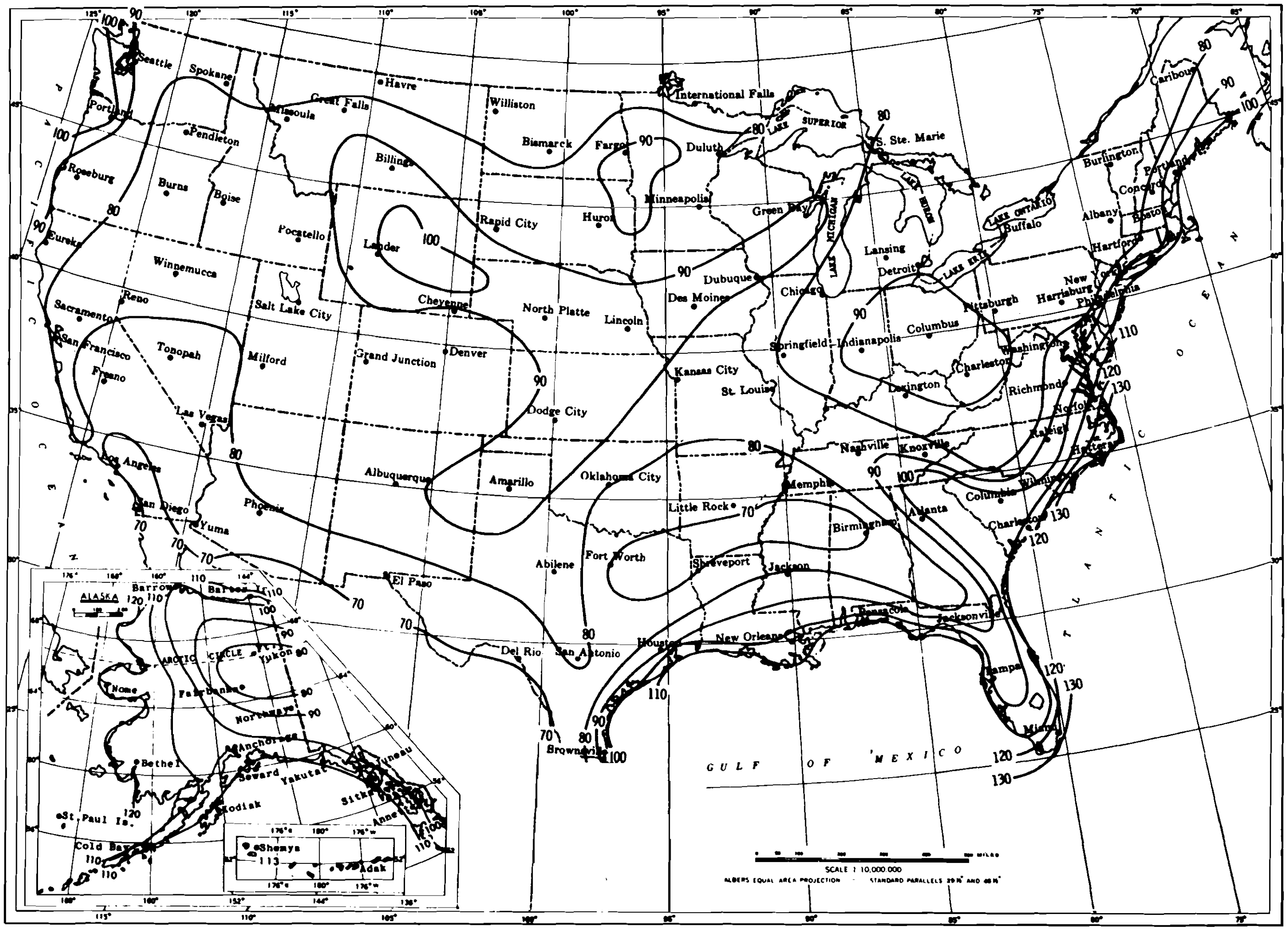
(B) 10-yr mean recurrence interval, isotach 0.10 quantiles, in mph

Figure 10-40 (Continued). Distribution of Extreme Winds in the United States (Ref. 14)



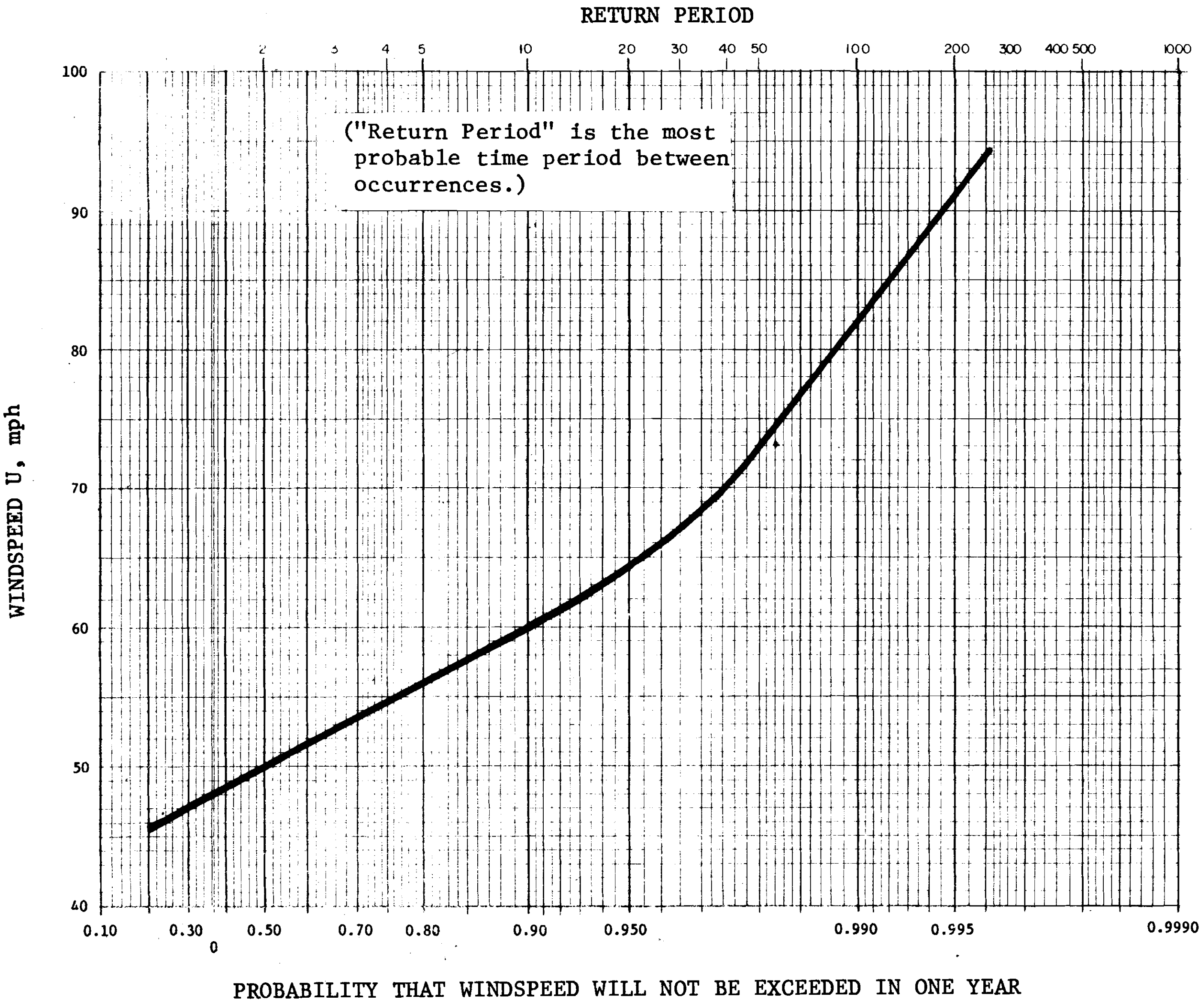
(C) 50-yr mean recurrence interval, isotach 0.02 quantiles, in mph

Figure 10-40 (Continued). Distribution of Extreme Winds in the United States (Ref. 14)



(D) 100-yr mean recurrence interval, isotach 0.01 quantiles, in mph

Figure 10-40 (Continued). Distribution of Extreme Winds in the United States (Ref. 14)



("Return Period" is the most probable time period between occurrences.)

Figure 10-41. Example of Windspeed Exceedance Probability Plot (Washington, D.C.)

TABLE 10-13

NINETY-PERCENT CONFIDENCE LIMITS ON EXTREME WIND PROBABILITY (Ref. 14)

Probability	Lower limit	Upper limit
0.50	0.407	0.593
0.90	0.827	0.945
0.96	0.827	0.982
0.98	0.908	0.992
0.99	0.955	0.995

lower limits at 90-percent confidence for the extreme wind probabilities. This means that the estimate of $F(u) = 0.983$ may be an error due to an inadequate data record or statistical variance. For the example cited, the value of $F(u)$ may be as low as 0.910 or may be as high as 0.993. For $F(u) = 0.993$, $u \approx 87$ mph; for $F(u) = 0.910$, $u = 61$ mph (0.993 and 0.910 are interpolations from Table 10-13). Thus, it can be determined with 90-percent probability that the extreme wind for that period for Washington, D.C., will be between 61 and 87 mph, with the most probable value being 75 mph.

For tall structures, the design windspeed should be calculated for various altitudes since the windspeed increases with altitude. The force exerted by the wind increases as the square of the windspeed, producing a torque that increases rapidly with the height of the structure. Hence, the design criteria figured at 10 ft are substantially different from those for 50 ft above the ground.

A knowledge of the extreme wind and its probability is not always sufficient for design purposes. The characteristics of wind gustiness and the possible dynamic or resonant excitation of a structure must also be considered. Peak windspeeds in gusts average about 1.3 times the extreme winds at the 30-ft level (Ref. 14), but that factor does not fully reflect how the gustiness affects the structure.

Most of the climatological data are derived from hourly (or 3-hourly) wind data collected at airport sites. These data contain little or no information about the turbulence or microstructure of the wind field. Hence, they are not the best data for design analysis of structural stress. When possible, onsite turbulence data are desirable. The instrument response and filtering characteristics should be carefully calibrated before, during, and after the measurement program.

10-8 TESTING AND SIMULATION

Testing of various items of materiel in order to determine their ability to withstand wind forces is accomplished either in the natural environment, shock tubes, or in wind tunnels. The infrequency and unpredictability of extreme winds in nature make it difficult to obtain engineering data from the natural environment except on an opportunistic basis. Therefore, practically all testing is accomplished in wind tunnels such as those that are employed to determine the aerodynamic behavior of aircraft. In fact, aeronautical research has provided the instrumentation and knowledge of fluid mechanics that makes rational interpretation of wind tunnel tests feasible.

As with aircraft it is not always possible to test full-scale models in a wind tunnel. Aircraft engineers, however, have developed the techniques for interpreting the results obtained from a scaled-down model of a structure. This allows wind tunnel testing of many of the larger structures or more radical designs before a design is frozen.

Wind tunnel testing of military aircraft, including helicopters and rockets, is required during their developmental cycle. Often, models of large surveillance radar antennas and similar structures are also tested in wind tunnels.

A large variety of wind tunnels are available that vary both in size and in windspeed capabilities. The larger wind tunnels may have dimensions of up to 80 ft and are capable of simulating all natural windspeeds. The smaller wind tunnels are designed to attain higher transonic windspeeds and are of little interest with respect to the natural wind environment. However, when it is necessary to test a scaled-down model of a particular item, then it is necessary to greatly increase the windspeed in the tunnel in order to obtain the same forces on the structure.

Testing of materiel items with respect to their ability to survive extreme winds may either encompass destructive testing wherein the ultimate wind survivability of the structure is determined or it may involve instrumentation to measure the forces exerted on the structure and their relation to its ultimate strength.

10-9 SPECIFICATIONS AND REGULATIONS

Requirements on materiel with respect to wind stresses are not often cited in specifications or regulations. Often, the ability to survive an extreme wind is obtained through specification of construction practices or material strength. These procedures have derived from the usual practices of civil engineers. However, in some cases the wind forces that a structure must resist are specified. For these applications such documents as "Wind Forces on Structures" (Ref. 45) contain much information on wind stresses on specific structures including buildings, bridges, and open-frame structures. Special attention is given to those structures that could be caused to oscillate by the wind.

Design criteria for Army materiel with respect to the wind are defined in AR 70-38 (Ref. 50). This document defines eight climatic categories ranging from wet-warm to extreme cold. The general criteria for wind are described for climatic category 2, wet-hot, for which it is stated that materiel with a life expectancy over 5 yr may be subject to winds of 55 kt for a 5-min period with gusts to 85 kt except at exposed coastal and mountain locations where sustained 5-min winds of 70 kt with gusts of 105 kt may be experienced. For materiel with a life expectancy of less than 5 yr, the predicted wind exposure is less. These windspeeds are defined for a height of 10 ft above the ground but data are given to allow extrapolation to other levels. Additional information is provided for blowing sand and dust as well as for snow. The only exceptions to these windspeeds are that winds beneath a forest canopy seldom exceed 5 kt and, in the cold and extreme cold climatic categories, the wind is less than 10 kt and 5 kt, respectively, at times of low temperature.

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CHAPTER 11

SALT, SALT FOG, AND SALT WATER*

11-1 INTRODUCTION AND DESCRIPTION

Salt is one of the most common chemical compounds, there being in excess of 4×10^6 cu mi of salt in the oceans and probably at least as much in the solid earth (Ref. 1). An estimated 1 billion tons of mineral matter, mostly salt, is transferred from the oceans to the atmosphere each year; of this, about 10 percent is blown over the continents, precipitated, and eventually returns to the sea in river waters (Ref. 2). Thus, even in midcontinent areas, it is impossible to avoid exposure to salt. In coastal regions, this exposure is greatly intensified and, in the marine environment, the exposure reaches its maximum (Ref. 3).

Materiel designers are aware that the corrosive nature of salt is not a result of its chemical reactivity. Salt does not explode, burn, or otherwise react rapidly. In the presence of water, a strong ionic solution is formed that promotes electrochemical reactions with metals. It is this property that has led to the strong association of salt with corrosion and to the use of salt-spray, salt-water immersion, and salt-fog testing as standard methods for determining corrosion resistance.

The widespread presence of salt in the environment and the acceleration of corrosion by salt are the reasons for focusing attention on salt as an important environmental factor.

Salt, as used here, is defined as sodium, chloride, sulfate, and magnesium ions. Most salts that affect materiel are sea-salt particles, although alkaline deserts, large salt lakes, and industrial wastes contribute locally to salt fallout. Salts occur in the atmosphere as crystals or in liquid droplets, depending on the relative humidity of the air. Materiel may be exposed to the effects of salt as the result of dry fallout from the atmosphere, aqueous precipitation, salt fog, or direct exposure to sea water.

Salt fog is a hydrometeor consisting of a visible aggregate of water droplets, many of which contain sea salts in significant amounts and which are suspended in the atmosphere at the surface of the earth.

Salinity is a characteristic of sea water and is defined as the ratio of the weight of the dissolved salts to the weight of the sample of water. In solution, the amount of salt is a function of the salinity which is stated as grams of salt per kilogram of water for which the symbol °/oo is employed. Standard sea water contains 35 grams equivalent of salt per kilogram of sea water at 20°C (35 °/oo), but salinity varies somewhat from area to area. Surface sea water is relatively fresh for considerable distances off the mouths of large rivers, while the highest surface salinities are found in semi-isolated areas in low latitudes (such as the Red Sea) where excessive evaporation takes place. Salt water is also found in land-locked lakes and seas; in fact, all natural waters are salty to a greater or lesser extent.

Parameters associated with salt, salt fog, and salt water depend on circumstances. Airborne salt may be characterized by pounds of salt per cubic mile of air and by its particle

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*This chapter is based on a manuscript prepared by Dr. William B. Brierly, U.S. Army Engineer Topographical Laboratories, Ft. Belvoir, Va.

size or size distribution, either by diameter or by weight. Saltfall, whereby the atmospheric salt is deposited on the land, is reported as pounds per acre per year (lb/acre/year). These values are convertible to the international system of units using the factors given in Appendix A located at the end of Part Two.

11-2 CHARACTERISTICS

11-2.1 SOURCES

Salt is a stable material which to a large extent remains in the oceans or the earth. A small fraction, however, is transported in a continuing cycle from the oceans to the atmosphere and back to the earth from whence it is returned to the oceans. This salt cycle may take a very short time or thousands of years.

In this discussion we are interested in that salt to which materiel is exposed. In the case of salt water, the sources include the oceans, inland seas, and the salt lakes. In the case of salt fog and deposited salt, the source is the atmosphere. Because atmospheric salt is important in materiel deterioration, the process by which salt becomes airborne is of interest.

Salt-saturated droplets or dry particles in the air are formed by bubbles produced on the sea surface or on the beach by breaking waves, by rainfall and snowfall on the sea surface, and by warming of sea water in the spring. Biological and chemical processes in the sea generate gases that also contribute to the continuous flow of bubbles to the surface. Bursting of a bubble produces a number of very small sea-water droplets while the collapse of the water into the cavity left by the bubble in turn jets additional droplets into the air. The droplets evaporate rapidly, at least in part, leaving a small droplet of concentrated brine to be picked up by the wind. Only one of the four or five droplets ejected from the bursting bubble is likely to remain airborne. The larger the bubbles, the greater the amount of salt released. Most bubbles are less than 200 μm in size (Refs. 4,5).*

The formation and bursting of bubbles increases with increased windspeed. The greatest amount of salt becomes airborne from strong, warm winds passing over breaking waves. The approximate critical relative humidity governing whether the salt, in equilibrium, will consist of droplets of solution or solid crystals is 76 percent (Ref. 7).

Major processes that contribute to the removal of sea-salt particles from the atmosphere are washout by liquid or solid precipitation, fallout under force of gravity, combining by surface obstacles, and encrustation of the ground and surface objects by salt-laden winds.

Washout by precipitation is the most important process. When temperatures are lowered sufficiently, salt particles serve as nuclei on which condensation forms. The agglomeration of these cloud droplets and the collection of particles during the fall of raindrops or frozen precipitation carry the salt particles to the earth. Rain usually has a salt concentration of about 1 ppm(0.001 $^{\circ}/_{\circ\circ}$). The larger the particle, the larger the raindrop and the greater its salt content. Typically, precipitation has been shown to contain roughly one-third of the total salt fallout (Ref. 8).

Dry fallout under force of gravity is important everywhere, but particularly in coastal areas where the larger salt particles are found. In Boston, Mass., a collecting bottle, continuously exposed to dry fallout and precipitation, collected 25 percent more chloride than a bottle open only to precipitation (Ref. 9). Dry fallout is important in continental interiors, such as those of the United States, where maritime airmasses

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*Other references to the formation of salt condensation nuclei, as well as to other aspects of atmospheric sea salts, are to be found in a bibliography on the subject prepared by W. B. Brierly (Ref. 6).

off the Pacific or tropical Atlantic contact cold polar air and precipitate both rain and dry sea-salt fallout. The average rate of descent of dry salt particles in the atmosphere has beer computed to be 1 to 2 cm s^{-1} (Ref. 8).

Impingement, or the combing of sea-salt particles from the air by bushes and trees, is difficult to assess because of lack of data. Analyses show that rainwater collected under trees in Sweden has much higher concentrations of inorganic ions than that collected in the open (Ref. 8). This phenomenon is attributed to dry salt accumulated on the trees by impaction. It is probably safe to state that this may be an important process in forested and bushy areas, particularly near the ocean.

Encrustment, or the coating of the ground and surface objects with a salt layer during driving windstorms, is an impaction process of local importance. The conditions under which this coating is deposited are believed to be associated with high speed, rainless winds. Encrustment causes much damage. For days after a windstorm in Halifax, Nova Scotia, the deposited salt layer interfered with the distribution of electricity when the pole insulators became conductors whenever a slight amount of moisture was precipitated on them (Ref. 10). Encrustments are likely to occur on television antennas after an intense storm in island or coastal areas.

Salt fog is an important means by which salt is deposited on exposed surfaces in maritime environments. In Chap. 9 the dependence of fog formation on the presence of condensation nuclei is pointed out. Salt particles from the sea are the most important of these condensation nuclei in the marine environment. Thus, fogs formed over the sea (which are advection fogs associated with temperature inversions) and steam fogs (which are formed in cold air over warm water) can have a high salinity level, characterizing them as salt fogs.

Salt fog is commonly associated with accelerated corrosion testing as discussed in par. 11-6.2.

11-2.2 PROPERTIES

Salt, salt fog, and salt water promote corrosion in metallic structures. At the same time salt is a necessary ingredient for life and is employed as a preservative for food. The diverse properties of salt are well documented in chemical literature. The properties of interest in this discussion are primarily those associated with salt in solution wherein it ionizes and provides a vehicle for the transport of electric charge. The salt solution with which we are most concerned is sea water, but even the effect of airborne salt deposited on materiel is similar to that of sea water. The composition is very similar although the concentration and thus the degree of the effect vary widely. Standard sea water has a salinity of 35 °/oo at 20°C.

Sea water is described by a number of physical and chemical parameters that are useful in measurement and analysis of materiel effects. The specific gravity of sea water, related directly to salinity and temperature, is shown in Table 11-1 where the values of specific gravity are given as specific gravity anomaly (specific gravity minus one).

The electrical conductivity of sea water, directly related to the salinity, is the property used for measurement in many salinometers. Comprehensive tables have been published by UNESCO (Ref. 11) from which the data in Table 11-2 are abstracted. Conductivity relative to that for standard sea water is used because the absolute conductivity is difficult to measure with sufficient precision, making the available data unreliable.

The freezing point of sea water also varies with salinity as shown in Table 11-3.

In sea water, the relative concentrations of the major dissolved elements are constant with the composition given in Table 11-4. In atypical conditions, this composition may

TABLE 11-1

SPECIFIC GRAVITY OF SEA WATER (Ref. 3)

in terms of specific gravity anomaly X 10^5, e.g., at 30°/oo and 10°C,
s.g. = 1.02308

	Temperature, °C			
Salinity, °/oo	0	10	20	30
0	-13	-32	-177	-433
10	801	750	586	315
20	1607	1532	1342	1057
30	2410	2308	2098	1801
32	2571	2464	2250	1950
34	2732	2619	2402	2100
36	2893	2775	2554	2250
38	3055	2931	2707	2400
40	3216	3088	2860	2550

vary. These conditions include those found in land-locked seas, estuaries, anoxic basins (oxygen-depleted deep basins), sea ice, warm shallow waters, and in the vicinity of submarine volcanoes.

Over 75 elements have been found in sea water. The concentrations of the minor elements (those not listed in Table 11-4) vary with time and place and contribute little to corrosive activity (Ref. 12).

TABLE 11-2

ELECTRICAL CONDUCTIVITY OF SEA WATER

Salinity, °/oo	Relative conductivity	
	15°C	20°C
30	0.87100	0.8713
31	0.89705	0.8973
32	0.92296	0.9232
33	0.94876	0.9489
34	0.97443	0.9745
35	1.00000	1.0000
36	1.02545	1.0254
37	1.05079	1.0506
38	1.07601	1.0758
39	1.10112	1.1008
40	1.12613	1.1257

TABLE 11-3

FREEZING TEMPERATURE OF SEA WATER

Salinity, °/oo	Freezing temperature, °C
5	-0.268
10	-0.535
20	-1.068
30	-1.621
35	-1.906
40	-2.196

Salt particles in the atmosphere are small, seldom larger than 40 μm in diameter, with those less than 2 μm in diameter estimated to be about 100,000 times more plentiful than giant sea-salt nuclei which have diameters ranging from 2 to 40 μm. However, of the total mass of sea-spray particles in marine air, 98 percent is composed of particles larger than 1.6 μm in diameter (Ref. 9).

Salt particles range in weight from 10^{-14} to 10^{-8} g and are primarily composed of chloride, sodium, and sulfate ions, although their relative composition may not be the same as sea water. Larger particles usually contain sodium and chloride ions in approximately the same proportion as sea water, but in small particles sulfate ions are present in greater proportion.

TABLE 11-4

COMPOSITION OF SEA WATER (Ref. 3)

Ion	Amount, g/kg of 35 °/oo water
Chloride	19.353
Sodium	10.762
Sulphate	2.709
Magnesium	1.293
Calcium	0.411
Potassium	0.399
Bicarbonate	0.142
Bromide	0.0673
Strontium	0.0079
Boron	0.00445
Fluoride	0.00128

11-2.3 LOCATION AND INTENSITY

Of the large quantity of salt entrained in the atmosphere over the oceans, only about 10 percent is carried to the land. Normal sea winds carry from 10 to 100 lb of salt per cubic mile of air but, during a storm, may carry up to 1,000 lb (Ref. 8). The highest fallout on the land is on the seacoast, mostly within 1,000 ft of the sea.

Fallout varies greatly from one coastal area to another, depending upon the salinity and temperature of sea water; the characteristics, depth, and turbulence of the maritime airmass; the direction, force, and persistence of the wind; the amount and type of precipitation; the relative humidity; the configuration and relief of the coast and its direction with respect to the prevailing winds; the elevation of the coastal features; and the extent and type of forest cover. The amount is highest in areas of heavy surfs and fogs. Observed coastal fallouts as high as 400 lb/acre/yr have been reported (Ref. 13) but are usually in the 40 to 200 lb/acre/yr range.

The amount of fallout decreases geometrically with distance from the seacoast for approximately 50 to 1,000 mi, depending on the geography of the landmass and the size and character of the maritime airmass. Beyond that distance from the coast, the decrease in fallout becomes essentially nil or at least insignificant—except for some local secondary sources of salt—and the concentration of salt in precipitation becomes fairly constant at about 2 lb/acre/yr or less (Refs. 6,9,14,15).

This pattern of decrease inland from the coast is explained by different vertical distributions of the sea-salt particles over sea and land as a result of vertical mixing (Ref. 9). In accordance with this postulate, the rapid decline in inland deposition reflects the dilution of sea-salt particles by dispersion throughout the lowest 2 to 3 km of the troposphere, where the rain is formed. This dilution occurs when maritime air moves inland, with the highest concentration of sea-salt particles being initially in its lowest layers. Coarse particles are lost, and convection tends to produce a uniform vertical and horizontal distribution of the remaining particles. Inland regions of more or less uniform fallout are those that lie beyond the point where this vertical mixing is completed.

Several exceptions to this process should be noted. The concentrations of salts in precipitation in industrial areas are likely to be higher than in nonurban areas. Monsoon-like inflows of maritime air over inland areas may cause higher saltfall than normal over long distances. Arid lands, where various salts are picked up from dry playas and salt lakes, may experience locally heavy saltfall, if the relative humidity is high enough. However, the transport of easily soluble salt from a desert surface to the atmosphere is normally unimportant when compared with the total number of sea-salt particles encountered in maritime airmasses over a desert area (Ref. 16).

The intensity of salt fallout varies widely over the world landmasses. Much of the interior of the United States, however, has a fairly uniform fallout of between 0.5 and 2 lb/acre/yr, with the lowest amounts occurring in an area bounded by Sheridan, Wyo., Goodland, Kan., Albuquerque, N.M., and Las Vegas, Nev., where the amount drops below 0.5 lb/acre/yr.

Although salt fogs are characteristic of maritime areas, fogs containing a lower proportion of salt nuclei occur at inland localities far from the seacoast. Boss (Ref. 17) indicates that coastal advection fogs along the southwest African coast contained concentrations of salt ranging from 30 to 2,000 mg/liter. From a series of 39 pairs of observations, he calculated that salt precipitation amounts to 107 lb/acre/yr.

According to Cunningham (Ref. 18), fog-water analyses on the northeast coast of the United States showed that a much larger chloride concentration in fog water originates from tropical airmasses than from polar air.

Tropical Atlantic air has a chloride content of about 35 mg/liter in fog water, while polar continental air contains only about 4 mg/liter.

Major problems in the interpretation of data related to worldwide salt fallout are:

(1) Lack of data in certain continental areas

(2) Inconsistencies in terminology, instrumentation, sampling, and measuring methods among reporting agencies

(3) Limitations of measuring devices.

Knowledge of the distribution of sea salt over the landmasses is incomplete. No systematic surveys for South America or Asia are known, and data on chloride concentration in precipitation are available for only a few stations in Africa. Distribution of chlorides in the atmosphere in these areas must be inferred from known relationships developed between environmental conditions and the distribution of sea-salt particles on other continents.

The data resulting from systematic surveys made in northwestern and central Europe, Canada, and the United States are relatively reliable. The individual analyses carried out in other parts of the world may be reliable but are difficult to evaluate.

Some of the difficulties in data interpretation arise from the use of different methods of instrumentation, sample collection, sample analysis, and units of expression. Much data are based on only one process of measurement and on isolated reports. Day-by-day sampling related to daily weather conditions is generally not available for analysis. Frequently, no information is provided about the devices used for collection and the procedures used in analyzing salt content. It is not always clear whether reported data are in terms of all sea salts, all chlorides, or sodium chloride alone. In general, the data usually refer to only one type of fallout and, since the ratio of one type of fallout to another varies from place to place in the world, the significance of the data is not easily determined. In humid areas of northwest Europe and the United States, the chloride content of rain and snow may be less than one-fourth of the total saltfall. Dry fallout and fallout from impingement and encrustment are seldom included in records.

Determination of the apparent sea-salt content of the air varies considerably according to the method used. Variation is due primarily to the range in particle or droplet size that the instrument can measure. In the wet candle method (see par. 11-3), only a small fraction of the amount of airborne salt that blows across the candle seems to be retained. It is probable that less than one-third of the fallout is being recorded at any one site and that this figure represents an even smaller fraction of the amount of sea salts actually in the air (Ref. 2).

In summary, although the data available for analysis of salt precipitation have serious limitations, the available data have been translated into results considered meaningful. When thus translated, the data fall reasonably well into atmospheric sea-salt design criteria areas discussed later in this chapter. While the data for any one area may be subject to error in varying degrees, the overall data related to worldwide distribution of saltfall are valid.

11-3 MEASUREMENTS AND INSTRUMENTATION

The design engineer has relatively few measurable parameters for describing the environmental aspects of salt, salt water, and salt fog. Desired information might include the following:

(1) Amount of salt in the atmosphere

(2) Concentration in rainwater

(3) Total salt precipitation

(4) Size distribution of atmospheric salt particles

(5) Salinity of salt water.

11-3.1 ATMOSPHERIC SALT

A large variety of measurement techniques have been applied to obtain data on aerosol salt. Several of the more important ones are described:

(1) *Chloride by precipitation method.* In this method, a precipitation gage or polyethylene bottle with a plexiglass funnel of known circumference is exposed during periods of precipitation. In areas where frozen precipitation is expected, a heating device is installed to melt the snow or ice. After a stipulated exposure time, the samples are collected and analyzed. The chloride content is turbidimetrically determined after the addition of silver nitrate to an acid solution.

(2) *Automatic flame counter.* In this instrument aerosol particles containing sodium chloride are counted automatically by the pulses of light emitted when they pass through a nonluminous flame (Ref. 19). A hydrogen flame is employed through which air is passed at rates from 5 to 300 liters s^{-1}. The image of the flame is focused on a photomultiplier tube through a narrowband filter for the sodium D emission line. The pulses from the photomultiplier are registered on a counter after passing through a threshold gate set to pass only those pulses originating from particles exceeding a defined minimum size. Generally, 1-μm-radius particles are the minimum size that are counted.

(3) *Filter collection.* Filters made from cellulose ester are available which can be used to remove all particles greater than 0.2 μm from the air passing through them (Ref. 20). Because of the electrostatic charge that builds up on the filter, the particles are retained on the surface and are available for examination. A 2-in. filter, supported on a porous carbon plate, can sample air at a rate of 30 liters/min. For microscopic examination, the filter can be dissolved in a liquid with the same index of refraction leaving the aerosols suspended in the solution. Analysis of the aerosol is facilitated by the chemical purity of the filter.

(4) *Microchemical techniques.* A particular technique that is very promising and simple to use for identifying particles of 1-μm radius or less involves the use of a thin gelatin film (Refs. 21,22). The aerosol is impacted on a gelatin film sensitized with a reagent that reacts with the particle to be detected. For chloride-containing particles, mercurous fluorosilicate and silver nitrate have been used. After impaction, a spot or halo is produced in the gelatin film which can be seen with a microscope. The mercurous chloride spots grow until the chloride is exhausted, the final radius being about nine times the radius of the original particle. This allows detection of salt particles as small as 10^{-14} g or 0.2-μm radius. Vittori (Ref. 22) was able to detect particles down to 10^{-16} g but only with very thin gelatin films that are difficult to prepare.

(5) *Wet candle method.* In this method (Ref. 9), three strips of gauze, which have been freed of chloride by repeated boiling in distilled water, are wrapped around the exposed portion of a test tube (3/4 by 5-3/4 in.) which protrudes through a rubber stopper from a 500 ml widemouthed flask, with the gauze falling into the liquid in the flask and acting as a wick. The flask contains 500 ml of an aqueous glycerine solution (20 percent glycerine by volume). The apparatus is covered with a sloping roof for protection from rain and sun, and the sides are left open for free air circulation. The site for exposure is carefully chosen and the apparatus is set up for a specific exposure period of continuous operation. After exposure, a chemical analysis of the chloride removed from the exposed wick by dissolving in water is made by titration (Ref. 18).

(6) *Other measurement techniques.* In addition to those methods described, other techniques employed to obtain information on atmospheric salt include:

(a) Bubbling measured volumes of air through chloride-free water

(b) Drawing measured volumes of air through refrigerated tubes or dew tubes

(c) Exposing wet, chloride-free cloths

(d) Measuring the chloride content of precipitation

(e) Collecting chloride as artificial dew on cold flasks

(f) Counting salt crystals on exposed slides

(g) Collecting salt by impactors or jets

(h) Precipitating, thermally, particles on glass slides

(i) Using glass plates and controlled humidity (isopiestic method)

(j) Using specially developed silver dichromate reagent films

(k) Exposing various metal plates and assemblies to the salt atmosphere.

A number of techniques depend upon accurate determination of small traces of chlorides by chemical analysis. In each method, all materials used must be free from chlorides. The results are given in terms of the chloride ion rather than salt content since the ratio of (Na^+) to (Cl^-) may vary from 0.48 to 2.43 (Ref. 9). In the physical methods, the counts are not always specific for chloride, as it is difficult to distinguish it from other salts. All of these methods are tedious and exacting.

No one procedure is entirely satisfactory for use in all environments. The most widely used methods for atmospheric salts are the measurement of chlorides in precipitation and the exposure of wet chloride-free cylinders (the "wet candle" method). These have been shown to give comparable results and to provide some relationship to the amount of corrosion experienced in the same environment.

11-3.2 SALINITY

The complexity of sea water makes it difficult to use direct chemical analysis to determine the total quantity of dissolved solids in a given sample. It is impossible to obtain reproducible results by evaporating sea water to dryness and weighing the residue, since some of the materials present (chiefly chloride) are lost in the last stages of drying. However, it has been found that, regardless of the absolute concentration, the relative proportions of the different major constituents of sea water are essentially constant, except in regions of high dilution (low salinity), where minor deviations may occur. From this fact, it follows that any one of the major constituents may be used as a measure of the others and of the total amount of salt, and that water samples having the same total salt content, regardless of their source, are for practical purposes virtually identical in their physical properties. Thus, the determination of any of the elements present in relatively large quantity can be used as a measure of the other elements and of the salinity (Ref. 23).

(1) *Titration.* Chloride ions make up approximately 55 percent of the dissolved solids in sea water and can be determined with ease and accuracy by titration with silver nitrate, using potassium chromate as an indicator. The empirical relationship between salinity and chlorinity is (Ref. 7):

$$\text{Salinity} = 0.03 + 1.805 \times \text{chlorinity}, {}^{\circ}/_{\circ\circ} \quad (11\text{-}1)$$

Both salinity and chlorinity are always expressed in grams per kilogram of sea water (i.e., in parts per thousand by weight) for which the symbol $^{\circ}/_{\circ\circ}$ is used, followed by "S" or "C" respectively when it is necessary to distinguish between them. Thus, a measure of chlorinity serves to measure the salinity values of sea water. The primary standard used in the determination of chlorinity is so-called normal water, i.e., sea water whose chlorinity has been adjusted to a standard value (about 19.4 $^{\circ}/_{\circ\circ}$) (Ref. 23). The titration method can be used to measure salinity to ± 0.00001 ‰.

Salinity can also be determined from the density of the water sample at a given temperature, and from the electrical conductivity of the refractive index, both of which depend upon the salinity (Ref. 3).

(2) *Density.* Determinations of density are rarely used as a basis for measuring salinity, since it is difficult and time-consuming to obtain an accuracy comparable to that obtained from the chlorinity titration method. When used, the methods can be classified into two groups. In the first, the mass of an accurately measured volume of water at a definite temperature is determined, for example, by using a pycnometer bottle. In the second method, some form of hydrometer or float is used, with density computed from the weight of hydrometer and the volume of the displaced water. Extremely accurate hydrometers are required for this purpose (Ref. 23). The free-floating total immersion hydrometer based on the principle of the Cartesian diver has been most successful (Ref. 3). In it a compressible float slightly less dense than water is immersed in the salt water and pressure is applied to the container until the float is neutrally buoyant. A mercury manometer is used to measure the applied pressure that is related to salinity. Accuracies to ± 0.02 ‰ S are possible.

(3) *Conductivity.* Measurement of the electrical conductivity of sea water is the favored method for obtaining salinity. Owing to the relatively high concentration of ions and the effect that temperature has upon conductivity, the apparatus and the technique employed are complicated. Measuring instruments are standardized empirically, using sea-water samples of known salinity (determined by silver nitrate titrations against normal water), and the values for the unknown samples are obtained by interpolation. In order to obtain results of adequate accuracy, extreme care must be taken to control the temperature of the conductivity cells, and the resistance must be measured accurately (Ref. 23). The conductivity must be measured to an accuracy of 1 part in 40,000 if the salinity is to be determined within ± 0.001 ‰ (Ref. 3).

A simplified diagram of the bridge circuit used in electrical conductivity measurements on sea water is shown in Fig. 11-1. *A* and *B* represent similar electrolytic cells. *R* is a variable resistance in series with *B*, the cell used for the unknown sample. Cell *A* contains sea water of known chlorinity or a standard potassium chloride solution of approximately the same conductance. *C* and *D* are fixed resistances and *S* is a slide-wire resistance. *H* is a source of alternating current, 600 to 1,000 Hz, at a potential of about 0.5 to 1.0 V. *T* represents the telephone receiver used to balance the bridge (Ref. 23).

(4) *Refractive Index.* The refractive index of sea water varies only slightly within the ranges of temperature and salinity encountered in the sea, an increase in salinity of 1 ‰ increasing the refractive index by about 0.0002, but, in an interferometer, differences in refractive index can be measured with extreme accuracy. At a given temperature such differences depend only upon the salinity; therefore, special types of interferometers have been developed for indirect determinations of salinity, using water of known salinity as a standard. Monochromatic light must be used because the refractive index varies with the wavelength. This method of determining salinity has not been widely used (Ref. 23) although it is capable of achieving accuracies of ± 0.01 ‰ (Ref. 3).

(5) *Exposure testing.* The corrosive ability of salt water is often measured by direct immersion of specimens either in natural sea water or in a prepared salt solution. The former method (natural sea water) gains the advantage of providing realistic data reflecting the synergistic effects of the various sea water constituents while the latter (prepared salt solution) yields greater scientific understanding. The use of both coated and bare metal test forms exposed for long-term periods provides the best information available for

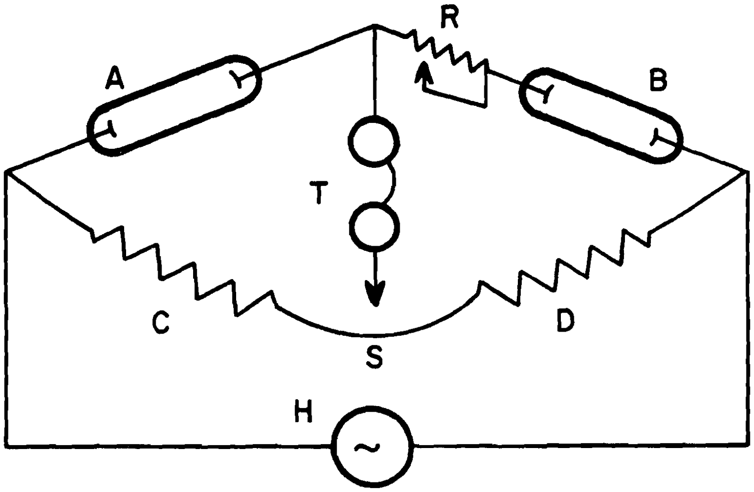

Figure 11-1. Circuit Used in Measurement of Electrical Conductivity as a Means of Obtaining the Salinity of Sea Water

practical design problems.

11-4 EFFECTS ON MATERIEL

The effects of salt on materiel almost always result from the combination of salt with another environmental factor. The two factors most commonly associated with salt are water and wind. Combinations of salt and water that occur in the atmosphere are precipitated in forms of rain, snow, fog, and dew. Salt water, of course, also makes up the oceans and some inland lakes. Wind provides the vehicle for transporting salt particles from the oceans to inland areas all over the world.

11-4.1 METALS

The principal effect of salt on materiel is its corrosive effect on metals. Although metal corrosion occurs in the absence of salt, salts greatly accelerate both chemical and electrochemical corrosion, and sufficient moisture is always present to produce these effects. Metal corrosion knowledge is largely a collection of empiricisms with perhaps the first being the observation that an iron nail will not long survive if asked to hold a copper plate on the hull of a ship.

A salt may contribute to the corrosion of metal in two general processes. It may serve simply as a neutral electrolyte for the conduction of electric current or it may ionize in water to form a strongly acid or strongly alkaline solution, in which case the free acid or alkali can react chemically with the metal. Both the electrolytic and chemical actions may occur simultaneously (Ref. 24).

As would be expected, the rate of corrosion resulting from exposure to a salt atmosphere is closely related to proximity to the sea, as has been shown in many tests. In tests of corrosion conducted in Nigeria, it was found that the decrease in corrosion with distance from the sea was very great, corrosion at only a few miles inland being appreciably lower than in inland rural Britain and, indeed, not much higher than in the dry climate of northern Nigeria (Ref. 7).

Wind direction has an obvious effect on the incidence of salt with the effect particularly important near the sea where most fallout occurs. In tests in Nigeria, screening of metals from the sea wind greatly reduced corrosion. Corrosion also declined during periods when offshore winds occurred.

Analyses of metal corrosion in sea water show that steel is corroded more rapidly by

TABLE 11-5

GALVANIC SERIES OF METALS (Ref. 26)

Metal	Potential relative to hydrogen electrode, V
Magnesium	-2.37
Aluminum	-1.7
Manganese	-1.04
Zinc	-0.76
Chromium	-0.6
Iron	-0.4
Cadmium	-0.4
Titanium	-0.33
Cobalt	-0.28
Nickel	-0.23
Tin	-0.14
Lead	-0.126
Copper	0.52
Silver	0.80
Mercury	0.85
Palladium	1.0
Platinum	1.2
Gold	1.5

tidal immersion than by total immersion, while brass is corroded more rapidly by total than by tidal immersions. Aluminum shows no consistent difference (Ref. 7).

The mixture of materials used in components and assemblies is a major factor in corrosion. Of the many types of corrosion that a marine environment encourages, the galvanic and crevice types are probably the most common and the most severe. Sea water greatly intensifies the galvanic interaction between different metals, as compared with their performance in fresh water. Shapes and joints that provide crevices into which oxygen does not have ready access may also set up a corrosion cell between areas of low and high oxygen concentration in the crevices (Ref. 25). In general, the wider the separation of the metals in the galvanic series, the greater the probability of corrosion (Table 11-5). The electrochemical potentials of some metals and alloys as measured in sea water are given in Table 11-6. The variation in surface conditions and composition causes considerable variation in observed potentials as can be seen by the wide ranges observed.

There is strong synergism between mechanical stresses, which produce cracks or changes in surface structures of metals due to stresses, and the effect of salt. The onset of stress corrosion is greatly accelerated by salt. The position of the metal in the galvanic series should be considered in the prediction of combined effects involving salt.

11-4.2 PAINTS

In paint films over metal, salt aggravates corrosion and film breakdown by increasing electrical conductivity (which favors formation of local electrochemical cells), promoting the development of alkalinity at cathodic areas (by virtue of high sodium content), facilitating steep gradients in ion concentration (which encourages osmosis through

TABLE 11-6

ELECTROCHEMICAL POTENTIAL OF SOME METALS AND ALLOYS IN SEA WATER (Ref. 27)

Relative to silver-silver chloride electrode

Metals	Range, V	
	Cathodic end	Anodic end
Titanium	0	-0.2
Monel	0.1	-0.2
Stainless steels (active areas)	0.12	-0.18
Cupro-nickels	-0.05	-0.3
Brasses and bronzes	0.1	-0.4
Nickel	0.12	-0.2
Copper	-0.04	-0.35
Lead	0.1	-0.45
Stainless steels (inactive areas)	-0.38	-0.58
Unalloyed steels	-0.55	-0.7
Aluminum alloys	-0.65	-1.13

coating films), and destroying metal passivity (owing to the high concentration of chloride ions). Paint blistering is probably the result of a combination of electrolysis and osmosis. Formation of alkali at cathodic areas, increased diffusion by virtue of the ion-concentration gradient, and the resulting internal osmotic pressure together result in blisters, and the alkali that is produced further degrades the film by direct chemical attack (Ref. 24).

11-4.3 CONCRETE

Some concrete compositions are cracked and disintegrated by salt water. Damage results from the penetration of the porous concrete by salt-laden moisture and consequent attack upon vulnerable components of the cement and aggregate by sulfate. Salts can cause disintegration of concrete in two ways. If crystal growth occurs in pores, the resulting pressure may be sufficient to disrupt the whole aggregate matrix. If chemical reaction occurs, the sulfates convert the calcium aluminate to calcium sulfoaluminate, and the chlorides produce calcium chloroaluminate, resulting in scaling and eventual disintegration (Ref. 24).

11-4.4 ELECTRICAL EQUIPMENT

Electrical equipment may be affected by salt. Sea fogs can impair insulators of overhead lines by depositing minute salt particles on their bottom surfaces, although they are protected by caps on top. Sea salt in the air, fog, dew, or precipitation impairs electrical equipment by depositing salt on the surface of insulants where it produces conductive coatings and causes or accelerates corrosion of insulating materials and metals. At relative humidities over 75 percent, the coating surfaces become strongly conductive and serious problems in distribution of electric power may result (Ref. 28).

11-4.5 MECHANICAL EQUIPMENT

Salt deposits or corrosion resulting from the salt may result in clogging or binding of moving parts of mechanical components and assemblies. High winds carrying sand, dust, and salt particles in dry areas may cause external abrasion of materials, thus accelerating corrosion processes by removing protective surfaces and coatings.

11-5 GUIDANCE FOR DESIGN

Guidance to designers on the considerations applicable to the salt environment consists primarily of:

(1) Establishment of design criteria

(2) Recommendations for protecting materials, parts, components, and assemblies.

11-5.1 PRELIMINARY SEA-SALT DESIGN CRITERIA AREAS*

It is important in design to understand the environmental conditions to which equipment and its component parts will be exposed. Although, as noted earlier, information on the extent of salt fallout on the landmasses of the world is far from complete, a preliminary map has been prepared showing worldwide sea-salt design criteria areas (Fig. 11-2). Four areas are outlined on the map:

(1) *Area I.* Oceanic islands and coastal areas

(2) *Area II.* Intermediate humid coastal and inland areas

(3) *Area III.* Subhumid to humid interior areas of low saltfall

(4) *Area IV.* Arid areas of light and variable saltfall.

The demarcated areas are general and represent the best estimates available for use by designers. Quantitative values assigned to these areas are only approximate and may not be realistic for any area near the boundaries. The salt content of the atmosphere, like the weather, changes from day to day or year to year, within statistically experienced extremes. Seacoasts are always vulnerable to exceptional windstorms and the amount of salt precipitated during one violent storm could exceed the total amount for the preceding year.

11-5.1.1 AREA I. OCEANIC ISLANDS AND COASTAL AREAS WITH HEAVY FALLOUT

Saltfall from all sources varies from a minimum of 25 to more than 300 lb/acre/yr. Individual 2- or 3-day storms may deposit as much as 30 lb/acre/storm. Daily saltfall during maximum periods may be as high as 20 lb/acre/day. Gale winds have been known (Halifax, Nova Scotia; Devonshire, England; Minorca; and Mauritius) to encrust the surface of the land and all exposed trees, buildings, and other objects with a salt cover and to scorch trees and crops severely for several miles inland.

Coastal areas of low-lying relief, and gaps in hills and mountain ranges that permit entrance of maritime air containing sea-salt particles into the interior of continents have a lower coastal fallout but a higher inland fallout. This is also true in the vicinity of embayments and inland arms of the sea that penetrate the landmasses. Areas with cuspate forelands, peninsulas, tombolos, exposed coral reefs, rocks awash, offshore sandbars, and islands in areas of moderate or more intense winds can be expected to have a high sea-salt fallout. Coastal areas that come under domination of cyclonic storms, trade winds, seasonal monsoon rains, hurricanes, tornados, and low pressure areas in general, along with areas subject to sea fogs, have high sea-salt fallout.

Considerable variation in salt fallout can be expected from year to year, but the amount of saltfall is always high. With a knowledge of certain weather conditions, saltfall can be predicted with reasonable accuracy in many areas.

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*A general reference for this paragraph is Ref. 2.

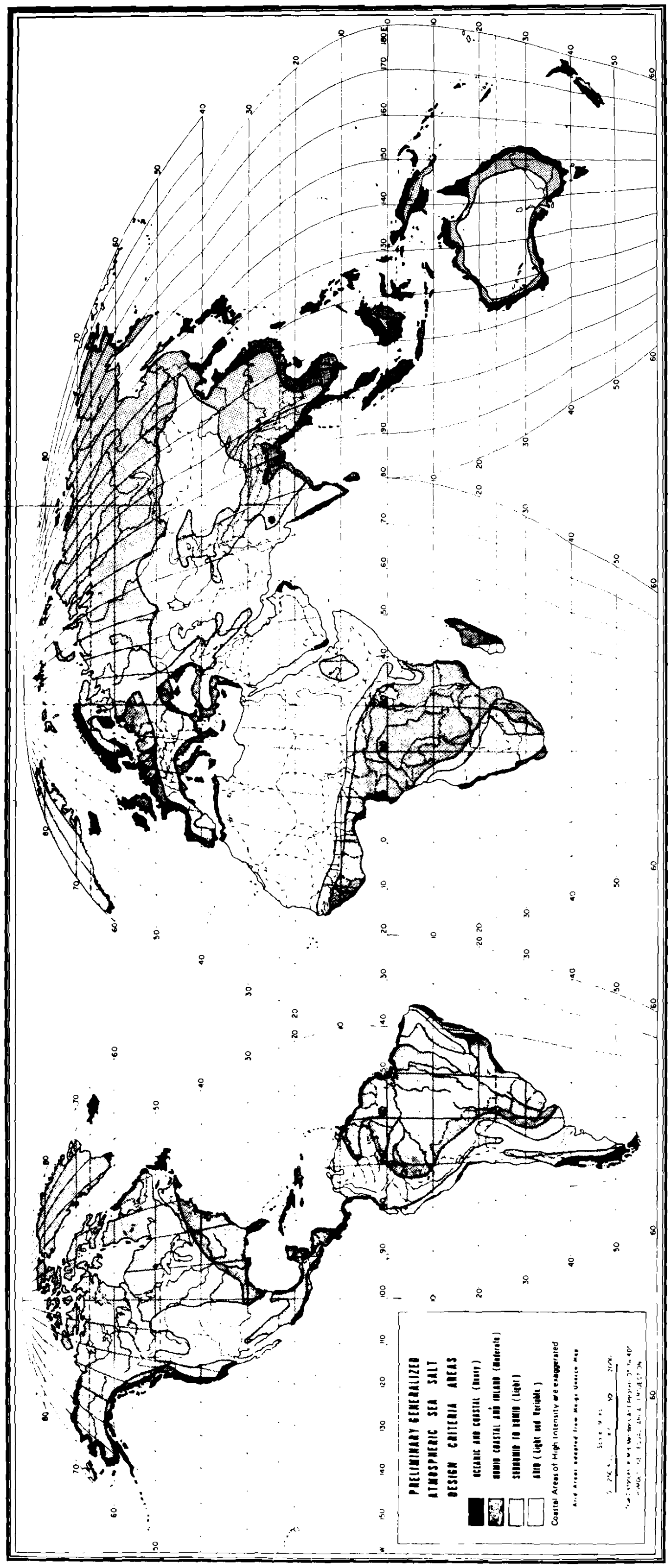

Figure 11-2. Preliminary Generalized Atmospheric Sea-salt Design Criteria Areas (Ref. 2)

11-5.1.2 AREA II. INTERMEDIATE HUMID COASTAL AND INLAND AREAS

Saltfall from all processes varies from a minimum of about 3 to a maximum of about 25 lb/acre/yr. A belt of decreasing amounts of saltfall extends from the coast, where offshore winds or winds that parallel the coast are dominant, to a point 50 to 1000 mi inland (depending on the continent) where saltfall variability is reduced to a minimum.

This area includes the industrial regions of northwest Europe, eastern United States, and southeastern Australia which are believed to contribute additional chlorides to the atmosphere in amounts sufficient to raise the annual fallout by several pounds per acre above that in adjacent regions.

In Area II, corrosion rates of ferrous metals and zinc decrease rapidly with distance from the coast. Inland areas experience little or no visible corrosion within a year. This area includes those humid parts of continents that are affected by large-scale air turbulence caused by maritime air passing from the relatively smooth sea surface to the uneven land surface. Relief varies from low-lying coasts with plainlike areas in the hinterland to cliffed coasts backed by mountain ranges that cause considerable uplift and orographic precipitation. Such coasts may be moderately saline, but salinity drops off very rapidly inland.

11-5.1.3 AREA III. SUBHUMID TO HUMID INTERIOR AREAS

Saltfall from all processes is less than 5 lb/acre/yr, as recorded by standard measurements. The areas are located primarily in the interior of continents but approach the coasts on the margin of arid areas. The boundaries nearest the coastline are determined by the uniformity of the distribution of sea-salt particles in the troposphere so that saltfall becomes approximately uniform. Inland boundaries are marked by salty surface soils that become airborne during windy periods thus increasing the saltfall in the area.

11-5.1.4 AREA IV. ARID AREAS WITH LIGHT TO MODERATE SALTFALL

Sea-salt fallout is normally less than 5 lb/acre/yr, but total localized saltfall may be abnormally high due to salt-laden winds from lakes of high salinity (some as high as 300 ‰), or to the windblown topsoil efflorescences from intermittent playa lake surfaces. Area IV includes not only regions of inland drainage, but also regions of coastal drainage where rainfall is not sufficient to remove the surface salts.

Winds may blow the sodium chloride and other salts onto installations and equipment, and salt particles may be injected into parts of operating machinery or vehicles where the relative humidity is high enough to cause internal corrosion. A unique feature of this area is the amount of external abrasion that results from driving sand, dust, and salt particles. Characteristics of this area are the seasonally continuous high temperatures or large daily ranges in temperature, low or negligible precipitation, and, consequently, little salt fallout from this process. The high evaporation contributes to the salinity of water bodies.

The area encompasses the low latitude hot-dry deserts that have resulted from the subtropical high pressure and trade wind belts. Such belts occupy the central and western sides of continents, lying for the most part in two belts between latitudes 15 and 35 deg N. and between latitudes 15 and 35 deg S. On the western side of the continents, where cold currents with local fog prevail, the area is from 5 to 10 deg closer to the equator. Also included in this area are the cold deserts, which extend from latitude 30 to 50 deg N. and occupy the enclosed interior basins of continents.

11-5.2 PROTECTION AND CONTROL

The principal effect of salt on materials is the acceleration of metal corrosion. Consequently, corrosion prevention must be a primary concern of the designer. The particular techniques that are most effective depend on the metal, the operating conditions under which it will be used, the extent to which it will be exposed to salt, and the alternatives for protection available to the designer.

Literature on the subject of corrosion prevention and control is extensive; therefore, the many procedures, techniques, and materials involved are not covered in detail in this chapter*. However, some of the major factors that must be considered by the designer are discussed and some of the more well-known protection methods are described in general terms.

Corrosion protection could be obtained by using a completely corrosion-resistant alloy, or by excluding from the surface of the metal one or more of the elements causing corrosion. The use of a completely corrosion-resistant alloy is rarely practicable in military equipment. Also, exclusion of oxygen (one of the elements causing corrosion) is difficult in equipment that must be more or less mobile. Protection, therefore, is usually sought either by employing an impermeable seal or mechanical barrier, or by reducing the corrosivity of the medium reaching the metal surface through the use of corrosion inhibitors. The two means may be employed simultaneously, as with inhibitive primers and paints, or alone as with cathodic electroplating, hermetic sealing, or vapor-phase inhibiting. Most corrosion prevention techniques are variations of these basic methods (Ref. 24).

11-5.2.1 PROTECTION THROUGH DESIGN**

Protection against corrosion must be a prime consideration from the earliest stages of design until its completion. It is essential that the most corrosion-resistant materials that satisfy the strength, weight, and other mechanical, metallurgical, and economic requirements be selected. The use of dissimilar metals should be avoided wherever practicable; when this cannot be avoided, the metals selected should be as close together as possible in the galvanic series. Combinations should be avoided in which the area of the less noble metal is relatively small; also, the more noble materials should be used for key components. Dissimilar metals should be electrically insulated wherever practical and spaced as far apart as possible. If complete insulation cannot be achieved, the use of high dielectric spacers, paint, plastic coating, tape, or other material at the joints to increase the electrochemical circuit resistance is helpful.

Materials well apart in the galvanic series should not be joined by threaded connections, since the threads will deteriorate excessively. Whenever possible, small replaceable sections (such as washers) of the less noble material may be installed at joints, and the wall thickness of the less noble material should be increased wherever practicable in the region adjacent to the joint. This will provide more material to corrode before failure occurs. In dynamically loaded structures, butt joints will help prevent entrance of water. Provisions for adequate plating, surface treatment, and finishing should be incorporated in the design. However, the galvanic effect should be considered before painting or coating steel or cast iron; it is frequently desirable to paint the more noble metal and leave steel bare, a complete reversal of the conventional practice. This is to prevent concentrated areas of attack at the inevitable pinholes in the paint which can lead to catastrophic failure. Unpainted base metal allows uniform large area corrosion while painting the noble metals decreases the rate of attack.

Positive precautions should be taken to insure against water traps in which salt-containing rainwater can be trapped. Free

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*See Refs. 29-36 for extensive background on corrosion.

**A general reference for this paragraph is Ref. 24.

drainage should be provided, even to the extent of filling cavities with a filleting compound after assembly. Structures operating in the open—such as tanks, automobiles, aircraft—are heated during the day and become cold at night, with subsequent moisture condensation on their parts, components, and assemblies. Provision should be made for removal of the accumulated water, which may contain high levels of salt. On relatively small assemblies, consideration should be given to hermetic sealing to insure that there will be no air or water transfer in the range of altitudes and barometric extremes contemplated for service. Sharp edges should be smoothed or rounded to prevent protective paint coats from becoming too thin. On materials subject to static and dynamic stresses, sharp corners, notches, and abrupt changes in section should be avoided since these areas may become focal points for stress corrosion cracking or fatigue corrosion. For materiel subject to vibration, precautions should be taken against fretting corrosion. The application of these measures in the basic design will provide a high degree of corrosion resistance, and will make additional corrosion protection and control measures more effective.

In spite of corrosion protection efforts, however, some amount of corrosion takes place in most items of equipment. Parts most subject to corrosion (e.g., those made of magnesium or aluminum) should be designed to be easily accessible for inspection and treatment.

11-5.2.2 PROTECTION BY MODIFYING THE ENVIRONMENT*

As noted earlier, a basic principle in corrosion protection is to prevent an electrolyte or oxidizer from reaching the metal surface, or to so modify the characteristics of the corrosive elements as to suppress or eliminate the corrosive reaction. Common methods include cathodic protection, application of inhibitors and passivators, and dehumidification.

In practice, iron or steel may be protected cathodically in one of two ways. In the first, it is connected to the negative side of a rectifier, the positive side of which is connected to an anode immersed in the solution surrounding the structure (or buried in the soil). In the second, the structure is connected to a metal, far removed from steel in the galvanic series, which functions as the anode. Magnesium, zinc, and cadmium are common anodic materials used. These anodic protectors are allowed to corrode and are thus sacrificed for the protection of the structural metal.

Inhibitors are substances that, when added in small amounts to a corrosive environment, effectively decrease the corrosion rate of metal. Generally, inhibitors serve to increase the polarization at the anode (anodic inhibitors) or the cathode (cathodic inhibitors). Among the most useful anodic inhibitors are chromates, for corrosion protection of steel, aluminum, and magnesium alloys. Other anodic inhibitors used primarily on steel are soluble hydroxides, phosphates, polyphosphates, nitrites, silicates, and carbonates. Calcium or magnesium carbonates have been used on magnesium, as have alkali metal or ammonium sulfides and fluorides. Red lead (plumbous orthoplumbate) is effective on iron and steel.

Magnesium, zinc, or nickel salts serve as cathodic inhibitors for iron and steel under conditions of partial immersion. Sodium mercaptobenzothiazole has been found to be an excellent cathodic inhibitor in aqueous systems involving copper and aluminum couples.

Inhibitors that appreciably change the electrode potential to a more cathodic value are called passivators. Anodic inhibitors, such as those containing chromate ions, are more likely to act in this manner than the cathodic inhibitors.

Dehumidification methods applicable to most commonly used materials consist of hermetic sealing and the use of desiccants. The objective is to control the amount of

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*A general reference for this paragraph is Ref. 24.

moisture in the air surrounding a part so that the quantities of water condensed on the surface will not be sufficient for a significant amount of corrosion to occur. Reduction to 40 to 50 percent relative humidity is sufficient for most items. A more complete discussion of humidity control methods is provided in AMCP 706-121, Engineering Design Handbook, *Packaging and Pack Engineering* (Ref. 37).

11-5.2.3 PROTECTION BY COATINGS AND SURFACE TREATMENT*

The most common methods for prevention of corrosion are the coating of the surface with a layer of another metal, chemically treating the surface, and protecting with a porcelain, ceramic, or organic coating.

In military equipment, iron and steel are the metals most commonly afforded protective metal coating and zinc alloys probably come next. Most other basic metals are corrosion-resistant except for aluminum and magnesium alloys, which require surface conversion treatments, usually followed by painting.

Metal coatings may be applied by a number of methods using a wide variety of coatings. The most commonly used method of application is electrodeposition. Other methods include metal spraying, deposition from a vapor phase, dipping into molten metal, adhesive-metal powder techniques, and metallurgical bonding through rolling.

The most frequently used plating metals on iron and steel are cadmium, zinc, nickel, chromium, tin, and lead. Under most conditions both cadmium and zinc are less noble than steel and therefore are used for galvanic protection. They also present a minimum of difficulty from dissimilar-metal contact with adjoining aluminum and magnesium alloys. Since a nickel coating is more noble than iron and steel, protection is afforded only by using the coating as an impervious barrier.

Chemical conversion treatments for metals usually are applied by dipping that causes a nonmetallic coating to be deposited on the surface. Such treatments reduce the probability of the basic metal entering into a galvanic couple and provide a controlled, roughened base for painting.

The principal types of chemical treatments used to prevent corrosion are:

(1) Chromate, widely used on zinc and cadmium surfaces

(2) Phosphate, used for steel, zinc, aluminum, and cadmium surfaces. Phosphate coatings may have a zinc, iron, or manganese base, depending on the particular characteristics required for the coated metal.

(3) Dichromate (Dow 7*), applicable to most magnesium alloys, provides the best paint base and corrosion protection qualities of all the dip treatments for magnesium–Iridite 15** (similar to the Dow 7) treatment and the sealed chrome pickle (Dow 10*) treatment are similar to the Dichromate treatment.

Coatings of inorganic materials are usually fused in place on the metal base. Ceramic coatings are used in applications requiring prolonged stability at high temperatures (red heat and above). Porcelain enamels are applicable at much lower temperatures. Ceramic coatings protect against intergranular corrosion of metals and alloys, serve as gas barriers, reduce hot-spot occurrence, permit the substitution of low-alloy metals for critical metals, and resist contamination.

Protection provided by a paint coating is due to its ability to act as a mechanical barrier, thus preventing the corrosive medium

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*General references for this paragraph are Refs. 24 and 38.

*Dow 7 and Dow 10 are trademarks of the Dow Chemical Company.

**Iridite is a trademark of the Allied Research Products Company.

from reaching the metal surface. Paint, as used in this discussion, includes all types of protective organic based coatings, applied hot or cold. Requirements for impermeability, adhesiveness, durability, and resistance to abrasion and erosion normally necessitate the use of more than one coating. The first coating is generally a primer that promotes maximum adhesion to the surface and may provide an inhibitive and continuing passivating effect. Passivating treatments are particularly important on very active surfaces such as magnesium, zinc, aluminum, and steel.

The primer normally contains a corrosion inhibitive pigment, frequently zinc yellow or red lead. However, heavy metal pigments such as red lead cannot generally be used on magnesium, aluminum, or their alloys; therefore, other primers are used on these metals. The paint coating, or coatings, applied over the primer provide the barrier.

The prime source of information on corrosion preventing coatings is the Coating and Chemical Laboratory, Aberdeen Proving Ground, Md.

11-5.2.4 PROTECTION BY OTHER MEANS

Other means of protection are frequently beyond the control of the designer. The location and use of materials and equipment in areas where saltfall is minimal reduces problems associated with salt but, for most items of military equipment, this alternative is not normally available. However, since the heaviest saltfall occurs within a relatively short distance of the shoreline, careful site selection for coastal facilities can greatly reduce the exposure to salt. Motor pools and other areas where equipment is exposed to the atmosphere should be located away from the beach and should take advantage of topographic features that influence saltfall.

Shielding equipment on a beach from sea winds substantially reduces corrosion. Sheet steel stored in the open about 600 ft from a beach corroded six times as fast as steel, from the same stock and in the same area, stored in the lee of a large building. Screening of equipment from direct salt fallout can be accomplished by placing a polyethylene covering on each item, or by erecting pieces of muslin or foliage on the windward side of the equipment (Ref. 7).

One of the most practical ways to reduce corrosion of steel beams and plates stored on a beach is to bury it in dry or impervious soil. Jungle plants adjacent to a beach also provide greater protection to equipment stored under their canopy than does simple exposure on the beach (Ref. 7).

Exposed fixtures such as antennas near a seacoast should be cleaned frequently and protective coatings applied, if possible. Frequently, design for drainage of the insulator proves advantageous.

11-6 TESTING

The objective of salt-fog and salt-water testing is to determine the resistance of materials, parts, components, assemblies, and equipment to the effects of a salt environment. Measurements are primarily concerned with the extent of corrosion of materials produced by the environment and the operability of test items after exposure.

11-6.1 TESTS IN THE NATURAL ENVIRONMENT

The effects of salt water and salt atmosphere may be measured by exposing materials, parts, components, and assemblies to the natural environment under controlled conditions of exposure and time. Test items generally are exposed at different distances from the seashore, at different heights, at different angles, under varying degrees of exposure to the wind, rain, sun, and other elements, and for different time periods. Samples are cleaned (sandblasting and pickling are common methods for metal) and weighed (Refs. 39,40). At the conclusion of the test, the test materials are cleaned of corrosion products, reweighed, and inspected carefully. Pit depths are measured and any other unusual results noted. Weight loss is normally expressed in terms of weight per unit of area per unit of time, such as $g/dm^2/mo$ or $mg/dm^2/day$. Damage to organic coatings is described in terms of chalking, flaking, blistering, etc. Components, assemblies, and equipment items are carefully checked for corrosion and any areas of corrosion are recorded and described (Refs. 39,40).

Similar tests are also performed on some types of naval equipment by exposing it either at dockside or on the weather deck of a ship for specified periods of time and measuring the results of the exposure. Such a procedure for torpedoes is described in MIL-T-18404 (WEP), *Torpedoes, Environmental Requirements; General Specification for* (Ref. 41).

Items operated totally or intermittently in sea water also are tested frequently by total and intermittent immersion in the sea for specified periods of time. MIL-T-18404 requires repeated immersion of the test item in natural sea water and tests for operability upon conclusion of the immersion cycles.

11-6.2 TESTS IN A SIMULATED ENVIRONMENT

Although it is recognized that no single laboratory test or combination of simulated laboratory tests presently in use can accurately reproduce the effects of outdoor corrosion due to a salt atmosphere, on all materials, the environmental engineer must have some test method or methods to give at least a rough approximation of the effects of salt-fog exposure conditions found in nature. During the early 1940's many governmental, industrial, and professional engineering organizations attempted to establish such tests. The pioneer work done by organizations working within the American Society for Testing Materials (ASTM) appears to have been adopted, both with and without modifications, by industry to meet its specialized needs, and without modification by the Government to meet its generalized needs. Detailed test methods developed during this 30-yr period have been refined and ultimately culminated in Method 509 of MIL-STD 810 (Ref. 42).

Originally the salt-fog solution was a 20-percent mixture of sodium chloride (NaCl) and pure water. Later, when ASTM determined that a 5-percent mixture produced more correlatable results, 5 percent then became the only one quoted (ASTM Method B117-6, *Salt Spray (Fog) Testing*). Some old detail specifications, however, still quote the 20-percent mixture that is still used exclusively in the testing of replacement parts procured against long-standing contracts that originated when 20 percent was the only value used.

Another salt-spray corrosion test method developed by the Society of Automotive Engineers (SAE), the Copper-Accelerated Acetic Acid-Salt Spray (Fog) Testing (Cass Test), ASTM B 368-61T, is still specified by some automotive engineering groups because they feel that it gives more realistic results.

Most testing of the effects of a salt atmosphere on material is performed in a salt-spray or salt-fog chamber. Descriptions of the test equipment, test conditions, and test procedures are given in Method 509 of MIL-STD-810 and will not be repeated here (Ref. 42). However, certain test deficiencies noted in the Military Standard are important, i.e.,

(1) The salt fog used in the test does not truly duplicate the effects of a marine atmosphere.

(2) It is highly doubtful whether a direct relationship exists between salt-fog corrosion and corrosion due to other media.

(3) The test is generally unreliable for comparing the corrosion resistance of different materials or coating conditions, or for predicting their comparative service life.

(4) The successful withstanding of the test does not guarantee that the test item will

prove satisfactory under all corrosive conditions.

The duration of the test is 48 hr or as specified in the appropriate equipment specification. At the completion of tests, items are inspected for corrosion, operated, and results are compared with pretest operating data. Items are operated again after being stored in the ambient temperature for 48 hr (or the time period specified in the equipment specification), and the results are again compared with pretest data.

It is highly desirable to supplement salt-fog chamber tests with field tests. If field service test data can be correlated with salt-fog chamber test data, some idea of the service life of different samples of the same or closely related metals, or of protective coating-base metal combinations exposed to marine or seacoast locations can be obtained. Correlation tests also show the degree of acceleration, if any, provided by the laboratory test.

Salt-water immersion tests (simulating sea water conditions) are normally performed in immersion tanks. Temperature, solution, speed, solution level, and other conditions are controlled. Items are immersed in the tank for specified periods of time and inspected for corrosion and operability.

11-6.3 TEST RANGES

Testing in the natural environment can be accomplished at any location, although for obvious reasons most such testing is done in coastal areas where saltfall is heavy. Tests have been carried out at Kure Beach, N.C.; Lighthouse Beach, Nigeria; Durban, South Africa; and a number of other locations (Ref. 43).

Tests of the effect of the salt atmosphere on Army materiel are conducted, for the most part, at the U S Army Test and Evaluation Command Tropic Test Center, Fort Clayton, C.Z. As mentioned earlier, the Atlantic coast of the Canal Zone has one of the highest salt fallout rates of any area in the world. Test items are exposed to the salt conditions on racks for specified periods of time to measure the effect of this environment on the material (Ref. 44).

The Naval Research Laboratory, Washington, D.C., maintains a Marine Corrosion Laboratory at the U S Naval Station, Key West, Fla. This facility has piers available for immersion and tidal testing, and a steel seawall for evaluating performance of galvanic anodes under conditions approximating those encountered in fleet operations (Ref. 45).

11-6.4 SIMULATION EQUIPMENT*

Simulation equipment consists primarily of salt-spray (fog) chambers. A high percentage of the chambers located at military installations are small, with dimensions of 4 by 4 by 4 ft or less. The specifications for a chamber to meet military testing requirements are contained in MIL-STD-810 cited earlier (Ref. 42).

For salt-fog testing of large items, a temporary salt-spray chamber can be improvised if a heated room or walk-in size high temperature chamber is available. Taking into consideration the basic item mass and the chamber volume requirement, a framework of standard stud lumber can be constructed in the heated room and covered with heavy-duty sheet vinyl plastic. The plastic is then heat-sealed at all joints and a plastic slide-type fastener is installed in one side for the "door". A suitable number of fog atomizers can be suitably located within this plastic enclosure and a condensate drain provided therein. A salt and water mixing tank and a circulating pump must then be provided externally with feed-throughs to the nozzles in the plastic enclosure. By controlling the temperature in the room supporting the plastic enclosure and the salinity of the salt-water mixture pumped to the nozzles, the test item placed within the plastic enclosure can then be tested to specification requirements.

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*A general reference for this paragraph is Ref. 45.

Salt-spray (fog) chambers are available at a large number of military installations, including most laboratories. The Army has test chambers at Mobility Equipment Research and Development Center, Ft. Belvoir, Va. (2); Electronics Command, Ft. Monmouth, N.J.; Tank-Automotive Command, Warren, Mich.; Test and Evaluation Command, Aberdeen Proving Ground, Md. (2), one of which is 10 by 10 by 10 ft; Armament Command, Rock Island Arsenal, Ill.; Picatinny Arsenal, Dover, N.J.; Missile Command, Redstone Arsenal, Ala. (2), one of which is a rain and salt-spray chamber 38 by 18 by 10 ft; Edgewood Arsenal, Md.; and Transportation Engineering Agency, Ft. Eustis, Va. There are test chambers at most Air Force and Navy research and test laboratories, as well as many other activities. The Naval Ordnance Laboratory, Silver Spring, Md., has three chambers, one of which is 28 by 4 by 14 ft. The Proving Ground, Eglin Air Force Base, Fla., has a salt-spray room that is approximately 29 by 13 by 18 ft in size.

A salt-water bath for immersion testing is located at the Naval Research Laboratory, Washington, D.C. This environmental tank measures 68 by 34 by 34 ft. The National Research Laboratory, Marine Corrosion Laboratory at Key West, Fla., has a sea-water pumping system capable of pumping clean sea water into the laboratory for salt-water corrosion tests.

11-7 SPECIFICATIONS

Basic procedures for salt-fog testing, apparatus requirements, chamber construction, and performance standards are contained in Method 509 of MIL-STD-810, 15 June 1967, *Environmental Test Methods* with Notices 1 (20 October 1969) and 2 (29 September 1969). Specific instructions regarding length of tests, number of repetitions, and test requirements after exposure are contained in individual specifications for components, assemblies, and equipment items (Ref. 42).

Instructions for cleaning, coating, and preserving metals to prevent corrosion are contained in MIL-HDBK-132, TB 700-8010-1, 31 October 1960, *Military Handbook: Protective Finishes* (Ref. 38). A large number of military and Federal specifications and standards are cited in this handbook relating to the several processes used to increase the corrosion resistance of metals.

Information and guidance on the prevention of corrosion of metals in storage, including descriptions of humidity control methods, standards, equipment, and procedures are contained in AMCP 706-121, Engineering Design Handbook, *Packaging and Pack Engineering* (Ref. 37).

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CHAPTER 12

OZONE*

12-1 INTRODUCTION

Ozone (O_3) is a gas that occurs in the lower atmosphere in varying, usually low, concentrations coming from both natural and artificial sources. Since it is highly reactive and can be harmful to both personnel and materiel, its presence as an environmental factor is of concern to design engineers who are charged with providing protection of personnel and preservation of materiel.

Ozone was recognized and named in 1845 by C. F. Schonbein (Ref. 1). Its molecular formula was determined later as being O_3, an allotrophic, or modified form of oxygen. Many measurements of ozone were made using either Schonbein's technique or some modification of it. This consisted of hanging paper or cloth that had been dipped in a solution of potassium iodide and starch in the air for a prescribed period of time. Ozone oxidizes iodide to elemental iodine producing a blue color in the presence of starch. Many of the early measurements were relative (referring to the relative intensity of the blue color) rather than absolute.

Schonbein's method of analysis is subject to many chemical interferences, both positive and negative, by other atmospheric constituents, particularly pollutants. The environmental ozone concentrations obtained in the mid-1880's were higher in rural areas than they were in city industrial areas, probably due to the effect of the sulfur dioxide in the city air on the measurement technique. These early environmental measurements were partially responsible for the erroneous conviction that "ozone is good for you", a view still held in some circles. Molecule for molecule, however, ozone is one of the most poisonous and most highly reactive substances known.

As stated, ozone is an allotrophic form of oxygen. Oxygen in its usual form, O_2, comprises about 21 percent by volume of the atmosphere. Ozone occurs naturally at the surface of the earth in concentrations usually under six parts per hundred million (pphm) by volume and is unlikely to be encountered even in hazardous situations at concentrations of more than a few parts per million (ppm). Its reactivity, however, frequently makes it a better oxidizing agent than molecular oxygen in spite of the far higher concentration of molecular oxygen.

In the literature on atmospheric ozone as an air pollutant, frequent reference is made to "oxidants". An atmospheric oxidant is defined according to the method used to measure it, but often it is defined as any substance that will oxidize iodides to iodine. Ozone is in this class of oxidants that includes nitrogen dioxide, hydrogen peroxide, peroxy organic acids, other hydroperoxides, peroxyacetyl nitrates (PAN), and other compounds.

Ozone is the most powerful oxidizing agent of the group and is usually the most toxic. Some of the other oxidants, PAN for example, cause specific biological effects that give them a special importance. These substances are generally considered to be generated by photochemical processes in the lower atmosphere, particularly in polluted air.

12-2 PROPERTIES

Table 12-1 contains a list of some of the

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*The primary author of this chapter is L. A. Ripperton of the Research Triangle Institute.

TABLE 12-1

PHYSICAL PROPERTIES OF OZONE (Ref. 2)

Molecular formula	O_3
Molecular weight	48.0
Gas, color	Colorless
Liquid, color	Dark blue
Solid, color	Blue-black
Boiling point	-111.9°C
Melting point	-192.7°C
Solubility (At 760 torr and 0°C)	0.49 ml/100 ml water
Vapor density	
At 0°C, 760 torr	2.14 g/liter
At 25°C, 760 torr	1.96 g/liter
Specific gravity (relative to air)	1.658

properties of ozone (Ref. 2). Pure liquid or solid ozone is explosive, but will never be encountered by anyone except those performing research with it. The only part of the environment that contains ozone is the atmosphere.

Two general systems are used to denote concentration of trace atmospheric constituents, i.e., mixing ratio and concentration per unit volume. There are, in turn, several ways of expressing each of these. A mixing ratio is an expression of the amount of ozone in a given amount of air *if* both are expressed in the same units. A "concentration per unit volume" type of unit is some expression of the absolute amount of ozone in a given volume of space. These can be related but conversion factors are not identical under all conditions (see Table 12-2).

12-3 OCCURRENCE AND SOURCES

12-3.1 OZONE SOURCES

The sources of ozone at the surface of the earth can be designated as (1) stratospheric-natural, (2) tropospheric-natural, (3) tropospheric-pollutant, or (4) direct generation from oxygen, usually by accidental or unguarded energy releases.

Stratospheric ozone encountered in unpolluted air at the surface of the earth is probably synthesized in the stratosphere and transported to the surface by atmospheric circulation. The natural concentrations encountered are in the parts per hundred million range and are unlikely to exceed 6 pphm.

Stratospheric ozone is produced by photochemical processes that begin with the absorption of solar radiation, a reaction that splits the oxygen molecule. The resultant oxygen atoms then combine with oxygen to form ozone. These reactions are:

$$O_2 + \underset{\text{(photon)}}{h\nu} \rightarrow O + O \ (\lambda < 240 \text{ mm})$$

$$O + O_2 + M \rightarrow O_3 + M \text{ (M is any third molecule).}$$

Synthesis of ozone in the troposphere, both in polluted air and in unpolluted air, takes place by a different set of photochemi-

TABLE 12-2

OZONE CONCENTRATION EQUIVALENCIES*

Type of unit	Units employed for concentration	Pressure		
		1 atm 760 torr	0.5 atm 380 torr	0.25 atm 190 torr
Mixing ratio	ppm	1	1	1
	μg O_3/g dry air	1.6	1.6	1.6
Concentration per unit volume	10^{-6} moles/liter	4.46	2.23	1.12
	10^3 μg/m^3	2.14	1.07	0.535
	10^3 μmb**	1.01	0.507	0.254

*All of the quantities given are for a 1 ppm concentration in a given air sample at the pressures indicated and 0°C

**μmb = micromillibar = 10^{-9} atm

cal reactions. The process can be represented in a simplified manner by the following set of reactions:

$$NO_2 + h\nu \rightarrow NO + O \ (\lambda < 380 \text{ mm})$$

$$O + O_2 + M \rightarrow O_3 + M$$

$$NO + O_3 \rightarrow NO_2 + O_2$$

Here, M behaves as a catalytic agent for the formation of ozone.

If only the inorganic gases are present, the net concentration of ozone produced at any time is small. If, however, organic vapors are added, a greater ozone concentration can be generated directly, possibly by reaction involving oxygen and organic free radicals (uncharged molecular fragments with one impaired electron, symbolized as R ·), or indirectly by oxidation of nitric oxide to nitrogen dioxide by some organic substance, possibly an organic peroxy radical. This latter step allows the ozone from nitrogen dioxide photolysis to accumulate rather than react with nitric oxide. The applicable reactions are of the type:

$$\left.\begin{array}{l} O + \text{olefin} \rightarrow R\cdot + R\cdot CO \\ R\cdot + 2O_2 \rightarrow RO\cdot + O_3 \end{array}\right\} \text{Direct}$$

$$\left.\begin{array}{l} R\cdot + O_2 \rightarrow ROO\cdot \\ ROO\cdot + NO \rightarrow RO\cdot + NO_2 \end{array}\right\} \text{Indirect}$$

Internal combustion engine exhaust contains the ingredients necessary to generate high atmospheric concentrations of ozone (still < 1 ppm).

In nature the sun can produce ozone by irradiating organic vapors from plants (e.g., turpentine vapors) and oxides of nitrogen from the soil, although, as a rule of thumb, synthesis in polluted air generally produces up to 10 times the natural concentration of ozone found at the surface of the earth.

Ozone also is produced by electrical discharge, both manmade and natural, by ultraviolet radiation, and by nuclear radiation. Potentially, any energy form, the quanta of which have energies exceeding that of the oxygen-oxygen bond, can generate ozone:

TABLE 12-3

OZONE GENERATION RATES (Ref. 4)

Source	Maximum yield, g kWh^{-1}	Maximum concentration, percent by volume
Electric discharge in O_2	150	6.
Electrolysis of H_2O	12	20.
Photochemical		
185.0-253.7 nm	25	0.25
140.0-170.0 nm	25	3.5
Radiochemical		
With O_2 gas	220	0.006
With O_2 liquid	108	5.
Thermal	56	0.33

$$O_2 + \text{energy} (> 117 \text{ kcal per mole}) \rightarrow O + O$$

$$O + O_2 + M \rightarrow O_3 + M$$

Electrical discharge, ultraviolet radiation, and nuclear radiation are used in the laboratory to generate ozone under controlled conditions. In commercial ozonizers, an electric discharge is generated between closely placed electrodes in the presence of oxygen or air. Concentrations of 10 to 14 percent ozone can be obtained in this manner, depending on the impressed voltage and the geometry of the ozonizers.

Ultraviolet radiation of < 0.24 μm (240 nm) wavelength and high energy nuclear radiation can form ozone in air or oxygen (Ref. 3). Generally, the radiation hazard is greater than the ozone hazard in the vicinity of the source, but the ozone generated in this manner can provide a useful supply as well as a significant hazard. Power lines that produce corona discharge also produce ozone. Table 12-3 indicates ozone yields per unit of energy and the approximate maximum ozone concentration obtainable (Ref. 4).

Many unshielded energy sources can generate undesirable ozone in a working or storage area. Although military electronic materiel can produce ozone, this condition will normally be associated with equipment malfunctions. High voltage power supplies associated with radar, communication equipment, and television are prone to electrical arcing when insulation degrades. Rotary electrical equipment will sometimes generate ozone if the brushes are dirty. Since such equipment is often located in a small enclosure, it is possible to obtain ozone concentration levels harmful to both personnel and equipment.

12-3.2 DESTRUCTION OF ATMOSPHERIC OZONE

In the environment, ozone is an active agent. This activity leads to its consumption or destruction by a variety of processes. The possible mechanisms for destruction of tropospheric ozone are (1) thermal decomposition, (2) photochemical reactions, (3) reaction with airborne particles, (4) reaction with the surface of the earth, and (5) reaction with airborne gases.

Thermal decomposition of ozone is too slow to be of importance at normal atmospheric concentrations (Ref. 5). Photolysis of ozone is also negligible due to the rapidity of the recombination of atomic and diatomic oxygen (O and O_2).

Reaction of ozone with airborne particles may be important under some conditions. Utilizing Junge's number density and size range for a continental aerosol (Ref. 6) and a collision yield (number of molecules destroyed/total number of collisions) calculated from Aldaz's rate constants (Ref. 7), a rate of destruction of about 4% hr^{-1} can be calculated for ozone. This will vary depending on time and place.

Comparison of various values for the rate of ozone destroyed in the troposphere (Ref. 6) and Aldaz's rate constants for reaction of ozone destroyed by various surfaces (Ref. 7) indicates that the surface of the earth is an important sink for ozone. Aldaz obtained rate constants from which collision yields of about 5×10^{-5} for the reaction of ozone with New Mexican soil and 3.5×10^{-6} for reaction with water were calculated. If reaction with the surface of the earth were the only ozone sink, the inference would be that the difference in surface reactivity would cause a large difference in concentration of ozone between surface *marine* air and surface *continental* air. No such difference has been observed.

Destruction of ozone by reaction with other gases has received little attention. Robinson and Robbins (Ref. 8) estimated the annual rates of evolution of the reactive gases—hydrogen sulfide, oxides of nitrogen, and hydrocarbons. On the assumption that all the oxides of nitrogen (NO_x) are nitric oxide (NO) and all hydrocarbons are mono-olefinic terpenes (reacting in bimolecular reaction with ozone), the ozone-equivalent quantities of the three categories of gases is 3.1×10^{13} mol yr^{-1}. The fact that ozone-destructive gases and ozone both exist in the atmosphere is proof that some ozone destruction takes place by gas phase reaction. Ozone is exposed to destruction by gas phase reaction before it is exposed to destruction by reaction at the surface of the earth. The reactive gases include nitric oxide, nitrogen dioxide, olefinic hydrocarbons, and possibly others, such as hydrogen sulfide and aldehydes.

Deliberate destruction of ozone on a small scale can be achieved by bringing ozone into contact with any of a number of substances such as rubber, manganese dioxide, and activated carbon. Many kinds of filters will pass ozone when clean but in operation these quickly pick up a coating of grease that subsequently destroys the ozone that contacts it.

12-3.3 SPATIAL AND TEMPORAL VARIATION OF OZONE

Much of the data on ozone concentrations are for the higher levels of the atmosphere because of scientific interest in the natural global generation and circulation cycles. Ozone levels in the lower levels of the troposphere are subject to a variety of influences that are only partially understood at this time.

Figs. 12-1 through 12-3 (Ref. 9) give representative data on the spatial and temporal variation of atmospheric ozone concentration on a global scale. As can be seen in the figures, ozone is more abundant toward the geographic poles than toward the equator. Ozone values are highest in spring and lowest in the winter. In Fig. 12-4, the variability in ozone concentration over a 7-mo period are plotted in order to show seasonal trends in the upper atmosphere. Figs. 12-5 through 12-10 are "ozonagrams" (vertical ozone soundings) from the data of Hering and Borden (Ref. 10). These show representative vertical distributions of ozone including the maxima in the stratosphere. As can be seen, the tropospheric values are much less than the stratospheric values.

The ozonagrams each consist of separate plots of ozone concentration and temperature as a function of altitude. Altitude is given in terms of pressure measured in millibars. In the

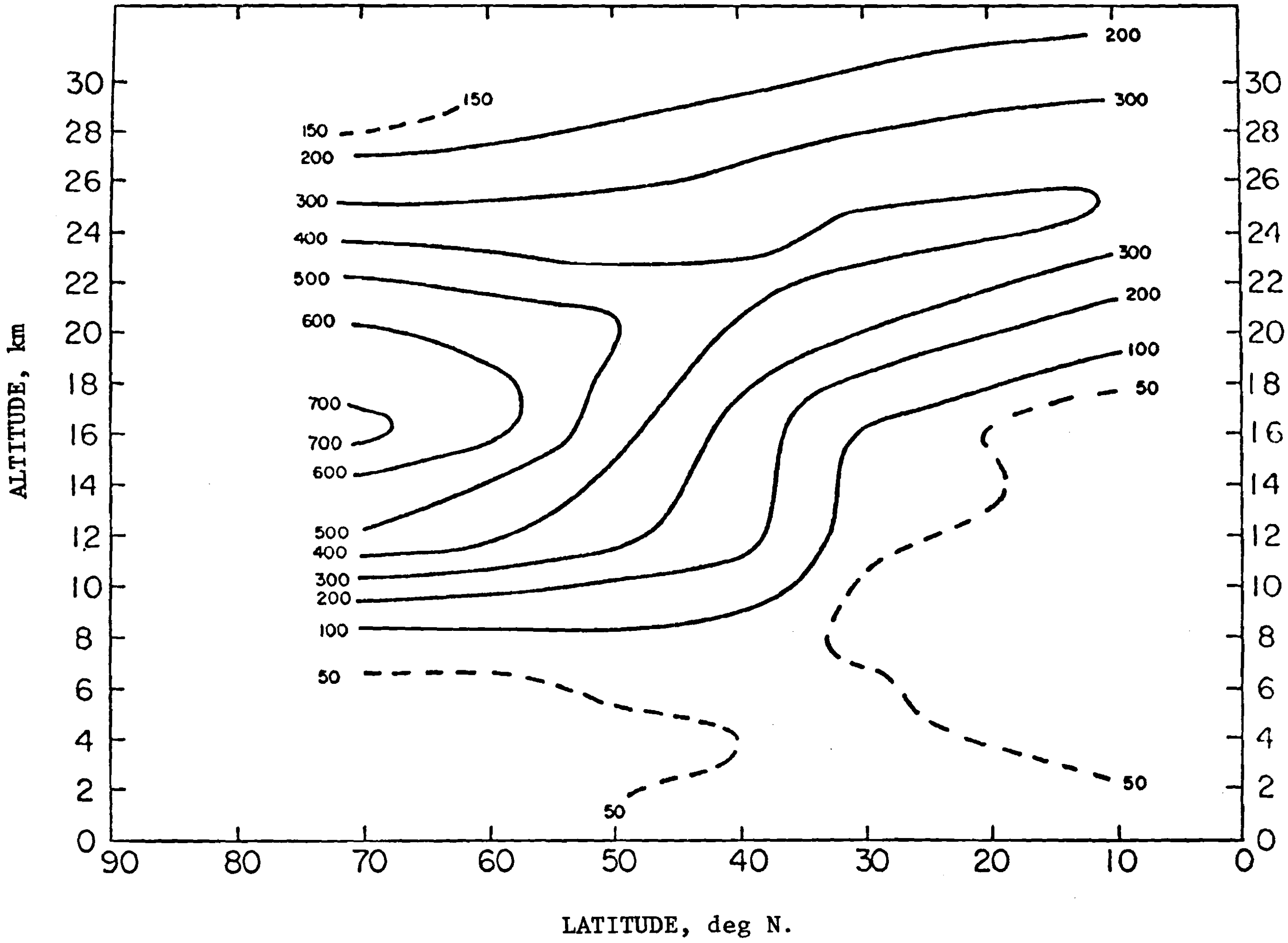


Figure 12-1. Mean Ozone Density for March-April 1963 (Isopleths for ozone concentrations in μg m^{-3})

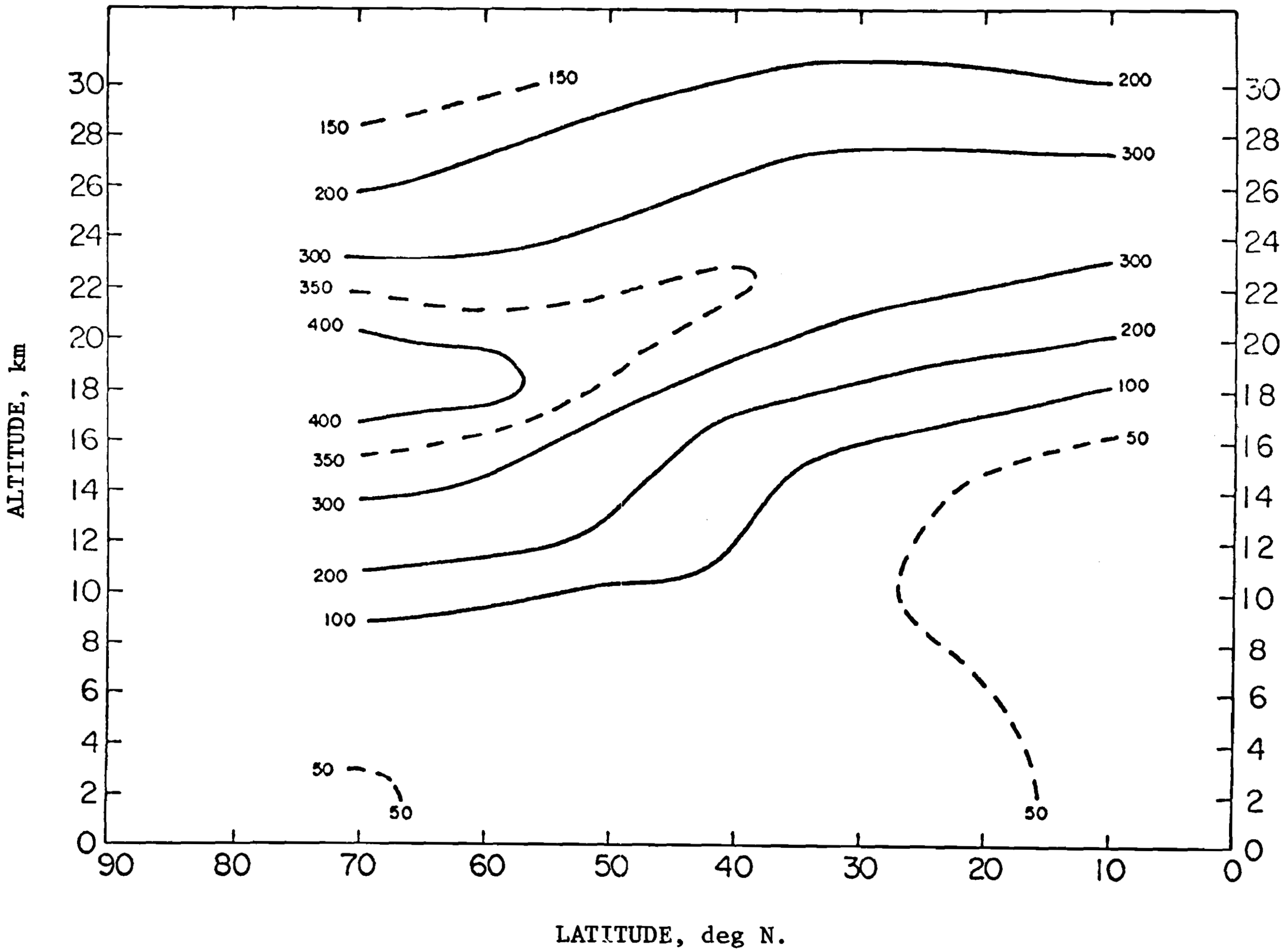


Figure 12-2. Mean Ozone Density for July-August 1963 (Isopleths for ozone concentrations in μg m^{-3})

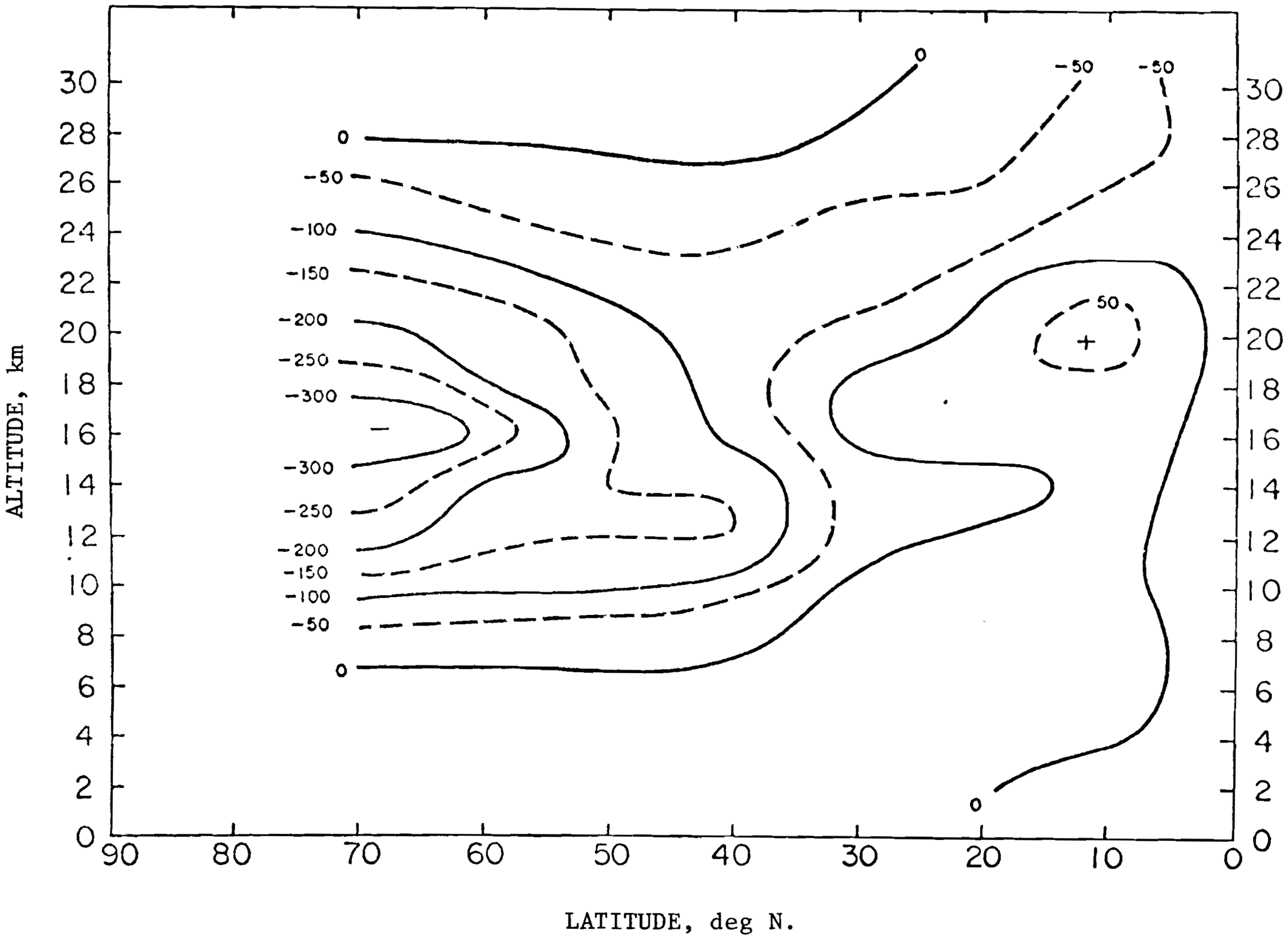


Figure 12-3. Changes in Mean Ozone Density, July-August 1963 Minus March-April 1963 (Isopleths for concentration changes in $\mu g\ m^{-3}$)

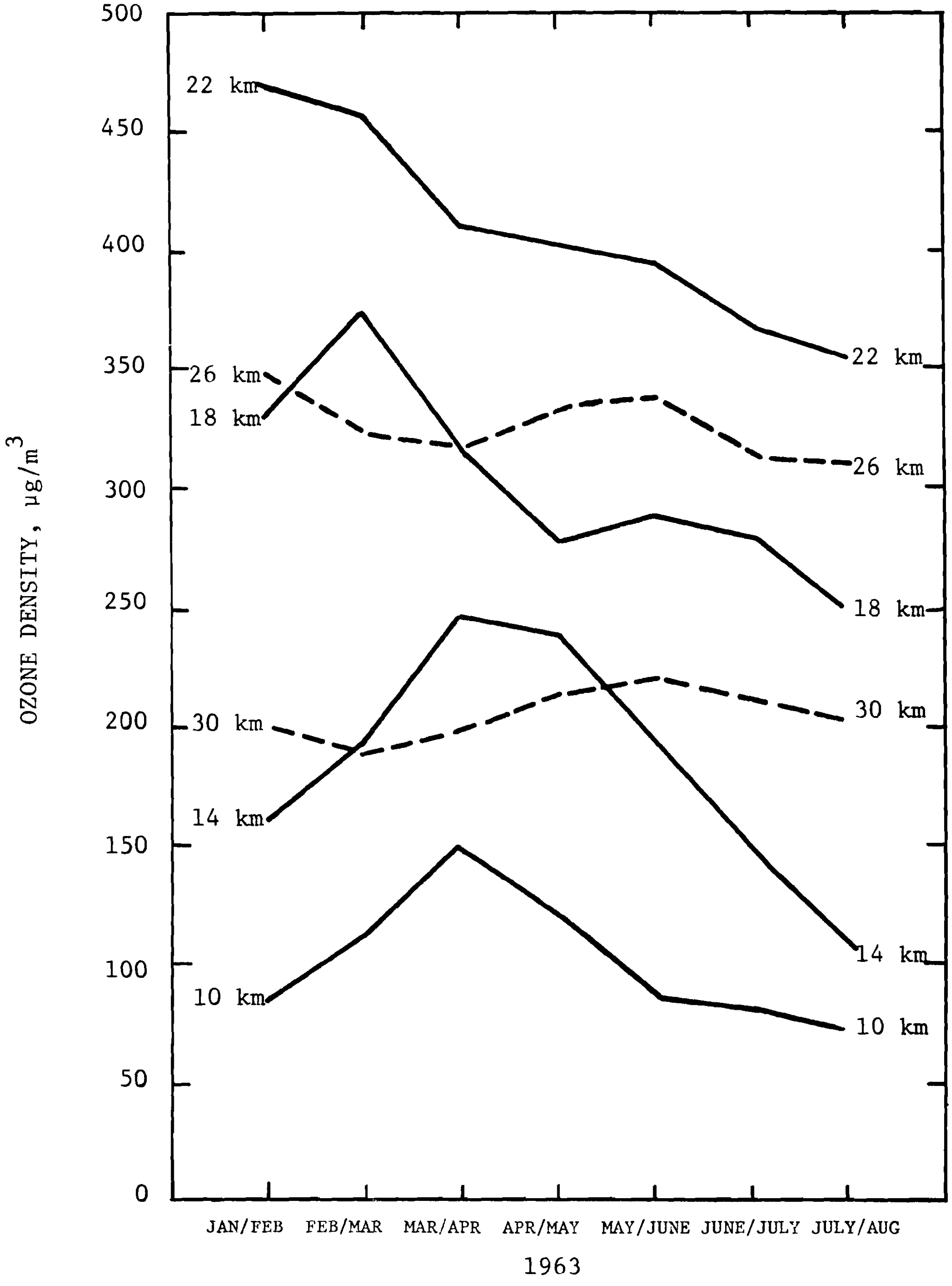
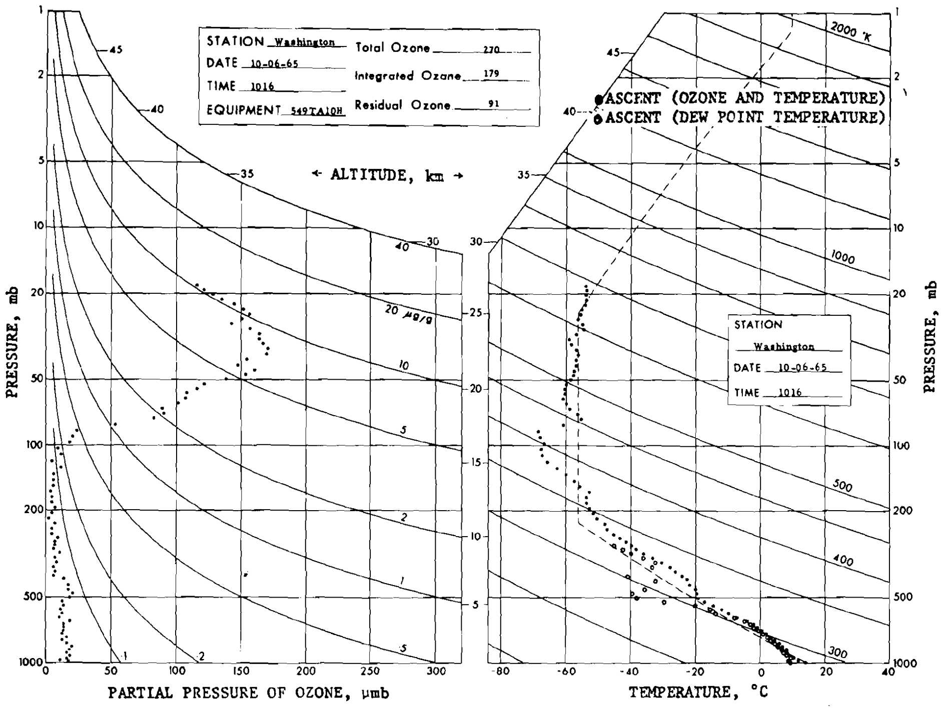


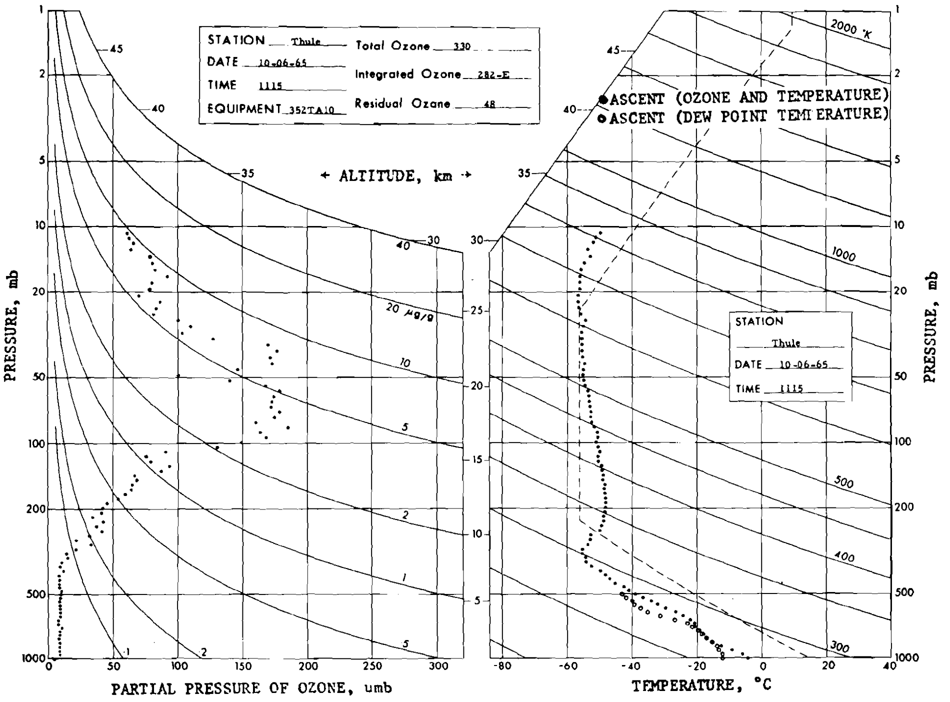
Figure 12-4. Seasonal Changes in Mean Ozone Density at Latitude 40 Deg N.



STATION Washington
DATE 10-06-65
TIME 1016
EQUIPMENT 549TA10H
Total Ozone 270
Integrated Ozone 179
Residual Ozone 91

STATION Washington
DATE 10-06-65
TIME 1016

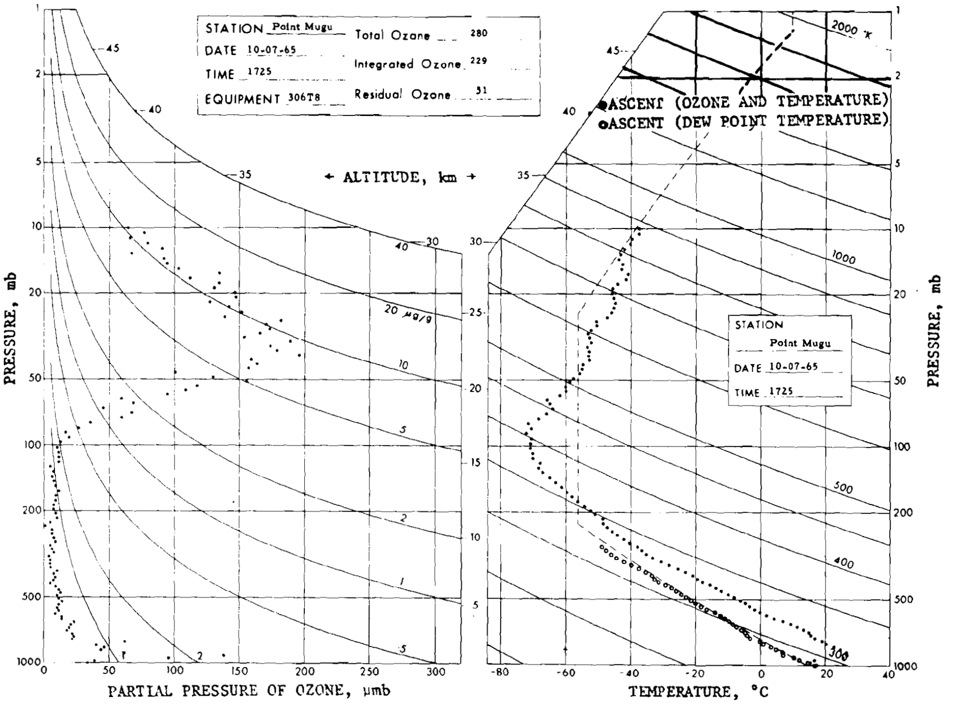
Figure 12-5. Ozonagram, Washington D.C. Station



STATION Thule
DATE 10-06-65
TIME 1115
EQUIPMENT 352TA10
Total Ozone 330
Integrated Ozone 282-E
Residual Ozone 48

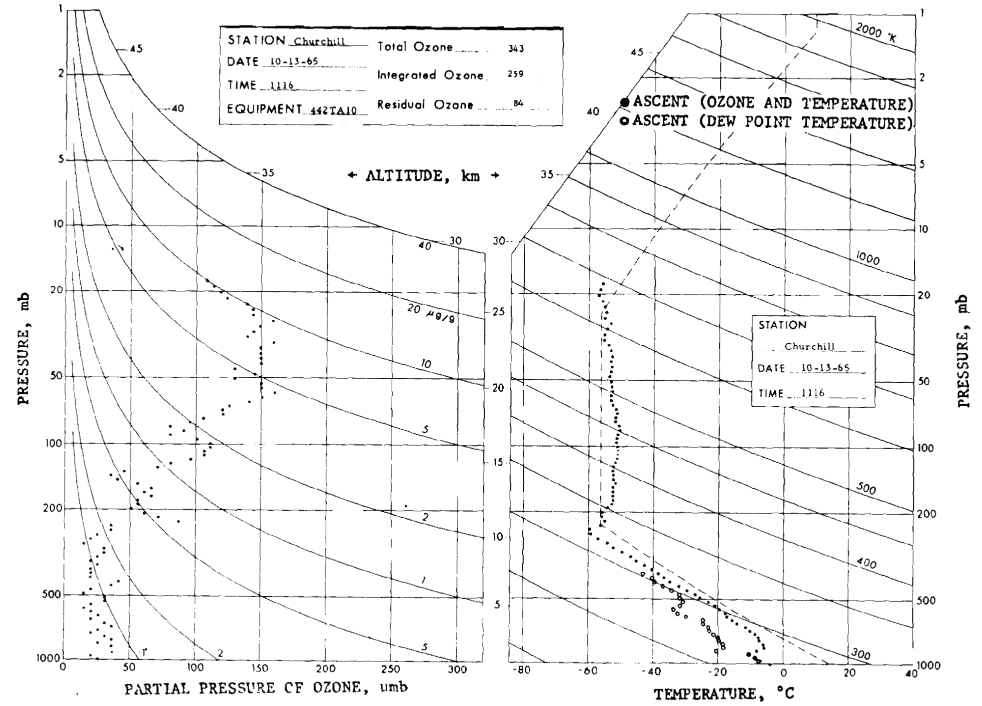
STATION Thule
DATE 10-06-65
TIME 1115

Figure 12-6. Ozonagram, Thule Station



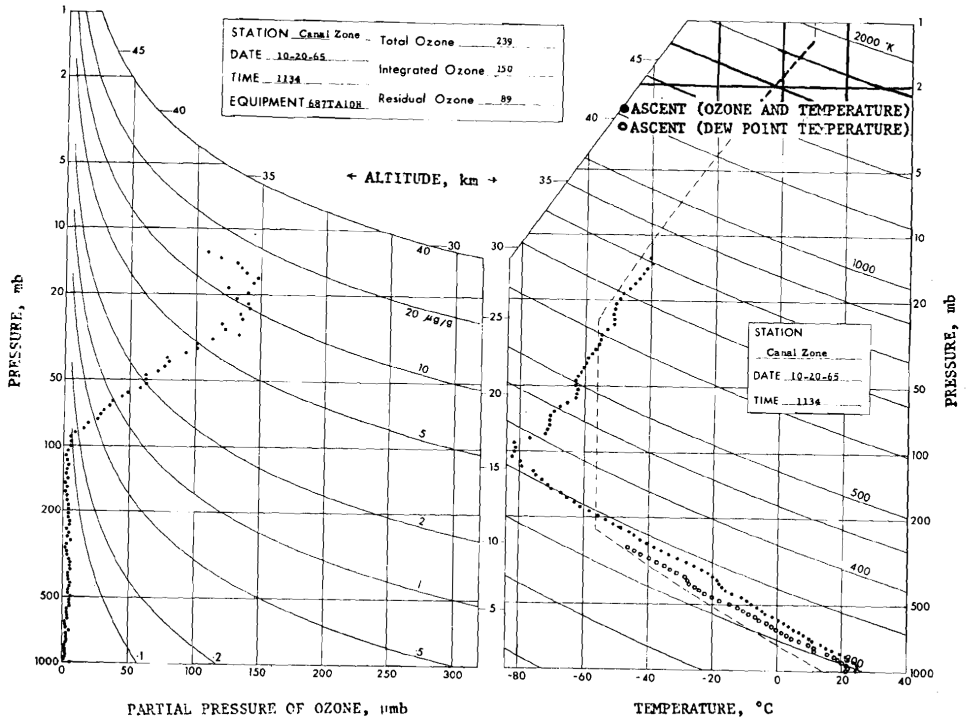
STATION Point Mugu
DATE 10-07-65
TIME 1725
EQUIPMENT 306T8
Total Ozone 280
Integrated Ozone 229
Residual Ozone 51

Figure 12-7. Ozonagram, Point Mugu Station



STATION Churchill
DATE 10-13-65
TIME 1116
EQUIPMENT 442TA10
Total Ozone 343
Integrated Ozone 259
Residual Ozone 84

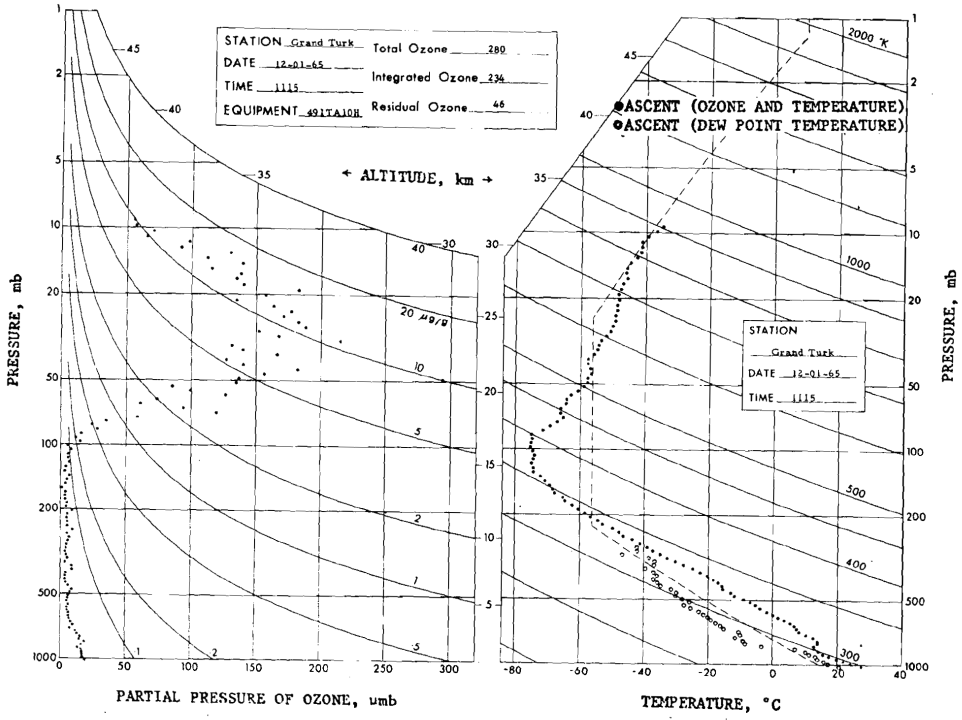
Figure 12-8. Ozonagram, Churchill Station



STATION Canal Zone
DATE 10-20-65
TIME 1134
EQUIPMENT 687TA10H
Total Ozone 239
Integrated Ozone 150
Residual Ozone 89

STATION Canal Zone
DATE 10-20-65
TIME 1134

Figure 12-9. Ozonagram, Canal Zone Station



STATION Grand Turk
DATE 12-01-65
TIME 1115
EQUIPMENT 491TA10H
Total Ozone 280
Integrated Ozone 234
Residual Ozone 46

STATION Grand Turk
DATE 12-01-65
TIME 1115

Figure 12-10. Ozonagram, Grand Turk Station

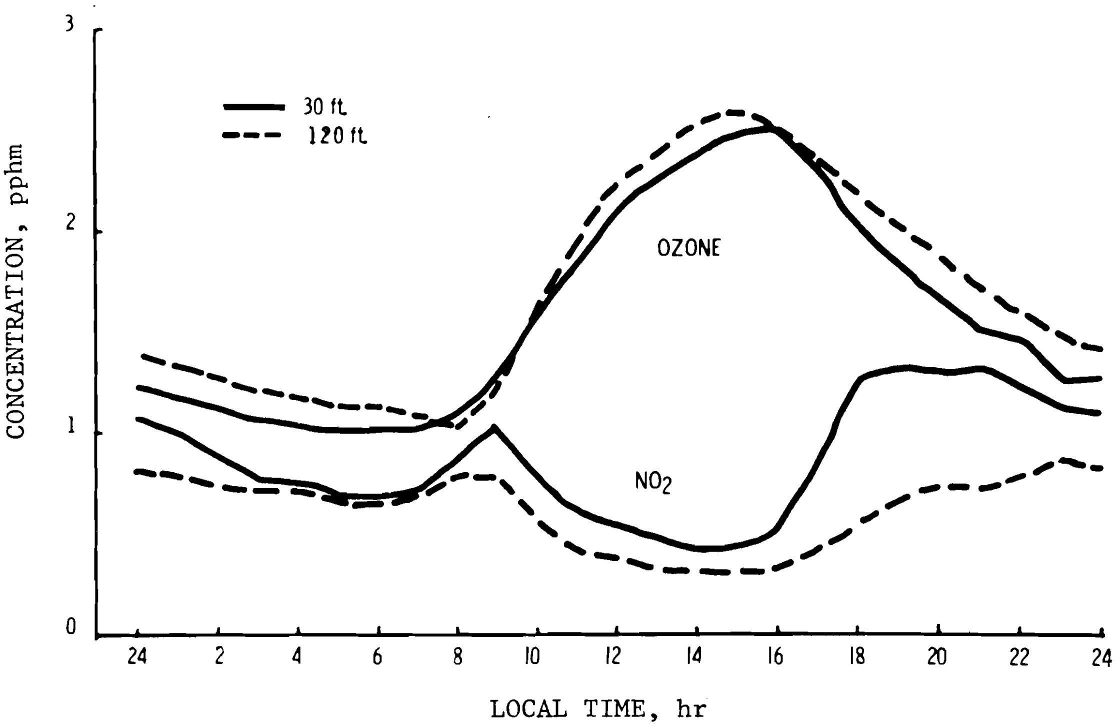


Figure 12-11. Diurnal Variations in Ozone and Nitrogen Dioxide Concentrations in a Rural Environment (Ref. 11)

ozone plot, data are given in terms of the partial pressure of ozone in micromillibars (10^{-9} bars) but a separate coordinate system is provided to give the concentration in micrograms per gram. The associated temperature curve is provided with a coordinate grid for potential temperature* in degrees kelvin as well as degrees centigrade. Data for the ozonagrams have been obtained in an extensive series of upper air soundings.

The underlying surface greatly affects ozone concentrations in the boundary layer (approximately the lower 1,000 ft). This is due both to the nature of the gases evolved from the surface and to the temperature and heat effects on atmospheric motion.

In continental air, whether natural or polluted, the usual diurnal variation in ozone concentration is to have definite concentration maxima in daylight hours with minima at night. A typical diurnal curve of ozone concentration (along with nitrogen dioxide concentration) at 30 ft and 120 ft in a rural environment is presented in Fig. 12-11 (Ref. 11). The maxima, however, can occur at night on a mountain top or ridge. Sometimes the diurnal trend is very weak or disappears completely. The ozone concentration may remain high in polluted air that has drifted some distance from the source of the pollution (Ref. 10).

The behavior of ozone in marine air has not been well established. Lodge et al. (Ref. 12) and Ripperton et al. (Refs. 13,14) have found little evidence of diurnal variations.

Table 12-4 provides representative ozone concentration values measured in different parts of the world (Ref. 6). In terms of planetary circulation, the tropopause is closest to the surface of the earth near the poles; consequently, ozone presumably can reach the surface more easily with less de-

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*The potential temperature is the temperature a volume of dry air would have if brought adiabatically from its initial pressure to the standard pressure of 1,000 mb. Potential temperature is a meteorological parameter indicative of degree of stability of the atmosphere.

TABLE 12-4

CONCENTRATIONS OF TROPOSPHERIC OZONE (Ref. 6)

Location, time, and remarks	Altitude	O_3, μg m^{-3}	
		Range*	Average*
Switzerland, 1950-51, high valley, daily maximum values	1,860 m	19-90	50
New Mexico, 1951-52	3,100 m 1,600 m	18-85 3-120	45 36
Nebraska, 1953	12.5 m above ground	30-100	60
Bodensee, Germany, 1952	20 m above ground	0-90	35
Lindenberg Obs., Germany, 1953-54	80 m above ground	0-50 0-50	30 27
Farnborough, England, 1952-53	0-12,000 m	26-50	38
Tromso, Norway, 1954	0-10,000 m	60-70	65
Mauna Loa Observatory, Hawaii	3,000 m	30-62	45
Little America Station, Antarctica	100 m	20-60	45

*As interpreted from the published data. The values sometimes represent absolute maxima, sometimes mean maxima.

struction in the polar regions. Cold waves in the temperate zone are frequently accompanied by elevated ozone readings, apparently due to deeper (or higher) mixing of the air near the surface.

In terms of ozone behavior, additional information should be kept in mind. Ozone is not emitted from the surface of the earth. Natural ozone from the stratosphere subsides from aloft. Ozone precursors, both natural and pollutant, are emitted from the surface; sunlight is necessary for the generation of ozone from surface-generated precursors. Most substances that act as precursors of ozone in tropospheric photochemical reaction will also react to destroy ozone.

Motion of the atmosphere, or the absence of motion, as by a thermal inversion layer, plays an important part in ozone behavior. At night, under an inversion, there is neither photochemical generation of ozone nor replenishment by natural ozone from aloft. Ozone destroyed under these conditions is not replaced so that nighttime values under a thermal inversion tend to decrease. Once the sun begins to shine, the synthesis of ozone from its precursors begins, which tends to increase ozone concentrations. In natural air, deeper mixing caused by warming of the ground usually leads to higher overall ozone values because the concentration of ozone synthesized near the ground generally is less than the natural concentrations aloft. On the other hand, the concentration due to *in situ* synthesis in polluted air is frequently greater than the concentration in the unpolluted air aloft. If an inversion "breaks" over Los Angeles on a smoggy day, there is often a dramatic decrease in ozone concentration due to mixing of the polluted, ozone-rich air with the air aloft that is *relatively* ozone-poor.

Examples of ozone levels and variations in urban areas are given in Figs. 12-12 through 12-15 along with similar data on total oxidants, nitric oxide, and nitrogen dioxide (Ref. 15). Gaps in the curves indicated by *M* represent gaps in the data arising from instrument malfunctions or other causes. Note that except for Fig. 12-12, the data–indicated by bars placed over the gases–are for mean concentrations obtained over a period of approximately 2 weeks. These may be compared with the diurnal curve in Fig. 12-11, which was measured at a rural site.

In thermal layering associated with thermal inversions, a layer of high ozone concentration can be transported a large distance. If this touches the surface, it can cause damage if the concentration is high enough (Ref. 16). Fig. 12-7 graphically shows such a layer over Point Mugu, Calif. This layer of elevated ozone concentration undoubtedly drifted from Los Angeles to Point Mugu, a distance of about 50 mi. The low level concentrations in this layer exceed 100 μmb or 10 pphm.

Ozone is a very reactive substance. Its generation by tropospheric photochemical reactions has been discussed. Important reactions of ozone with other airborne substances include the oxidation of nitric oxide, nitrogen dioxide, and olefinic organic compounds. The reactions of ozone with sulfur dioxide and carbon monoxide are too slow to be of atmospheric importance. Although little is known of the roles of atmospheric reaction of ozone with aldehydes and ketones, it should be remembered that ozone can oxidize aldehydes to peroxy organic acids.

In polluted air the generation of ozone is usually accompanied by the appearance of light-scattering aerosols. Natural haze is thought by some (Ref. 17) to be caused by photochemical reations in natural air similar to those in smog. Actually, the direct reaction of ozone with certain hydrocarbons, both natural and anthropogenic, will generate light-scattering, visibility-reducing particles in the atmosphere (Refs. 18,19).

12-4 MEASUREMENT OF OZONE

The measurement of ozone presents a number of problems, one of the most important of which is calibration. An ozone generator for producing a steady concentration of test gas must have a steady electrical power input, a constant flow rate of air or oxygen, and a constant temperature. Fig. 12-16 (Ref. 20) is a diagrammatic representation of a practical ozone generator. The calibration blend made in this manner will contain no interfering substance.

Determination of the concentration of ozone in the test gas is performed manually according to the procedure described in the *Federal Register* (Ref. 21) or the slightly different procedure published by the Intersociety Committee (Ref. 22). This procedure is also used to monitor ambient air.

It is impractical, tedious, and sometimes dangerous for most laboratories to prepare primary standards for ozone calibration by producing pure ozone, weighing it, and diluting it to ambient concentrations (Ref. 23). For this reason the referee KI (potassium iodide) method is used to determine the concentration of ozone in the calibration gas. For calibration, the readings from the apparatus to be used in actual environmental work must then be compared with the readings taken (preferably simultaneously) with the referee method. Since the calibration analysis has serious interferences from substances found in polluted atmospheres, it is not recommended for atmospheric sampling.

Test atmospheres for other oxidants are generally not used, but can be prepared by evaporating a known amount of the oxidant into a known amount of air in a vessel made of an inert substance (e.g., glass, Teflon*, Mylar*). The blend so prepared can be used as a calibration gas, but should be prepared fresh

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*Mylar and Teflon are trademarks of E. I. du Pont de Nemours and Company.

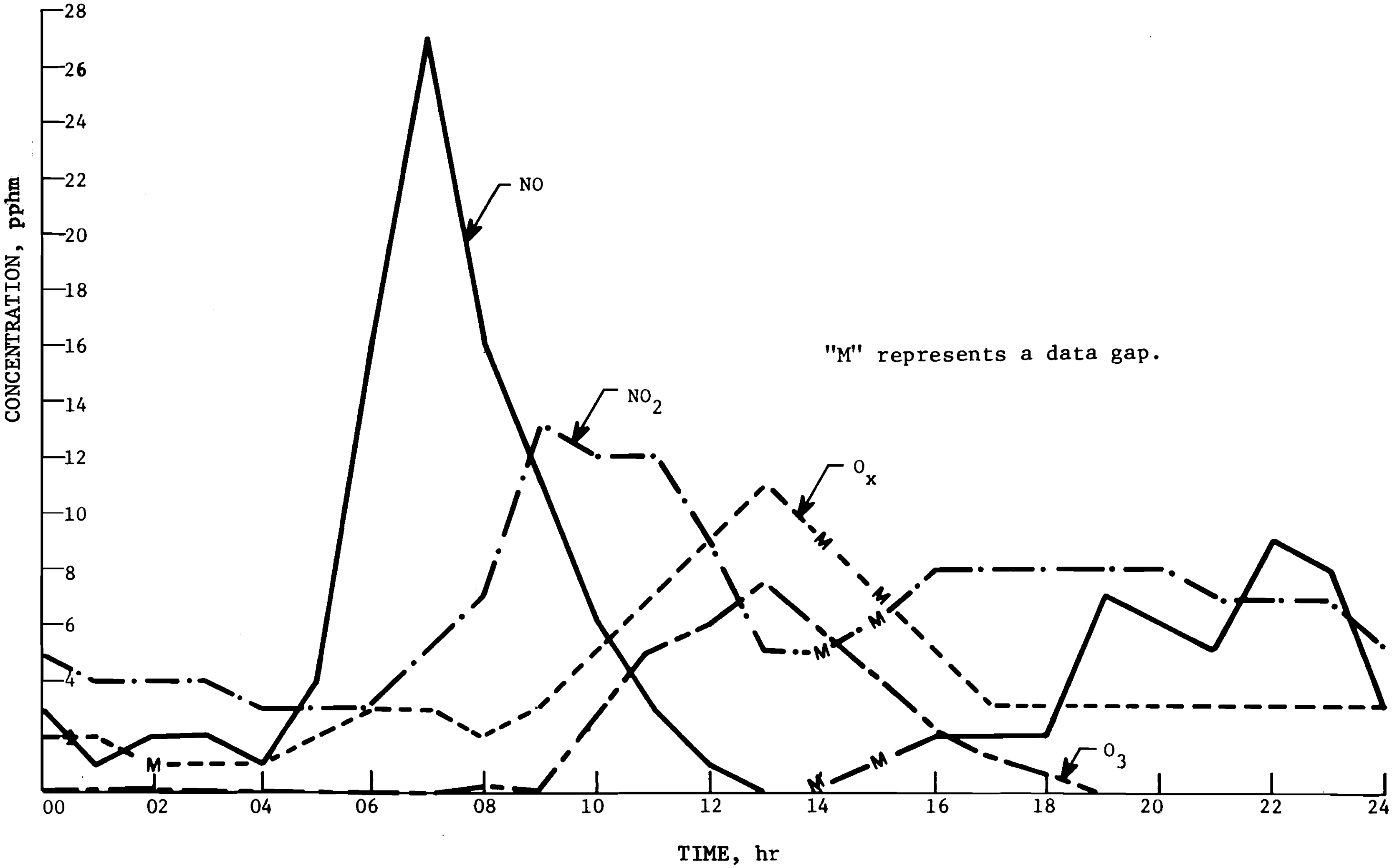


Figure 12-12. Diurnal Curves for Nitric Oxide, Nitrogen Dioxide, Ozone, and Total Oxidants in Washington, D.C. (Based on hourly averages, 3 Oct 67)

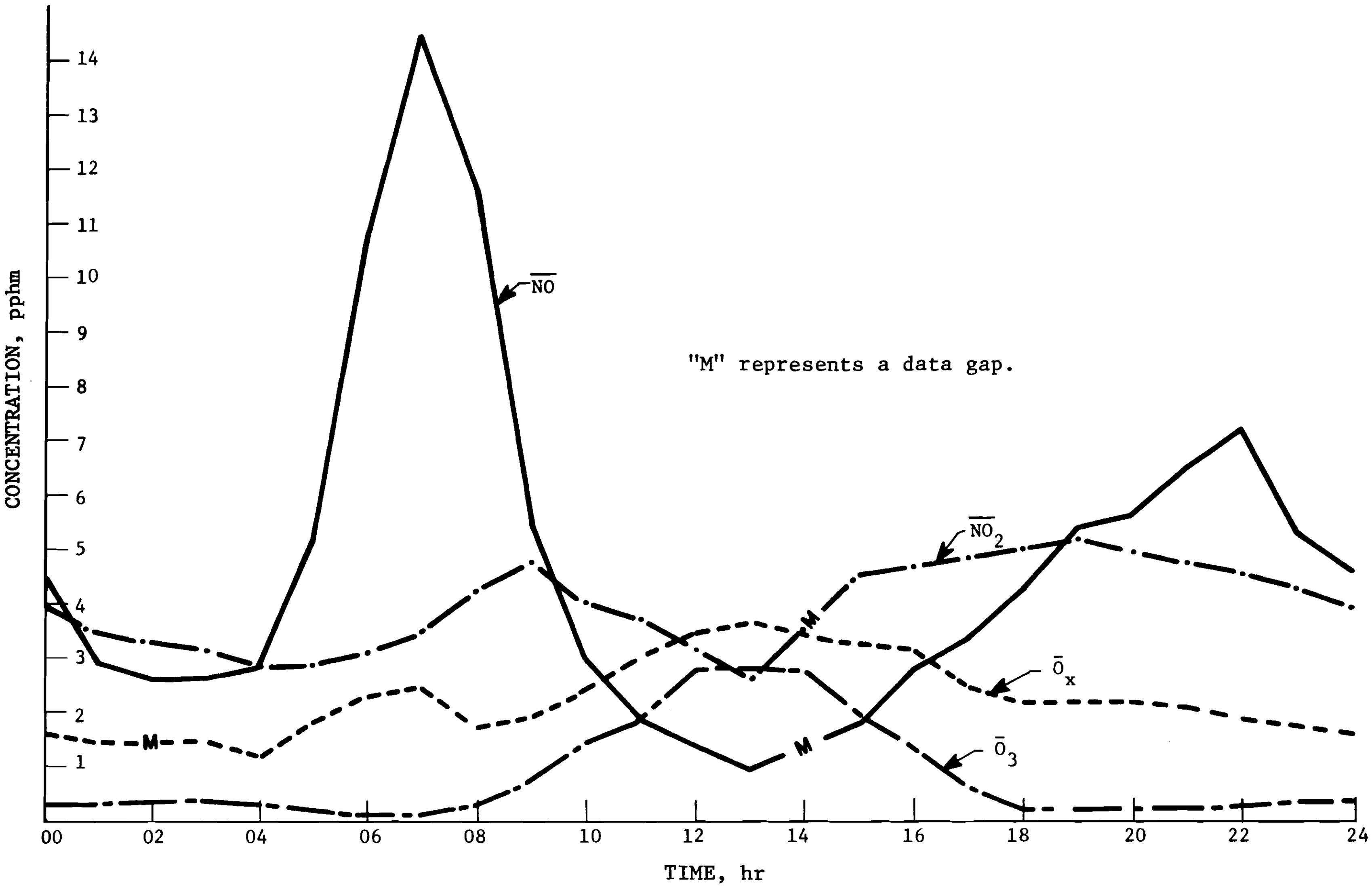


Figure 12-13. Diurnal Curves for Nitric Oxide, Nitrogen Dioxide, Ozone, and Total Oxidants in Washington, D.C. (Period 2-16 Oct 67)

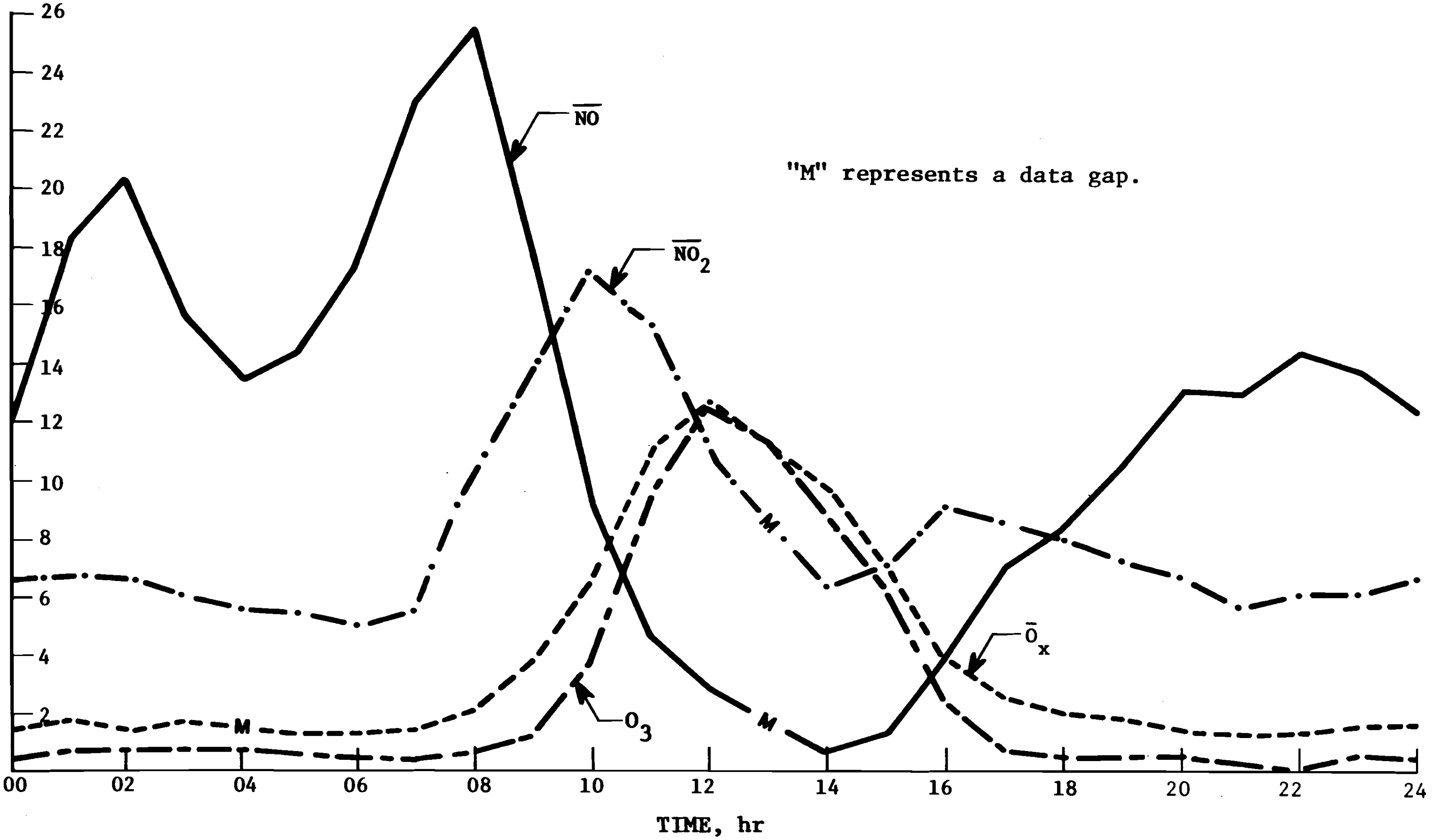


Figure 12-14. Diurnal Curves for Nitric Oxide, Nitrogen Dioxide, Ozone, and Total Oxidants in Los Angeles, Calif. (Period 2-19 Nov 67)

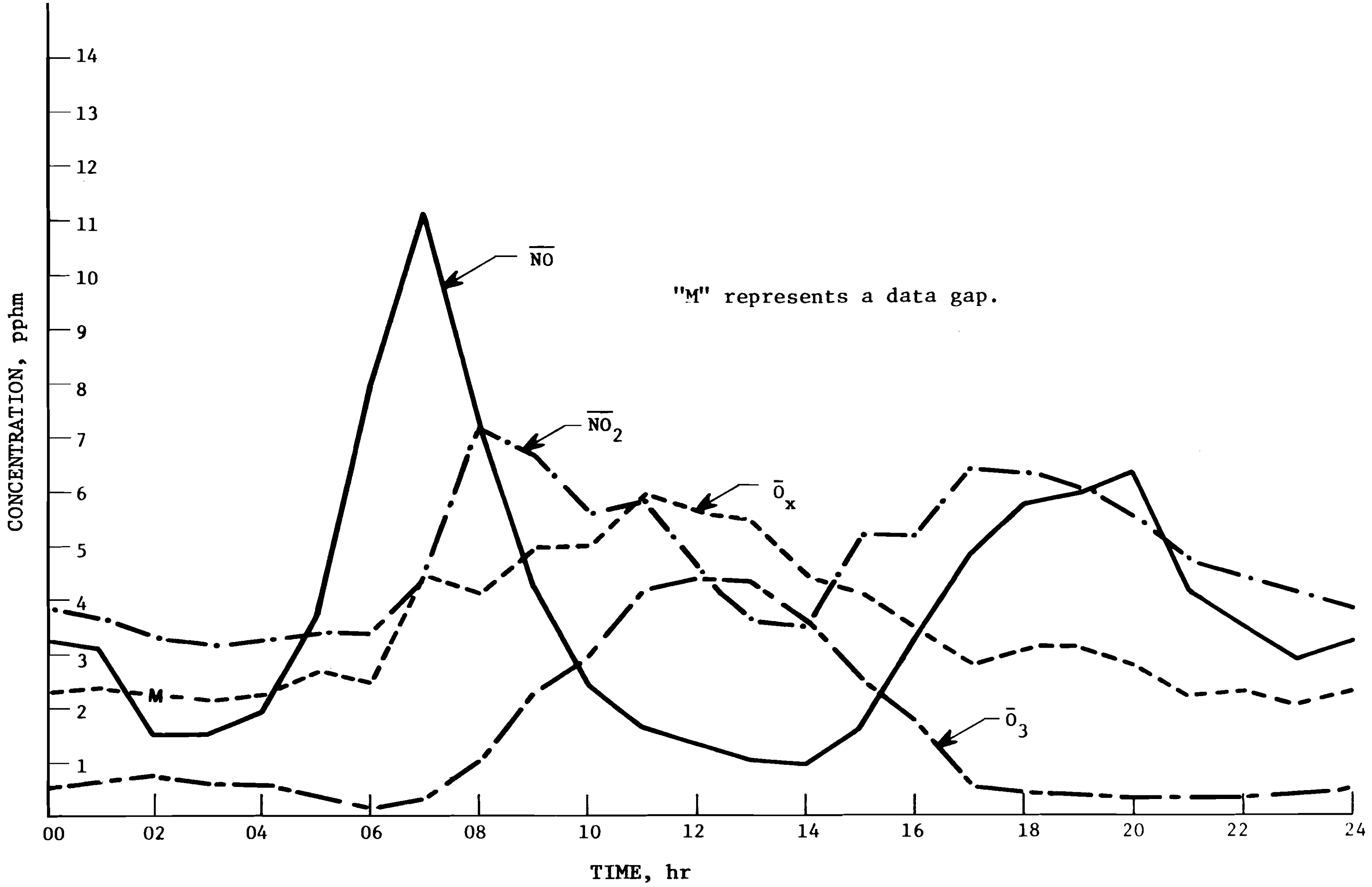
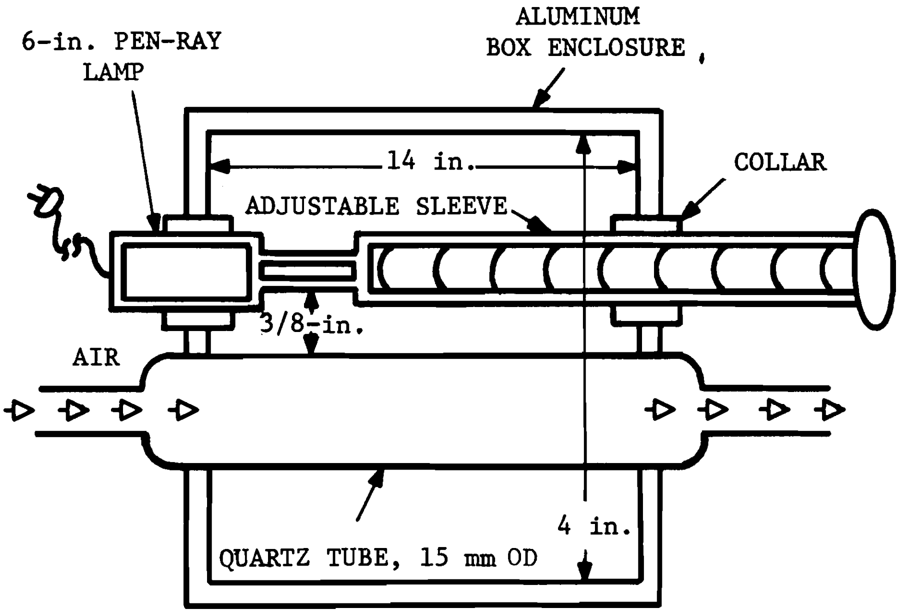
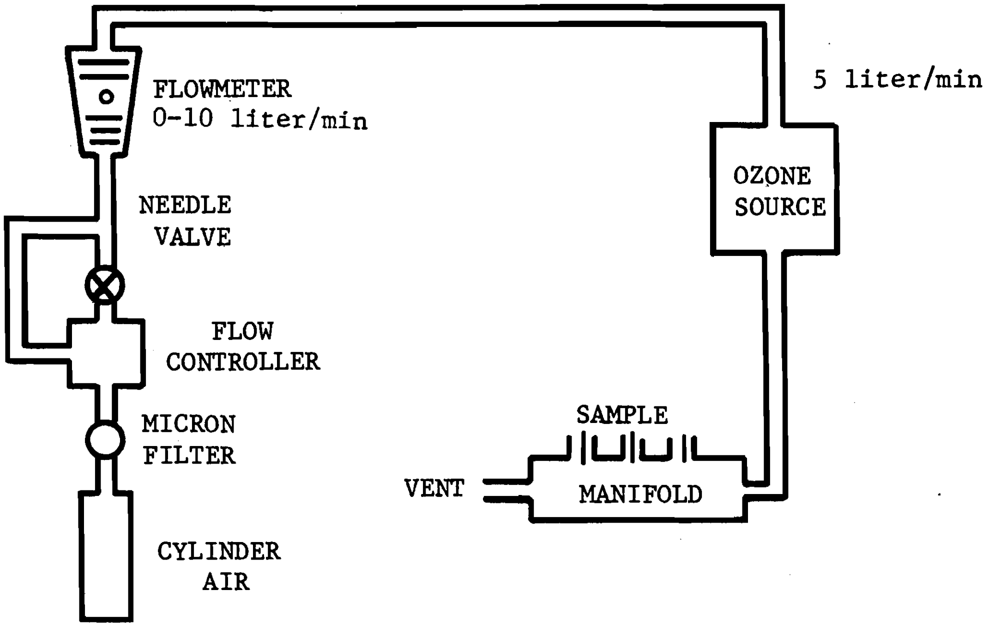


Figure 12-15. Diurnal Curves for Nitric Oxide, Nitrogen Dioxide, Ozone, and Total Oxidants in Denver, Colo. (Period 17 Oct-1 Nov 67)



(A) Source



(B) Flow Diagram

Figure 12-16. Diagrammatic Representation of an Ozone Generator each time, since such substances often decompose rapidly even in presumably favorable conditions.

Total oxidant (i.e., ozone plus all other oxidants) is often reported as "ozone", i.e., as if all the readings observed in the measurement were caused by ozone. One technique of analysis used both manually and instrumentally is colorimetry. Since potassium iodide in solution is colorless, the yellow color of the iodine generated by oxidation is a measure of ozone present in the sample.

Instrumental methods of monitoring ozone include continuous KI measurement (colorimetric and coulometric), chemiluminescent measurement (reaction with nitric oxide, ethylene, or rhodamine-B), and direct spectrophotometric (UV or IR).

Descriptions of several common types of ozone monitors currently in use are presented (Ref. 24):

(1) *Chemiluminescent ozone analyzer.* The operation of the chemiluminescent ozone analyzer is based on the chemiluminescent reaction between ozone and rhodamine-B adsorbed on a silica-gel disk, causing the emission of a minute amount of light. This emission of light is measured using a photomultiplier (PM) tube with the current output from the PM tube being a function of the concentration of ozone passing over and reacting with the rhodamine-B disk. This technique, based on the work of Regener (Ref. 25), is highly sensitive and specific for ozone. This analyzer operates in a cyclic mode and features a self-contained, ultraviolet ozone generator for dynamic calibration of the system every 5 min. A schematic diagram is given in Fig, 12-17. Calibrate and measure signals are alternatively displayed every 5 min with a purge cycle of 75 s on either side. The length of the sampling cycle can be varied.

The linear range of the chemiluminescent ozone meter is 0 to 0.5 ppm. The minimum detectable concentration for this detector was reported to be 1 ppb (Ref. 26). Since a cyclic mode of operation is employed, lag time and total rise time to 95 percent are equal to the total time for one cycle, i.e., purge-calibrate-purge-measure = 5 min. Response time to a given concentration of ozone is approximately 5 to 10 s.

No known components of the lower atmosphere other than ozone have been observed to give chemiluminescence with the reactive surface. Regener reported no interference from nitrogen dioxide, sulfur dioxide, or PAN (Ref. 25). Recent experiments by Hodgeson et al. have demonstrated that sulfur dioxide, hydrogen sulfide, nitrogen dioxide, propane, water, ammonia, nitric oxide, molecular chlorine, and hydrogen peroxide do not interfere (Ref. 27).

(2) *Gas phase chemiluminescent ozone analyzer.* A gas phase chemiluminescent ozone analyzer is also available (see Fig. 12-18). The theory of operation of this instrument is based on the gas phase chemiluminescent reaction of ozone with ethylene (Refs. 28, 29). The ethylene reaction is reported to be specific for ozone and has no known interferences. Ozonized air (1 liter/min) and ethylene (30 ml/min) are mixed countercurrently in concentric glass tubes closely coupled to the cathode face of a photomultiplier tube. No internal calibration source is required.

The dynamic range of the gas phase chemiluminescent ozone analyzer can be set to 0 to 0.5 ppm or can be expanded. The minimum detectable concentration for ozone is reported to be 0.02 ppm (Ref. 26). Lag and response time and total rise time to 95 percent were nominally 0.2, 1.0, and 3.0 min, respectively, depending upon the time constant of the output/measurement instruments.

No known components of the lower troposphere other than ozone have been observed to give chemiluminescence with this reaction.

(3) *Coulometric total oxidant analyzer.* The principle of operation of the coulometric total oxidant analyzer is based on the well-

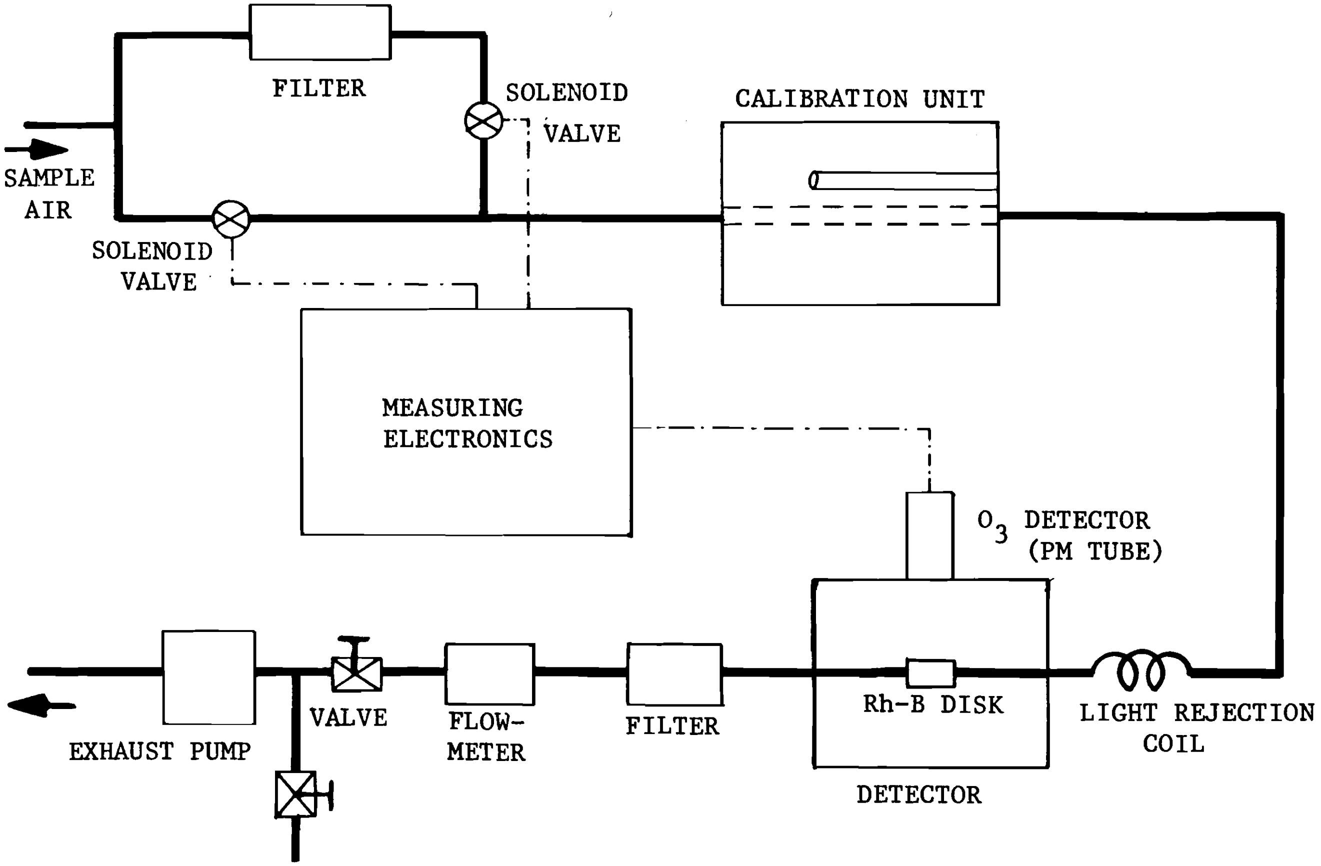


Figure 12-17. Schematic Diagram of the Chemiluminescent (Rh-B) Ozone Analyzer

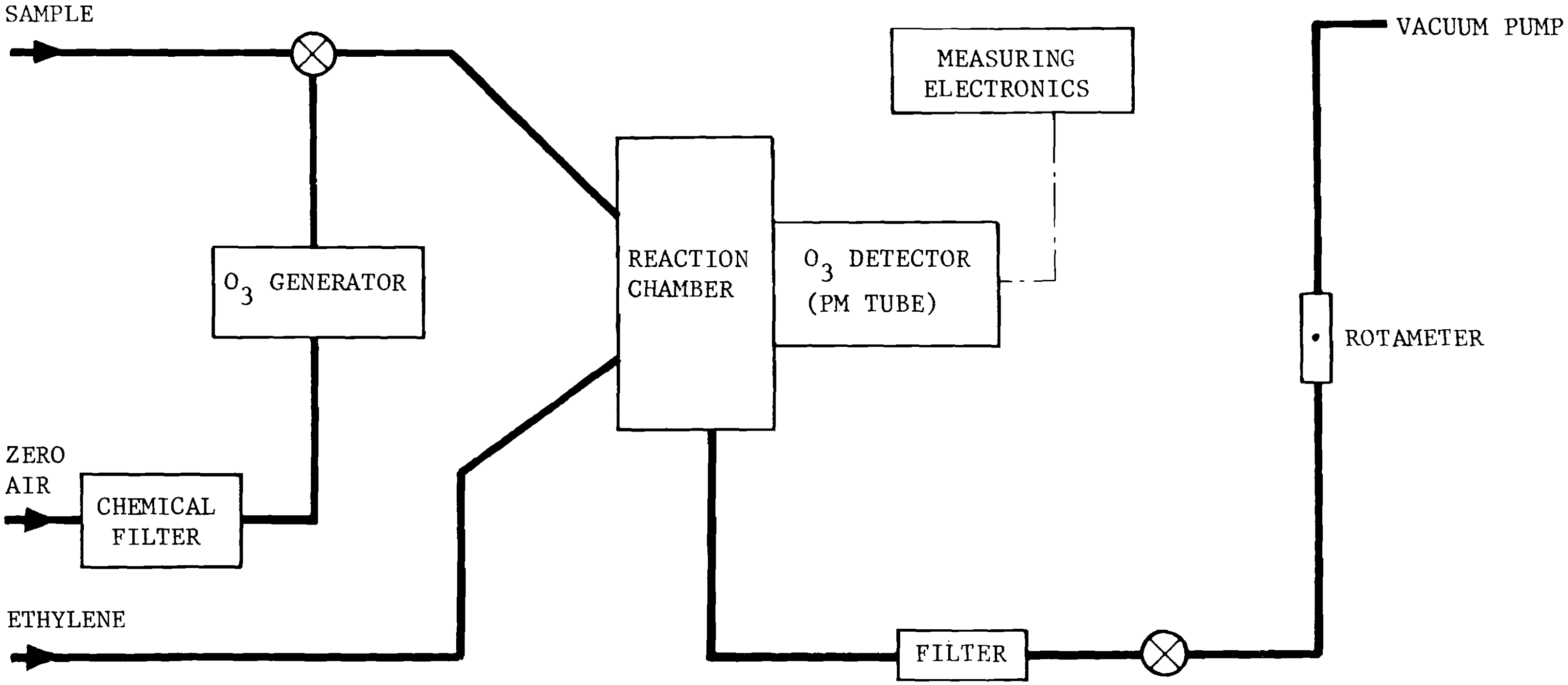


Figure 12-18. Block Diagram of Gas Phase Chemiluminescent Ozone Analyzer

known oxidation-reduction of potassium iodide contained in the sensing solution. Any oxidant (ozone, PAN, nitrogen dioxide, chlorine) present in the sample air stream and capable of oxidizing potassium iodide to iodine will produce an instrument response. The oxidation reaction takes place on the cathode portion of the electrochemical cell. A thin layer of hydrogen is also produced on the cathode by a polarization current. When free iodine is liberated by reaction with oxidants, it immediately reacts with the hydrogen layer. Removal of hydrogen from the cathode causes a repolarization current of two electrons per molecule of oxidant to flow in an external circuit. The rate of electron flow (current) is directly proportional to the mass per unit time of oxidant entering the sensor. A gas flow diagram of such an instrument is shown in Fig. 12-19.

The minimum range of the coulometric analyzer can be adjusted from 0 to 0.5 ppm full scale. The minimum detectable concentration is 0.01 ppm. Lag time, response time, and total rise time to 95 percent were determined to be < 1.0, < 1.0, and < 2.0 min, respectively.

Any oxidant (PAN, nitrogen dioxide, molecular chlorine, etc.) capable of oxidizing potassium iodide to iodine constitutes a positive interference in the ozone measurement, while sulfur dioxide and other reducing agents contribute a negative interference. A "CrO_3 scrubber"* can be employed which oxidizes sulfur dioxide to sulfur trioxide, a species that does not interfere. Sulfur dioxide was determined to be 1:1 interferent with the ozone measurement, while nitrogen dioxide contributed a 10.3 percent error.

(4) *Colorimetric total oxidant analyzer.* A colorimetric analyzer uses the well-known neutral buffered potassium iodide method. A flow diagram is shown in Fig. 12-20. The magnitude of the instrument response varies widely with the oxidizing power of the species being measured. The iodine liberated by the oxidation of iodide ion is analyzed colorimetrically at a wavelength of 352 nm and is a measure of the total oxidant concentration. Negative reductants are removed by means of a "CrO_3 scrubber". An internal ozone generator is also provided for stabilization and conditioning of the chromium trioxide column and the entire absorption system to ozone.

The dynamic range of the colorimetric total oxidant analyzer can be set to 0 to 0.5 ppm and the minimum detectable concentration is 0.012 ppm. Lag time, response time, and total rise time to 95 percent were 2.6, 3.3, and 5.9 min, respectively.

Oxidants other than ozone (i.e., PAN, nitrogen dioxide, molecular chlorine, etc.) and reducing agents (sulfur dioxide, etc.) interfere with ozone measurement using the colorimetric technique. Interference tests run with 0.2 ppm sulfur dioxide and hydrogen sulfide demonstrated quantitative removal by the "CrO_3 scrubber". Nitrogen dioxide interference with the ozone measurement is 17.5 percent, while nitric oxide oxidized to nitrogen dioxide by the "CrO_3 scrubber" yields a 9 percent response at concentrations up to 1 ppm.

(5) *Ozone spectrophotometer.* The principle of operation of the ozone spectrophotometer is based on the absorption of ultraviolet (UV) light within a sample volume of air. As shown in the block diagram in Fig. 12-21, the gas stream is divided into two gas lines. A scrubber removes ozone from the air sample in one line. Both the unfiltered gas and filtered gas enter the sample chamber through an electrically operated three-way valve. The absorption chamber has two windows at opposite ends through which UV light can pass. The ultraviolet source is at one end and the absorption detector is at the opposite end.

Measurement begins when a signal from the electrically operated valve indicates that filtered air (air minus ozone) is flowing through

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*"CrO_3 scrubber" is the nomenclature applied to a filter made by heating the reaction products of sodium dichromate and sulfuric acid absorbed on a passive substrate material (fiberglass, firebrick). The active layer formed is largely chromium trioxide (CrO_3).

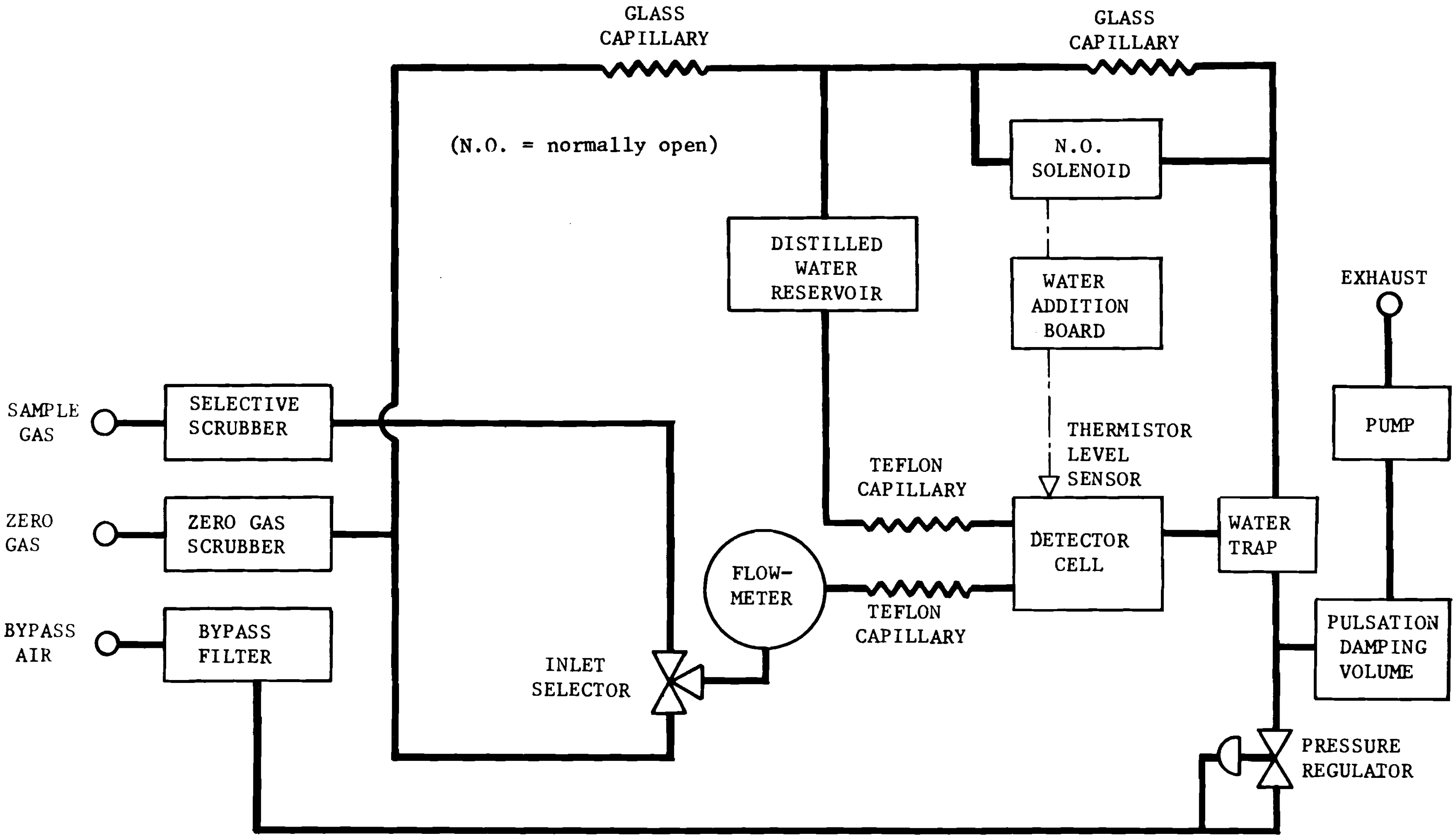

Figure 12-19. Gas Flow Diagram for Beckman 908 Oxidant Analyzer

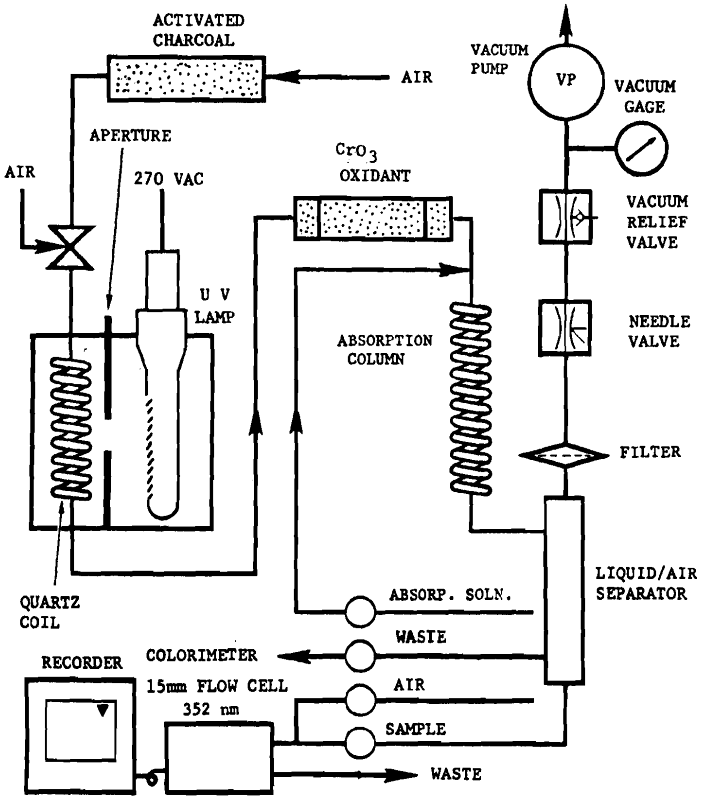

Figure 12-20. Flow Diagram of Colorimetric Total Oxidant Analyzer

the absorption chamber. At this time, the absorption detector starts to measure photon flux and to integrate the result. At the same time the reference detector starts measuring the photon flux and integrates it until a preset total is obtained. The integrated totals are compared at that point. The sequence is repeated again for the unfiltered gas. The difference between the integrated results for the filtered gas and unfiltered gas is computed and displayed digitally as the output concentration.

The range of this instrument is 0 to 9.9 ppm. The minimum detectable concentration is 0.01 ppm. The time required to complete one measurement cycle is approximately 12 s.

It appears from the principle of operation that mercury and other compounds having an absorption peak at 2,537 Å could interfere with measurements using the spectrophotometer.

12-5 EFFECTS OF OZONE

12-5.1 EFFECTS ON BIOLOGICAL SYSTEMS

The effects of ozone on various biological systems have been summarized (Ref. 30) and are presented in Tables 12-5 and 12-6. Conclusions drawn regarding biological effects when various levels of ozone are reached in the ambient air follow*:

(1) Long-term exposure of human subjects:

(a) Exposure to a concentration of up to 390 $\mu g\ m^{-3}$ (0.2 ppm) for 3 hr a day, 6 days a week, for 12 weeks, has not produced any apparent effects.

(b) Exposure to a concentration of

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*This summary is derived directly from *Air Quality Criteria for Photochemical Oxidants* (Ref. 30).

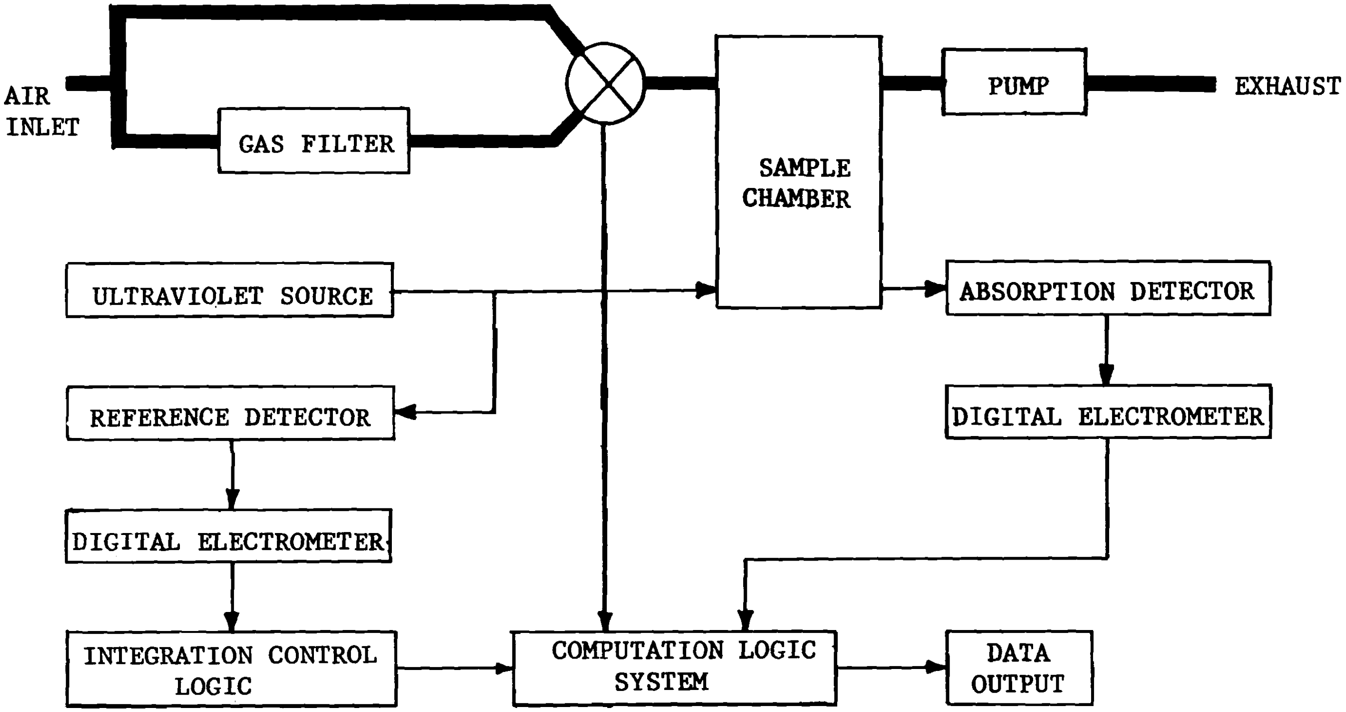

Figure 12-21. Schematic Diagram of UV Absorption Ozone Instrument

TABLE 12-5

SUMMARY OF TOXICOLOGIC STUDIES OF OZONE EXPOSURE

Effect	Ozone concentrations		Length of exposure
	ppm	μg m^{-3}	
Morbidity			
Local effects			
Perception of pungent odor (man)	0.02	40	< 5 min
Increased frequency of breathing. Decreased tidal volume (guinea pigs)	0.34	670	2 hr
Chemical changes in lungs (rabbits)	1.00	1,960	1 hr
Engorged blood vessels and excess leukocytes in lung capillaries (mice)	1.00	1,960	4 hr
Increased flow resistance (guinea pigs)	1.08	2,120	2 hr
Increased lung weight. Decreased tidal volume, decreased minute ventilation (rats)	2.00	3,920	3 hr
Gross pulmonary edema (rats)	3.20	6,290	4 hr
Decreased lung compliance (guinea pigs)	5.00	9,800	2 hr
Gross pulmonary edema. Increased lung serotonin (rats)	6.00	11,800	4 hr
Decreased tidal volume, decreased oxygen consumption (rabbits)	15.00	29,000	30 min
Bronchitis, bronchiolitis, emphysematous and fibrotic changes; acceleration of lung tumor development (mice)	1.00	1,960	continuous (at least 1 yr)
Systemic effects			
Decreased voluntary running activity (mice)	0.20	390	6 hr
Increased liver weight. Increased liver alkaline phosphatase (rats)	3.10	6,100	20 hr
Decreased brain sertonin (rats)	6.00	11,800	4 hr
Structural changes in heart myocardial fibers (mice)	0.20	390	5 hr day^{-1} 3 weeks (total 105 hr)

TABLE 12-5 (Continued)

SUMMARY OF TOXICOLOGIC STUDIES OF OZONE EXPOSURE

Effect	Ozone concentrations		Length of exposure
	ppm	$\mu g\ m^{-3}$	
<u>Mortality</u>			
Increased susceptibility to streptococcus (Group C)	0.08	160	3 hr
Increased susceptibility to Klebsiella pneumoniae (mice, hamsters)	0.84	1,650	4 hr/5 days 2 weeks
Increased susceptibility to Klebsiella pneumoniae (mice, hamsters)	1.30	2,550	3 hr
Increased susceptibility to histamine (guinea pigs)	5.0	9,800	2 hr
Increased mortality with exercise (15 min/hr) (rats)	1.0	1,960	6 hr
Decreased mortality with age. Young--50% mortality old--10% mortality	4.0	7,800	4 hr
Decreased survival time due to stimulated thyroid activity (rats)	6.0	11,800	4 hr
*LD_{50} mice	21.0	41,000	3 hr
LD_{50} rats	21.8	42,000	3 hr
LD_{50} cats	34.5	67,980	3 hr
LD_{50} rabbits	36.0	71,000	3 hr
LD_{50} guinea pigs	51.7	101,400	3 hr

*LD_{50} = Lethal dose for 50 percent

TABLE 12-6

POTENTIAL OCCUPATIONAL EXPOSURES TO OZONE

Air treaters
Arc cutters
Arc welders, argon shielded
Arc welders, electric
Arc welders, heliarc
Arc workers, electric
Bactericide makers
Electroplaters
Food preservers (cold storage)
Hydrogen peroxide makers
Industrial waste treaters
Odor controllers
Oil bleachers
Organic chemical synthesizers
Ozone workers
Photoengravers
Photographers
Plasma torch operators
Sewage gas treaters
Textile bleachers
Ultraviolet lamp workers
Water treaters
Wax bleachers

980 µg m^{-3} (0.5 ppm) for 3 hr a day, 6 days a week, has caused a decrease in the 1-s forced expiratory volume (FEV$_{1.0}$) after 8 weeks.

(2) Short-term exposure of human subjects:

(a) Exposure to a concentration of 40 µg m^{-3} (0.02 ppm) was detected immediately by 9 of 10 subjects. After an average of 5-min exposure, subjects could no longer detect ozone.

(b) Exposure to a concentration of 590 µg m^{-3} (0.3 ppm) for 8 hr appears to be the threshold for nasal and throat irritation.

(c) Exposure to concentrations of from 1,180 to 1,960 µg m^{-3} (0.6 to 1.0 ppm) for 1 to 2 hr may impair pulmonary function by causing increased airway resistance, decreased carbon monoxide diffusing capacity, decreased total capacity, and decreased forced expiratory volume.

(d) Exposure to concentrations of from 1,960 to 5,900 µg m^{-3} (1.0 to 3.0 ppm) for 10 to 30 min is intolerable to some people.

(e) Exposure to a concentration of 17,600 µg m^{-3} (9.0 ppm) produces severe illness.

(3) Effects on vegetation and laboratory animals:

(a) Exposure to concentrations of about 60 µg m^{-3} (0.03 ppm) ozone for 8 hr or to 0.01 ppm peroxyacetyl nitrate for 5 hr has been associated with leaf lesions in the most sensitive species, under laboratory conditions.

(b) Exposure to ambient air containing oxidant concentrations of about 100 µg m^{-3} (0.05 ppm) for 4 hr has been associated with leaf injury in the most sensitive species.

(c) Experimental exposures of laboratory animals to ozone concentrations of from 160 to 2,550 µg m^{-3} (0.08 to 1.30 ppm) for 3 hr has resulted in increased susceptibility to bacterial infection.

12-5.2 EFFECTS ON MATERIALS*

The extent of damage to materials caused by atmospheric levels of ozone is not known. To date research has been primarily concerned with elastomers and textiles. Within these two groups, certain specific organic compounds are more sensitive to attack by ozone than are human beings or other animals.

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*This section is derived directly from *Air Quality Criteria for Photochemical Oxidants* (Ref. 30).

Ozone is so active that, when concentrated, it becomes a materials-handling problem. In general, any organic material is incompatible with concentrated ozone (Ref. 31). Bailey has reviewed the literature thoroughly from 1939 to 1957 for reactions of ozone with organic compounds, and he describes the reaction mechanisms in detail (Ref. 32). Although it is incorrect to assume that all of these reactions will occur at atmospheric concentrations of ozone, it is possible that some will be operant.

Many polymers are sensitive to atmospheric concentrations of ozone (Ref. 33). Both chain-scissioning and crosslinking take place in polymers exposed to atmospheric ozone. Chain-scissioning results in increased fluidity and a loss in tensile strength. Crosslinking increases the rigidity of the polymer, reducing elasticity so that brittleness may result.

The sensitivity of polymers to chain-scissioning, therefore, is related to the prevalence of double bonds in their structure. Since almost all rubbers possess such a chemical structure, they are prone to this type of oxidative attack (Refs. 34, 35). A similar type of attack has been proposed for the degradation of dyes (Ref. 36).

12-5.2.1 EFFECTS ON RUBBER

Rubber is highly sensitive to ozone attack. The most vulnerable generic formulations are natural, styrene-butadiene, polybutadiene, and synthetic polyisoprene (Ref. 37). These types account for 85 percent by weight of the estimated 1969 national production of rubber (Ref. 38). With the exception of natural rubber, the major use for each of these elastomers is in tires (Ref. 39). Thus, most of the rubber that is susceptible to ozone-cracking is exposed to the atmosphere in a state of tensile stress. Butyl, halogenated butyl, polychloroprene, vinyl-modified nitrile-butadiene, and carboxylated nitrile rubbers have some ozone resistance but require special formulation for optimal performance. Synthetic rubbers with saturated chemical structures, such as silicones, ethylene-propylene, chlorosulfonated polyethylene, polyacrylate, and fluorocarbon rubbers have inherent ozone resistance (Refs. 34, 40-46). These special-application materials account for only a small fraction of the market on a weight basis.

A tensile stress is necessary to produce ozone-cracking of rubber. If strained as little as 2 or 3 percent and exposed to an atmosphere containing 20 to 40 $\mu g\, m^{-3}$ (0.01 to 0.02 ppm) ozone, cracks will develop perpendicular to the stress axis (Refs. 41, 42). Rubber in a relaxed state can be exposed for long periods of time to relatively high concentrations of ozone without visible cracking (Ref. 47). The rubber is apparently protected by the formation of an ozonide film on the surface (Ref. 34). The embrittled film cracks when strained and exposes fresh surface to the atmosphere. The strong dependence of crack-growth on nominal tensile stress has been explained in terms of fracture mechanics (Ref. 48). However, this only partially explains observed relationships between number and size of cracks as a function of strain (Refs. 35, 48). Crack-growth rate is also ozone concentration dependent (Ref. 48), which suggests that the rate of diffusion of ozone to the root of a crack is the rate-controlling factor.

Knowledge of the fracture behavior of various rubbers allows compounding of special rubbers for ozone resistance and other desired properties (Ref. 49). Blends of natural rubber with an ethylene-propylene copolymer are more resistant to ozone-cracking than natural rubber. Specimens with from 0 to 50 percent ethylene-propylene were strained from 5 to 100 percent and exposed to 980 mg m^{-3} (500 ppm) ozone in air. Microcracks were observed in all of the blends, the crack density increasing with decrease of ethylene-propylene copolymer raises the critical stored energy necessary to propagate the observed microcracks characteristic of ozone damage.

Antiozonant additives, such as p-phenylenediamine derivatives, have been developed and protect elastomers from ozone degradation. These chemicals are expensive, however, and add to the cost of rubber products. The

TABLE 12-7

FORMULATION OF HIGHLY OZONE-SENSITIVE RUBBER (Ref. 41)

Ingredient*	Parts by weight	Percent by weight
Rubber	100	35.91
Tire reclaim	125	44.88
SRF black	33	11.85
Stearic acid	1.5	0.54
Pine tar	8.4	3.02
Zinc oxide	4.7	1.69
Mercaptobenzothiazole	0.8	0.29
Diphenyl guanidine	0.1	0.03
Sulfur	5	1.79

*Cured 40 min at 45 psi steam

addition of 1.5 percent antiozonants to automobile tires costs up to $0.50 per tire. Antiozonants are also used in conveyor belts, automotive rubber parts, wire and cable, and other products as well as tires.

The use of antiozonants has its limitations. The amount required to be effective increases with the anticipated amount of ozone to be encountered (Ref. 50). In some cases these inhibitors provide only temporary protection against ozone damage, because they migrate to the surface of the rubber product with usage (Ref. 34). Oils, gasoline, and other chemicals tend to extract antiozonants from rubber, leaving it again susceptible to ozone attack. Thus, in spite of preventive measures, ozone-cracking of rubber products is still a major problem.

A number of factors affect the rate of attack of ozone on rubber (Ref. 34): (1) the amount of tensile stress, (2) the type of rubber compound, (3) concentration of ozone, (4) period of exposure, (5) rate of diffusion of ozone to the rubber surface, and (6) temperature. Dose-response data, therefore, are necessarily dependent on these factors. Also, the method for reporting damage varies from one researcher to another. For example, damage may be expressed as time to initiate either microcracks or visible cracks, or it may be expressed in crack depth or crack-growth rate. The examples of dose-response data that follow should be considered with these factors in mind.

Bradley and Haagen-Smit evaluated the rubber formulation indicated in Table 12-7 for susceptibility to ozone-cracking (Ref. 43). This formulation was selected for its sensitivity to ozone. Strips were strained approximately 100 percent by bending. These specimens, if exposed to 39,000 mg m^{-3} (2 percent or 20,000 ppm) ozone in air, would crack instantaneously and break completely within 1 s.

Results of Bradley and Haagen-Smit's standard tests, using a gas flow rate of 1.5 liter/min through a 13-mm tube at room temperature, are given in Table 12-8.

Edwards and Storey have determined the effects of ozone on "hot" (Polysar-S) and "cold" (Polysar-krylene) styrene-butadiene rubbers (SBR) containing various amounts of antiozonant (Ref. 50). The ingredients added to the base polymer are listed in Table 12-9. The results are given in Table 12-10.

Thin polybutadiene specimens were exposed, under constant load, to room air for which the average concentrations of ozone had been determined (Ref. 51). The specimens exposed in the summer months to

TABLE 12-8

EFFECT OF OZONE ON RUBBER* (Ref. 41)

Ozone concentration**		Time to first sign of crack at 4X magnification, min
µg m^{-3}	ppm	
40	0.02	65
510	0.26	5
880	0.45	3

*Special formulation of Bradley and Haagen-Smit, strained 100 percent

**Determined by neutral KI

average ozone concentrations of about 94 µg m^{-3} (0.048 ppm) failed by breaking into two separate parts after 150 to 250 hr. In the fall, at average ozone concentrations of 82 µg m^{-3} (0.042 ppm), specimens failed between 400 and 500 hr. In the winter, at average ozone concentrations of 47 µg m^{-3} (0.024 ppm), failures occurred between 500 and 700 hr. These data show the strong dependence of cracking rate on the average concentration of ozone.

The behavior of rubber exposed to ozone under laboratory conditions correlates well with the service behavior of tires in localities where atmospheric ozone concentrations are high (Ref. 52). The relative susceptibility of white sidewalls made from different formulations remains the same, whether in a laboratory test, in which they are exposed to as much as 980 µg m^{-3} (0.5 ppm) ozone, or in the ambient air of the Los Angeles area. The rate of cracking is thus a function of ozone concentration.

As the tread wear on passenger car tires improves, more or better antiozonants will have to be added to sidewall formulations to prevent sidewall cracking from becoming the limiting factor in tire life. Thus, part of the cost of premium tires will be due to atmospheric ozone.

TABLE 12-9

TIRE SIDEWALL FORMULATION (Ref. 48)

Ingredient	Parts by weight
Polymer (hot or cold SBR)	100
Circosol 2 X H	10
FEF black	30
SRF black	10
Zinc oxide	3
Stearic acid	2
Antiozonant (Santoflex AW)	Variable
Crystex	2

TABLE 12-10

EFFECTS OF OZONE ON SIDEWALL FORMULATIONS CONTAINING VARIOUS ANTIOZONANT CONCENTRATIONS* (Ref. 48)

Polymer	Antiozonant concentration, (Santaflex AW), percent	Rate of cracking, 10^{-4} in./hr	Time to first sign of crack,** min
"Hot" SBR (Polysar-S)	0	0.92	65
	0.32	0.69	87
	0.63	0.35	170
	1.25	0.13	460
"Cold" SBR (Polysar-drylene)	0	1.58	38
	0.32	0.85	71
	0.63	0.57	105
	1.25	0.24	250

*Specimens were strained initially at 100 percent and exposed at 120°F to an ozone concentration of 490 ± 100 μg m^{-3} (0.25 ± 0.05 ppm).

**Added to enable comparison with data in Table 7-2. First sign of crack was assumed to be 10^{-4} in. crack depth, visible at 4X magnification.

12-5.2.2 EFFECTS ON FABRICS AND DYES

Ozone attacks cellulose by two mechanisms (Ref. 53). One is a free-radical chain mechanism involving oxygen in the propagating step, and the other appears to be an electrophilic attack on double bonds. Bogaty et al. (Ref. 54) have shown that ozone attack at atmospheric levels results in the deterioration of wet cotton textiles. Two types of cotton fabric, duck and printed cloth, were exposed, both wet and dry, for 50 days to an atmosphere containing between 40 and 120 μg m^{-3} (0.02 and 0.06 ppm) ozone. The deterioration of the two fabrics was shown by comparing dissolved fabric fluidity values before and after exposure. The value for the wet duck cloth increased from 2.6 to 9.5 rhe (a calibrated measure of fluidity that is inversely proportional to viscosity), while the value for the wet printed cloth increased from 8 to 16 rhe. Both fabrics, when wet, also showed a 20 percent loss in tensile strength due to the exposure. When exposed dry, neither fluidity values nor tensile strengths were changed appreciably. The fabrics demonstrated that increasing the ozone concentration increased the amount of damage to the cellulose.

Morris et al. (Ref. 55) found that light as well as humidity is necessary to appreciably change breaking strength and cellulose fluidity. In the absence of light, 980 μg m^{-3} (0.5 ppm) ozone at 21°C (70°F) and 72 percent relative humidity for 1,200 hr had little degrading effect on Acala 4-42 and Pima S-1 cotton fabrics (Ref. 56). In a later study, Kerr et al. (Ref. 57) showed that light was not necessary to degrade cotton in air containing ozone. Cotton print cloth dyed with C. I. Vat Blue 29 was exposed at 25°C in an airtight chamber containing a shallow pan filled with water so as to increase the relative humidity

TABLE 12-11

SUBJECTIVE COLOR CHANGE OF DYED COTTON EXPOSED TO OZONE CONCENTRATIONS BETWEEN 980 AND 1960 $\mu g\ m^{-3}$ (0.5 AND 1.0 ppm)

Number of days treated	Washed fabrics		Soaked fabrics	
	Gray scale	NBS units*	Gray scale	NBS units*
12	4.0	1.5	2.5	4.5
24	2.5	4.5	2.0	6.0
36	2.5	4.5	1.0	12.0
48	2.0	6.0	1.0	12.0
60	2.0	6.0	1.0	12.0

*NBS units = $\Delta L^2 + \Delta a^2 + \Delta b^2$ where:

$L = 10\sqrt{Rd}$ (Rd = reflectance)
a = measure of green to red color change
b = measure of blue to yellow color change
Δ = difference between exposed and unexposed

in the chamber. Purified air to which oxygen had been added was passed through another chamber containing three 4-W ozone bulbs and then directly into the exposure chamber. The concentration of ozone was adjusted by varying the number of ozone lamps in operation, the amperage used, and the amount of pure oxygen added to the air intake. The concentration of the ozone fed into the chamber was 1960 ± 200 $\mu g\ m^{-3}$ (1 ± 0.1 ppm), and the exit concentration, recorded with a Mast Ozone Meter, was 980 $\mu g\ m^{-3}$ (0.5 ppm). Specimens were removed at 3-day intervals and either washed or soaked. Control specimens were kept in lightproof chambers at 21°C (70°F) and 65 percent relative humidity and were given the same cycle of washing or soaking. After 60 days of exposure, the washed fabrics had an 18.2 percent greater strength loss than did the controls. Cellulose fluidity values also indicated degradation caused by exposure to ozone. The washed fabrics exposed to ozone had a fluidity value of 9.27 rhe as compared with a value for the control samples of 5.37 rhe.

Peters and Saville (Ref. 58) have reported that, in their experiments, the effects of high ozone concentrations on breaking strength are significant for white nylon and polyester fabrics but are not significant for cotton, acetate, or fiberglass. Based on these results and the results of other researchers, the relative susceptibility of different fibers to ozone attack, in increasing order, is cotton, acetate, nylon, and polyester.

The first evidence that ozone causes the fading of dyes was obtained when acetate fiber samples dyed with Disperse Blue-27 (developed for nitrogen dioxide resistance) were field evaluated (Ref. 59). These samples were exposed to the atmosphere in lightproof containers in Pittsburgh, Pa., where the nitrogen dioxide concentration is high, and Ames, Iowa, where a low nitrogen dioxide concentration is recorded. After 6 mo, samples in Ames had faded but had not in Pittsburgh. Laboratory exposure of similar samples to 200 $\mu g\ m^{-3}$ (0.1 ppm) ozone duplicated the fading observed in Ames. It was further found that all blue anthraquinone dyes were sensitive to change as were certain anthraquinone red dyes. Azo red and yellow dyestuffs and diphenylamine yellow dyes were not sensitive to ozone. Thus, fading in Ames was attributed to naturally occurring high levels of ozone.

In previously described research, Kerr et al. measured the fading of vat-dyed cotton fabrics caused by ozone (Ref. 57). The results presented in Table 12-11 indicate that the rate of fading and the maximum amount of fading are both dependent upon the environment. The soaked fabrics faded in ozone more rapidly and to a greater extent than did the laundered fabrics. It was suggested that laundering produced a change in the dye and improved its ozone resistance.

Salvin exposed wool, cotton, nylon, acetate, Orlon, and polyester fabrics–all dyed with ozone sensitive dyes–to the atmospheres of the cities of Chicago and Los Angeles and the rural, nonindustrial areas of Sarasota, Fla., and Phoenix, Ariz. (Refs. 60, 61). In Los Angeles where ozone concentration is high, the dyes were most affected, whereas those exposed in Chicago were the least affected. In humid Florida, dyes faded more than they did in dry Arizona. The extent of ozone fading was related to different concentrations and durations of exposure in the different localities.

Customer complaints of fading have been attributed to attack by ozone (Refs. 62, 63). The fading of polyester materials was not a problem until cotton/polyester fabrics were finished for permanent press. The type of permanent press treatment that resulted in fading used a magnesium chloride catalyst that formed a soluble complex with the blue dyes used on polyester. The dyes migrated to the finish, where they are susceptible to ozone fading (Ref. 62).

A combination of high humidity and ozone has caused fading of nylon carpets (Ref. 63). The fading rates of any one dye in ozone-containing atmospheres is a function of the nylon structure as well as the environment. This observation is attributed to the differences in adsorption onto and diffusion into different nylons. The greater the surface area exposed and the more open the microstructure, the more sensitive the nylon is expected to be to ozone fading. Swelling of nylon due to high humidity should increase both the surface area and the rate of diffusion into the fiber (Ref. 63).

12-5.2.3 SUMMARY

It is highly probable that present knowledge of ozone damage to materials is only a small fraction of the total. The interaction effects between ozone and other pollutants on materials have not been investigated. From thermodynamics, it would be expected that ozone would oxidize both nitrogen tetroxide (N_2O_4) and sulfur dioxide (SO_2) to nitrogen pentoxide (N_2O_5) and sulfur trioxide (SO_3), respectively. At the low concentrations found in the atmosphere, the kinetics of the reactions in the gas phase may be too slow to be considered. When adsorbed on solid surfaces of materials, however, the reactions may be catalyzed to appreciable rates. Nitrogen pentoxide and sulfur trioxide form nitric acid and sulfuric acid, respectively, when dissolved in water. Many materials are attacked by these acids, and the diurnal condensation-evaporation cycle of atmospheric moisture on material surfaces would be expected to concentrate these dissolved acids if they did not react immediately with the material. In this manner, damaging concentration levels could be reached.

An example of this type of behavior was reported by Morris (Ref. 56). A good statistical correlation was obtained between breaking strengths of cotton fabrics and the pH values of water extracted from them. The breaking strength decreased with a decrease in pH. Correlations were also obtained with relative humidity and the amount of sunlight at the exposure sites. Breaking strength decreased with increases of both humidity and amount of sunlight. The amount of nonfibrous material obtained from fabric samples exposed in California in May and June was 1.32 percent and the pH of the water extract was 4.93. In contrast, the value for the unexposed sample was 0.29 percent, with a pH of 6.65.

Much more dose-response data are needed before the full impact of ozone on materials can be calculated. Although there may be sufficient data for rubber, data for other organic materials such as fabrics, dyes, paints, and plastics are lacking. There have been no investigations to determine the dose-response relationships of combinations of ozone with other pollutants on either organic or inorganic materials.

Although the total extent of ozone-associated damage to materials is not known, ozone may very well be a major contributor to the "weathering" of materials. Ozone is an extremely active compound, and, generally, any organic material is incompatible with concentrated ozone. Many organic polymers are subject to chemical alteration from exposure to very small concentrations of ozone, including some ambient concentrations. This sensitivity usually increases with the number of double bonds in the chemical structure of the polymer.

Rubber is an economically important material that is highly sensitive to ozone attack. Although a tensile stress is necessary for ozone to produce cracking of rubber, rubber products are usually used in this state. Although rubber in a relaxed state can be exposed for long periods of time without visible cracks forming, cracks can develop from exposure to an atmosphere containing 20 to 40 $\mu g\ m^{-3}$ (0.01 to 0.02 ppm) ozone if the rubber is under a strain of as little as 2 or 3 percent. Antiozonant additives have been developed and are capable of protecting elastomers from ozone degradation.

Ozone attacks the cellulose in textile fabrics through both a free-radical chain-mechanism and an electrophilic attack on double bonds. Light and humidity appear to be factors that must be present before an appreciable alteration occurs in the breaking strength and fluidity of fibers. The relative susceptibility of different fibers to ozone attack, in increasing order, appears to be cotton, acetate, nylon, and polyester.

Certain dyes are susceptible to fading during exposure to ozone. The rate and extent of fading appear to be dependent on ozone concentration, length of exposure, type of material used, and environmental factors such as relative humidity and the presence or absence of other atmospheric pollutants. Technology is capable of selecting combinations of fabrics, dyes, and processing that can eliminate ozone fading, but the cost of this will be passed on to the consumer in the form of increased costs.

12-6 TESTING AND SIMULATION

Test procedures are of two general types, (1) those performed in environmental chambers with known concentrations of ozone, and (2) those performed by exposing material to the environment and monitoring the ambient ozone concentrations. There are advantages and disadvantages to both types of evaluation.

The environmental chamber is used to determine the effects of known concentrations of ozone on material, particularly for accelerated tests. In an accelerated test, concentrations of ozone much higher than in the environment are used. This allows rapid comparison of a number of substances with regard to their resistance to ozone attack. Accelerated tests can be related to environmental exposure. This is done by a combination of experience and proper calibration of the tests. There is some correlation between damage caused by the product of ozone concentration in the test chamber and the time duration of the test exposure with the product of environmental ozone concentration and exposure time. The disadvantage of chamber exposure is that not all of the many significant conditions of the environment are duplicated in the chamber. An additional limitation of exposure chambers is the number or size of articles that can be tested.

As an example, a commercially available

ozone test chamber* provides a volumetric ozone concentration range from 0 to 250 pphm with a chamber temperature range from ambient temperature to 250°F. Automatic generation, control, and monitoring systems are available and test chamber sizes range from 1 to 600 ft^3.

Direct exposure to the environment with appropriate sampling of ozone concentrations has the advantage of demonstrating exactly what the environment is doing to material. With this type of direct exposure, the effects of the environment of different locales can be obtained. Obviously, exposure conditions are not controlled but only monitored. Interpretation of the contribution of ozone attack compared with overall environmental deterioration is more difficult to determine than in the controlled atmosphere studies. Environmental exposures may have to be carried on for years before interpretable results are obtained.

In order to make comparisons of ozone damage, one must define and measure damage. The kinds of ozone damage of most concern are those that weaken material and thereby limit its use or its useful lifetime. Also important is the fading of colored material. In determining damage to rubber from ozone, a number of criteria have been used: subjective visual observation of the damaged material, counting the total depth of cracks in a cross section of the exposed material, determination of the stretching ratio under standard stress, and determination of the breaking point of a standard piece of material. Dye fading can be determined either visually by comparison with dyestuff that has had a standard exposure to ozone, or by some instrumental colorimetric technique.

Evaluation of a large scale problem would best be left to a testing agency or consulting research laboratory. For testing small objects, bench scale ozone exposure chambers are commercially available or can be constructed. Evaluation of the effects of environmental exposure are made by sealing test material in an airtight container and comparing it from time to time with material exposed to the environment.

In general there are three kinds of ozone-containing atmospheres to consider: (1) the natural atmosphere (concentration average 2 pphm; range 0 $\approx$ 6 pphm), (2) the urban or polluted atmosphere (average daytime concentration, 5 to 20 pphm; range up to 90 pphm), and (3) indoor air contaminated by an artificial ozone source (concentrations can be as high as several parts per million). There are also three periods—manufacture, storage, and use—during which exposure of material to the atmosphere provides different problems.

To protect material against ozone damage, there are a number of techniques, not all of which are applicable to all substances or circumstances. If the ozone causing the damage is from a manmade source, it may be possible to shield the source. If damage occurs during storage, there are several possibilities. The items of interest could be packaged to prevent contact with the atmosphere. If the ozone is entering from the outside, it will help either to reduce or eliminate ventilation or to run incoming air through an ozone destructive filter (activated carbon is effective). Special antioxidant greases, etc. will protect against ozone; actually, any type of coating will provide some protection. If a protective coating or covering cannot be used, applied, or maintained when an ozone-susceptible item is in use in the ambient environment, the only recourse is to replace the susceptible material with a similar but ozone-resistant material. The change in types of rubber used in automobile tires is an example of this substitution procedure.

12-7 AGENCIES MONITORING ATMOSPHERIC OZONE

The only agency conducting a regular ozone-monitoring activity in the world is the U S Environmental Protection Agency (EPA). The California Air Resources Board and the Los Angeles Air Pollution Control

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*Available from Ozone Research and Equipment Corporation, Phoenix, Ariz.

District also perform a great deal of air monitoring. The ozone observation program of the U.S. Air Force (Cambridge Research Laboratories) has been suspended (1972), whether temporarily or permanently is not certain. In addition, the Atmospheric Sciences Laboratory of the U.S. Army Electronics Command at White Sands Missile Range, N. Mex., has both an upper atmosphere and surface monitoring program.

The Air Pollution Control Association (4400 Fifth Avenue, Pittsburgh, Pa. 15213) publishes a directory of governmental air pollution agencies. This directory contains numerous Federal, State, and local agencies, most of which have some ozone-monitoring capability. Federal air pollution control implementation regulations require ozone monitoring as evidence of compliance with air quality standards.

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CHAPTER 13

MACROBIOLOGICAL ORGANISMS

13-1 INTRODUCTION

This chapter on macrobiological organisms includes all of those living organisms that are sufficiently large to be observed individually by the unaided eye and have an impact on military materiel design. Its purview includes all plants and animals except those discussed in Chap. 14, "Microbiological Organisms", of Part Two of this handbook, which is confined to micro-organisms. Major categories include insects, marine borers, rodents, birds, and vegetation. These are of concern because they have identifiable effects on materiel.

The interactions between these larger biological entities and the other environmental factors are discussed in other chapters of this handbook. Vegetation, for example, has a large influence on temperature, humidity, solar radiation, fog, and pollutants and is an important consideration in terrain. Discussion of these interactions is excluded from this chapter; discussion of the jungle canopy and its temperature regime is found in Chap. 3, "Temperature", of this handbook, for example. Micro-organisms are intimately related to the larger biological species but, again, are excluded from this chapter. Rather, the intent has been to confine this discussion to direct effects on materiel or materiel requirements.

Since the intended reader of this handbook is primarily the materiel design engineer, a legitimate question concerning his interests has pervaded the preparation of this chapter. Is the subject to be "materiel" or is it to be broadened to include "materiel requirements"? Thus, mosquitoes do not contribute to materiel degradation, but they do influence materiel requirements—mosquito netting, screening, repellants, insecticides, and drainage equipment are required, at times, to combat mosquitoes. The design engineer must know that habitable structures may require screening. He should be aware, in the design of clothing, that protection is desirable and whether equipment capabilities are required for insecticide dispersal or destruction of breeding habitats. It would be easy to eliminate a number of candidate animals, insects, or plants from the discussion of this chapter if the narrower perspective were adopted. However, this approach would fall short of filling the needs of the user of the handbook. An attempt is made to give a balanced treatment but omissions will be obvious.

In other chapters of this handbook, the organization of the information is (1) to describe the factor, its measurement, and its distribution; (2) to describe the effects of the factor on materiel and the procedures for designing so as to avoid adverse effects; and (3) to enumerate the testing and simulation procedures that assure adequate design. In this chapter, the subjects are so diverse as to make that organization intractable. However, for each subject considered, the factor description, effects and design procedures, and test and simulation procedures format is followed. When information on a specific macrobiological organism is presented, that presentation is complete within the paragraph in which it appears. The chapter subdivisions, therefore, are different from those of the other chapters.

In order that proper attention be given to the more important macrobiological organisms, several of the less important ones are discussed briefly in this introduction and references are given for additional information sources. These include the reptiles and the larger mammals.

Snakes are maligned in the popular literature out of all proportion to their actual threat or damage. American military forces have never experienced enough casualties from snakebite to jeopardize a mission or to attract much attention. However, the threat of snakebite may create a morale problem sufficient to delay or otherwise impede a mission. Even in those areas of the world such as Southeast Asia where snakebite deaths are relatively high, American troops equipped with antitoxic serum, protective footwear, and adequate mechanical equipment do not experience the snakebite mortality rates characteristic of the indigenous population.

In any case neither snakes nor other reptiles constitute a hazard to materiel nor do they normally create a requirement for specialized materiel items. Thus, snakes do not represent a significant environmental factor in the context of this handbook and no additional discussion is warranted. Complete information on poisonous snakes may be found in *Poisonous Snakes of the World* (Ref. 1), while additional information is found in *A Field Guide to the Snakes of South Vietnam*, (Ref. 2) and *Snakes of the World* (Ref. 3).

Like reptiles, the larger mammals are of little concern to materiel design engineers. Although, in some instances, materiel is damaged by the ravages of the larger mammals, this occurs too infrequently to warrant extensive consideration. Bears, for example, are known to have destroyed instruments at remote weather stations and will damage and destroy other materiel in their search for food. Bears are not numerous and the incidents in which they are involved occur infrequently.

The large mammals, in general, have survived the spread of civilization only because their natural habitat is still remote from man's habitation. Thus, the deer and caribou of North America, the cats in many areas of both hemispheres, the varied mammalian species of Africa, and the sea mammals generally avoid man and his incursions into their habitats. Most species of large mammals are so decimated as to require protection in order to survive.

Only when military operations are necessitated in remote areas of the world will large wild mammals constitute a problem of any kind to military materiel, and even then it will usually be of secondary importance.

13-2 INSECTS AND OTHER ARTHROPODS*

Of the various animal species visible to the naked eye, arthropods constitute the most numerous general grouping and the most important in causing deterioration of materiel and discomfort and health problems for personnel. Although more than 750,000 different kinds of arthropods have been named and described, only a small number of them are harmful to Army materiel and personnel. Arthropods are found in an almost infinite variety of natural environments as well as in manmade or modified natural situations. Their food and behavior patterns are extremely varied. Numerous articles made from materials of animal or vegetable origin provide food or shelter or both for arthropods. These materials can be damaged or totally destroyed by their attack. This may occur during one or more of various distinct stages of a given animal's life cycle—such as the egg, the larva, the pupa (resting stage), or the adult beetle, for example. Life cycles can last from less than a few months to several years.

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*The Arthropoda are a phylum of animals comprising more than 75 percent of the classified animals in the world; about 90 percent of them are insects. Arthropods include insects, arachnids, crustaceans, and myriapods. Arachnids, which include spiders, scorpions, ticks, mites, and chiggers, differ from insects in having four pairs of legs; in having only two body regions (head and thorax combined into one); in having no antennae, real jaws, or compound eyes; and in other ways. Insects have only three pairs of legs, three body regions, and usually, two pairs of membranous wings (bees, beetles, flies, wasps, and mosquitoes). Crustaceans are marine arthropods characterized by exoskeletons and include lobsters, shrimps, crabs, and barnacles. Myriapods, such as millipedes and centipedes, have numerous similar body sections, nearly all of them having true jointed legs.

Inasmuch as arthropods are cold blooded and have a body temperature dependent upon the environment, they are able to survive weather extremes. The superior sensitivity of some animals to small changes in pressure, temperature, and humidity enables them to be very responsive to impending changes in weather.

A given species of an insect or other arthropod seeks the most suitable microclimate within its environment–one providing suitable shelter, adequate food, and a proper environment for laying eggs. For instance, many species of female mosquitoes search over large areas for stagnant pools in which to lay their eggs. The mobility of flying insects allows them to be selective in choosing a suitable habitat. Since certain habitats are apt to be infested with insects and other arthropods known to be harmful to certain materials, they should be avoided or cleared of infestation before use.

Many arthropods are detrimental to the comfort and health of personnel. A piece of equipment may be difficult to field test or use in an environment in which these pests cause annoyance and injuries to personnel. Such a problem might be solved by the use of protective devices for a limited period, but well coordinated control measures may be needed before completing a longer mission. A fundamental knowledge of the harmful insects and their control is often essential for successful operations.

Depending upon the density of the arthropod population, their characteristics, and their degree of persistence, effects can be manifested in various degrees and ways. Arthropods are often a nuisance by their presence; by their sounds; by the bad odors and tastes of their secretions; by crawling over the human body; by getting into the eyes, ears, nose, and mouth; or by depositing their eggs or waste substances on the body. Flying, buzzing, and creeping creatures are particularly annoying when a soldier is concentrating on a task or is simply trying to rest. They can hamper visibility as well as a soldier's ability or even his will to perform efficiently.

Injuries inflicted by insects can be more serious than their annoyance of personnel. These injuries, mostly bites and stings, are usually painful, may be accompanied by other serious symptoms, such as fever, nausea, and swelling, and are often infectious or toxic. Some insects eject secretions harmful to the skin or eyes; accidental squashing of some arthropods against unprotected human skin can produce a serious reaction.

Because of their nuisance and injury capabilities, arthropods pose a threat far exceeding those of the larger animals. Many protective and control measures have been developed; many of them must be improved and new techniques developed in the ever-present battle with harmful species.

Additional information beyond that provided in the paragraphs that follow on the complicated and sometimes controversial use of numerous insecticides is provided in *The Handbook of Pest Control; the Behavior, Life History, and Control of Household Pests* (Ref. 4), *Destructive and Useful Insects: Their Habits and Control* (Ref. 5), and in the *Military Entomology Operational Handbook* (Ref. 6). Various Federal and State organizations have conducted research on safe and economical methods of arthropod control and the U S Public Health Service provides information on this subject. Private industrial firms, particularly chemical companies, have also conducted much research and furnish considerable information, especially on the insecticides that they have developed.

13-2.1 TERMITES

Termites are the most destructive of the biological agents, damaging wood and other cellulose-containing products. These pale-colored, social insects are found in highly organized colonies. Most species seek habitats in or near wood. Moisture requirements of termites vary greatly with different species. Except during their colonizing period, termites shun light and exposure.

Although termites are not found in arctic and antarctic areas, they occur in most other major geographic regions as shown in Fig. 13-1. In the United States termites are most common in the South and Southwest. Members of the genus *Reticulitermes* are widespread in this country below elevations of about 2,000 m. They are also found in a band extending from the western Mediterranean region across southern Eurasia to southern China.

Once a wooden building or other wood product becomes infested with termites, the damage they cause may be extensive before it is discovered as is illustrated in Fig. 13-2. Decontamination and repair of damaged wood, especially in buildings, adds greatly to the cost of maintenance. It is important that careful consideration be given to termite protection when planning and constructing wooden buildings. Buildings can be fully protected against damage by termites at a modest cost.

An older but still useful and comprehensive treatment of termite problems is to be found in *Termites and Termite Control* (Ref. 9). Other useful references are *Our Enemy the Termite* (Ref. 10) and an agricultural bulletin on termites (Ref. 11).

13-2.1.1 SUBTERRANEAN TERMITES

The two broad classes of termites are the subterranean and the nonsubterranean, of which the former is more common and more destructive. The subterranean termites are discussed in this paragraph.

(1) *Description.* Subterranean termites live in colonies in the ground but often travel in secret passageways above ground to obtain food; they must have a ground contact mainly to insure an ample supply of moisture. Each colony—distinctly separated from all others—consists of reproductives, workers, and soldiers. Examples of these types and stages for the western subterranean termite are shown in Fig. 13-3. During their lifetime, the members of each caste pass through three stages—egg, nymph, and adult. Adult workers and soldiers are always wingless, grayish or creamy-white, thin-skinned, maggotlike, blind, and similar in appearance except that the soldiers have larger, harder, and longer heads with sicklelike jaws. The workers, by far the most numerous and destructive, include both males and females; they do all the labor, including feeding and grooming other members of the colony. The function of the soldiers is to protect the colony against its chief enemy, the ant. Termites are a popular food for other insects and for fauna during swarming periods.

The temporarily light-seeking swarms of subterranean termites consist of reproductives or sexual adults. They have yellow-brown or black bodies and two pairs of long, whitish, opaque wings, which are about twice the length of their body. In temperate areas the queens are 12 to 20 mm in length, in the tropics they are 50 to 100 mm long.

Since termites are far more destructive than but similar in appearance to reproductive forms of true ants, it is important that the two insects be distinguished. Their contrasting features are shown in Fig. 13-4. Termites have a thick waistline, which contrasts sharply with the very narrow waistline characterizing all ants. True ants also have two pairs of temporary wings that are transparent and unequal in length while, for termites, the two pairs of wings are equal in length. Termites are characterized by straight, beadlike antennae; ants by elbowed antennae. As to habitat, ants are often observed in open, drier situations; termites are normally hidden in relatively warm, moist sites.

(2) *Distribution.* Subterranean termites are found in most tropical and temperate areas. They are common in most parts of the eastern half of the United States, especially in the deep South, and in California (Fig. 13-5). Moreover, within these areas the extent of damage from termites varies greatly from one specific locality to another, depending on type of ground, moisture, and local building practices.

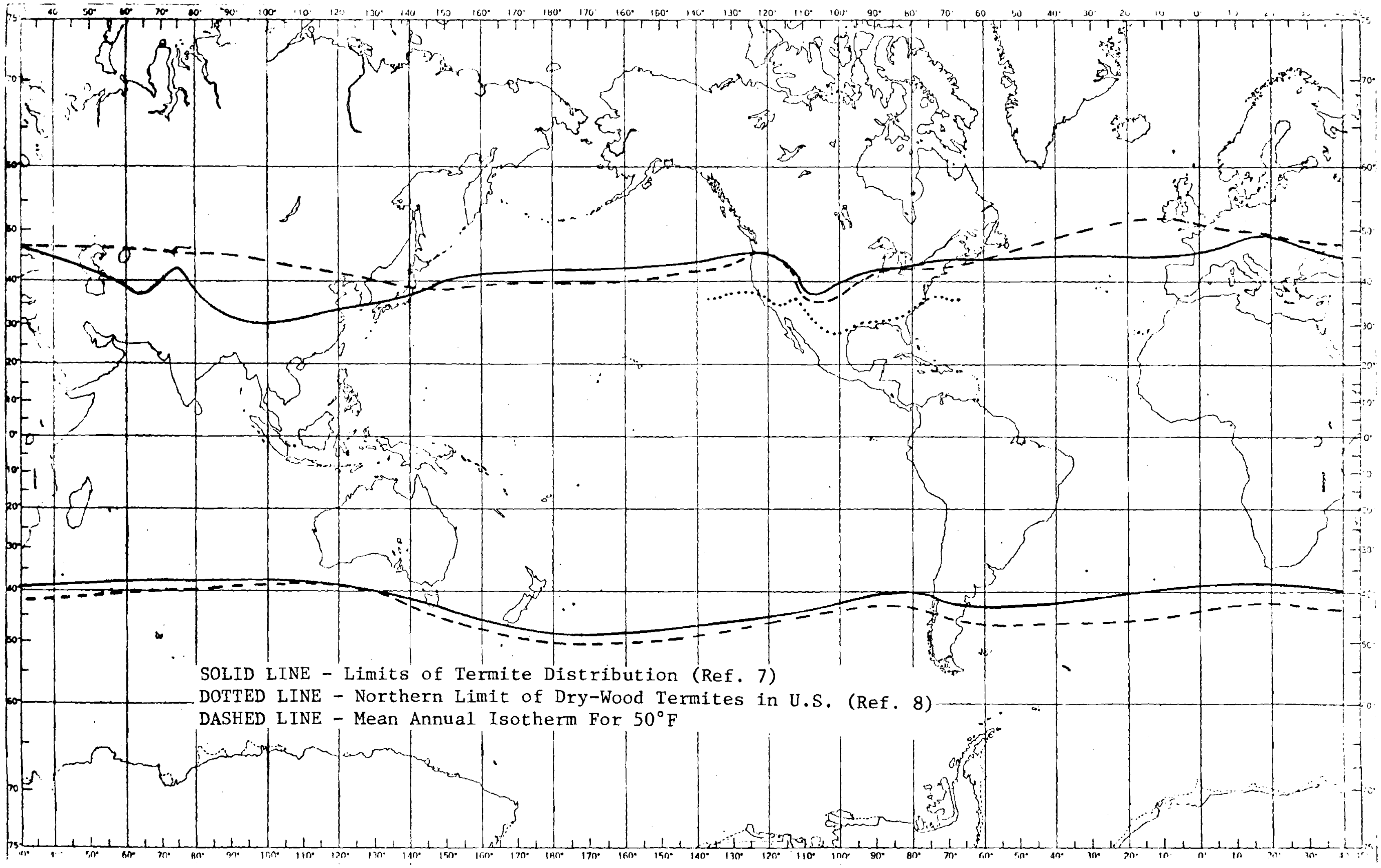
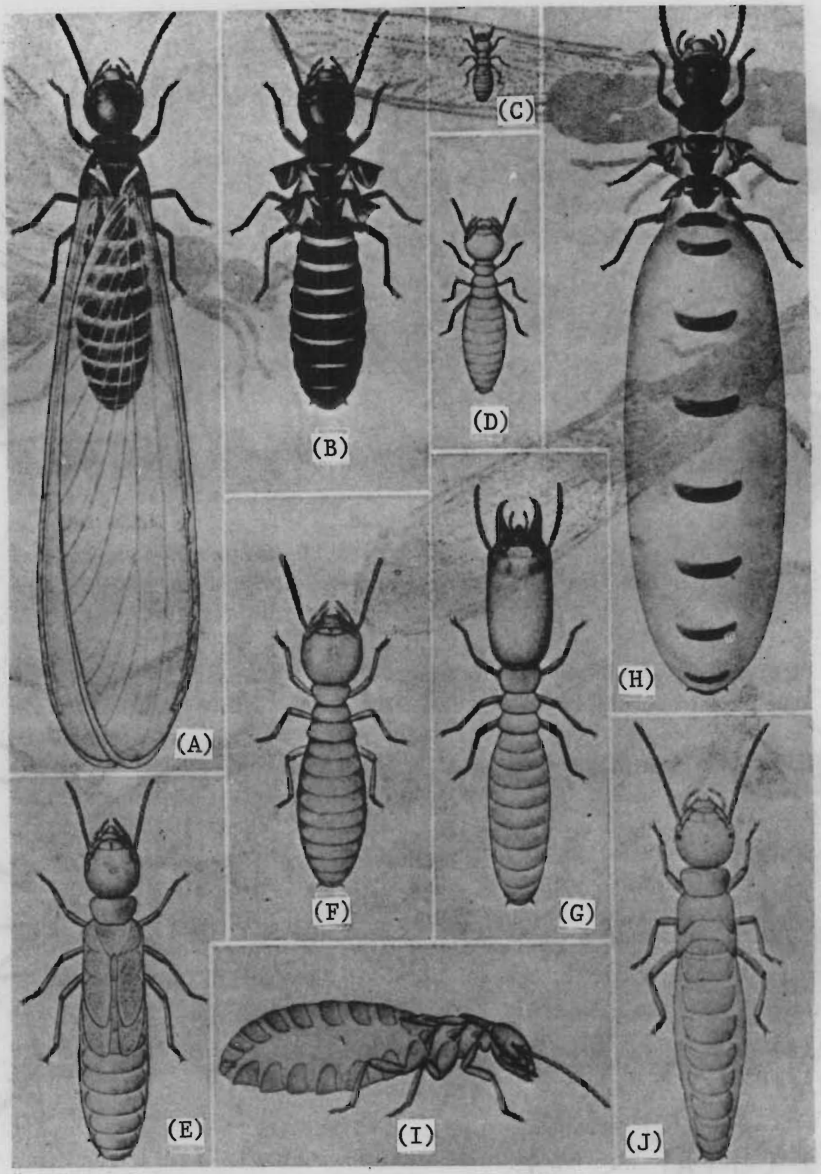


Figure 13-1. Worldwide Termite Distribution

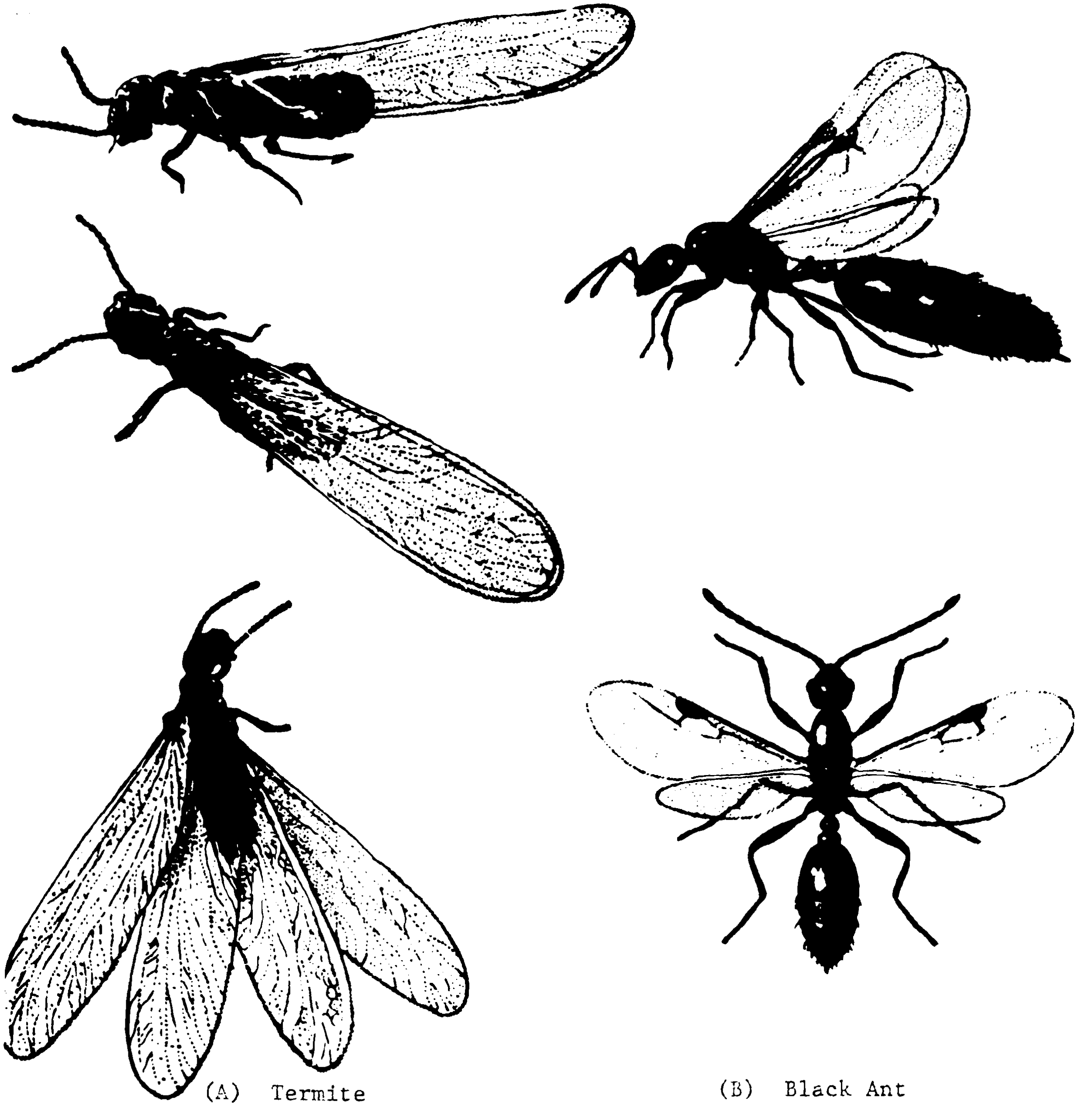
Figure 13-2. Termite Damage to Utility Pole (Ref. 6)



The different castes and young, or nymphal, stages (instars) of <u>Reticulitermes hesperus</u>, the western subterranean termite. All drawn to same scale (× 9).

(A) Winged reproductive, or alate, ready for swarming. This is the only form in which termites are commonly seen outside of their burrows. Males and females are very similar in appearance. (B) Dealated reproductive whose wings have been shed after swarming. (C) Very young nymph in first nymphal instar, or growth stage, not long from the egg: caste not yet evident. (D) Middle-sized nymph, in third instar: caste still not evident. (E) Late nymph of reproductive caste with wing pads, or immature wings. (F) Individual of the worker caste, fully developed. (G) Individual of the soldier caste, fully developed. (H) Old breeding queen, enlarged, or physogastric. (I) Short-winged, brachypterous, or second form individual of the reproductive caste, called a supplementary reproductive. (J) Wingless, apterous, or second form individual of the reproductive caste, also called a supplementary reproductive.

Figure 13-3. Life Cycle Stages of Termite (Ref. 6)



(A) Termite

(B) Black Ant

Figure 13-4. Flying Forms of Termites and Ants (Ref. 6)

In some parts of the world, subterranean termites that build high mounds are known as mound-building termites. They are found locally in Central and South America and in Australia, Africa, and Southern and Southeast Asia.

Although the distribution of termites over broad areas continues to remain essentially unchanged, infestations in buildings have increased because of the introduction of central heating and of changes in building practices and materials. Heated basements also extend termite activity to include winter weather and thus contribute to greater losses.

(3) *Evidence of infestation.* Often, the first indication of a well-established subterranean

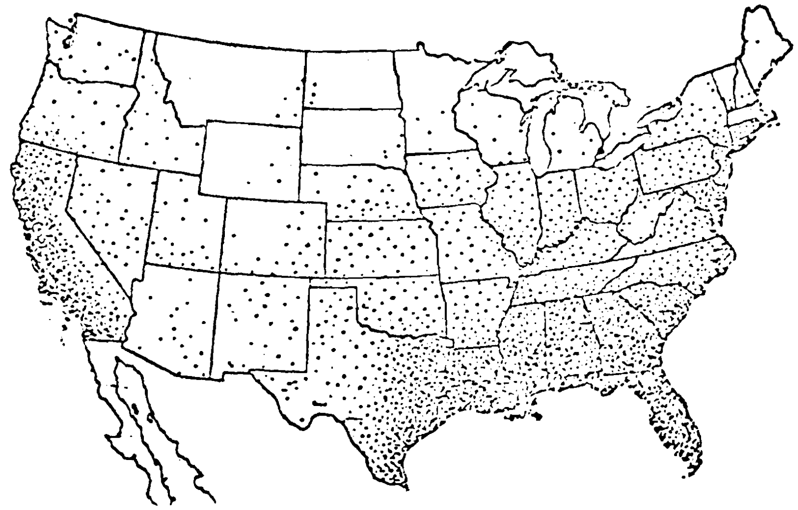


Figure 13-5. Subterranean Termite Infestation in the United States (Density of dots is proportional to the termite population density.)

termite colony is large numbers of young reproductives emerging, or "swarming", from the ground or wood. In temperate areas these colonizing flights most frequently occur after several warm days of spring, often after a warm rain, but may occur almost any time during the warmer months. In the tropics such a migration occurs after heavy rains. Since the nonflying queens in the tropics become so large, a subterranean termite infestation is confined to the nearby vicinity.

The young reproductives emerging inside heated areas in temperate areas are attracted by strong light and gather around a window or glassed portion of a door in an effort to get outside. Unless they are caught in an outside air current, subterranean termites seldom travel very far before shedding their wings. The presence of discarded wings in lighted places provides good evidence that termites emerging inside a building were unable to escape.

Most of the reproductive adults perish. In temperate latitudes a few newly formed pairs sometimes succeed in flying away and establishing new colonies. The wingless termites merely seek adjacent moist sites near a source of wood. By the time a colony is 5 or 6 yr old, it may contain several thousand termites. A colony of termites is unlikely to do much damage to a building in less than 8 yr unless other colonies of termites were already in the ground before a building was erected.

Subterranean termites provide little evidence of their presence and may remain unnoticed by casual observers for many years. The workers, which are soft-bodied, numerically dominant, and the most destructive caste in a colony, excavate secretive galleries within materials that they attack. The inside of their galleries are covered with grayish specks of excrement and earth. They neither reduce wood to a powdery mass nor push their waste materials through outside openings, as do certain types of wood-boring insects. Termites are also careful to keep the outer surface of the wood intact. This conceals their destructive mining activities and helps to preserve the vital moisture in the wood, which is required by most termites.

(4) *Favorable conditions.* Subterranean termites become most numerous in warm, moist ground containing abundant and suitable food. Poorly ventilated space beneath the first floor of buildings where an ample supply of wood is in direct or indirect contact with the ground provides favorable conditions

for termite infestations, particularly at porches, steps, or terraces. Cracks or voids in foundations and concrete floors also make it easy for termites to reach wood that is not in contact with the ground. Heat radiated through basement walls in temperate latitudes fosters termite activity during cooler periods.

(5) *Damage*. The principal food of termites is cellulose, obtained from wood and other plant tissues. Termites damage wood in buildings, utility poles, fence posts, and other wood in contact with the ground or adjacent to masonry or concrete through which they travel to reach food. Subterranean termites feed on the cellulose-rich spring wood and leave the non-nutritious summer wood. This results in the excavation of alternate bands of wood.

Other cellulosic products often damaged include paper, fiberboard, and various types of fabrics derived from cotton and other plants. They may also penetrate such noncellulosic materials as asphalt (especially expansion joint fillers and moisture-proofing paints used on basement floors or walls of buildings), asbestos, leather, electrotype blocks, wet battery cases, and cellulose-acetate fabrics. However, most damage is confined to woodwork in buildings.

(6) *Control*. It should be reemphasized that the best time to provide protection against termites is during the planning and construction of a building, because some faulty methods commonly used in building construction contribute to the danger of termite infestation. The following preventive and remedial measures are suggested:

(a) Surplus cellulosic material, such as stumps, scrap, and form boards should be removed from the building site prior to and after construction.

(b) If an area is already infested with termites, chemicals should be applied to the ground to kill them, although such treatments lack permanent value. They are no substitutes for proper construction.

(c) A gap of at least 15 cm should be provided between woodwork of building and soil or fill.

(d) Building foundations should be impenetrable to termites. Sound construction practices eliminate voids in walls and floors. Reinforced poured concrete is better than discrete unit masonry construction in minimizing the possibility of termite entry.

(e) Well-designed and carefully installed metal shields are no substitute for good construction but may serve to supplement good construction.

(f) Appropriate openings in foundations of wood construction should be provided to insure sufficient ventilation of moisture-accumulating pockets under buildings.

(g) Thorough drainage of ground adjacent to and beneath buildings should be provided for.

(h) Sufficient clearance beneath buildings for making annual inspection (45 to 75 cm) should be provided.

(i) Wood impregnated with standard (Federal Specification TT-W-571 d) preservatives, which provides protection against termites, should be used.

(j) Impregnated fiberboards or wall panels with toxins such as copper, arsenic, or chlorinated phenols during the manufacturing process afford them protection against termite damage.

(k) The slow-growing heartwood of certain tree species grown in the United States and in the tropics, which are naturally resistant to termite attack, can be used.

(l) Chemicals often used in treating new and old building sites to control termite infestation are sodium arsenite, coal-tar creosote, trichlorobenzene, orthodichlorobenzene, and pentachlorophenol. Important safety precautions must be followed in their use, for they can be extremely harmful to people, animals, or plants under certain conditions. For detailed information on their use, consult the appropriate literature (Refs. 4,7).

In any remedial measure, it is well to keep in mind that a colony of subterranean termites will soon perish when either their passageway to a vital ground contact or their access to a source of cellulose is blocked by corrective alterations to a building.

13-2.1.2 NONSUBTERRANEAN TERMITES

Nonsubterranean termites, the second major class of termites, have a cycle similar to the ground-nesting forms. They differ in that most species do not require a ground contact.

(1) *Description.* Immature nymphs are the workers. The soldiers are relatively large and wingless. As protectors of the colony, they have powerful jaws with teeth on their inner edge (subterranean species do not).

The reproductive adults, ranging in length from 8 to 25 mm, may be light yellow to dark brown or black. They differ from subterranean species in having branches in the upper part of their wings. The reproductives have wings initially and can fly short distances, after which they shed their wings. If a female and male find suitable wood, they enter it and enlarge it laterally. Later they seal the openings with small particles of excrement and a dark cementlike substance secreted from their mouths.

Nonsubterranean colonies grow more slowly, are less common, and less injurious than subterranean colonies. An old colony may consist only of a few thousand termites.

Each colony consists of a number of chambers distributed throughout galleries in the wood. The nymphs remove all excreta of partially digested wood from galleries either to unused inner chambers or to the outside through small openings, differing in this habit from the subterranean termites.

(2) *Distribution.* Nonsubterranean termites have been found in temperate, subtropical, and tropical regions. Fortunately, they are common only in a relatively few localities throughout the world.

In North America they occur chiefly in warm coastal areas. In the United States dry-wood termites (*Kalotermes*), the most common species, are found in a narrow strip from Cape May, N.J., across Florida, along the Gulf Coast and the Mexican-border States to Northern California. Southern Florida and California are most affected by these insects (Fig. 13-1).

These termites are most destructive in the tropics and subtropics, especially in New Zealand, Ceylon, parts of eastern and southern Africa, South and Central America, Cuba, Puerto Rico, and Haiti. They are found in elevations up to 8,000 ft in parts of Latin America. Their damage is less serious in Mediterranean Europe, North Africa, and southern United States.

(3) *Evidences of infestation.* Except during dispersal flights, nonsubterranean, like other termites, are rarely seen. An accumulation of shed wings is evidence of local infestation, for termites never crawl freely over exposed surfaces at other times, as ants do.

These insects seal all openings in wood with a brownish or blackish cementlike substance that they secrete. The termite plugs are usually paper thin and often contain partially digested pellets of excreta. The sealed openings may have been made by boring beetles, entrance holes made by the original colonizing male and female, exit holes for colonizing flights, or holes cut for regulating temperature and humidity.

Nonsubterranean termites excrete pellets of partially digested wood; subterranean termites do not. The pellets, similar in color to the excavated wood, are found in tunnels and in piles where they were ejected from infested chambers. Unlike the pellets ejected by the powder-post beetle, termite pellets can be identified by their concave surfaces. This evidence is often the first warning of termite activity.

These insects sometimes construct thick, narrow shelter tubes of secreted substance and excretal pellets to serve as passageways between sources of wood. They may also close in the crevices between masonry, concrete, wood, or between a combination of these materials.

These termites excavate chambers and tunnels precariously close to the surface, leaving only a surface film of unpainted wood (blister) or only a flimsy coating of paint. Infested wood may be detected by tapping wood with finger tips or a piece of metal. This may produce a hollow sound or papery rustle. Either of these sounds may reveal the presence of termite caverns beneath the surface.

(4) *Damage.* Nonsubterranean termites attack wood and wood products containing cellulose in a variety of environments. They infest structural timbers and other woodwork in buildings, furniture, utility poles, lumber, paper, cloth, fiber insulation panels, and numerous miscellaneous items.

Damage to wood made by nonsubterranean termites differs considerably from that caused by subterranean termites. Unlike subterranean termites, nonsubterranean species cut across the grain and excavate irregular chambers connected by tunnels that are about the overall diameter of a termite. Nonsubterranean termites destroy both spring and summer wood; subterranean termites consume only the spring wood.

Although damage by various nonsubterranean species varies considerably with the locality in the United States, damage by these insects is most severe outside the country. For instance, most Cuban cities prohibit the construction of wooden floors. In rural areas in that country, termite-resistant woods are used.

(5) *Preventive measures.* All lumber, especially old lumber, should be inspected carefully for evidences of infestation. Infested lumber should never be used. The transportation and reuse of such lumber is prohibited in Panama, Honolulu, and Pasadena (Calif.).

Screening of all doors, windows, and other ventilation openings with a noncorrodible metal (20 meshes to the inch) should prevent winged termites from entering a building.

Utility poles, construction timbers, and other cellulosic building materials can be pretreated or impregnated with chemical wood preservatives to prevent termite attack but these services are expensive. Considerable protection can be provided by dipping wood for 3 min in 5-percent solution of pentachlorophenol in light petroleum-based oil, or applying three coats of this solution with a brush. All exposed surfaces must be treated.

Several coats of heavy paint on exterior wood surfaces provide appreciable protection against termite entry.

Where the danger of infestation is significant, various termite-resistant woods should be used. For construction timbers, the close-grained heartwood of foundation-grade redwood, heartwood of southern tidewater red cypress, and very pitchy longleaf pine can be used. Eastern red cedar is fairly resistant and is more readily available for use as poles, posts, bridge timbers, or similar purposes. Except for black walnut, termites attack all furniture woods native to the United States. Heartwoods of true mahogany and Spanish cedar make resistant cabinet woods.

Although the use of steel, concrete, stone, or brick instead of wood in buildings provides good protection against nonsubterranean termites, wooden materials inside such buildings are susceptible to attack unless a building is thoroughly screened.

(6) *Remedial measures.* Once wood becomes infested with nonsubterranean termites, a number of remedial measures must be undertaken to prevent further damage. Infested wood in buildings should be removed, destroyed, and replaced with chemically treated wood or other termite-resistant material. Infested lumber should neither be transported to another area nor reused, since these insects remain and continue to damage the wood.

A second way to destroy nonsubterranean termites is by heat or cold treatment of infested wood. Placing infested furniture in a chamber heated to 60°C (140°F) for 4 hr will kill termites and most other similarly harmful insects (Ref. 8). Exposure of termites in wood to a temperature of −9°C (15°F) for 4 days will also kill them. In the northern climates, infested furniture may be moved outdoors; in the tropics infested items may be kept in a refrigerating unit for the designated period.

If the wood has been damaged considerably but not significantly weakened by termite excavation, an insecticide in a liquid or dust form may be injected into their galleries. The same chemicals used in killing subterranean termites also kill nonsubterranean termites, although minor differences in strength and method of application may be pertinent because of different habits. The poisonous residues of some chemicals injected into galleries prevent other termites from establishing colonies in the same areas.

Nonsubterranean termites can also be checked by fumigating tightly sealed, isolated, infested buildings with a toxic gas, such as methyl bromide. This has the advantage of controlling termites in buildings with inaccessible infested timbers. The method is also quicker and frequently cheaper than the use of toxic liquids and dusts. However, fumigation leaves no poisonous residue in galleries to prevent termites entering the same chambers. Furthermore, fumigation is extremely dangerous and should be conducted only by licensed personnel.

13-2.2 POWDER-POST BEETLES*

The powder-post beetles comprise several families of woodborers that honeycomb hardwoods and softwoods. These insects are so named because of the excreted flourlike powder deposited mainly in burrows bored by their larvae; other insects in this general group excrete pellets of wood. Aside from the holes bored where insects entered the wood and the small piles of excretions occasionally spilled from holes, little or no evidence may be present to reveal their workings. The larvae of these beetles feed mostly on seasoned lumber or wood products, although some species attack live or unseasoned wood. Given sufficient time, they bore an intricate network of burrows inside a thin outer shell and between some intervening partitions of undisturbed wood. Excreted wastes are usually packed tightly behind larvae, so their presence is often concealed until after serious damage has been done.

At least some species of powder-post beetles can be found in all parts of the world and cause considerable damage to lumber, furniture, woodwork of buildings, tool handles, packing cases, cots, tent stakes, and innumerable other wood items.

The five most harmful families of powder-post beetles include the following in order of worldwide importance: Anobiidae, Cerambycidae, Bostrichidae, Lyctidae, and Curculionidae. All have four distinct stages in a life cycle that lasts from 3 mo to a number of years. The stages include the egg, the larva, the pupa (resting stage), and the adult beetle. Completion of the cycle is much faster in the warmer latitudes. Eggs are usually deposited in crevices of wood, in open joints of furniture, and in open pores of wood surfaces. The larva stage is the most destructive. The larvae borings reduce structural strength of wood and expose its interior to moisture and microbiological deterioration.

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*General references for this paragraph include *Defects in Timber Caused by Insects* (Ref. 12) and the *Military Entomology Operational Handbook* (Ref. 6).

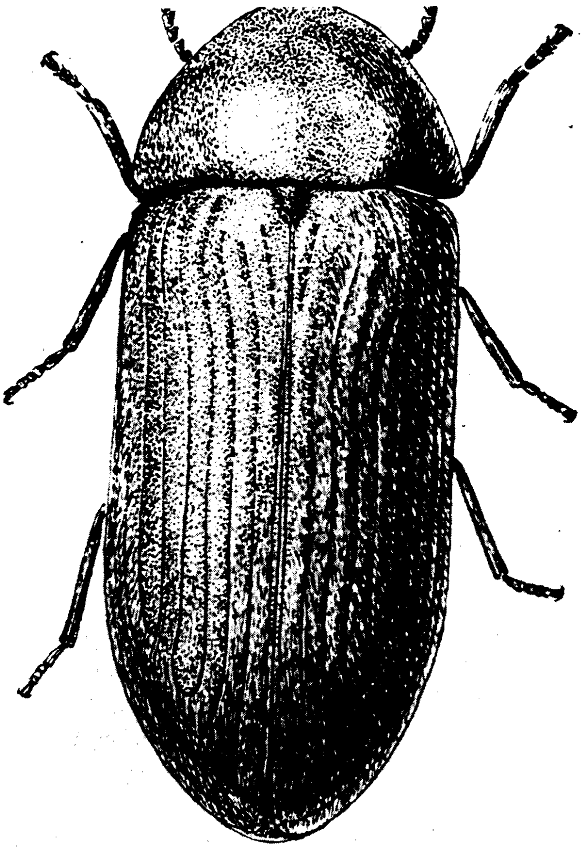

Figure 13-6. Adult Anobiid Powder-post Beetle (Ref. 6)

Anobiid beetles cause significant damage in many parts of the world, especially in the humid tropics and subtropics. They also are found in temperate areas. These beetles feed on sapwood and heartwood of seasoned hardwoods and softwoods. Workings of this family can best be detected by fine pellets that have fallen from the (1.6 to 3.2 mm) holes in the surface of the wood. A characteristic of the group is the hooded head as shown in Fig. 13-6. Two of the better known anobiid beetles are the deathwatch beetle and the furniture beetle. Depending largely on the species, these adult beetles range from 2.5 to 8.0 mm in length.

Although the Cerambycidae family includes numerous species, only a few of them infest well-seasoned wood. The old house borer is widespread in this country and in numerous other countries. An adult beetle, about 18 mm long, is black with grayish trim on its wing covers. The creamy-white larvae of this insect often attack pine or spruce subflooring and framework in wood buildings. They make a rasping or ticking sound while cutting oval tunnels about 6 to 12 mm in diameter. Since the larvae avoid piercing the outer surface of wood and pack powdery wood waste in tunnels behind them, they may continue mining wood for years without being detected.

The bostrichids, called the large powder-post beetles, have a worldwide distribution and cause significant damage to wood products. They prefer well-seasoned sapwood, reducing it to a fine-to-coarse dust. With possibly a few exceptions, bostrichids differ from the other four families in that they usually lay their eggs in remote recesses of their tunnels.

The Lyctidae family, as illustrated in Fig. 13-7, constitutes the so-called true powder-post beetles. They are distributed worldwide and are especially harmful to seasoned sapwoods of high starch content. These beetles damage lumber, woodwork of buildings, wooden military supplies, tool handles, and furniture.

The *Lyctus* beetles range from 4 to 6 mm in length and its color varies from rusty red-brown to black. The beetles live from 3 to 4 weeks and feed on the sapwood of various seasoned hardwood trees. Except for the exit holes, which are made by the adults, the whitish larvae do the boring, mainly at night, and leave a flourlike dust.

The curculionids, or weevils, do considerable damage to timbers and framework of buildings. One species bores into seasoned softwood, producing a fine powdery or granular dust and giving the wood a honeycombed appearance. This weevil is small, being only 3 to 5 mm long, including its relatively long snout.

By taking proper precautions, much damage can be prevented. Storage of susceptible sapwood and of nonsusceptible heartwood in

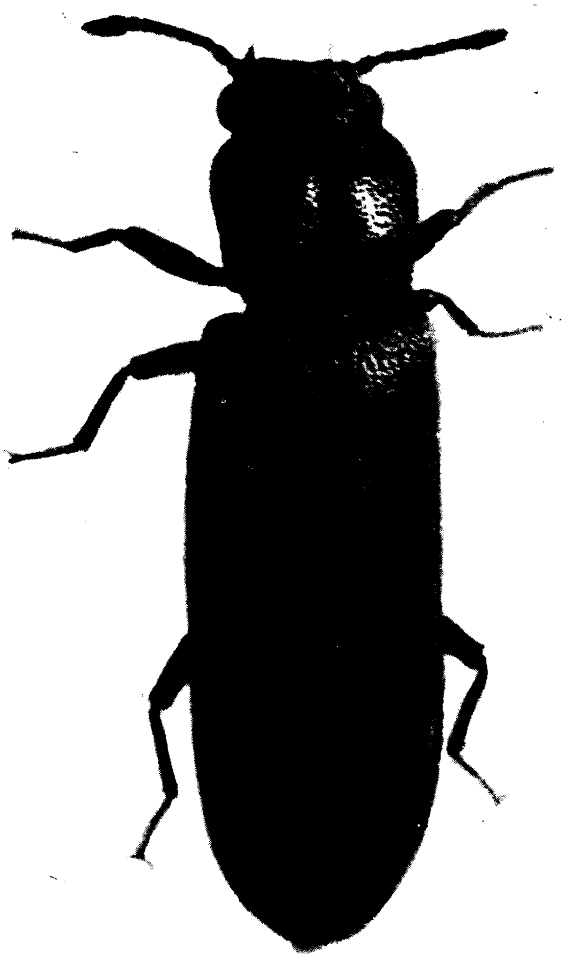

Figure 13-7. Adult Lyctus *Beetle (Ref. 6)*

different places helps to confine the problem. Periodic inspections are recommended. Restricting inventories to reasonable amounts also reduces the chance of infestation with wood-boring insects. Considerable protection can be obtained by soaking or dipping wood in a solution of 5 percent DDT in fuel oil, or in 5 percent pentachlorophenol in a petroleum-based oil. Where infestation is severe, impregnating wood with an improved preservative by a standard vacuum process is completely effective.

Extermination of powder-post beetles already in wood is accomplished by heat treatments applied by special machines or by chemical application. The latter includes spraying, brushing, dipping, or fumigation. Fumigation is particularly effective in treating relatively inaccessible places, such as the wood between the inner and outer walls of a building.

13-2.3 CLOTHES MOTHS*

Several species of clothes moths damage unprotected animal fibers including wool, mohair, fur, hair bristles, feathers, and down. Clothes moths are destructive only in the larva stage; adult moths do not harm materials.

Larval damage consists of holes eaten into materials. Relatively minor damage often makes an article unsuited for further use. Damaged items are said to be moth-eaten.

Clothes moth larvae do not normally feed upon synthetic fibers, (nylon, or viscose rayon), upon vegetable products (cotton, linen, or burlap) nor upon silk. However, when these fibers are mixed with animal-derived fibers, the larvae eat the mixed fabrics. Furthermore, when an area becomes excessively infested or when food becomes limited, larvae are more prone to eat synthetic, vegetable, or mixed fabrics. As larvae approach maturity, they sometimes attack other materials to use for constructing cocoons. They also attack cotton or silk, to obtain the sizing or other additives. Clothes moth larvae cannot digest synthetic or cellulosic fibers that are nonprotein in origin. Such fibers are excreted in a chemically unchanged form. In some instances larvae are found in cotton batting, burlap, cotton or linen fabrics, or flax straw for the pupation or resting period.

(1) *Description.* The common webbing clothes moth is distributed widely except in the tropics. It is the best known and most destructive of clothes moths in the United States, particularly in the South. Photographs of typical moths, larvae, and their tunnels are shown in Fig. 13-8. The adult webbing clothes moth is about 0.5 in. in length. Its shiny,

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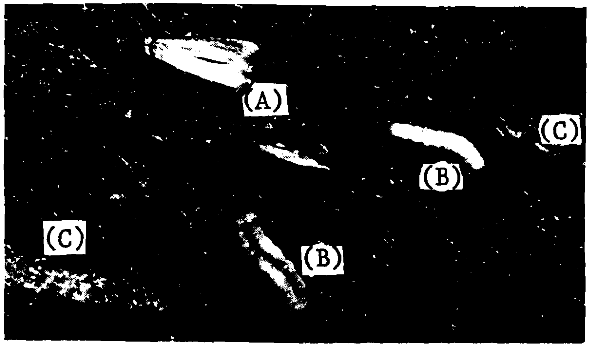
*General references for this paragraph are the Department of Agriculture bulletin on cloth moths (Ref. 13) and the *Military Entomology Operational Handbook* (Ref. 6).



(A) Adult

(B) Larvae

(C) Silken tunnels

Figure 13-8. Webbing Clothes Moth (Ref. 6)

golden-buff or putty-colored wings are unspotted, narrow, and fringed with long hairs. When resting, the wingspread ranges from 6 to 8 mm.

When clothes moths are disturbed in clothing or fabrics, these insects disappear quickly in folds of the fabric, or in other secluded or darkened places. Although they may flit about in the margins of dimly lighted areas, they keep away from bright lights. An important way to distinguish this clothes moth from the larger outdoor species of moths whose larvae feed on vegetation is that the latter flit around lights. The presence of these moths inside a building is no cause for concern.

The female clothes moth deposits nearly invisible eggs between fibers of any fabric, either singly or in groups. Since she adds a secretion that causes the eggs to adhere to threads, they are not easily dislodged. If environmental conditions are favorable, the eggs hatch in about 4 days compared to 3 weeks in less suitable habitats, but in no case can the embryo survive a long incubation period. After hatching from the eggs, the larvae are active, white, shiny, translucent, and about 1 mm in length. Thus they can enter storage areas or containers having openings of only 0.1 mm and infest clothing or fabrics. In artificially heated buildings, eggs hatch, larvae feed, and adult moths emerge, but at a slower rate than during summer.

Three factors favoring optimal development and rate of emergence of clothes moths are (1) ample supply of suitable food, (2) temperature at about 27°C, and (3) relative humidity of 60 to 80 percent. Any lowering of temperature is particularly critical in reducing reproduction, growth rate, and amount of damage to materials attacked by larvae. Their activity ceases at 10°C.

The larvae, especially the larger ones, can withstand relatively long periods of adverse environmental conditions, such as subfreezing temperature, low relative humidity, and insufficient food. Such conditions, however, limit their ultimate size which may exceed 12 mm, and prolong the duration of larval period from 1 mo to 29 mo. Under unfavorable conditions, the larvae become inactive or dormant; they neither feed nor grow during such periods. Larva may become inactive for no apparent reason, only to resume feeding at a later time. Since clothes moths feed only in the larval stage, they must consume enough nutrients to last through their pupal and adult stages.

The presence of larval clothes moths in animal fibers is indicated by webbing. A larva may spin a nonportable cocoon (a tube), gradually enlarge one, abandon a cocoon and construct a new one, or merely spin a patch here and there on infested material.

The life span of the clothes moth may vary from 55 days to 4 yr, but under normal conditions they live from 65 to 90 days. Adult moths normally live from 1 to 4 weeks. Although the ability of these insects to fly appears erratic and uncertain, they have infested places 300 or more ft from breeding areas.

(2) *Control.* A number of methods can be employed to control moths, but no single

method is entirely suitable for preventing or destroying them in all situations. Before fabrics are stored, they should be moth free. Frequent dusting, brushing, or, preferably, vacuum cleaning are important control measures. Thorough vacuuming of remote cracks and secluded places, such as under baseboards and around heating units, are good preventive measures. Feltlike fibers that accumulate in those places provide sources of food for small larvae. Such measures may be inadequate for destroying moths already inside such materials as upholstered furniture or blankets. Clothing that is used almost daily is rarely damaged by clothes moths, since use inhibits deposition of eggs, hatching of eggs, and feeding of larvae.

Once an area becomes infested with clothes moths, more drastic control measures must be taken–the same as those for controlling carpet beetles. Two of the more frequently used methods for controlling moths are residual spraying and fumigating.

When a fabric is treated with a residual moth spray, it must be wetted thoroughly by some detergent in water or an organic solvent. An insecticide deposited on fibers of a fabric is usually absorbed by them but may remain as a residue on the surface of material. Toxic deposits protect fibrous material against attacks by clothes moth larvae as well as carpet beetles for several months to sometimes years. Some of the more common residual sprays include DDT, dieldrin, and chlordane.

Clothes and other textiles that are both washed and dry cleaned should be treated with mothproofing chemicals resistant to both. If a fabric is either washed or dry cleaned, its mothproofing agent should be resistant to the cleaning process recommended.

Some of the better residual sprays protect upholstered furniture, blankets, clothing, and other treated finished textiles for only 3 or 4 mo. Thus, the insecticidal or deterrent benefits of so-called "mothproofers" is temporary rather than permanent. No treated textile continues to provide protection when exposed to wear, light, dry cleaning fluids, and laundering. However, if the same or other suitable moth insecticides are reapplied periodically, adequate protection against moths and carpet beetles is provided.

Mothproofing chemicals applied to unfinished textiles in a bath during manufacture insures saturation and by far the most permanent results. These give excellent protection for many years. Such mothproofing agents make wool unpalatable, indigestible, or toxic to moth larvae.

Of the residual mothproofing insecticides, DDT is often used for temporary control in relatively small places. It is used as a 3 to 6 percent solution in a deodorized oil-based spray and can be applied with an electric or compressed air sprayer. A solution higher than 3 percent requires an aromatic solvent. If the sprayer is not held too close to a fabric, the DDT crystals that do form can be easily brushed off. Otherwise they would have to be dry cleaned to remove the stains.

Compared to the mothproofing effectiveness of DDT, lindane is far less permanent, more volatile, and more toxic to personnel. Nevertheless, lindane sprays at 0.1 percent are useful where an infestation must be quickly cleaned up.

Chlordane used in amounts of 2 to 3 percent by weight of a fabric is effective as a temporary residual mothproofer. This slightly volatile insecticide is highly toxic to insects in difficult-to-reach cracks and crevices. Chlordane films do not dull finished fabrics and are resistant to vacuum cleaning. Furthermore, chlordane sprays do not stain materials unaffected by a water- or oil-based carrier. Because a chlordane spray is toxic to personnel, a major consideration concerning its use is the need for dry cleaning of all clothes or other fabrics before they can be used.

Fumigation of a building or a storage area has often proved successful against clothes moths. As long as an infested enclosure can be tightly sealed against circulation of air, many fumigants may be used. Hydrocyanic acid gas is most often used.

Sometimes the toxic gases do not penetrate in sufficient strength to kill all moths. This emphasizes the need to arrange clothes, blankets, upholstered furniture, and other fabrics in such a way as to facilitate better penetration of fumigants into them. The general practice is to expose them to twice the dosage needed to kill large larvae.

Only personnel thoroughly experienced in using fumigants can handle them with reasonable safety and even then only in reasonably isolated areas well secured against entry by unauthorized personnel.

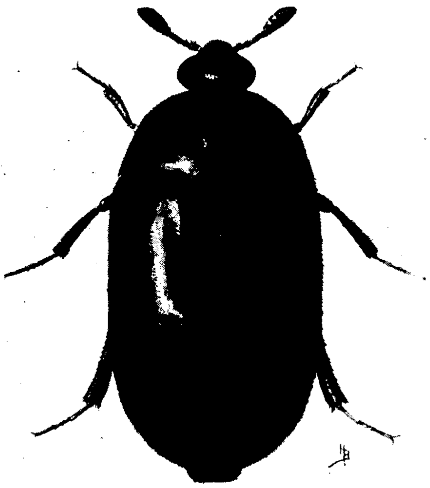
Larvae of clothes moths can withstand low temperatures for a considerable time but are much less tolerant of quick changes in temperature. A sudden lowering of the temperature to –8°C (18°F) for several days followed by a rapid increase to 10°C (50°F) for a short while and subsequent maintenance at 4°C (40°F) was found to kill all moths (Ref. 13). Two or three rapid fluctuations of that magnitude are desirable before stabilizing the temperature at 4°C. Aside from being expensive, cold storage of infested materials at this level prevents feeding of larvae but does not necessarily kill them.

Although exposure of clothes moths to high temperature is more effective than to low temperatures, heating is used infrequently. Exposure of larvae of clothes moths to temperatures of 43°C (110°F) or higher kills them in about 30 min. However, clothes moths can live at a temperature of 33°C (91.4°F).

13-2.4 CARPET BEETLES

Both the black carpet beetle and the common carpet beetle attack materials containing animal products, including fur, silk, wool, leather, feathers, meat, and milk solids. Like the clothes moths, adult carpet beetles (also called buffalo moths) cause no damage. Their larvae, usually brown and fuzzy, consume the same materials as clothes moths and likewise tend to be scavengers. Some species feed on cereal products. It takes from 3 mo to 1 yr for a carpet beetle to complete its life cycle, depending upon the species and the environment. An adult beetle and its larva are shown in Fig. 13-9.

(A) Larva



(B) Adult

Figure 13-9. Black Carpet Beetle (Ref. 6)

Carpet beetles are found throughout the world although more are found in the warmer zones. In some places much damage attributed to clothes moths is that of the more numerous carpet beetles. They are common pests in dwellings, industrial plants, and warehouses.

Control of beetles requires careful procurement and storage of the materials that they attack. By use of procurement inspections, short storage periods, sanitation in storage areas, good packaging practices, and maintenance of low storage temperatures, beetle infestation can normally be avoided. Where infestations exist, use of residual spray and aerosol insecticides is effective, as is the fumigation of containers or structures (Ref. 6).

13-2.5 SILVERFISH AND FIREBRATS*

These insects are among the most primitive of all insects. They have a slender body with a relatively broad front end, which tapers gradually to the rear, vary in length from 12 to 18 mm, are always wingless, and have silvery or grayish scales, short legs, long feelers, and a bristly tail. Of the four species of silverfish, one species is called a firebrat because it prefers temperatures over 90°F. A firebrat is shown in Fig. 13-10. Another reaches its best development between 72° and 80°F with a relative humidity of 75 to 97 percent, while the other two species are less restricted in temperature and moisture requirements but require heated shelter during cooler periods in middle latitudes. When a silverfish is exposed to a lighted environment, it moves rapidly to a sheltered place, such as behind a baseboard or molding.

The feeding habits of all silverfish are similar. When necessary, they travel a considerable distance in search of food. Silverfish eat carbohydrates and protein of both animal and vegetable origin, and infest flour and other cereals. These insects are infamous pests of paper, particularly highly refined chemical papers. They are particularly fond of the sizing in paper, including starch, casein, gum, and glue. Thus, they remove glaze from paper as well as paste from beneath wall paper. Silverfish also etch book bindings and nibble on the glue in books. Although their damage to wool and silk is negligible, they eat cotton and are fond of linen and rayon, particularly those containing starch.

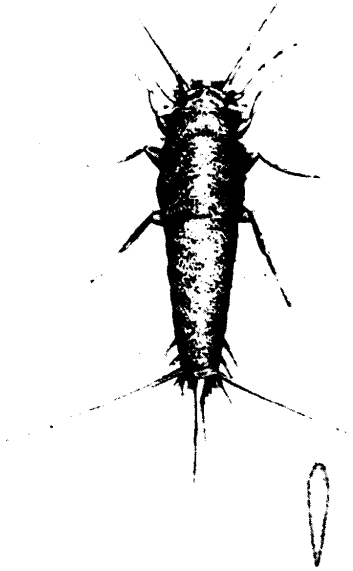


Figure 13-10. Firebrat (Ref. 6)

Damage by silverfish may be determined in a number of ways. They make minute scrapings on book bindings, cut notches in the edges of paper, and in some extreme instances cut irregular holes in paper. Their infestation of paper or textiles may also be determined by identifying visible feces, microscopic scales, irregular cuts in fabrics, or by minute yellowish stains on linens. Their control involves the use of residual sprays or dusts of insecticides such as diazinon, malathion, and dichlorvos (Ref. 6).

13-2.6 ANTS*

Ants are among the most abundant terrestrial faunas, and, as a group, are worldwide in distribution. The various species

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*General references for this paragraph include the *Military Entomology Textbook* (Ref. 6), "Silverfish, A Paper-Eating Insect" (Ref. 14), and "The Biology of the Silverfish Ctenolepisma Longicandata Esch. With Particular Reference to Its Feeding Habits" (Ref. 15).

*General references for this paragraph are Refs. 5 and 6.

range from the arctic to the tropics, from sea level to timberline, and from very moist to desert areas. Certain species are more abundant and annoying in some localities than in others. Ants have a remarkable ability to adapt themselves to a varying environment, including a wide variety of climatic and soil conditions.

Most species of ants can be easily distinguished from other insects. Ants are usually brown, yellow, red, black, or combinations of these colors. Generally, ants range in length from about 0.8 mm to 1 cm although larger ants are found. The head, thorax, and abdomen of ants are well separated, the thorax usually being the slenderest of them. The one or two enlargements on the short, slender pedicel separating the thorax from the abdomen distinguishes ants from the infinitely more destructive and superficially similar termites (see par. 13-2.1). Because of important differences in the habits and destructive effects between these two pests, they must be identified before appropriate control measures can be undertaken.

Ant heads vary greatly in size and form. Their mandibles are extremely important organs. Ants use their mandibles for almost everything: biting, pricking, piercing, cutting off heads, building, sawing, gnawing, cutting, carrying, leaping, and even bounding, but never for eating. Their typically elbowed antennae attached to the head are particularly sensitive to touch and smell, but their eyesight is poor.

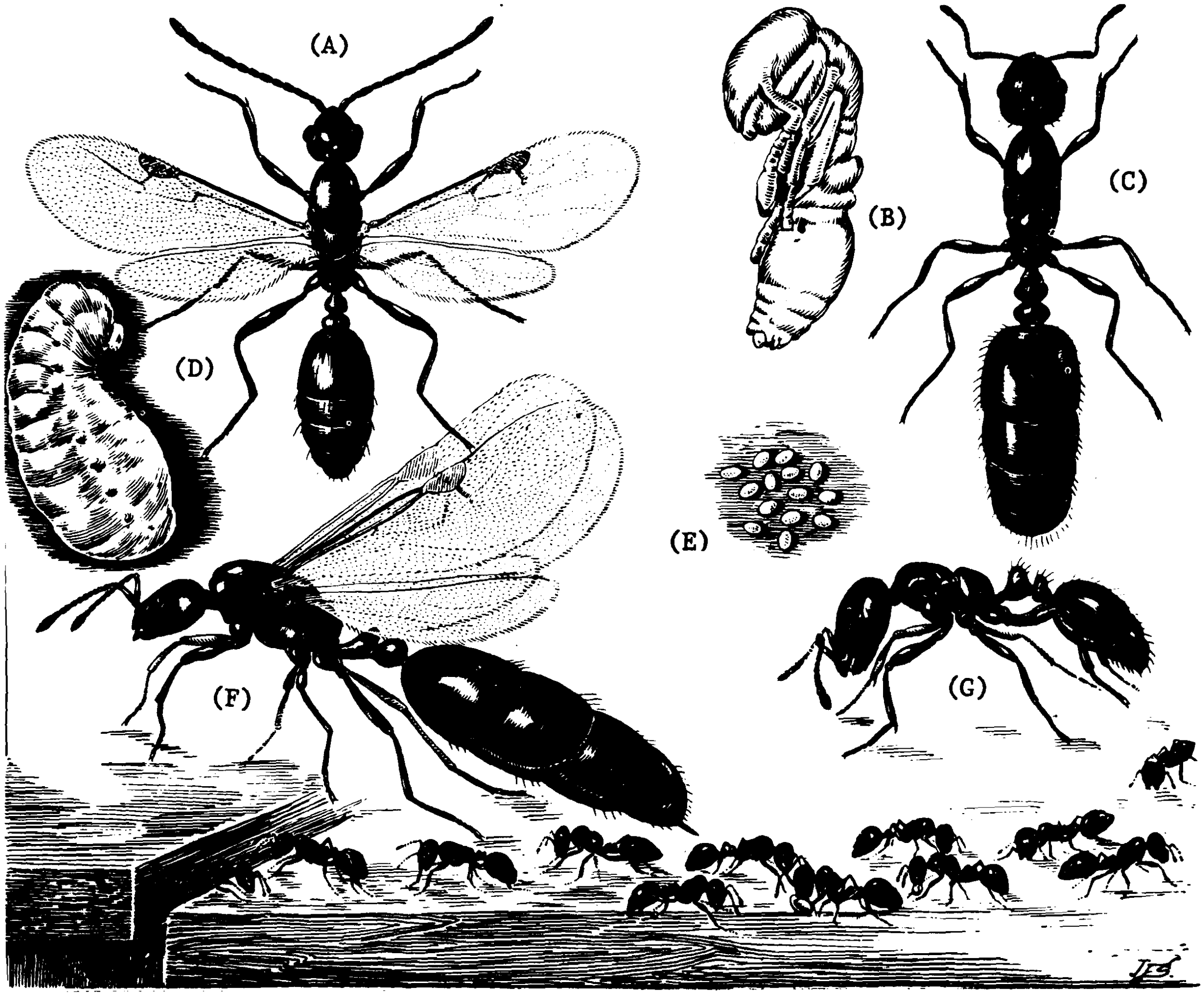
The diet of ants is even more varied than that of man. Ants are fond of sweets, fruits, proteins, meats, greasy substances, starchy materials, seeds, nectar of plants, honeydew, secretions of insects and plants, and almost all other plant and animal materials. Adult ants consume food only in liquid form.

The presence of ants on exposed or inadequately protected foods or liquids make them unfit for human use since ants may transmit disease organisms. Their crawling over the human body can also be an exasperating annoyance. In addition, a few species of ants make painful bites or toxic stings (see par. 13-2.7).

In many situations, aside from infestation of food and health considerations, ants are a distinct nuisance by their infestation of outdoor areas, materials, or by nesting in equipment, furniture, scientific apparatus, machinery, or where their presence complicates military activities. Carpenter ants carve intricate nesting places in partially decayed timbers and sometimes in sound wood such as utility poles. Some ants eat soiled fabrics; others disfigure lawns and other outdoor areas by building circular earthen mounds up to 1 m high.

Ants have perhaps the most highly organized social life of all insects. A colony consists almost always of wingless workers, in addition to temporarily winged males and females. The workers, or underdeveloped sterile females, are frequently of different sizes, shapes, and perform different duties within the same species. The workers, as the name implies, do all the work, such as excavating the nest, obtaining the food, feeding the young and queen, protecting the colony, and causing the damage and annoyance both at and away from the nest. The various members of the common black ant family are illustrated in Fig. 13-11 along with the several life stages.

The migration of winged males and females of different colonies of a given species often occurs on the same day in a particular locality, but how this happens remains a mystery. Ants generally mate during their dispersal flights. At other times ants are crawlers. Except during the brief period of migration, workers are the only ants normally observed outside the nesting area. The males soon die after mating. Each female normally flies but may crawl to a nesting site, where she breaks off her wings. A female most often establishes her nest in drained soil, especially beneath stones, logs, or rubbish. Other ants prefer hollowed out parts of trees or other



(A) Winged king

(B) Pupa

(C) Queen after losing wings

(D) Larva

(E) Eggs

(F) Winged queen

(G) Female worker

Figure 13-11. Black Ant (Ref. 6)

plants and sometimes buildings.

After a fertile female makes a small cavity or occupies an existing one, it becomes a part of her permanent home. She then seals its opening and lays a small number of eggs for her first brood. The larvae hatched from the white eggs are creamy white, helpless, maggotlike grubs, without legs, and nearly headless. Except on close inspection the larvae look like eggs. The queen nurtures the larvae to the adult stage by a salivary secretion from her mouth. During this period, all nutrition for herself and her young is derived solely from the reserves of her wing muscles and abdomen. She is almost always the conspicuously largest individual (or individuals) in a colony. Once the initial workers of a colony have matured, they take charge of all domestic duties; from then on the queen does nothing except for eating the food given her and laying eggs.

Compared to other insects, ants are strong and have a relatively long lifespan. The workers may live from 4 to 7 yr and a queen may live up to 15 yr. She is fecundated only once and may produce offspring as long as she lives. Many colonies have secondary queens. Should all the queens die or be killed, specially fed workers may take over the egg-laying function. Some ant colonies are 30 to 40 yr old.

Although a variety of ant species cause damage, the Argentine, harvester, and carpenter ants typify the problems encountered and are among the more troublesome species. They are discussed in the subparagraphs that follow.

13-2.6.1 ARGENTINE ANTS

The Argentine or fire ants are among the most persistently troublesome species. Their slender workers vary from light to dark brown, have a single segment in the pedicel, and range from 2.2 to 2.8 mm long. They have a slight, greasy, musty odor when crushed. An adult fire ant is shown in Fig. 13-12.

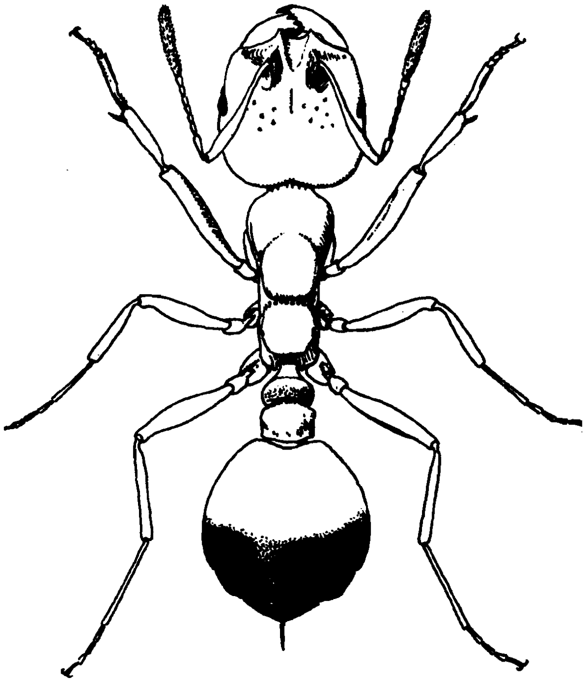


Figure 13-12. Fire Ant (Ref. 6)

Although Argentine ants have poor eyesight and only a limited sense of smell, they are prodigious foragers. Their scouts patrol every square inch of an infested area, operate both day and night, and can travel 145 ft per hr. The food-gathering workers always travel in definite trails and less than 1 percent of the workers can provide the queens and the immature offspring with adequate food. This points up the futility of control methods that kill up to 99 percent of the foraging workers. Because of their rapid rate of reproduction and gregarious habits, control measures must be carried out simultaneously over extensive areas for longer lasting results.

The Argentine ants are well established in the United States throughout the Southern States, in California, and in Hawaii. Isolated infestations also occur in a number of other states. In the colder States, these ants live indoors. They are also found in Brazil, Portugal, France, Australia, and the Union of South Africa. Their general distribution is restricted mainly by aridity or cold winters. However, this tropical species can survive short periods of freezing cold temperatures.

Argentine ants are both annoying and harmful in areas of human habitation. Although they do not sting, they can bite severely and prevent people from sleeping. Although they are relatively small, they are extremely aggressive, persistent, courageous, and tenacious. They drive out other ants and insects that interfere in their activities, attacking with vigor and always in sufficient numbers to insure ultimate victory. Argentine ants have no important natural enemies other than man. They infest all kinds of foods, especially sweets. Their small size allows access to some closed containers and some packaged foods. Their presence on human feces and other filth indicates that they could spread typhoid fever and other diseases. By protecting and promoting an increase in honeydew-producing insects, they cause injury directly to gardens and indirectly to shade trees.

The spreading of Argentine ants requires some means of transportation either man provided or natural. For example, an entire colony may be carried by flood waters during which the colony is kept together by forming a ball of ants, with the young on the inside, until a landing can be made. These as well as other ants are resistant to drowning, and can either swim or walk on water. Their natural spread to other areas is only a hundred meters per year.

Argentine ants adapt to a wide variety of situations. They seek to nest, however, in dark places, usually in the ground, with a suitable supply of moisture and a food supply close by. Huge nests may be found beneath boards, rocks, buildings, or in tunnels containing hot conduit pipes. Areas beneath or adjacent to lawns are also favored environments.

Unlike most ant species, individual Argentine ants are friendly with all members of their species, including those from remote localities. The same amiable relationship applies regarding the queens. A large colony may contain several hundred queens. The queens are brown and from 4 to 6 mm in length, decidedly the largest individuals within a colony. Contrary to most ant species, the queens not only feed and clean themselves but participate in feeding and grooming the young. Argentine ants have a high productive potential largely because of the numerous queens in compound colonies, great adaptability of workers, and no important rivals for the food of these omnivorous ants.

Argentine ants enter living and dining quarters, storage areas, and other buildings in great numbers and with great persistence. During spring and summer the workers seek a large quantity of food to feed an ever-increasing number of young. Summer showers wash away the honeydew from plants, drastically reducing an important source of food. On hot sunny days Argentine ants enter buildings to minimize the desiccating effect of the bright sun and to seek moisture. When the weather is cold and rainy, the ants seek the warmth and protection of an indoor environment.

13-2.6.2 HARVESTER OR AGRICULTURAL ANTS

The harvester ants of Southern and Western United States are well known for their vicious stings and bites of children, adults, and animals. Its infestations of door steps, paths, lawns, and grounds make such places unsuitable for recreation and numerous other purposes.

The red to dark brown workers from 6 to 12 mm (0.25 to 0.5 in.) long are exceedingly aggressive when something interferes with their activities. They not only fight ferociously but actually search for and chase any intruder apprehended. Once they bite a man, their powerful jaws remain locked, even when the rest of the body is pulled away. Their sting is an even more formidable defensive and offensive weapon. Its toxin is highly irritating, causing prolonged pain and some swelling. Thus, reasonable precautions against injury must be taken when traversing an infested area.

Harvester ants sometimes cause indirect damage to roads by removing soil-binding vegetation beside them. They also tunnel under roads and airplane runways, causing erosion and breakdown of paved surfaces.

The cleared, flat, barren, circular area around each entrance hole to a nest of harvester ants may range from 3 to 35 ft in diameter. The vegetation-free areas prevent excessive accumulation of moisture around the nest and permit rapid warming of the nurseries. The pathways leading from each of the holes range up to 200 ft long. Their almost innumerable subterranean tunnels and sometimes hundreds of chambers may be the home for more than 10,000 ants. Their principal food consists of seeds collected and stored mainly during autumn. A colony may survive for many years.

The winged females and males swarm in enormous numbers from June to October but mainly in August and September, especially in the afternoon after a rain. Since birds, toads, lizards, and other ants prey on them heavily for food, few survive. The males die after mating. Each surviving female selects a nesting site, removes her wings, and establishes a new colony.

The activities of California harvester ants are closely related to temperature. The entrance to colonies remains closed throughout the 3 or 4 coolest months and every night during the rest of the year. These light-red ants with somewhat lighter colored legs are 5.5 to 6.0 mm long. They are sluggish at 70°F and are most active between 90° and 115°F, but for only short periods at temperatures over 120°F.

13-2.6.3 CARPENTER ANTS

Figure 13-13. Carpenter Ant (Ref. 6)

Carpenter ants, as illustrated in Fig. 13-13, are among our largest, most familiar species. These ants are found from sea level to over 2,800 m altitudes. Their workers are polymorphic and range from 6 to 10 mm in length; the queens range from 13 to 15 mm. These usually brown to black ants are long legged and fast moving. Their eyesight is better than that of most other ants. When crushed, carpenter ants have a distinct acid (formic) odor.

A colony is ordinarily initiated by a winged female which occupies a small cavity beneath a rock or board or in an insect-bored tunnel in wood, where she seals herself in for 2 to 10 mo. She lays a small number of eggs and takes care of her offspring until they mature sufficiently to forage for food for the colony. From then on, the queen lays eggs; the workers assume responsibility for all other duties.

Carpenter ants are encountered in woods, lawns, walks, and wooden buildings. Infestations of frame buildings may be initiated by a fertile female and her progeny or by migration of a part or all of an existing colony. Entry into buildings is usually by obvious routes near ground level, but occasionally carpenter ants enter on a utility wire or a branch of a tree. Infestation is greater near wooded or recently cleared areas.

Buildings most subject to attack are loosely constructed wooden buildings, those with low foundations, without basements, or with partial basements. The ants prefer structures having moist rotting timbers near the foundation or ground. Sometimes, especially as a colony increases in size, carpenter ants tunnel sound dry wood in any part of a building.

Evidence of infestation by carpenter ants is not likely to go unnoticed because of numerous worker ants or by the appearance of swarms of large winged ants. Swarms occur only from colonies established for 2 or more years. When carpenter ants in a nest are suddenly disturbed, a faint rustling sound can be heard by placing one's ear against the wood. Where carpenter ants dump their borings, a characteristic pile of "sawdust" in some out-of-the-way place (i.e., basements, dark closets, etc.), constitutes an essentially foolproof sign that a nest exists. The ants mine the wood only to provide nesting space for their colony, not for food. A colony may consist of more than 3,000 workers. If the infestation is controlled in its early stages, all that may be required is to get rid of the ants.

13-2.6.4 CONTROL OF ANTS

Ants inside buildings are controlled by residual dusts or deodorized oil sprays. Chlordane is particularly toxic to ants. Its action is not dependent on their feeding habits, for chlordane acts as a contact poison and appears to be effective against all common species of ants. A number of other insecticides are also used (Ref. 6).

For the control of indoor ants, chlordane oil-based or water-emulsified sprays are used at concentrations of 2 to 5 percent. Oil-based sprays may also be applied with a brush. Dieldrin may be used indoors at a concentration of 0.5 percent. Reasonable care must be exercised to avoid possible damage to some materials. Excess liquid insecticides should be removed with a clean rag.

In addition to treating ant trails, special effort should be made to locate and treat entries to a building, such as window sills, baseboards, thresholds, crevices, around sinks, and water and drain pipes as well as other places where ants are seen crawling.

Since ants often nest below the main level of a building or in the general vicinity of it, preventing their entry into a building eliminates the problems associated with indoor infestation. Oil-based or emulsified chlordane sprays may be applied to basements or to the underside of buildings and around open foundation stones. Provided the residues of wettable chlordane powders are not objectionable in basements, they may be applied successfully.

Another effective control is to apply an insecticide completely around a building, such as a 2- to 5-percent chlordane dust or solution in deodorized kerosene. This application repels ants and remains effective for about a month. The treatment is most effective when made just before the onset of cool weather or sometime in autumn in the intermediate latitudes.

To keep ants out of buildings, their nests in the immediate vicinity of buildings should be located and thoroughly treated with an appropriate insecticide at recommended strength. Where outdoor areas are extensively infested, spraying or dusting extensive areas with chlordane at 1 to 1.5 lb per acre will destroy turf-infesting species. An application of dieldrin or heptachlor at 2 lb per acre controls the Argentine fire ant.

Occasionally, residual insecticides, such as chlordane and lindane, do not completely control ants that invade buildings containing foods. For instance, the small Pharoah ants and other grease-eating ants can usually be controlled by distributing toxic baits, such as those combining thallium sulfate in a syrup.

The eradication of Argentine ants can be realized only if an intensive campaign is conducted over an extensive area. Because of so many queens in their compound colonies, the main objective is to kill the queens. Merely poisoning the young and the workers is a secondary consideration, for this gives only temporary relief without reducing the reproductive capacity of the colony.

The best way to control the Argentine ant is by using a syrup or jelly with thallium sulfate, provided that this dangerous poison can be used safely as a bait. Sodium arsenite is also used in ant bait formulas. The latter poison is more easily detected and avoided by ants; thus, it is less effective but safer to use than the faster acting thallium sulfate.

The best time to use toxic baits is during the first approach of autumn, for this is a period of cold weather in the middle and higher latitudes and, for many areas, increasingly rainy weather and a diminishing food supply. The rain washes honeydew from plants and honeydew-secreting insects diminish in number. Nectar in flowers decreases drastically and soon disappears. Consequently, the ants are more willing to feed on ant poisons. Since the ants have an absolute minimum of natural foods during winter, the size of the colony is greatly diminished and is confined to a limited area where they are more inclined to accept the less tasty baits. If ants can still be observed during warm, sunny, calm days of spring, toxic baits should again be made available.

13-2.7 VENOMOUS INSECTS

A variety of biting and stinging insects and other arthropods are spread throughout the world. These include wasps, bees, scorpions, ants, and similar species as enumerated in Table 13-1. Generally, the importance of these insects is more as a nuisance than as a dangerous or harmful factor in the environment. However, in some circumstances they can be of major importance. The body louse has had major impact on military operations; mites and mosquitoes make some regions of the earth uninhabitable; and ants and bees can kill people.

Complete information on venomous insects can be found in the *Military Entomology Operational Handbook* (Ref. 6), including descriptions of the various species, their life habits, their importance, and control methods. The control methods include descriptions of necessary equipment and of the various insecticides employed.

13-3 MARINE BORERS*

Marine borers have caused tremendous damage throughout the world by attacking the timbers of unprotected piers and vessels in immense numbers and riddling them to such an extent that they become worthless in a surprisingly short time. In extreme instances, newly built marine structures have been destroyed in less than 1 yr. Marine borers consist of two distinct groups, the molluscan and the crustacean borers, each of them having a characteristic appearance and a unique method of attacking wood. The molluscan borers, commonly called shipworms, are the most destructive of the marine borers.

13-3.1 MOLLUSCAN BORERS

The molluscan borers are characterized by long, wormlike bodies tapering toward the posterior end with only the head remaining in the bivalve shell. These animals pass through a long series of complicated metamorphoses before reaching maturity. These mollusks are minute embryonic organisms, which settle on a convenient piece of wood. They burrow into the wood, leaving holes about the size of a pinhead, and gradually enlarge the burrows as they move through the wood, thereby making the tunnels longer and larger to compensate for their rapid growth. Heavily infested wood rapidly becomes honeycombed inside, although a series of minute holes is the only external indication of the damage. The infestation is difficult to detect by surface inspection.

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*General references for this paragraph are the *Military Entomology Operational Handbook* (Ref. 6) and *Marine Fouling and Its Prevention* (Ref. 16).

TABLE 13-1

STINGING AND BITING ARTHROPODS (Ref. 6)

Common name	Distribution	Importance	Control
Mosquito	Worldwide	Fierce biters causing discomfort, limit normal activities, make some areas of world uninhabitable, transmit disease.	Elimination of breeding areas, application of larvicides and pesticides, screening
Biting flies Stable or dog fly Horseflies and deerflies Black flies Sand flies Punkies	Worldwide with different species being associated with particular habitats	Annoying and painful biting on man, kill animals, transmit a variety of diseases.	Elimination of breeding grounds, repellants, screening
Bedbugs	Worldwide in close association with man	Primarily annoying to man	Insecticides
Lice	Worldwide in close association with man	Have had more important effect on history of man than any other insect. Transmit typhus and destroy morale of troops.	Use of insecticide powder, fumigation of clothing
Fleas	Worldwide	Transmit diseases such as bubonic plague and murine typhus, bites may produce extreme itching and dermatitis.	Insecticide powders, repellant-impregnated clothing, rodent control

TABLE 13-1 (Continued)

STINGING AND BITING ARTHROPODS (Ref. 6)

Common name	Distribution	Importance	Control
Ants	Worldwide	Many species bite but do not sting. However, havester ants attack man and inflict painful bites and stings. In the tropical rainforest, stinging ants produce large blisters and sores on man.	Insecticide dusts and sprays, poisoned baits, sanitation
Cockroaches	Worldwide, usually in buildings, sewers, and damp areas	Carry organisms of intestinal disease, contaminate food.	Sanitation, prevention of entrance to buildings, elimination of hiding places, insecticides
Ticks	Worldwide although specific species have limited habitat	Carry typhus, Rocky Mountain spotted fever, and other diseases.	Area control with insecticides, repellants, protective clothing, personal inspection
Chiggers and mites	Warm areas of world	Extreme itching; in Pacific area, chiggers cause scrub itch and scrub typhus.	Treatment of clothing with repellant, spraying and dusting with insecticides

TABLE 13-1 (Continued)

STINGING AND BITING ARTHROPODS (Ref. 6)

Common name	Distribution	Importance	Control
Scorpions	Warm areas of U.S., Mexico, Central and South America, Middle East and North Africa	Poisonous venom causes extreme pain.	Avoidance, cleanup, trapping, residual dusting, and spraying with pesticides
Spiders (black widow and brown recluse)	Temperate and tropical zones	Most spiders are harmless; however, dangerously venomous spiders live in many parts of the world; in some places they are abundant.	Destruction of webs and nests, insecticide dusts and sprays containing chlorinated hydrocarbons
Centipedes	Widespread throughout world	Most are harmless but a few species inflict painful bites; there are no recorded deaths	Screening and avoidance (examine boots and clothing that have been on ground during night before putting on), can be killed with contact sprays
Caterpillars and Moths	Worldwide	Cause rashes; some cause intense burning pain on contact	Insecticides
Wasps and bees	Temperate and tropical zones	Painful stings, often with severe allergic reactions (50 deaths per year in U.S.)	Insecticides on nests, treated screens, avoidance

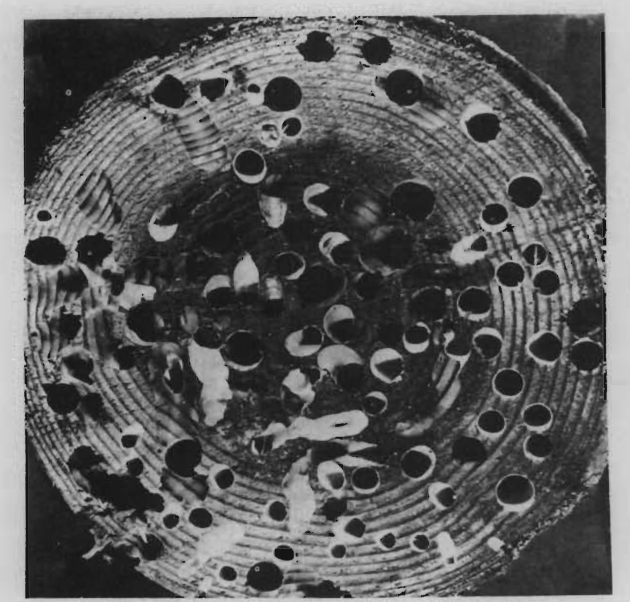

Figure 13-14. Shipworm (Bankia) *in Piling (Ref. 6)*

The unique appearance of the burrows is shown in Fig. 13-14. Aside from the faintly visible pinholes on the outside surfaces, the much larger holes inside the wood are similar in arrangement to those found in Swiss cheese. The holes made by shipworms run in all directions but never join, although some partitions between them may be as thin as paper. The holes are always lined with irregularly laid shell and generally go with the grain. The whitish shell-like material distinguishes shipworm infestation from that of other marine borers.

The rapidity and extent of activity by shipworms vary greatly, depending upon the boring species, the intensity of infestation, the temperature and the salinity of the water, the amount of food (particularly plankton), and freedom from industrial wastes. The rate of boring may range from 2.5 cm per mo in arctic waters to a rate that is eight times faster in tropical waters. The zone of the shipworm's devastation is comparatively large. In some places, their attack is most serious between high and low tide levels, but elsewhere it is most destructive at a depth of 30 ft or more or at the mud line.

The hardest oak is attacked as readily as the softest pine. The toughest knots are penetrated. Teak alone resists attack.

Other molluscan borers, called boring clams, resemble small clams that have their entire body enclosed in a bivalve shell. Some species bore into clay, sandstone, shale, marble, and inferior concrete; others may burrow holes in wood.

Mature boring clams are shaped like a blunt carrot. The broad end does the tunneling of wood, usually at right angles to its surface. The drilled holes also conform to the shape of the shell. Like the shipworm, boring clams enter wood in their embryonic stage and cut increasingly larger tunnels as they advance through the wood until reaching their maximum growth. These animals seldom exceed 60 mm in length and 25 mm in diameter. In the United States, boring clams occur from Cape Hatteras southward and around Florida and the Gulf Coast. In general, they are much less destructive than are shipworms.

Molluscan borers never use the wood they excavate as food; the removed wood merely passes through their bodies. This has greatly complicated many attempts to poison them by applying toxic coatings or by impregnating the wood with poisonous or noxious compounds. Creosote and other fossil oils are the remedies providing the best results. The forcing of protective compounds into wood by means of high air pressure is expensive. These treated woods have met with varying degrees of success. Copper-sheathed vessels are free of attack, although copper paint, creosote, or coal tar frequently applied may be equally effective. Piles containing closely driven broad-headed nails provide considerable protection, for shipworms apparently avoid wood impregnated with iron rust.

13-3.2 CRUSTACEAN BORERS

Of the crustacean borers, the *Limnoria* is the most widespread and destructive. One important species is often called gribble and thrives in both tropical and arctic waters. Although a mature gribble is no larger than a grain of rice, its strong jaws constitute an effective boring tool. It cuts interlacing, branched burrows in pilings seldom more than 12 mm below the wood surface. *Limnoria* eat the softer spring wood before the harder summer wood. Infested areas extend from half-tide level to the mud line and as the infested surface layers become intricately honeycombed, the delicate outer surfaces are eroded more rapidly by waves and tides as is shown in Fig. 13-15. In the meantime, *Limnoria* continue to bore into the wood and spread slowly from initially infested areas. Where their attacks are severe, the diameter of pilings can be reduced 1 or 2 in. a year. Pilings infested with *Limnoria* acquire a familiar hourglass shape.

Sphaeroma, called pill bugs, often feed on the caulking from seams of boats. A number of species are found in many parts of the world but are most common in the tropics and subtropics. This genus is a good swimmer, lives among other marine shells, leaves little evidence of its own damage, and is one of the few marine borers that thrives in either fresh or salt water.

Chelura resemble minute lobsters, are slightly larger than *Limnoria,* and are found in the coastal waters of many countries of the world. *Chelura* enlarge cavities cut by *Limnoria,* making holes distinctly more rounded. These crustacean borers greatly increase the destruction of harbor structures, particularly in spring and autumn.

Crustacean borers are believed to survive for considerable periods without wood before infecting an area. The spread of infection and its intensity, however, depend in large measure on the duration and strength of water currents. Marine borer attack ceases when strong currents of water are flowing. Since wooden vessels under way are unlikely to be attacked by these borers, harbor timbers are most vulnerable where currents are weakest or where an intense flow is of relatively short duration.

*Figure 13-15. Piling Damage by Crustacean Borers (*Limnoria*) (Ref. 6)*

Control of crustacean borers is similar to that for molluscan borers.

13-4 RODENTS*

Rodents constitute an environmental factor of concern to the military because they destroy or deteriorate materiel as well as carry and transmit diseases and pests that can be harmful to man. The rodents of primary concern are rats and mice, but squirrels,

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*General references for rats and mice include the *Military Entomology Operational Handbook* (Ref. 6), *Biological Factors in Domestic Rodent Control* (Ref. 17), and *Control of Domestic Rats and Mice* (Ref. 18).

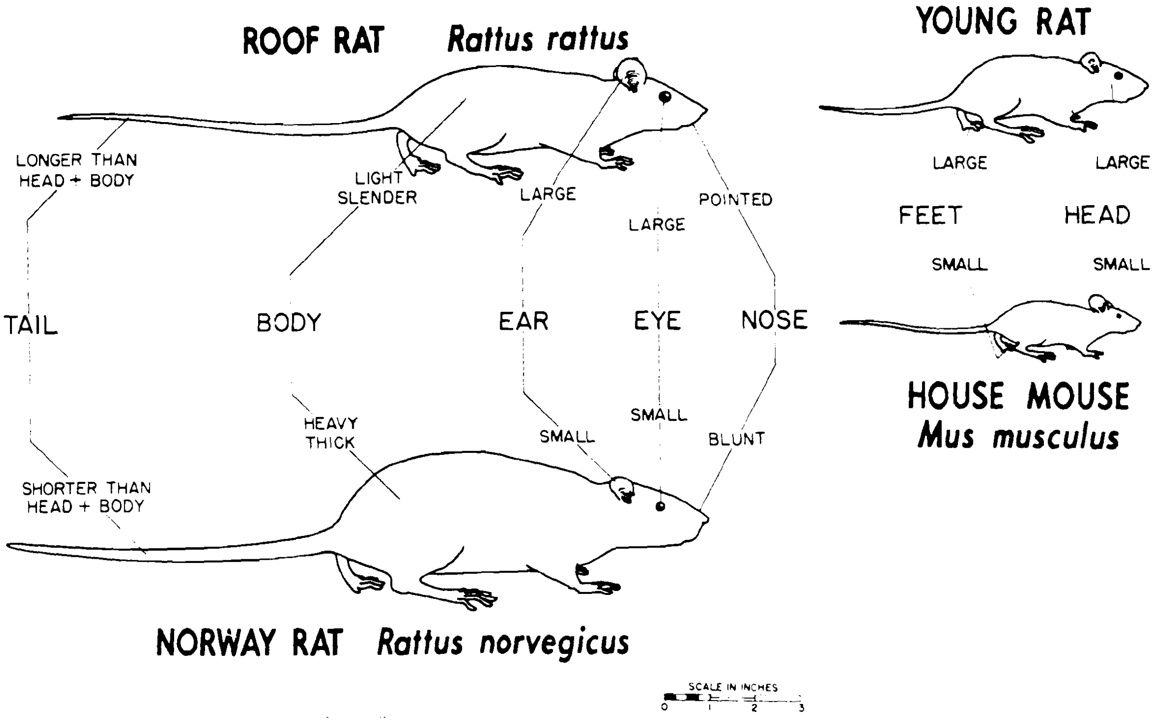

Figure 13-16. Field Identification of Domestic Rodents (Ref. 17)

woodchucks, gophers, porcupines, and beavers are also members of this order of mammals characterized by a single pair of upper incisors. The rabbits and hares, which are related to but biologically different from rodents, are included here.

Because of their relative importance, rats and mice are the primary concern of this discussion. All of the other rodents are discussed briefly as a group in par. 13-4.2.

13-4.1 RATS AND MICE (MURINE RODENTS)

The Norway or brown rat is the most common species of rats in the United States and is widely distributed in other parts of the world. This rat is also called the wharf rat, gray rat, sewer rat, and water rat. It is particularly dominant in most parts of the temperate latitudes. The Norway rat can live far from inhabited areas or thrive in densely populated places.

The black rat or ship rat and its subspecies, the roof rat and the white-bellied rat, differ in many ways from the Norway rat in appearance but are generally similar to each other. The roof rat is more common than the black rat in the United States. The distinguishing features of the roof rat as compared to the Norway rat and house mouse are shown in Fig. 13-16 and enumerated in Table 13-2. Its gray back gradually becomes light gray on its under side. The roof rat and the black rat are the two that are more dependent on man and like to nest between walls or floors of buildings in which food can be obtained. The white-bellied rat can usually be identified by a sharp line of demarcation between its brown back and white or bright-yellow belly. This rat lives mainly in trees, shrubs, and vines. During winter, however, the white-bellied rat sometimes occupies remote parts of the buildings used by people but is decidedly more wary of man than either the Norway or black rats.

Both house mice and black rats have increased where rat control measures have been maintained, for such actions are more effective against Norway rats. The latter rodents also drive out black rats and house

TABLE 13-2

CHARACTERISTICS AND MEASUREMENTS OF ADULT MURINE RODENTS (Ref. 6)

Species	Norway Rat (*Rattus norvegicus*)	Roof Rat (*Rattus rattus*)	House Mouse (*Mus musculus*)
Weight	280-480 g (10-17 oz)	110-340 g (4-12 oz)	14-21 g (0.5-0.75 oz)
Total length (Nose to tip of tail)	325-460 mm (12.75-18 in.)	350-450 mm (13.75-17.75 in.)	150-190 mm (6-7.5 in.)
Head and body	Blunt muzzle; heavy thick body 180-255 mm (7-10 in.)	Pointed muzzle; slender body 165-205 mm (6.5-8 in.)	Small 65-90 mm (2.5-3.5 in.)
Tail	Shorter than head plus body, carried with much less movement, comparatively, than roof rat. Lighter-colored on under side at all ages 150-215 mm (6-8.5 in.)	Longer than head plus body, generally moving whiplike, uniform coloring top and bottom at all ages and for all subspecies 190-255 mm (7.5-10 in.)	Equal to or a little longer than body plus head 75-100 mm (3-4 in.)
Ears	Small, close set, appear half buried in fur. Rarely over 20 mm (0.75 in.)	Large, prominent, stand well out from fur Generally over 20 mm (0.75 in.)	Prominent, large for size of animal, 15 mm (0.5 in.) or less
Hind foot	Usually over 40 mm (1.5 in.) from heel to tip of longest toe	Generally less than 40 mm (1.5 in.) from heel to tip of longest toe	Feet are shorter, darker and broader than most wild mice, Generally, less than 20 mm (0.75 in.) from heel to tip of longest toe

mice from at least the more accessible places.

Although cosmopolitan house mice are well known, they can be confused with young black rats of comparable size. Their superficially similar traits are apparent in Fig. 13-16. The differences can best be distinguished by the shape of the head and size of the eyes. Furthermore, the normally dusky slate-gray stripe along the back of the house mouse tapers gradually to an ashy-gray belly. A house mouse has moderately prominent brownish ears and a dull-brown tail equal to half its total length.

A number of other species of rats and mice seldom inhabit structures and, therefore, constitute only a small nuisance with respect to materiel.

13-4.1.1 DESCRIPTION

Although rats are omnivorous, the different species of rats and even individuals within a species have food preferences. Norway rats show a preference for meat and other food high in fat content. Black rats prefer succulent seeds, fresh fruits (except citrus fruits), vegetables, and eggs to cereals and meats. Among the cereals, they prefer wheat and corn. Rats sometimes carry favored pieces of food to their nests. However, when favored foods are unavailable, they readily eat other foods; if the food is consumed, removed, or tentatively blocked by ratproofing, rats usually go elsewhere but, in some instances, eat about anything that contains nutrients. They may even gnaw out greasy spots in clothing. Their gnawing on hard, nonnourishing materials, such as soft metals, is not caused by hunger; it is to maintain their teeth at proper length and strength or, occasionally, to gain access to other areas.

Rats have prodigious appetites. An average adult rat consumes about 28 g (1 oz) of food and 56 g (2 oz) of water per day. They waste a high percentage of what they sample and thereby rule out its safe use by human beings because of probable contamination.

The Norway rat, a moisture-loving creature, is basically more dependent on available water than is the black rat, but both species are good swimmers. The Norway rat commonly infests streams, sewers, and drains where it obtains drinking water and food. Wherever this rat infests buildings, it must have a ready access to drinking water, but the black rat can go for weeks without drinking water if moist foods are consumed. In some situations, the black rat can obtain adequate water from flat roofs, gutters, condensation on water tanks, or in holds of ships.

Rats infest areas having a protective refuge for both adults and their young or a place where they can prepare a suitable shelter by burrowing and gnawing.

Norway rats almost always nest in burrows, especially where they can be constructed under buildings, paved areas, or localities not likely to be traversed or disturbed. These tunnels are 5 to 8 cm in diameter and vary considerably in length. Their burrows normally have at least 2 or 3 entrances and often one or more emergency exits with the latter having a superficial, inconspicuous closure cleverly hidden among weeds or other obstructions somewhat farther from the main part of the den. Their tunnels seldom extend more than 0.5 m below the ground. However, in unusual situations, rats have burrowed to a depth of 1 m to get into or out of a building. Black rats and roof rats normally seek shelter inside or under buildings, rock piles, rubbish, boxes, or lumber stored in open areas, assuming that the more aggressive Norway rats are not present. Both black rats and roof rats like cavernous spaces between walls and floors if they have adequate access. Rat nests can consist of small bits of soft material such as rags, paper, twine, or dried plant fibers. The nests are loosely packed but are generally reminiscent of a bird's nest.

Once rats find a place that provides an adequate supply of suitable food, water, and shelter, their population increases. The actual rate of increase depends on a multiplicity of factors, such as species of rat, food supply, the age and health of females, suitability of shelter, competition among rats, temperature, and climate. The black rat has a greater number of young in warm climates, but the Norway rat is more fertile in cold climates. The number of young in a litter of Norway rats ranges from about 6 to over 20 and the number of litters varies from about 1 to 3 per mo for periods of 6 mo or more. The lifespan of rats may vary from less than 1 yr to about 5 yr.

The female rat has the sole responsibility in caring for her young. Since she must protect them from male rats as well as other enemies, she is reluctant to wander far for food and water. If a nest of helpless young rats is found, they should be killed at once or, in any case, before leaving them for more than a few minutes. Their mother will quickly remove them to a safer place as soon as she gets an opportunity.

The males are more adventuresome than

the females. They migrate from buildings in search of better food and less competition from other rats. At the onset of cold winter weather, they seek sheltered places in and around buildings where food is available.

The Norway rat has largely replaced other rat species in or near the ground level because it is stronger, larger, more vicious, more adaptable, and usually more prolific than other species. Because of their greater climbing ability and better agility, roof rats and black rats can compete successfully in places well above the ground, such as on ships or in overhead locations in buildings. Superior climbing ability is of prime importance in those places. On the other hand, the Norway rat can adapt itself to conditions in a cold storage building, where its color becomes more grayish.

To properly ratproof a structure or otherwise control rats, a better understanding of a rat's climbing finesse is helpful. In general, rats can climb any vertical surface on which they can apply a toehold or pressure. They can easily climb vertical sheet metal edges and glass tubing by exerting pressure on both sides and can walk on horizontal wires by using the tail for balance. Rats can go up or down the edge of a steel door about as fast as they can run on the ground. Rats can easily climb 8-cm pipes. If a pipe is smooth, a rat will not climb a 10-cm pipe to any great height; but if rough, it will provide access into a building. Rats will also climb large pipes that are close to buildings by forcing their bodies between pipes and building.

Experiments with black rats indicate that they can jump about 0.5 m upward or jump horizontally about 1 to 1.5 m, especially when cornered. Black rats normally avoid horizontal jumps greater than 0.25 m. They can also drop great distances without any apparent harm. In an unusual test, two black rats were deliberately dropped from a grain elevator window that was 55 m above the ground. Both of them spread out their legs and glided in an air current off to one side. They hit the ground with no apparent harm and promptly ran for cover.

Rats are seldom seen far from cover. In populated places they sometimes cross alleys but rarely cross a highway. In an open area, a man can easily outrun a rat on either a smooth or a rough surface; their efforts at dodging or avoiding being caught are clumsy. An expert can catch one barehanded with little fear of being injured. Because of possible serious complications from a ratbite, no amateur should risk getting a disease by taking a needless chance.

In sheltered areas where they are not disturbed, rats roam as much during the day as they do at night. Their natural wariness of lurking enemies in most habitats accentuates the impression of nocturnalism. In typical situations, they feed twice a day, just after dusk and just prior to the rise in forenoon activity by local fauna. Most enemies of the rat are inactive at night.

House mice are usually brought into buildings while hidden inside boxes of supplies or equipment but may also enter through existing cracks or holes that are smaller than 0.5 in. or via a seemingly harmless opening, such as an opening in a door or window screen. When mice enter a building in which quantities of food are kept, they may appear relatively harmless at first. Damage caused by a few mice is slight and difficult to detect. Thus, most people tend to be more tolerant of the house mouse than they are of rats.

House mice readily adapt themselves to environmental changes made by man. Although they will eat almost any edible substance having nutritional value when more suitable food is unavailable, they normally consume foods similar to those eaten by human beings, such as cereals, grains, meats, dairy products, seeds, fruit, and vegetables. They prefer dry cereals with ample water but can exist for months on moist foods without water. They also prefer sweet liquids to water. Unlike rats, mice eat 15 or 20 times a day.

Unless mice are disturbed, they travel established routes in a comparatively small area seldom farther than 9 m. They are curious creatures—a weakness that frequently calls attention to their presence—and like to dash in and out and around their sheltered area. Except for sight, mice have well-developed senses and can climb, jump, and swim well. A mouse rarely falls into anything that he can neither climb nor jump out of.

House mice breed equally well throughout the year. At the age of 2 to 3 mo the female is sexually mature; her gestation period is 20 days; she has 6 to 8 litters annually. Although the life span of house mice is not accurately known, it averages 15 to 18 mo. The female is usually productive for 15 mo. Thus, if no mice die from disease or by being killed, a single pair can cause a rapid increase in mouse population.

The most important evidences of rat and mouse infestation are droppings, runways, tracks, and gnawings. Other signs include burrows, live or dead rodents, nests, odor, and excitement of domestic pets. The most reliable signs of rat infestation are related to droppings. The excreta of the rat are rod shaped, straight or slightly curved, dark-colored, firm masses with rounded ends varying in size from 1.5 by 6 mm to 6 by 18 mm. Droppings of the Norway rat are longer than those of the black rat and the former are more widely distributed along the paths of activity.

The urine of the rats causes dark stains and is fluorescent under ultraviolet light. Inspectors use this property in determining its presence.

A second important indicator of rat infestation is tracks. These can be seen with oblique light in a runway covered with a light layer of dust. A rat has four-toed front paws and five-toed rear paws. When a rat moves slowly, it drags its tail. Individual toe prints are seldom visible except on surfaces with a thin coating of dust. An excellent technique for observing rat tracks is to sprinkle flour in areas of frequent activity.

Rats follow pathways, often called runways, beside walls or other obstructions, on the inner side of pipes, or on wires. Dirt and grease from a rat's body soon darken the surfaces touched by each passing rat. The locating of runways is important for blocking such routes, especially those leading to buildings or rooms containing food and nesting spaces.

When a number of dead rats are discovered, the colony of rats may have been poisoned or may have succumbed to a disease. The sighting of live rats during the day generally indicates a large infestation in an area with numerous hiding places. The presence of rats causes an offensive odor detected by some people in nearby areas even when the rats cannot be seen.

13-4.1.2 DISTRIBUTION*

Rodents are most abundant in eastern and southeastern Asia. All evidence indicates that the Norway rat, the roof rat, and the house mouse are native to Asia and have spread from there throughout the world.

It appears that the house mouse first moved from Asia into the Mediterranean area and then into Western Europe. From there man carried it to the New World during his early explorations. Because the mouse is so small and requires so little food, it has spread much farther than the rats. Today it is found from the tropics to the arctic regions all over the world. In North America it is found throughout the United States, southern and western Canada, and the Alaskan coastal regions and Aleutian Islands. It probably has the widest distribution of any mammal except man.

The roof rat was busy over most of Europe by the 11th century. In Europe the roof rat has two distinct color phases; the black rat of

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*This section is adopted from *Biological Factors in Domestic Rodent Control* (Ref. 17).

Western Europe, and the brown alexandrine rat common around the Mediterranean. Roof rats were well known throughout the French, English, and Spanish colonies of North America. Here the two color phases from Europe interbred freely. As a result, today in North America all the colors are present in one population. Often a single litter of young roof rats contains both black and brown animals.

Evidence indicates that the Norway rat is a later, more highly developed species originating in or near the center of origin of the Rattus group on the plains of Central Asia. It is characteristic among mammals that the most advanced species of a group are found closest to the center of origin, where they replace the more primitive forms. So it appears to be with rats. As the more highly developed, more aggressive Norway rat spread outward from Asia, the more primitive roof rat disappeared over much of its original range.

The Norway rat first appeared in Europe in the 18th century. It spread so rapidly that the Europeans called it the "Wanderatte" or migratory rat. Soon after the Norway rats reached Western Europe, it was carried to the New World. Here it spread outward from the seaports, especially along the east coast of North America.

The present distribution of the Norway and roof rats appears related to two factors, competition between the two species and the reaction of both to different climates. When the aggressive Norway rat and the roof rat compete for the same area, the Norway rat becomes dominant and the roof rat disappears. Only under special conditions do both live in the same area. In one eastern seaport, roof rats live in the top of a grain elevator and Norway rats live in the bottom. This is probably because roof rats are better climbers than Norways. It is generally only in such situations as these that roof rats are found living in Norway rat territory.

It appears that the Norway rat is definitely an animal of the temperate climates. In its original range in Asia, it is restricted to temperate regions. It is found in the tropics only in seaport areas. On the other hand, the roof rat is common throughout the tropics. In these areas roof rats commonly inhabit regions far removed from man's activities.

While it appears that warmer climate slows the advance of the Norway rat, it does not stop it. In southwestern Georgia, from 1946 to 1952, Norway rats overran 1,000 mi^2 of country where the roof rat previously had been dominant. This is an advance of 20 mi overland in 6 yr in a relatively warm climate. Today in this area the roof rat has disappeared and the Norway rat is dominant. The importance of information of this kind cannot be overemphasized. Knowing the species that is likely to be dealt with is of obvious value in rodent-control planning.

The present distribution of the three rodents in the United States is such that the roof rat is confined mostly to the warm Southern States and along the Pacific Coast into western Canada. It is found only sporadically in the northern part of the continent. The Norway rat and the house mouse are found throughout the United States and southern Canada. In the West, their distribution extends along the coast well into the main part of Alaska. Distribution of all three species is scattered in the arid and mountainous regions of the West.

13-4.1.3 EFFECTS

Among the rodents, rats are the most destructive to Army materiel and constitute an important health problem. Rats are attracted particularly by foods kept outside buildings (including those thoroughly packaged against adverse environment) at military installations. In their search for food and shelter, rats damage a variety of materials and equipment. Where present in large numbers, accumulated damage is immense. Holes gnawed in packing cases by rats result in contamination of foodstuffs and spillage or waste of supplies during transport to other places. Rats destroy vital seals and expose foodstuff or sensitive equipment to moisture, insects, and fungi. Rats often gnaw on plastic and glued surfaces as a source of food. They can cut holes in plastic rubbish barrels or plastic hose (or tubes) used to convey liquids and gases. They ruin stored fabrics, clothing, parachutes, tentage, and paper by cutting passageways and shredding the materials for their nests. Chemical deterioration is greatly accelerated where droppings and urine are deposited on fabrics. Rats occasionally damage insulation on electrical or communication wires or other parts of equipment, causing short circuits and fires. Rats have been known to carry matches to their nests and to gnaw the phosphorous or paraffin coating, thereby igniting the matches. Since nesting materials usually include highly inflammable materials, the risk of spontaneous combustion adds to the fire hazard. Rats also gnaw hard substances such as lead and aluminum, creating a potential hazard from spillage or fire.

When house mice become well established in a building containing an abundance of good food and suitable cover, the mice population increases rapidly. The accumulated damage of many mice may equal or exceed that of rats. In establishing a habitat, mice damage a variety of materials. Examples are foodstuff, clothing and fabrics, tentage and parachutes, paper and cardboard containers and often their contents, and household furnishings in transit. Any contact of mice or of their liquid or solid wastes with foods renders them unfit for human use. Their gnawing on woodwork, electrical insulation, and furnishings increases maintenance requirements.

Plague is a bacterial disease of the human circulatory and respiratory systems, with a high mortality rate. It is essentially a rat's disease. The black rat is particularly susceptible and is a major carrier of the disease to human beings. Infected rats carry plague-infected fleas that transmit the disease to people. The highly contagious human plague, or rat plague, actually consists of four types: bubonic, septicemic ("black death"), pneumonic, and sylvatic plagues.

Rats contributed greatly to the spread of the plague in Europe in the 14th century leading to the death of millions of inhabitants over a 50-yr period. Epidemics still occur in parts of Asia; relatively minor ones have occurred infrequently in the United States within the present century. The defoliation of the South Vietnam countryside in 1970-1972 led to a mass migration of people, rodents, and insects to new areas and has resulted in a situation similar to that occurring in Europe in the 14th century. Plague deaths in South Vietnam have increased from 40 to over 4,000 annually (Ref. 19).

Other serious human illnesses commonly associated with rodents are murine typhus fever, food poisoning, poliomyelitis, and trichinosis. Rats also transmit rabies, typhoid fever, and dysentery. In badly infested areas, rats consider sleeping human beings, especially infants, a source of food. Once a rat tastes human blood, some authorities believe that it will make subsequent attacks on individuals.

Infected mice, like rats, are important carriers of disease-producing virus. House mice transmit disease to man by infecting human food with their urine and droppings, by biting or other physical contact, indirectly after being eaten by dogs or cats, through blood-sucking insects, and possibly from organisms of a dead mouse polluting a water supply. Diseases that may be transmitted include Weil's Disease, food poisoning (via *Salmonella* organisms), eggs of tapeworms of the genus *Hymenolepis*, favus (a fungus disease causing bald spots), and ratbite fever (usually by rats but sometimes by mice).

13-4.1.4 CONTROL*

Control of rats and mice is possible through the use of poisons and by fumigation but the

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*The control of rats and mice is discussed in *Control of Domestic Rats and Mice* (Ref. 18) and other publications (Refs. 6,17).

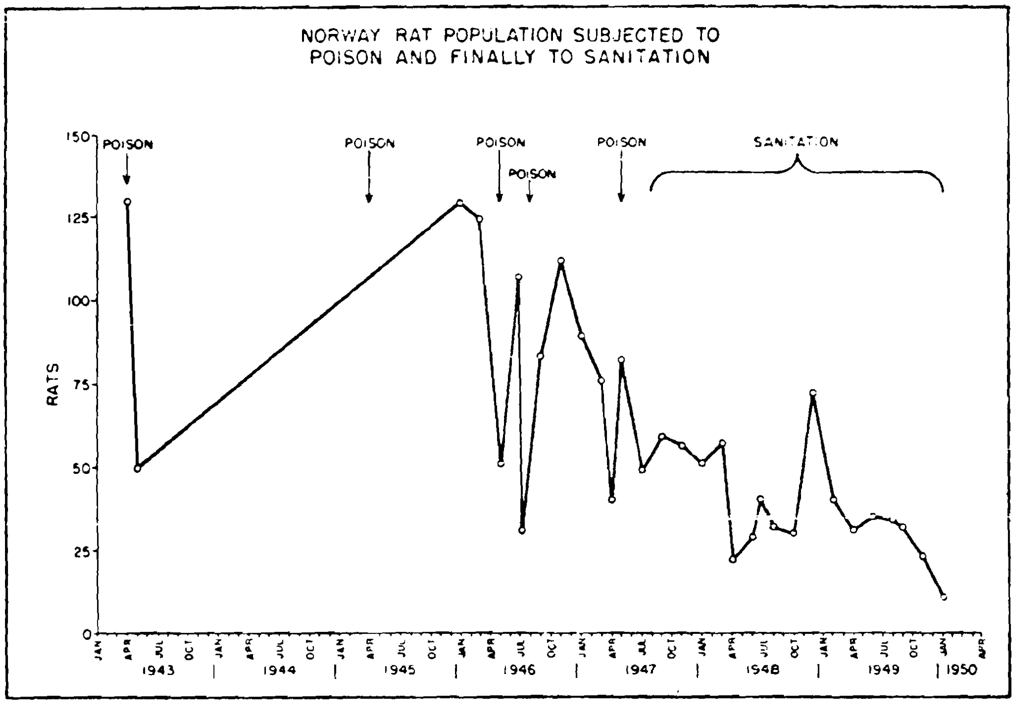

Figure 13-17. Results of Poison and Sanitation Controls on Rat Population (Ref. 15)

best methods involve good sanitation and the ratproofing and mouseproofing of buildings. This is illustrated in Fig. 13-17, which plots the rat population of a city block as affected by repeated poisonings and, finally, by an intensive sanitation program. To reduce the population permanently, the sources of food and water must be removed.

The destruction of rodents by rodenticides is more effective when the behaviorial characteristics of the rodent are studied in connection with poison baits and after a detailed survey of the infested area. Rats are more easily lured away from their regular food sources by foods having the distinctly pronounced odors and tastes preferred by most rats. A few of them used to good advantage include raw bacon (preferred to cooked bacon), strong molasses, pork fat, ground salmon or sardines, and vegetable or nut oil; these also help to disguise the taste or odor of poison mixed with bait. Some foods have a further use in binding other foods together. Rats can usually detect extremely minor differences in mixed combinations of food.

Although most rats are inclined to use certain runways or living areas for feeding, they sometimes feed where food is found or may take a bite and run for cover. Ample poisoned bait should be placed in carefully selected areas so that all rats sampling it may obtain a lethal dose.

On the other hand, attempts at rat poisoning encounter serious problems. Rats are extremely suspicious of strange objects; unsuccessful acceptance of bait makes succeeding efforts more difficult. Baits must be presented in a way that discourages its being carried away. Most poisons, although mixed with any combination of foods, make bait less attractive to rats and are likely to be less attractive than their regular food.

Since poisoned baits may result either in complete failure or, rarely, up to a 90 percent kill of a large rat colony, surviving rats can readily associate the toxic bait with the unpleasant symptoms that followed; they will avoid the offending poison used and the harmless food mixed with it for a period of time varying with the severity of the

TABLE 13-3

LIST OF COMMON RAT POISONS AND THEIR GENERAL EFFECTIVENESS

Faster-killing poisons Strychnine sulfate Strychnine alkaloid Sodium fluoroacetate	Stronger poisons Strychnine sulfate Strychnine alkaloid Phosphorus paste Zinc phosphide White arsenic Thallium sulfate ANTU Sodium fluoroacetate (1080) Warfarin
Slower-killing poisons Red squill* Thalium sulfate	Weaker poisons Barium carbonate Red squill*

* Red squill is an emetic obtained from the bulb of a lily that grows in the Mediterranean region. Because rats cannot vomit, the emetic effect does not protect them from the poison which causes heart paralysis.

symptoms, taste preferences of individual rats, and the relative preference of the foods regularly available. Because of the tendency of rats to take a few nibbles of strange foods, prebaiting in an appropriate feeding area is advisable so that all rats in a colony will not only become familiar with nontoxic bait but will also accept it. When a poison is added and well mixed with the bait, extreme care must be exercised in preparing and presenting it; the only differences are the addition of a correct amount of poison and an ample quantity of bait. The consumption of about a teaspoonful of a properly prepared mixture of solid bait per rat should prove lethal.

Depending upon the kinds of results desired, rat poisons can be divided into different categories as given in Table 13-3, based on relative toxicity and on the speed with which the poison becomes lethal. The use of a highly toxic rodenticide increases the risk that it may harm or kill personnel, pets, or harmless warmblooded animals. The two main requirements of any good rodenticide are that only a small amount of it need be consumed to be lethal and that rats accept it in baits. Any of the stronger poisons listed meets one of the requirements. The slow-killing poisons make it possible for poisoned rats to leave a building, thereby reducing the possibility of repulsive odors arising from dead rats in inaccessible places. Furthermore, rats killed in the vicinity of human habitation make it easier for disease-carrying parasites to attach themselves to human hosts.

Where rat and mouse harborage areas are

relatively inaccessible, such as in burrows, between walls of buildings, or among stored items in warehouses, the use of fumigants may be the most practical means of exterminating them. Fumigants commonly used include hydrocyanic acid gas, chloropicrin, and methyl bromide. Carbon monoxide from a gasoline engine is also effective when piped into burrows.

Sanitation has proved to be a more permanent means in controlling rats. This approach increases competition among rats by decreasing the amount of food, and living and nesting space. The proper disposal of garbage is of extreme importance. It can be kept temporarily in metal containers with tight lids. Rubbish dumps, trash heaps, and supplies stored on or close to the ground for extended periods provide rat harborage areas and should be eliminated.

Rats, especially Norway rats, must have an ample supply of water, so its availability should be eliminated or restricted wherever possible both inside and outside buildings by blocking entrances to them or their runways between water and food.

Ratproofing of buildings accompanied by vigilant maintenance is also a major control measure that can produce a lasting reduction in rat infestation. This can be done in new construction, but many corrective measures are feasible in blocking rats from existing structures, especially masonry ones situated well above the ground. Losses caused by rats can be largely avoided by using materials resistant to gnawing; by eliminating all possible dead space between walls, between ceilings and floors, under stairways, and around pipes; and by making certain that all openings are either permanently closed or protected by closely fitted doors, windows, gratings, and vents.

In mouseproofing a building, attention is focused on eliminating their hiding places insofar as possible and either doing away with their food supply or taking special precautions to make all sources of food unavailable to them. Special effort is needed in removing any spilled food—even minute particles—and keeping food supplies in well protected places.

The opportune time to make a detailed inspection of a building is in early autumn so that the necessary repairs can be completed before the onset of cold weather. Critical places requiring attention include damaged doors, cracks under doors at ground level, defective basement screens, and protective barriers around pipes or vents. Ordinary building materials are adequate for keeping out mice. Since most mice are carried into buildings, personnel who handle cartons or crates damaged by mice or other rodents should check the possibility that rodents may be inside items being moved.

Of the several natural enemies of rats and mice other than man, owls are the most useful. Certain breeds of dogs, like the terriers, can easily catch and quickly kill a rat in open places but are greatly hampered once a rat reaches its inaccessible retreats. Dogs often call attention to the presence of rats around buildings, rubbish, and other favored harborages. Domestic house cats will prey on mice and on young or half-grown rats, but few will attack a full-grown Norway rat. In some localities, certain species of snakes kill and swallow a substantial number of rats, mice, and other rodents. Other important predators of rats include ferrets, the mongoose, weasels, and skunks.

13-4.2 OTHER RODENTS

In addition to rats and mice, other rodents in particular circumstances may have an impact on materiel. The burrowing members of the squirrel family—ground squirrels, prairie dogs, and woodchucks—occasionally cause extensive damage due to their digging. Their greatest importance on military installations arises from the diseases and parasites that they harbor. Pocket gophers also carry plague but, in addition, construct mounds of earth that create safety hazards on airfields and training grounds. Rodents such as shrews, moles, bats, and the related rabbits and hares constitute an occasional nuisance but do not significantly affect materiel. More information on these rodents is in the *Military Entomology Operational Handbook* (Ref. 6). Identification of various members of these species can be accomplished using the key given in Table 13-4.

13-5 BIRDS

Birds are attractive and useful contributors to the environment in which we live. The many forms in which these positive characteristics of birds are expressed must be emphasized in considering the relatively few detrimental characteristics of birds as an environmental factor. Birds carry diseases and insects that are harmful to people, are a hazard to aircraft, are sometimes dirty and noisy, can contaminate food, can deteriorate equipment, and often destroy crops.

Birds are an environmental factor of concern to design engineers when their presence creates a hazard, when their depredations on materiel cause deterioration, or when their nests, feces, or feathers cause damage. The most notable example of a hazard due to the physical presence of a bird is the crash of an aircraft due to collision with birds. Specific examples of depredation include damage to wooden structures and power poles by woodpeckers and the destruction of food supplies. Bird droppings are not only unsightly, but are corrosive to material, soil fabrics, and initiate biological decay.

Although the damage created by birds may not be an important factor in the overall operations of the military, the damage frequently tends to be concentrated in small geographical areas or in narrow fields of human activity.

Aircraft collisions with birds is a major concern. Typical results of such collisions are shown in Figs. 13-18 and 13-19. Records kept by the Federal Aviation Agency show that danger is frequently greatest at takeoff and landing and when flying at low levels at high speeds (Ref. 20).

The gull is the one species that poses the most serious threat to aviation on a worldwide basis. Many kinds and species of birds, however, have been involved in collisions with aircraft: herons, vultures, kites, swallows, and crows have been identified. A flock of starlings was responsible for the crash of an airliner at Boston and an astronaut in a jet trainer died as a result of a collision with a snow goose. The U S Naval Air Station on Midway Island was plagued by albatrosses soaring over the runways (Refs. 20,21).

Aircraft-bird mishaps are not due entirely to random collisions. In the words of one expert, "Most airports are so attractive to birds that you may well think they were designed to be wildlife refuges" (Ref. 20). For example, the construction of Logan International Airport in Boston increased the available habitat and thus the population of birds. In addition to providing a desirable habitat for birds, Kennedy International Airport in New York is actually located on the migration route of hundreds of thousands of swallows. Garbage dumps in the vicinity of airports attract birds. Additional thousands of gulls can be attracted to the vicinity of a coastal airport by a neighboring garbage disposal area. Inland airports, by providing an "edge" (the margin between urbanized areas and wildlife habitats), increases the attractiveness of a region to birds (Ref. 20). Flocks of migrating birds cause hazards to aircraft on a seasonal basis. An additional problem to navigation has arisen because of the echoes and images created by birds flying within the sweep of radar beams.

Commercial crop damage is generally not the concern of the military. A strange chapter in military history, however, the "Emu War" of the 1930's, was brought about by crop damage by birds. Emus, the second largest birds in the world, stand about 1.5 m tall and weigh about 45 kg. To protect fences and crops against their depredations, the government of Australia dispatched a military

TABLE 13-4

KEY TO COMMON RODENTS OF THE UNITED STATES (Ref. 6)

Common characteristic: Hindlegs two or more times longer than front legs

Uncommon characteristics:

I. Tail with definite brush of hair on tip; animal has external cheek pouches	
A. White markings on head	Kangaroo rat (*Dipodomys*)
B. No white markings on head	Pocket mouse (*Perognathus*)
II. Tail without definite brush at tip	
A. Tail (bones) longer than one-half body and head length	
1. Tail is scaly and has rings	
a) Head short and thick; neck not evident	Cotton rat (*Sigmodon*)
b) Head long and slender; neck evident	Domestic rat (*Rattus*)
(1) Tail shorter than head and body; ears small	Norway rat (*Rattus Norvegicus*)
(2) Tail longer than head and body; ears large and prominent	Roof rat (*Rattus rattus*)
2. Tail without scaly rings	
a) Half of tail nearest body is slender and round	
(1) Whiskers reach to or beyond base of front leg	Wood rat (*Neotoma*)
(2) Whiskers do not reach to base of front leg	
(a) Body uniform in color, back and belly	
i) Upper, front teeth grooved	Harvest mouse (*Reithrodontomys*)
ii) Upper, front teeth not grooved	House mouse (*Mus musculus*)
(b) Back of body and tail dark; belly and under tail is light or white	Deer mouse (*Peromyscus*)
b) Half of tail nearest body not slender or rounded (brushy or fluffy)	
(1) Whiskers reach to front leg	
(a) Tail as long as head and body	Tree squirrel (*Sciurus*)
(b) Tail shorter than head and body	Wood rat (*Neotoma*)
(2) Whiskers do not reach to front leg	
(a) Stripes on cheeks	Chipmunk (*Eutamia*)
(b) No stripes on cheeks	Ground squirrel (*Citellus*)
B. Tail (bones) length equal to or less than one-half that of head and body	
1. Tail slender and pointed (fine hairs)	
a) Claws on front feet longer than on hind feet	
(1) Grooved, upper, front teeth	Gopher (*Geomys*)
(2) No grooves on upper, front teeth	Gopher (*Thomomys*)
b) Claws on front and back feet about equal length	
(1) Tail with white tip	Grasshopper mouse (*Onychomys*)
(2) Tail without white tip	Meadow mouse (*Microtus*)
2. Tail hairy, not slender and pointed, fluffy or brushlike arrangement of hair	
a) Crown of head dark or black with or without a few white hairs	Marmot (*Marmota*)
b) Crown of head same color as back	
(1) Back tan or light brown color; hair lies close to body (like that of a short-haired dog)	Prairie dog (*Cynomys*)
(2) Back dark brown or gray; hair soft, like fur	Ground squirrel (*Citellus*)

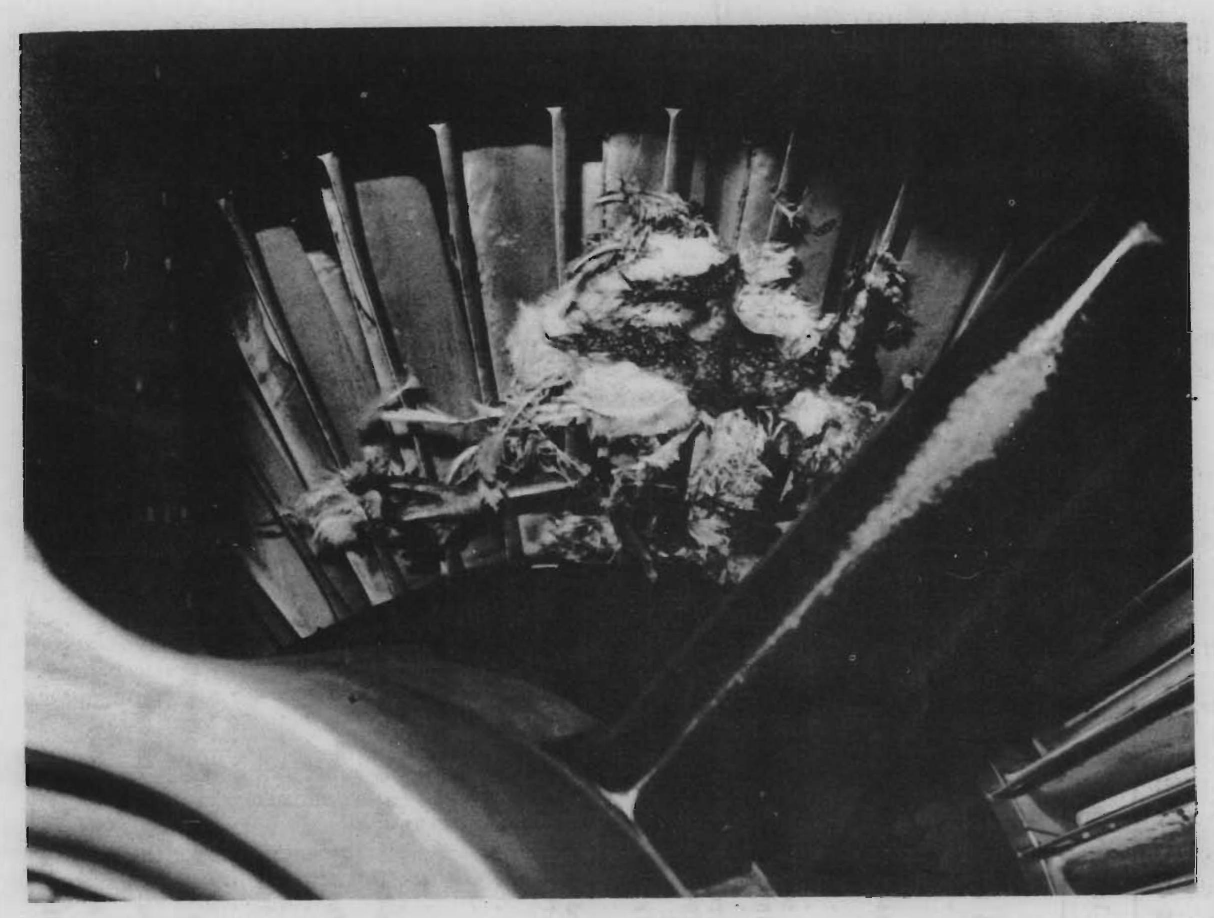

Figure 13-18. Sea Gull Ingested by Jet Engine (Ref. 6)

machine gun unit to deal with them. The press had "war correspondents" covering this expensive action. The emus, although flightless, had greater maneuverability than the machine gun unit and effectively eluded the danger (Ref. 22).

Damage to power and communication lines is commonly due to short circuits or line breakage. Short circuits are often caused by birds such as gulls rising under and colliding with power lines, by eagles dropping from transmission towers upon takeoff and contacting the lines, by perching swallows weighing down a top line to touch a line underneath, by ospreys dragging nesting material across lines, and by crow nests that cross wires and become wet. Damage to wood poles is caused by woodpeckers, which drill holes in the wood in their search for food, thus weakening the poles and causing them to fall. The right-of-way of powerlines is cleared in wooded areas. This strip offers an ideal "edge", which is productive of wildlife and which attracts birds (Ref. 23).

Swarming of birds in large communal roosts can create acute local problems. Starlings, American robins, blackbirds, grackles, and cow birds may number in the millions at a single roost. Swiss brambling flocks have numbered in the tens of millions and the African queleas congregate in flocks of two million or more. The continuous noise and contamination by bird droppings lead to health problems, damage structures, and make the area generally uninhabitable (Ref. 21).

The solutions to environmental problems presented by birds are (1) to provide protective barriers around materiel, (2) to remove the affected materiel from the

Figure 13-19. Aircraft Damage Due to Bird Strike (Ref. 6)

bird-occupied area, or (3) to remove the birds.

A barrier between the birds and the affected materiel is sometimes accomplished with little effort, e.g., a tarpaulin to prevent bird droppings from fouling material stored in the open or under a bird roost. In the case of emus, the solution is to provide a stronger fence to keep out the flightless birds (Ref. 22). In any case the method will usually be obvious.

Removal of affected materiel or an installation may not be easily accomplished in all cases. To remove portable equipment stored under a tree in which birds are perched is not as difficult, for example, as moving an air field.

The location of various installations should take local bird habitats into consideration. Location near a popular bird food source should be avoided, if possible. An installation located on a major bird flyway should allow for the seasonal passage of large numbers of birds. Often, the constraints imposed by operational needs and topographical features outweigh the difficulties caused by the presence of an undesirable number of birds in the local environment. In this case other solutions must be found.

Removing birds from trouble areas can mean killing the birds, removing a local attraction, replacing the attractive feature with another in a more advantageous area, or scaring the birds away. Killing is not usually a satisfactory solution for a large-scale bird problem–often pressure is brought by conservationists against killing. Killing the birds may not be easy. The machine gun unit was unable to cope with an estimated 20,000 emus in Australia and the killing of over 75 million queleas in Africa did not remove the problems caused by the depredations of those birds (Ref. 22). The proposal to kill albatrosses to prevent damage to naval planes on Midway Island was abandoned because of public protest. Special permission must be obtained to kill many kinds of birds.

If the trouble area itself, such as an air field, is the attraction for the birds, obviously, there is difficulty in making the area less attractive. If something external such as a garbage dump is the attraction, it may be possible to remove it. A study of Logan Airport showed that when local garbage dumps were closed, the number of sea gulls attracted to the airport vicinity dropped from thousands to a few dozen. At Midway Island, the albatrosses were attracted to the area at the end of the runway by thermal updrafts. By bulldozing the big sand dunes that caused the updraft and by paving level areas within 750 ft of the center of the runways to discourage nesting in the area, aircraft damage was reduced approximately 80 percent. To prevent eagles from shorting high voltage wires when they launched themselves from the tops of powerline structures, a perch was provided on the structure that was high enough to allow the eagles to clear the wires on takeoff. Ospreys have been provided with platforms or duplicate, more attractive poles in order to keep them from alighting on the cross bars at the top of powerline poles.

Scaring birds away is accomplished in a variety of ways and is a method frequently employed (Ref. 24). For example, birds flying into windows or through doors into storage areas are frightened away by silhouettes of predators such as eagles or hawks, which are placed on the glass or hung in the entryway. These and other visual detriments such as scarecrows, flashing lights, or metal signs do not discourage birds permanently or over large areas. As the birds become accustomed to the displays, they ignore them. Light, especially large flashing lights, can sometimes be effective in frightening many birds over a large area. Any such device is more effective if it is not used too consistently or kept at the same location too long.

Noise makers, including guns, rockets, firecrackers, and sound records of these are effective, especially if they are used at irregular intervals. The sound of .22 caliber bullets seems particularly effective. Automatic exploding devices that use acetylene are effective but have needed frequent repairs. Birds rapidly adjust to regular or repeated noise. The explosives must be staggered and the source moved for continued effectiveness. Often, the annoyance to personnel may be greater than that to the birds. The recorded distress and alarm calls of offending species of birds, when played to scare birds, have produced excellent results. Birds become accustomed to this too, however, and learn to ignore it. People subjected to broadcasts of starling distress calls have preferred the live birds.

Sources and descriptions of bird-control devices as compiled by the Fish and Wildlife Service include (Ref. 25):

(1) Automatic exploders. These machines ignite acetylene or propane gas to produce loud explosions at regular intervals. Acetylene is produced by dripping water on calcium carbide or is obtained from a tank of compressed acetylene gas. Most machines are stationary with some makes having a revolving model. Machines are not injurious to birds, but the loud reports may be objectionable in residential areas.

(2) Chemical coatings to prevent roosting. These sticky materials (available in various forms) are intended to keep birds from roosting on ledges, sills, trees, and other places.

(3) Electric devices. Wires are permanently installed on ledges to disrupt bird roosting by means of electrical impulses. The birds are not killed. Consult local building contractors, especially those in the scaffolding, roofing, insulating, or pest control fields for those experienced in installing these devices.

(4) Exploding shotgun shells. These are 12-gage shotgun shells, (except as noted) containing, instead of pellets, a king-sized firecracker, which is projected a distance of 150 yd or more.

(5) Metal projections or wires. These sharp devices are installed along building ledges,

window sills, etc., to discourage birds from roosting.

(6) Live traps. These are cages or other traps in which birds are trapped to be removed to a remote location.

(7) Moving and whirling devices. Whirling, bright-colored or shiny objects act as scare devices; move or change them frequently.

(8) Models of hawks and owls. It has been reported that these simulated models of their natural enemies have repelled some birds.

(9) Poisoned perches. This is a metal rod device containing a wick immersed in a lethal solution. When birds land upon the perch, their feet pick up the toxic chemical.

(10) Protective netting. Light, nonmetallic netting is designed to protect trees, plants, and small shrubs from bird attack. In some cases, a supporting framework is necessary.

(11) Pyrotechnics. Firecrackers, salutes, skyrockets, Roman candles, and other devices have been used to drive birds from crops and discourage roosting. These standard items may be purchased from regular firecracker manufacturers. Investigate local city ordinances and State laws regulating the possession or use of fireworks or explosives. Firecrackers, inserted at intervals in slow-burning fuse ropes, have been useful in keeping birds away from agricultural crops.

(12) Revolving lights. The lights revolve automatically, flashing alternate colored beams. They may repel birds from both inside and outside of buildings.

(13) Sound devices. These devices produce sounds (sonic and ultrasonic) to either repel or attract birds.

Ref. 25 provides lists of commercial sources of these devices. Further information on bird-control techniques may be obtained from Bureau of Sport Fisheries and Wildlife, Fish and Wildlife Service, U S Department of Interior, Washington, D.C. 20240.

13-6 VEGETATION

The material design engineer concerned with off-road mobility equipment, earth-moving and site-clearing equipment, ground-detection equipment, and even ordnance has a prime interest in vegetation because it often constitutes the prime environmental stress or operational limitation on the materiel for which he is responsible. Examples of the effects of vegetation are numerous, a contemporary example being the protection that the forest canopy offers hostile forces in Southeast Asia. In this case, proximity fuzes can be triggered prematurely by the top of the forest canopy resulting in ineffective detonation of the ordnance. The forest prevents detection of troop movements, provides secure refuges, and prevents effective reconnaissance by many types of vehicles. The importance of this form of vegetation is evidenced by the massive efforts to alter the vegetative nature of the battleground by using herbicides, incendiaries, and bombs.

This example is, however, only the most prominent. Throughout the recorded history of military operations, the vegetative nature of the operational area has played an important role. In support operations, vegetation is equally important. Support bases, roads, airfields, and other facilities often require vegetation clearing. Personnel must operate in regions characterized by all types of vegetation, which often determine the nature of various other environmental factors: temperature, humidity, microbiological factors, wind, and rain.

The effects of vegetation are not all adverse. Vegetation can supply materials for construction, prevent erosion, protect from the adverse factors, provide subsistence, stabilize the ground for vehicular traffic, and, generally, provide a more suitable environment for operations. The challenge is to adapt to and to employ vegetation to advantage, to modify it when required, and to have full knowledge of the types of vegetation that will be encountered.

More extensive data on vegetation as an element of terrain is included in Chap. 2 of this handbook.

13-6.1 BOTANICAL DESCRIPTION

Vegetation occurs throughout the world in almost limitless forms. Highly resistant spores of microscopic bacteria can be detected even in the stratosphere. In contrast, some trees constitute the largest (and oldest) living organisms in the world. The majority of plants contain the green pigment chlorophyll and carry on photosynthesis. This process is basic to terrestrial life because it is the primary means by which solar energy is made usable. In addition to providing food for animals, the green plants maintain the atmospheric oxygen supply necessary for animal life. During photosynthesis, carbon dioxide produced by respiration is consumed and gaseous oxygen released. This paragraph describes the major categories of common vegetation and indicates their impact upon military operations. The small forms of plant life, the micro-organisms, are discussed in Chap. 14 of this handbook.

Biological terminology in general constitutes a language that is foreign to the nonspecialists. Common terminology is employed in this paragraph except when scientific terminology is unavoidable. A major part of effective biological communication is the system of bionomial nomenclature. Every living thing now has a "scientific" name consisting of two Latin words. The first describes the genus. This generic name, when followed by the specific name, describes the species. The former is always capitalized, the latter usually not. Both are either italicized or underlined. Thus, contemporary man is classed as *Homo sapiens.* For plants, the name of the botanist first describing a new species is often abbreviated in parentheses. For example, the common bean plant *Phaseolus vulgarus* (L.) was named by Linnaeus, the 18th century Swedish scientist called the father of taxonomy (systematic classification of living organisms).

A "species" is a type of organism capable of reproducing itself with a consistent general structure. A "genus" is a grouping of several similar species. A "family" is a group of related genera, and an "order" combines related families. When the generic name is understood, as in a list of several species of the same genus, only the initial generic letter is written, followed by the species, e.g., *P. vulgarus.* When the species is not known, the abbreviation *sp.* is used, e.g., *Phaseolus sp.* Botanists all over the world recognize the scientific names. This is particularly important among species that have a variety of different local common names.

The naming of plants is doubly useful because it also designates current concepts of evolutionary development. The discovery in 1941 in Western China of living specimens of the genus *Metasequoia,* believed to be extinct, caused a resurgence of interest in paleobotany. This study of fossil plants provides evidence of past climatic changes around the world. Plant names, particularly wildland species, continue to be changed. For example, Douglas fir, formerly *Pseudotsuga taxifolia,* now is *Pseudotsuga menziesii.* The Sierra Bigtree, formerly *Sequoia gigantea,* is now *Sequoiadendron giganteum.* Field identification of plants around the world depends greatly upon published descriptions of endemic species in books called "local flora". These usually contain "keys", which are systematic lists of characteristics distinguishing each species. Taxonomy is based primarily upon the plant's reproductive structures, which are less subject to variation than the vegetative portions (leaves and stems). Therefore, it is important to collect flowers or fruit when attempting to identify unknown plants.

The relation of plants to each other and to their environment has been investigated for centuries. Most interest centers around agriculture, with much less known about wild land plants. A knowledge of the requirements and behavior of individual plants is a prerequisite to understanding groups of plants.

Our present knowledge of plant life includes a classification system ranking plants from "primitive" to "advanced" as they show greater specialization (Ref. 26). The major adaptation of land plants has been a reduced dependence upon free water for nutrition, reproduction, and mechanical support. All plants are composed of the basic microscopic unit of life–the cell. For example, the simplest, most primitive plants are one-celled organisms that remain continuously in liquid water. Bacteria are in a special category, somewhere between plants and animals. Fungi are another unique plant type, without chlorophyll and unable to photosynthesize. The most primitive green plants are the algae. Liquid water generally is required for growth of all these plants.

Somewhat more advanced than algae, but still without true roots, stem or leaves, are the mosses and liverworts. These small plants grow only in damp locations. Still higher levels of independence from aquatic locations are reached by the club mosses, horsetails, and ferns. These, and all the higher levels, are called "vascular plants" because they have special internal systems for conducting water to their leaves. Therefore, they can grow larger, even approaching treelike dimensions.

The highest level of plant life is reached by the plants that produce seeds. Of these, the gymnosperms are considered the most primitive. They do not have true flowers, and the seeds are not enclosed in fruit at maturity. The majority, such as pine, are cone bearing, and, therefore, called conifers. The true flowering plants, or angiosperms, are further divided into two groups–the dicotyledons and monocotyledons. The dicots, such as roses and beans, are less specialized than the monocots, such as onions and grasses. Seed-producing plants have reproductive structures arbitrarily designated as male (pollen forming), or female (seed forming). In conifers these arise in separate strobili, often erroneously called flowers. The true flowers may contain both structures in the same flower or in separate ones, either on the same or on different plants. Appendages of perennial seed plants are shed by the process of abscission. When this occurs simultaneously over the plant, it is called deciduous; when it is sporadic, the plants are evergreen.

In addition to their taxonomic classification, seed plants also exhibit a number of different life forms. The most conspicuous form is that of the woody perennials, either conifers or dicots, which last from a few to thousands of years. These plants produce wood as well as bark in the vascular cambium, a reproductive layer between the wood and the bark. Usually one layer of wood is produced each year, a process which increases the trunk diameter. These "annual rings" are apparent on the cut surface of a stump or log. Monocots do not have this type of cambium. Growth in length arises from the activity of apical meristems at the tips of branches and roots.

The largest woody plants are trees, usually over 20 ft tall and usually with a single trunk. Shrubs usually are under 20 ft tall and have several stems. Lianas are tropical vinelike plants using trees for support. Herbaceous plants are nonwoody and include the grasses. Nongrass herbaceous plants are called forbs. Succulent plants are specialized herbaceous forms with thick, fleshy leaves designed to retain especially high water contents.

The study of the structure of plant tissues and organs involves morphology (form and structure) and histology (microscopic structure). The functioning of plants is studied by physiologists. A field of study of ever-greater concern is that of ecology. This involves the interactions of living organisms with their environment, both plants and animals, individually or collectively. Here, as in taxonomy, changing concepts are evident.

The concept of the "ecosystem" as a basic unit of study has achieved greater acceptance (Ref. 27). Essentially, this is the complex set of parameters classed as climatic, edaphic (soil), and biotic (flora and fauna). Over extended time periods a sort of dynamic equilibrium develops (Ref. 28). A system of checks and balances leads to this condition, often called homeostasis.

Plants comprise the more obvious biotic elements. The long-term status quo has been termed the climax vegetation on any given locality. The process by which this is established is called succession (Ref. 29). Examples can be seen in the establishment of vegetation on landslides, lava flows, sand dunes, marshes, and burned-over forest lands. Increasing awareness of the impact of human activity is needed to evaluate the current status of vegetational trends. Agricultural practices, logging, and man-set wild fires have all created extensive disturbances (Ref. 30). A more recent type of disturbance involves the mass application of insecticides and herbicides, as well as industrial waste disposal.

It is becoming more apparent that the team approach to ecological studies is needed. No one person can become sufficiently familiar with all aspects to operate effectively. Through interdisciplinary cooperation the specific techniques for the various parametric observations can be integrated into a meaningful matrix. Nowhere is this more applicable than in planning military operations on a global scale.

13-6.2 DISTRIBUTION

Plants, because of their immobility, must endure all the extremes of weather occurring in a specific area. For that reason the local vegetation is a good indicator of local climate (microclimate or mesoclimate) in contrast to the general climatic data (macroclimate). The former is more representative of the environment in which field troops must operate. A number of efforts have been made to describe these areas parametrically. Certain climatic regions have unique problems relating to vegetational impact on operations. Some of the more important aspects of plant life will now be discussed in relation to the broad geographic zones of polar, temperate (midlatitude), and tropical, as well as the more localized mountain and desert types.

The Antarctic Continent can be dismissed with the comment that its vegetation is insignificant. There are but two species of seed plants and a few scattered species of lower plants (Ref. 28). The Arctic, or north polar region, has a more luxuriant flora where snow cover is intermittent (Ref. 31). The characteristic vegetation formation is the tundra. Extensive areas of lichens and mosses develop in the short growing season. Very few trees occur—mainly birch, aspen, and spruce, which are dwarfed. The general appearance is one of uniformity, but considerable local variation does exist. The arctic bog or muskeg occurs sporadically (Ref. 32). Here the mossy vegetation appears firm, but actually is partly floating. Personnel and vehicles attempting to traverse these areas in summer become hopelessly mired. The most favorable time to cross such areas is after they have frozen in the winter. Another unique feature of polar regions is the permafrost, a permanently frozen layer of soil a few inches below the ground surface (Ref. 33).

South of the tundra a true forest develops in a circumpolar belt. This is the boreal forest, called the taiga in Asia. Prominent species are mainly conifers, such as spruce, jack pine, and balsam fir. Extensive areas of dense stands offer shelter and concealment, but restrict vehicular mobility. During the short summer, large areas may be subject to forest fires. Here also, the close interrelation between plants and soil becomes evident (Ref. 34). In contrast to many parts of the tundra, where the peatlike surface soil is almost all organic matter, the soil here is classed as a podsol. This is highly acid, and, when the layer of decaying leaves (duff) is removed, a whitish, bleached layer of sand can be seen. Traction is much greater here than in the organic soils of the tundra.

This, forest blends into a mixed forest containing increasingly more hardwoods to the south. Imperceptibly, this transition leads from arctic conditions to what has been called the temperate zone at midlatitudes. Actually, it is somewhat of a misnomer for the areas in the interior of continents. Here, blazing summer heat alternates with frigid winters. In contrast to the tundra and boreal forest, where temperature is the main growth-limiting factor, the mixed forest contains areas that also experience seasonal limitations on moisture supply (drought). Farther south the deciduous hardwood forest is characteristic, as are the extensive grasslands (prairies, steppes) (Ref. 35). However, much of these latter vegetation categories have been altered greatly by man for agriculture and industry. The main effect of such vegetation is through their former impact upon the type of soil formed under them. Hardwood trees produce a nearly neutral soil, with more mineral nutrients and higher clay content than under conifers. Grasses usually produce an alkaline-type soil and generally receive a lower annual rainfall than the adjacent hardwoods, although the rainfall is usually evenly distributed throughout the year. Grass fires are a summer threat, often spreading faster than men can run.

In areas of pronounced dry seasons, the vegetation becomes unique. The "Mediterranean" climate (winter rain and summer drought) produces a typical vegetation wherever it occurs in the world (Ref. 28). This is characterized by shrubby plants with leathery sclerophyll leaves. From a distance this landscape appears subdued and easy to penetrate, but it is often nearly impenetrable, and the stems possess many sharp branches. Low moisture and high oil content in the foliage result in frequent, severe fires. The burnt branch stubs are hazardous to vehicle tires. Resprouting after fire is prompt, often within 2 mo.

With increased periods of drought, or a lower precipitation/evaporation ratio, plants become more scattered and approach a semidesert. The definition of desert is not exact, although it usually refers to areas with less than 25 cm of rain annually and little cloud cover. Contrary to popular impression, regions classed as deserts are far from being all sand dunes and devoid of plant life. Nearly half the plant species in these areas possess thorns dangerous to personnel and, in some cases, to vehicles. Some of the succulent plants can be a source of water (or juice) in emergencies (Ref. 36).

These deserts and semideserts straddle the Tropics of Cancer and Capricorn and toward the Equator merge into the broad region variously termed "tropical" or "equatorial". The distinction between Southern and Northern Hemisphere is less evident here. Annual precipitation tends to increase toward the Equator and the thorny plant areas often contain a greater proportion of grasses. These savannas are quite variable in composition, but fire is a threat here in the dry season. The tall elephant grass in Africa restricts visibility for dismounted troops. Lightweight periscopic devices would be of use here.

Further increases in precipitation toward the Equator are shown by the successive appearances of tropical deciduous forests, semievergreen forests, and, ultimately, the tropical rain forest. These are all rather complex associations of plants. The "monsoon" forests of Southeast Asia show the importance of considering the annual distribution of rainfall versus the total amount received. The true rain forest does not occur where rainfall is appreciably reduced in any month.

Rain forest plants have a certain similarity. The forests contain several "layers" of trees, and light intensity on the forest floor is 1 percent of that outside (Ref. 28). Decomposition of plant remains is rapid, so little debris accumulates. Climbing plants, lianas, and epiphytes are abundant. The jungle trees characteristically have a laurel-type leaf with leathery surfaces that shed water quickly. Tree trunks often exhibit widespread "buttress root" development, which impedes movement around them. Along seashores the mangrove develops in salt water, with the stiltlike roots accumulating silt and debris, making access difficult (Ref. 37).

Visibility is quite poor in the tropical rain forest due to low light intensity and the many hanging plants. Mobility, however, is not as bad in the undisturbed forest as in areas formerly cultivated. Here a tangle of secondary succession plants creates a "machete stage" where paths must be cut through each area traversed. This is often the case in the riparian vegetation along streams as well.

Mountains in the tropics are a special case. A characteristic sequence of vegetational zones is often encountered (Ref. 38). The tropical montane forests are quite different from temperate montane forests. The montane and subalpine forests of midlatitude mountains are often extensions of the boreal forest, and the alpine regions resemble tundra vegetation. Differences do exist, however. Mountain types, although cooler than adjacent areas, receive more solar radiation than similar vegetation closer to the poles. Moreover, the diurnal temperature range is much greater.

In general, a 300-m rise in elevation is equivalent to moving 500 km closer to the nearest pole. The various boundaries between vegetation zones, such as the timberline, become higher as latitude decreases (Ref. 39). Also, they tend to be higher on larger mountains than on smaller ones. In the tropics, maximum precipitation and vegetation density is reached at 1,800 to 3,000 m. Decreased moisture and increased wind tend to create smaller plant forms. In fact, south slopes may become semideserts.

Worldwide maps of those areas of the world characterized by various types of vegetation are available in common reference sources such as atlases. These provide very general guidelines. More detailed information is available in area topographic maps provided by the Army Topographic Command or the U S Geodetic Survey. One such general map indicating worldwide vegetation patterns is given in Fig. 13-20.

13-6.3 MEASUREMENT

Biological phenomena in general exhibit a high degree of variability due to the large number of factors acting and interacting simultaneously. Equipment and techniques are being developed and applied for remote sensing of vegetation patterns and changes, for meteorological data acquisition, and for analysis. They are providing new precision to studies of worldwide as well as local vegetation changes and processes. These techniques, combined with computers to process the collected data, will provide new precision to studies of vegetation.

Also, standard weather records are accumulating over appreciable periods of time, providing a broader base for characterizing climatic parameters. These general observations of the macroclimate are now being related to the more restricted conditions of the mesoclimate and microclimate. The latter is representative of the environment within which plants grow and personnel operate.

There are, at this time, no universally accepted measures of plant distribution and productivity in wild plants as there are for cultivated crops. Moreover, the boundaries between different vegetation formations usually are of a gradual transition. Therefore, maps of regional categories of vegetation often differ markedly when prepared by different agencies for the same geographic area. Additional irregularity is introduced by the fact that subcategories of vegetation usually are not uniformly distributed throughout a major category. The most typical arrangement is that of a mosaic, with scattered "islands" of plant types within a larger matrix of vague dimensions.

Certain general guidelines are apparent. It is convenient to categorize worldwide natural vegetation as either forest (dominated by trees) or nonforest. Different subdivisions can then be applied—such as coniferous, broadleaf, deciduous—for the forests; and grassland, savanna, or brush for the nonforests. Also, the Southern Hemisphere has distinctly different species than the Northern Hemisphere, in spite of certain similarities of life forms. For example, the pines are limited to the Northern Hemisphere.

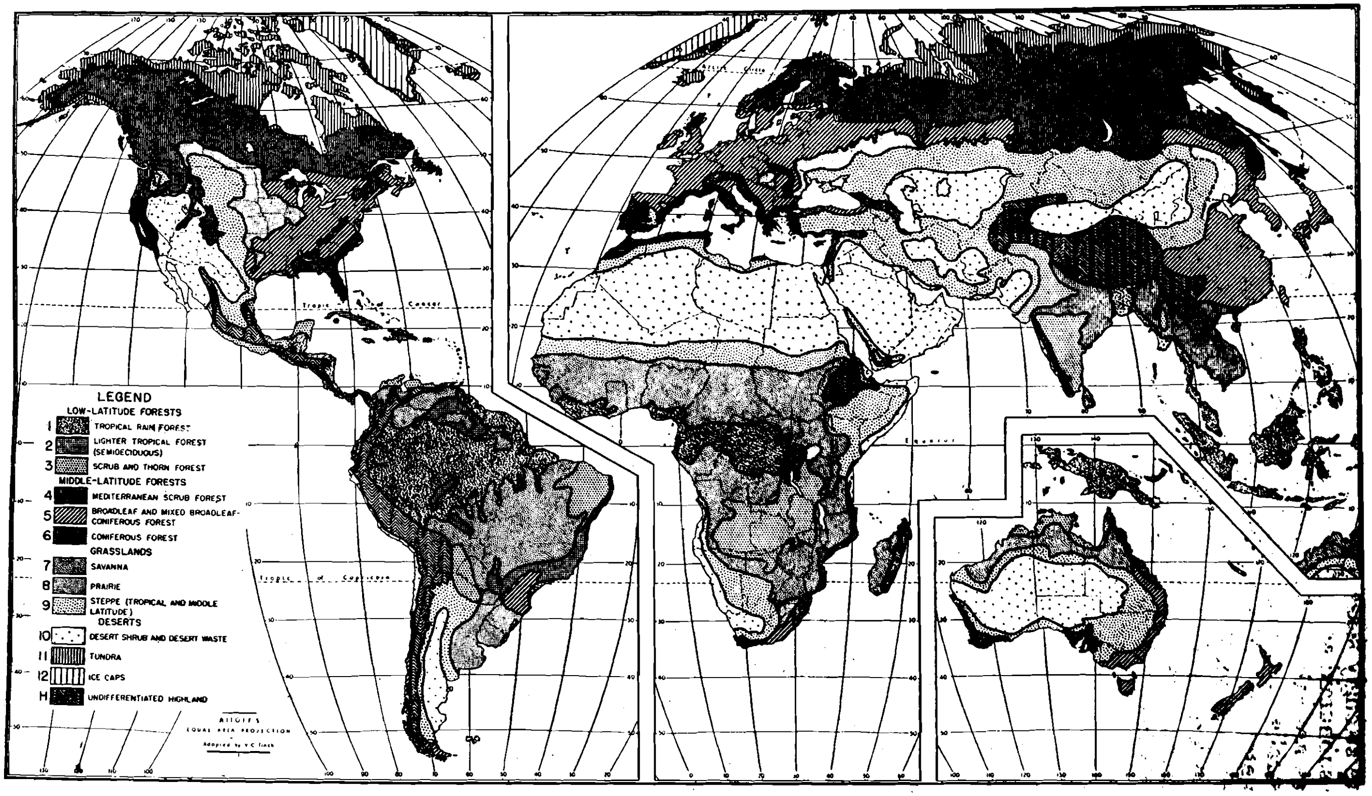

Figure 13-20. Worldwide Distribution of the Principal Vegetative Formations (Ref. 40)

The close relationship between climate and kinds of vegetation has long been recognized, and several classifications of vegetation regions have been based upon climatic data (Ref. 41). This emphasized the basic difference between what *ought* to be growing and what *is* growing in each locality as shown by current surveys. Such analyses of environmental parameters have been attempted both on a worldwide scale and more limited areas (Ref. 42). All have definite limitations.

Foresters have developed several techniques for assessing wild land vegetation. Sample plots have been measured over the years in a variety of forest areas. As a result "yield tables" exist to estimate the numbers, size, and productivity in basal area or cubic contents of such stands at different ages. Basic measurements of trees include total heights of trees and DBH (diameter at breast height, 4.5 ft above ground). The earliest method of "cruising" timberlands by ground plot measurements is now giving way to photogrammetry. Stereoscopic examination of aerial photographs permits acceptable estimates of forest land inventory. These can then be supplemented by spot checks from the ground. Continued improvement in cameras, films, and interpretive equipment indicates that this method will supplant all others in the rapid inventory of current vegetation status (Ref. 43).

13-6.4 EFFECTS

Vegetation affects both personnel and materiel in diverse ways. Some effects are primarily of a military nature; others are more general. The vascular plants generally are more conspicuous, due to their larger size and widespread distribution. Therefore, they receive the most attention in connection with supply, maintenance, visibility, and mobility of troops.

Clothing perhaps has the greatest personal significance to individual troops. Clothing requirements are different in a forest than in a grassland. From the comfort aspect, the protective shield of tree growth modifies the extremes of weather (temperature, precipitation, and wind) by the shading and shielding effect. It also reduces "windchill". However, certain plants are sources of danger themselves, and require protective clothing. Examples are toxic plants such as poison oak, and thorny plants such as cactus. Another danger in forests is from falling limbs.

Plants can also provide a source of food in a theatre of operations, either as cultivated crops or wild plants. When precautions are taken, they may reduce the demands on normal supply lines or supplement survival diets in emergencies. However, considerable local knowledge is essential to prevent undesirable consequences.

Field expedients derived from local plants also may supplement construction supplies. Logs and timber may be used for construction of shelter, fortifications, bridges, and roadways. Similarly, firewood can supplement liquid fuel supplies in emergencies. Effects on ordnance are more indirect. Overhanging vegetation near artillery emplacements can produce premature bursts. Also, the use of incendiary projectiles or flame throwers must consider the consequences on friendly troops in areas of highly flammable vegetation. Maintenance problems can be either increased or reduced, depending upon the type of vegetation present. Clothing and equipage, as well as vehicle tires, suffer excessive wear and tear in the vicinity of thorny plants. On the other hand, the storage of temperature-sensitive materiel is aided by the protection of forested areas, which reduce the range of extreme heat or cold. Danger from accidental fire in forest or grass must be considered at all times. Mobility—by wheeled or tracked vehicles, by air, and by foot—has various levels of limitation due to vegetation. Shrubs and grass may obscure dangerous rocks, ditches, or bogs. Dense thickets of plants may prevent adequate penetration by dismounted troops, while stands of trees may seriously impede vehicular maneuvers even when fairly open. Knowledge of the vegetation types is needed to determine the relative ease of removal of these obstacles. In some cases, clearing an area of trees may result in raising the water table sufficiently to create a swamp within a few weeks. Aquatic plants such as water hyacinth may have grown so thickly on lakes as to impede passage of boats and stall motors.

Certain agricultural practices, such as inundated rice paddies, create difficult terrain mobility over extensive areas. Even helicopters are limited by tall vegetation and require some vegetation removal in order to land. The consideration of airborne drop zones must include the nature of the local vegetation. The vegetation affects both the effectiveness of personnel dropped by parachute as well as the impact of free-fall materiel packs. Amphibious landings encounter problems with plants even before land is reached. Certain coastlines have extensive kelp patches off shore, which impede navigation. Low tide may expose slippery areas of sea weed, with uncertain footing. Mangrove swamps may limit landing attempts.

Visibility problems frequently arise in areas of dense, tall vegetation. Some grasses may grow well over the height of a tall man. Some investigations into the distances at which objects can be detected in a variety of forest types have been made. Two types of problems are involved; detection of enemy, and camouflage of friendly troops. Great variation exists in lighting, line of sight, and coloration–depending upon species of plants, growing condition, and time of year. In some instances, visibility can be improved by climbing tall trees for scouting and reconnaissance. Leafy branches, clumps of grass, and other bits of vegetation have been used throughout history for military camouflage. However, the color changes of foliage during the growing season can direct attention to the camouflage. It is well to know the length of time such material is usable. Some species retain their color much longer than others, particularly those with thick, leathery leaves.

Recently, herbicides or "weed killers" have been used for two purposes. In some cases wild vegetation is killed so that the plants thus defoliated are not effective screening material. In other cases the enemy crops are attacked to disrupt the food supply. Effectiveness of these techniques has not yet been evaluated sufficiently.

13-6.5 DESIGN

The designer of equipment and materiel should consider various effects of the vegetation in the area where use is intended. In some cases this effect may be insignificant, in others very important. For example, clothing for jungle troops emphasizes lightweight materials because of the high temperatures. However, many plants in these areas possess abundant thorns and spines. Therefore, a fairly resistant clothing material is desirable to protect from lacerations, which can serve as infection points.

The "layer principle" of removable outer clothing has proved to be of value in cold climates. The principle can apply also for adaptations to vegetational effects. Since plant cover often is highly variable in type and distribution over an area, troops must be able to adapt rapidly. This is especially important in mountainous areas. One consideration is color of vegetation. Reversible or color-combination layers can provide varied camouflage potentials quickly. Also, protection from vegetation, either because of toxicity or sharpness, can be countered by a protective layer of permeable but tough material.

Designers of vehicles must consider vegetation. Rubber tires can be lacerated or worn out prematurely by excessive contact with desert thorns. The burned or broken-off stems of chaparral brushfields pose a similar threat. Greater demands for vehicular mobility make it important to provide tools for the rapid removal of vegetation. Fire is one way, but it is unpredictable and potentially dangerous to friendly troops. Chemical weed killers usually are harmless to human beings, but are slower acting and depend upon the weather and growth state of plants. Mechanical methods of vegetation manipulation have improved greatly in recent times. The gasoline-powered chain saw permits rapid felling and dismemberment of the largest trees. Smaller circular saws quickly "mow down" small thickets of saplings and brush. Special attachments on bulldozer blades have been designed for clearing forested areas. These permit more flexibility in the use of armored vehicles.

13-6.6 SIMULATION AND TESTING

It is difficult if not impossible to simulate vegetational influences in any meaningful manner. Plants exert their influences primarily as large groups, and synergistically with associated terrain features and climatic elements. Therefore, laboratory testing for these influences are of dubious value. Controlled environment chambers of the "phytotron" type, which are used for plant growth studies, may be enlarged or expanded to provide effective living replicas of various vegetational microenvironments for test purposes.

General vegetational properties can be predicted for given areas of land, but great differences in microsite can exist within short distances. The character of each microenvironment determines the conditions under which personnel and equipment must function. However, unless troops are completely immobilized, these conditions usually change from place to place, and diurnally and seasonally as well.

Field tests can be of extreme value if certain criteria are met. Some of the basic considerations of testing under extreme conditions are contained in MIL-STD-210 (Ref. 44). The problems of field testing, however, are insidious. Superficially similar field areas can be sufficiently different to negate the value of comparison tests. A single test can be carried out under conditions not representative of the area. Therefore, repetitive tests are essential.

Furthermore, standardized procedures must be followed specifically. Whether the test conditions met the planned objectives is not as important as knowing what conditions did prevail while testing. With repetitive testing, the aberrant tests are identified. Such data also provide a broader statistical base for establishment of prediction schedules of performance within the limits of acceptable risk.

In this regard, AR 70-38 establishes broad guidelines for extreme environmental categories (Ref. 45). These are described in Table 13-5. Almost all the parameters considered heretofore have been climatic. This has led to the expansion of the climatic analog concept. Nearly all of the land surface of the earth has been categorized and compared with certain test sites that, theoretically, allow performance testing of equipment corresponding to the climate anywhere in the world.

It is useful to examine the eight broad climatic categories in AR 70-38 with vegetational distribution. Category 8 (extreme cold) shows a geographic distribution comparable to the ice and tundra regions, plus the boreal larch of eastern Siberia. Category 7 (cold) has a southern boundary similar to that of the boreal forest. The intermediate zones (Categories 5 and 6) are characteristically complex, and include the various temperate climate vegetation types of mixed and deciduous forests, grasslands, and semidesert scrub vegetation.

The hotter climatic categories show closer similarity with vegetation boundaries. The nonseasonal wet-warm region (Category 1) coincides with the tropical rain forest. The wet-hot climate (Category 2) applies to regions that also experience seasonal dry spells such that the vegetation is more complex. In Africa and South America this area contains broadleaf tree savannas. In

TABLE 13-5

CLIMATIC CATEGORIES (Ref. 45)

Type	Description
1. Wet-warm	Typified by conditions under the canopy of heavily forested tropical areas with temperatures very close to 75°F, a relative humidity above 95 percent, and negligible solar radiation
2. Wet-hot	Typified by open tropical areas with wet-hot conditions occurring frequently or seasonably. Temperatures range from 78° to 95°F, relative humidity from 74 to 100 percent, and solar radiation can be intense.
3. Humid-hot coastal desert	Typified by coastal regions around water bodies with high surface temperatures. Temperatures range from 85° to 100°F, humidities from 63 to 90 percent, and solar radiation can be intense.
4. Hot-dry	Desert regions with temperatures from 90° to 125°F, humidities under 20 percent, and intense solar radiation.
5. Intermediate hot-dry	Seasonal dry periods of wet-hot regions as well as large regions of the midlatitude of both hemispheres where high temperatures range from 70° to 110°F, humidities from 20 to 85 percent, and solar radiation can be intense. This climatic category may be seasonal alternating with an intermediate cold climatic.
6. Intermediate cold	This climate is found in midlatitude regions of the Northern Hemisphere where low temperatures range from -25° to -5°F, relative humidities are near 100 percent, and solar radiation is negligible.
7. Cold	Cold conditions are found only in the Northern Hemisphere where minimum temperatures range from -50° to -35°F, humidity is close to 100 percent, and solar radiation is negligible.
8. Extreme cold	This describes those arctic regions where temperatures of -70°F occur for periods of 6 hr or longer.

Australia and Central America this is the semievergreen or deciduous tropical forest zones. In Southeast Asia the monsoon forests are prominent. Both Category 3 (hot-humid coastal desert) and Category 4 (hot-dry) contain semidesert scrub. In Africa, Australia, India, and South America, this climate also includes extensive thorn tree savannas.

Thus, certain generalities apply. The general life-forms of vegetation can usually be predicted. However, the exact species present and their actual distribution on the ground is highly variable. In most cases the transitions from one type to another are gradual. Other areas contain mosaics of distinct "islands" of vegetation. More specific information is needed to relate plant characteristics to the performance of personnel, materiel, and equipment in any given part of the world.

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CHAPTER 14

MICROBIOLOGICAL ORGANISMS

14-1 INTRODUCTION AND DEFINITIONS

Microbiological organisms* constitute a more important environmental factor relative to materiel degradation than is recognized by the average design engineer. The design engineer may often accept rot, decay, corrosion, and other microbiological deterioration processes without recognizing their causes of adopting optimal preventive measures. In this chapter, microbes will be introduced to the design engineer in such a way that he can better recognize their degradative mechanisms and provide suitable preventive measures.

The degradative mechanisms associated with microbes are closely related to—often indistinguishable from—similar mechanisms discussed in other chapters of this handbook. Humidity, temperature, salt, solar radiation, and macrobiological organisms are factors that influence, accompany, or contribute to microbiological degradation processes.

Since the terminology of microbiology may be foreign to many engineers, it is necessary to provide the definitions given in Table 14-1. Note that the taxonomy of microbes lacks the precision and stability sometimes found in engineering. Distinguishing classifications of small organisms is often much more difficult than for the larger organisms, e.g., plants and animals. This chapter will not clarify these basic problems in microbiology for the engineers but will attempt to provide a semantic facility sufficient for design usage.

Information on microbes is dispersed throughout a large body of literature. Much of the information contained in this chapter is so general that specific references would be meaningless. The list of references can also be considered a bibliography that provides more information and pathways to the specific references. The references included in the text are specific to the subject discussed at the point of reference.

Those who make, store, service, test, or use military equipment and supplies are confronted with problems concerning microbiological degradation, decomposition, or corrosion. Various paragraphs in this chapter name materials that can be biodegraded, the microbes capable of such activity, the processes by which the breakdown is brought about, and the environmental conditions contributing to the decomposition. Measures are suggested to control or stop the action of the microbes concerned, and methods are listed for evaluating usefulness of treatments for resistance. Essential for biodegradation is the triangle of three components; a living organism, a susceptible substrate, and a favorable environment.

The air we breathe is filled with microbes, largely bacteria and fungus spores. Fortunately, relatively few are able to attack living cells. In the soil are found the majority of saprophytes, i.e., microbes that live on inanimate matter. When a small soil sample is floated in a drop of sterile water on a glass slide and examined under a microscope, a multitude of bacteria, fungi, and nematodes are revealed that are competing with each other for food and space.

Microbial biodeterioration is any undesirable change in the properties of a material caused by the vital activities of the microbe.

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*The terms "microbiological organism," "micro-organism," and "microbe" are synonymous. The single term "microbe" will be used hereafter in this chapter.

TABLE 14-1

GLOSSARY OF MICROBIOLOGICAL TERMS

Acetylation	The addition of an acetyl group to a compound
Actinomycetes	An order of bacteria characterized by a tendency toward branching
Aerobic	A microbe that grows only in the presence of air and uses molecular oxygen
Algae	A large informal classification of microbes, which are highly diverse with respect to habitat, size, organization, physiology, biochemistry, and reproductive processes and are closely related to plants
Aliphatic	Organic compounds with an open structure, primarily the paraffin, olefin, acetylene hydrocarbons, and the derivatives of these compounds
Alkane	Saturated hydrocarbons, or those in which all carbon molecules contain the maximum number of hydrogen atoms possible
Alkenes	Hydrocarbons with two less hydrogen atoms than the corresponding alkane. They are also called the unsaturated hydrocarbons.
Anaerobic	A microbe that grows only in the absence of air or molecular oxygen
Aromatic	An organic compound that has at least one benzene or closed-ring structure
Ascomycetes	A large class of fungi that includes the yeasts
Ascospore	Sexual spore produced inside a spore case, the ascus, by certain fungi
Assimilation	To take into a cell and utilize as a carbon or energy source
Autotroph	A microbe that utilizes carbon dioxide as its principal carbon source. Usually these microbes use light or a reduced inorganic compound as the energy source.

TABLE 14-1 (Continued)

GLOSSARY OF MICROBIOLOGICAL TERMS

Bacteria	Unicellular, vegetable microbes existing as oval, spherical, rod, or comma-shaped organisms
Basidiomycetes	A large class of fungi which produces spores and includes the rusts, mushrooms, and puffballs
Binary fission	A form of reproduction in which a mother cell splits into two daughter cells
Biostat	Compound that inhibits the growth of living cells. It usually refers to an inhibitor for bacteria, fungi, yeasts, or blue-green algae.
Biodegradation	The deterioration of physical or chemical properties by the action of a microbe or other living cell
Biodeteriogens	Agents of biological deterioration
Biodeterioration	Synonymous with biodegradation
Biosphere	That volume of the earth in which living cells exist
Blue-green algae	Procaryotic photosynthetic microbes with a characteristic blue-green color which are motile and form chains and filaments
Branched chain (hydrocarbon)	A hydrocarbon that has a one-carbon branch on an interior carbon atom
Budding	To reproduce by pinching off a small part of the parent cell
Cellulose	The principal carbohydrate constitutent of the cell membranes of all plants
Cellobiose	A disaccharide formed by the partial hydrolysis of cellulose
Chromosome	Any one of the separate nuclear bodies formed during mitosis and splitting during that process. They carry the hereditary factors in each species.

TABLE 14-1 (Continued)

GLOSSARY OF MICROBIOLOGICAL TERMS

Commensal	Condition in which microbes of different species grow in more or less intimate association without harm to either and with some benefit to both
Conidia	Nonmotile reproductive spores borne directly on the hyphae.
Cytochrome	An iron-containing pigment that participates in oxidation-reduction reactions
Cytoplasm	The protoplasm of a cell that is not in the nucleus
DDT	Dichlorodiphenyltrichloroethane. This contact insecticide is believed to have many serious side effects on higher animals.
Desiccation	Removal of water
Diploid cell	A cell that bears two chromosomes of each linkage group
Dissimilation	Catabolism or destructive metabolism of a compound or substrate
DNA	Desoxyribonucleic acid, an acid occurring in the nucleus of living cells different in varying species and distinguishing normal from malignant cells. It is the genetic trait carrier in the gene.
Endospore	A dormant cell (spore) produced by two bacterial genera, <u>Bacillus</u> and <u>Clostridium</u>, which is the most resistant biological entity known to man
Enzymes	A catalytic substance formed by living cells, having a specific action in promoting a chemical change
Eucaryote	A microbe that has a true nucleus
Facultative	A microbe that can grow in the presence or absence of molecular oxygen
Flagellum	An appendage or organelle of locomotion

TABLE 14-1 (Continued)

GLOSSARY OF MICROBIOLOGICAL TERMS

Fungi	Plantlike, spore-bearing microbes that lack chlorophyll and are unable to synthesize their food
Generation time	The time required for a mother cell to divide into two daughter cells
Golgi apparatus	A cell component that plays a role in secretion of cell products. Found in eucaryotes
Halophile	"Salt loving". A microbe that grows only in high salt concentrations, often devoid of all cell walls
Haploid	A cell that carries only one chromosome of each linkage group
Heterotroph	A microbe that utilizes organic carbon as a source of protoplasmic building blocks
Hydrocarbon	A compound composed of only hydrogen and carbon atoms
Hydrophobic	Lacking in an affinity for water
Hypha	A single filament of a mold or actinomycete mycelium
Lignin	A polymer found in wood (25-30%). Structurally, aromatic alcohols similar to coniferyl alcohol
Lyophilization	The drying of a material in the frozen state under vacumn
Lyse or lysis	Dissolution of a cell by disintegration. Results from breaking of the cell wall
Mesophile	A microbe whose optimal temperature for growth is moderate (22° to 44°C)
Mesosome	Invagination of cell membrane into the cytoplasm of bacteria which functions in oxidative metabolism and cell division
Microbe	An organism of microscopic or ultramicroscopic size. Generally a procaryote. Synonymous with micro-organism

TABLE 14-1 (Continued)

GLOSSARY OF MICROBIOLOGICAL TERMS

Micro-organism	An individual living organism which is so small as to require a microscope for observation.
Mitochondria	Cell structure in eucaryotes concerned with oxidative metabolism
Mineralize	Totally degrade a substrate. Results in virtual absence of organic byproducts
Mold	Used synonymously with fungi but primarily those fungi that form slimy or cottony growths on foodstuffs and leather
Mycelium	Mass of hyphae
Nematodes	A class of bilateral symmetrical true roundworms
Oomycetes	A class of filamentary or unicellular fungi important in agriculture and living in water, soil, or seed plants
Oxygenase	An enzyme that incorporates oxygen into a compound
PCB	Polychlorinated biphenyl and pesticide that is potentially toxic to higher animals
Photolysis	Chemical decomposition using light energy. Generally refers to splitting of H_2O during photosynthesis
Phospholipid	A polar lipid molecule containing glycerol, fatty acids, phosphate and usually another derivative, e.g., serine, inositol, propyl amine, etc.
Photosynthesis	Process whereby light is used as energy for growth
Phycology	The study of algae
Polymer	A chemical compound formed by polymerization (combining of small molecules) and consisting mainly of repeating structural units
Polysaccharide	A polymer consisting of sugar residues

TABLE 14-1 (Continued)

GLOSSARY OF MICROBIOLOGICAL TERMS

Procaryote	A microbe with little cell organization with a primitive nuclear membrane
Protists	Organisms that do not have any extensive development of tissue, that is, systems of distinctive cell types performing different functions
Psychrophile	An organism that grows best at cold temperatures (2° to 10°C)
Respiration	Oxidation of a chemical compound by an organism resulting in the release of energy. Aerobic: the electron acceptor is molecular oxygen. Anaerobic: the electron acceptor is an inorganic substance (SO_4^-, NO_3^-) other than oxygen.
RNA	Ribonucleic acid, an acid found in both the cytoplasm and the nucleus of plant and animal cells
Saprophyte	An organism that obtains its nutrients from dead organic matter
Slime molds	A group of organisms characterized by the formation of a highly organized structure through the cooperative action of a large number of individual cells and involved in protein synthesis
Substrate	A chemical compound that undergoes a chemical change due to enzyme activity. Usually refers to the source of building blocks (carbons) provided in a growth medium
Taxonomy	Orderly classification of plants and animals according to their presumed natural relationships
Yeasts	Various unicellular fungi species that are rich in water soluble vitamins and are capable of fermenting sugars
Zygomycetes	A class of fungi characterized by sexual reproduction through the union of two similar gametes

Microbes can mineralize all natural products and, as a consequence, microbes with degradative abilities are widespread in the biosphere. Biodegradation or mineralization are not the only forms of damage to material that can result from microbial growth. Pipes may be clogged by the growth of manganese-oxidizing microbes, and the lubricating grease in moving parts of sensitive instruments may be assimilated by microbes, thus causing excessive wear or corrosion. Excretory products of a microbe's metabolic activities may cause corrosion of metallic surfaces, and optical equipment can be damaged by growth of algae or fungi on the surface of glass or glass coatings.

Moisture is the critical growth factor for microbes within their most important temperature range. To prevent such growth, materials must be kept dry, i.e., below 10 percent in moisture content. Consequently, it should be remembered that warm air absorbs water, which condenses as dew on exposed surfaces when the air cools. This water film permits spores to germinate, microbes to grow, and materials to degrade.

Microbes that degrade materials exist in all phases of the environment; water, soil, and air. The water may be hot or cold, fresh or saline, "pure" or with a high osmotic concentration, e.g., osmophilic yeasts live in sugar concentrations that would cause the collapse of ordinary cells by water withdrawal. Soil may be coarse or fine, alkaline or acidic, inorganic or organic: it will still harbor biodeteriogens. Whether the air is low or high in oxygen, a jet stream, or a smog or fog, microbes are found in it.

The biosphere is composed of three distinct systems—plant, animal, and microbial. The microbial biomass on earth is quantitatively equivalent to the total combined biomass of plants and animals. Microbes and their activities are indispensable elements in the biosphere. The role of the microbe in the evolution and continuation of all life on earth can be briefly summarized as follows:

(1) The energy on earth comes from the sun.

(2) This energy is used in photolysis of matter and the incorporation of carbon dioxide into plant material.

(3) Plant material is directly or indirectly the source of energy and food for animal life.

(4) The accumulated products of living systems (animal waste, dead plants, and dead animals) are mineralized by microbes, and their constituents are returned to the biosphere. Since the carbon dioxide in the atmosphere would be depleted in 30 yr at the present rates of photosynthesis and metabolism, the constant replenishment of carbon dioxide is essential. Since over 80 percent of the carbon dioxide released into the biosphere each year comes from microbial degradation, biodegradation (biodeterioration) is one of nature's way of balancing the elements of life.

The microbe is the major agent of total biodegradation, and microbe species have evolved that attack all naturally occurring compounds. To prevent biodegradation of materials of value, the normal degradative processes must be impeded. Although microbes can also biodegrade many synthetic materials, the manufacture and dissemination of many other nonbiodegradable products has led to ecological problems. Examples are certain plastics (polypropylene, nylon, polyethylene), dischlorodiphenyltrichloroethane (DDT), polychlorinated biphenyl (PCB), and methyl mercury.

14-2 THE MICROBIAL ENVIRONMENT

In order to describe the microbial environment, it is necessary to first identify its inhabitants, then to describe their life habits, and last, to discuss their distribution. These subjects are discussed in this paragraph by major groups, and a general discussion on growth is included.

14-2.1 MICROBIAL SPECIES

The biological kingdom known as Protista includes those microbes that lack an extensive development of tissues, i.e., systems of distinctive cell types performing different functions. It includes all microbes as well as some larger organisms such as seaweed (algae). The protists are divided into two large groups based on different structures in the cell nucleus. In the lower protists, the cell nucleus is not enclosed in a membrane but rather is in direct contact with the cytoplasm. Such cells are termed procaryotic, and the lower protists characterized by these cells include bacteria and the blue-green algae (Ref. 1).

The higher protists are characterizied by eucaryotic cells wherein the nucleus is contained in a membrane. These include the fungi, protozoa, and algae except for the blue-green algae. Plants and animals are also classified as eucaryotes (but not protists).

14-2.1.1 LOWER PROTISTS (PROCARYOTES)

All procaryotes are exceedingly small. One bacterium on the average weighs 10^{-12} g and is about 1 μm in diameter. Although some procaryotes (blue-green algae) exist as long chains, the diameter of the filament rarely exceeds 1.5 to 2.0 μm. Since all microbes are 70 to 85 percent water, the dry matter in a bacterial cell is a little over 1 pg. When bacteria grow in a clear liquid medium, at least 1,000,000 bacteria per milliliter must be present before any turbidity is evident.

Bacteria, like fungi, are without chlorophyll but are less complex than fungi. They are usually unicellular and are disseminated or scattered in air or water currents, but some are self-motile. Many bacteria secrete a gelatinous covering or sheath of polysaccharide material about themselves for ease of movement (zooglea) or for protection against unfavorable climate or environment (capsule). When active, they synthesize and excrete abundant enzymes that induce transformation of materials into forms that the cell or thallus can absorb through its cell wall. The enzyme systems of most bacteria cannot tolerate alkalinity above pH 8.5. Yet, one has been found that can grow at pH 11.0 and metabolize inorganic nitrogen and organic carbon.

Multiplication occurs by simple division (fission or splitting) of each cell into two cells at intervals as short as 15 min. This rapid geometric division results in large populations in a short time when the environment including food supply is optimal. The bacterial cell also can undergo structural changes that convert it into a spore, which can survive heat or drying for many years. Bacteria readily adapt themselves to new environmental conditions.

Bacteria are present in soil, water, air, animals, and plants. They are more universal than fungi because they can survive greater extremes of environment. Normally, bacteria are less sensitive to temperature. Growing temperatures have been reported from 27° to 167°F. While the majority grow best at pH 6.0 to 8.0, some remain alive in 12 percent sulfuric acid solution.

While organic carbon compounds are chiefly used by bacteria as energy sources, others can use carbon dioxide. Some bacteria can "fix" nitrogen from the air while others release it or transform it into nitrites, nitrates, ammonia, or complex organic substances. Aerobic bacteria must have free molecular oxygen, anaerobic bacteria cannot exist in the presence of free oxygen, and others can adjust their life processes to the amount of oxygen present. Bacteria can combine oxygen with ammonia and with some sulfur and iron compounds to obtain energy for their metabolism.

The basic difference between species in the classification of procaryotic microbes is in function rather than structure. Metabolic diversity in these microbes is apparently unlimited and the number of cell structures observed in the microbial world is small. Rods of various lengths, cocci, spirals, and chain-forming structures are generally all that are observed. Some bacteria are motile by the use of whip-like appendages called flagella, or they may utilize an axial filament connected to the poles of rod-shaped organisms for movement. Movement is in a corkscrew motion by contraction and relaxation of the filament.

A bacterial cell has little internal organization. A nuclear area in the cell is unbound by a membrane. Extensions of the cell membrane called mesosomes appear as invaginations within the cell and are involved in the oxidative and metabolic activities of the cell. Around the cell membrane is the cell wall. The cell wall is inert metabolically and serves mainly to keep the cell intact in the osmotically unfavorable environment in which most microbes live. Bacteria often contain intracellular storage granules that differ in composition; e.g., sulfur-utilizing bacteria contain sulfur granules. In come instances fats or inorganics are stored in vacuoles in the cell.

The usual method for rendering the minute procaryotic cell visible under the microscope is by staining with a dye. The Gram stain is the technique most often used in coloring the bacterial cell. In this method cells are described as gram-positive, those retaining the primary stain (crystal violet) on washing with ethanol; or gram-negative, those that are decolorized by the alcohol wash. Vital stains, those that stain only living cells, are often used to determine whether the cells observed under the microscope are viable.

The elemental composition of microbial cells reflects both the composition of bacterial protoplasm and that of accessory materials such as stored polysaccharides or fats. A bacterial cell is about 50 percent carbon, 12 percent nitrogen, 3 percent phosphorus, 10 percent hydrogen (as water), 20 percent oxygen, and the remainder ash. The ash generally contains those anions and cations required for microbial growth. For the most part, all living cells have the same biochemical composition. The eucaryotes have more elaborate phospholipids, cerebrosides, sterols, etc., but the composition of proteins–nucleic acids and most lipid material–is similar in all living tissue. Bacteria contain the B vitamin complex (thiamine, riboflavin, biotin, etc.) and the amino acids (glutamate, aspartate, alanine, etc.) associated with all cells. Bacteria are the only living entities that can synthesize vitamin B_{12}. The bacterial DNA is made up of the same four nucleic acid bases (adenine, guanine, cytosine, thymine) and RNA, the same bases (adenine, guanine, cytosine, and uracil) as found in all cells from viruses to man.

Bacteria form endospores that survive boiling, desiccation, and other physical factors that destroy all other forms of life. Different species of this group can use a considerable range of simple organic compounds as carbon and energy sources. These microbes are important in spoilage of food, cane sugar, and any materials containing available substrate. The capacity to form spores allows bacteria to survive in most environments where they can subsequently grow and cause biodeterioration. This is particularly true if moisture is available.

The aerobic *Pseudomonads* are a bacterial genus of widespread occurrence whose only metabolic process is the respiration of organic compounds. Some microbes in the genus have a fantastic ability to use a broad spectrum of substrates as sources of carbon and energy. A single species among the *Pseudomonads* can degrade and grow on well over 100 separate compounds of diverse structure. These microbes are important agents in degrading a wide variety of substrates. Many *Pseudomonads* grow on hydrocarbons and cause corrosion in fuel· tanks and fouling of fuel lines in equipment that uses petroleum.

Blue-green algae are procaryotes of widespread occurrence in soil and water. The limiting factor in their growth is the supply of nitrogen. These microbes can cause fouling both in water and on material where water accumulates. They will also grow readily in untreated drinking water. Blue-green algae grow on painted surfaces in humid climates and the organic mass produced can provide a substrate for microbes active in corrosion. Often blue-green algae and fungi grow in a loose relationship or can establish a commensal relationship as observed in lichens (Ref. 2).

Actinomycetes are a large class of procaryotes closely related to bacteria and grow on a wide variety of substrates including fuel oil. They can be the causative agent of biodeterioration of natural fibers and foodstuff. The musty odor of the metabolic products of these microbes can cause difficulty. This is particularly so in drinking water and stored fiber where the objectionable aroma can cause significant loss of material (Ref. 3). Reproduction in blue-green algae is more sophisticated than the simple binary fission of bacteria, but the overall process is equivalent. The cell division in Actinomycetes, however, is more complex, and fruiting bodies are formed that bear reproductive bodies called conidia. One genus of Actinomycetes, Actinoplanes, actually produces spores within sporangia and has evolved reproductive mechanisms markedly similar to those in the lower fungi.

Actinomycetes cause disease in animals and plants, break down plant and animal residues, and inhibit the growth of bacteria and fungi. Of greatest recent interest has been the discovery that they synthesize antibiotic substances useful as chemotherapeutic agents for the treatment of disease of man, animals, and plants.

14-2.1.2 HIGHER PROTISTS (EUCARYOTES)*

The higher protists include the fungi, the algae, except for the blue-green group, the Protozoa, and the slime molds. Well-known microbes such as mushrooms, yeasts, and most molds are fungi. Fungi do not photosynthesize and are typically organisms of decay.

Fungi do not have leaves, stems, or roots and lack chlorophyll. The body of a fungus may be a single cell (yeast) or hyphal filaments that transform or assimilate external materials. Usually, the individual colony consists of mycelium, which is a mass of intertwined hyphal threads. The asexual reproductive bodies of fungi are called spores. They may be transparent or colored and one fungal colony may produce a few, thousands, or millions of spores. Spores are readily disseminated in nature and, like bacteria, are present in virtually all environments. Since microbial presence can be presumed, growth is determined by the availability of moisture and food under suitable conditions, rather than by the confirmed presence of the fungal type. The primary necessity for germination and outgrowth is a source of water. Usually, a film of water is required, but some spores can absorb water for germination from the atmosphere if the relative humidity is over 90 percent. Toxic substances will inhibit the activation of spores, as will insufficient oxygen or the absence of carbon dioxide.

A vast array of substances can be altered or biodegraded by the life activities of eucaryotic microbes. An estimated 100,000 plus fungal species are present on earth. They are found at the polar ice caps, at hot springs, in tropical rain forests, in deserts, in the upper air, and in both fresh and salt water.

The living fungal cell has a more complex cell structure than the bacteria. Fungal hyphae are from 2 to 10 times the width of bacterial cells (2 to 20 μm). Fungi have a membrane-bound nucleus, more compartmentalization, and more differentiation than found in the primitive procaryotes. Chemically, they are similar to bacterial cells except that they contain cellulose and chitin. Fungi also produce sterols and other cellular constituents not found in the procaryotes.

The substrate requirements for fungal growth are relatively simple. Glucose, sucrose, and maltose are suitable carbon and energy sources for fungi. Some grow on more complex materials such as cellulose and starch. These microbes are not limited to the utilization of carbohydrates, however, and effectively degrade fuel oil, proteins, many fibers, and some plastics. Some are obligate plant or animal parasites. Fungi have the same trace element requirements as bacteria and can use both inorganic and organic nitrogen. All require some form of organic carbon for growth.

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*General references for this paragraph are Refs. 2 and 4 through 12.

Some fungi will grow at 0°C and cause spoilage of stored meat and vegetables. Thermophilic fungi grow at 65°C but the optimal temperature range for most species is 22° to 30°C. The pH range of growth is 2.0 to 9.0 with an optimum on the acid side at 5.5 to 6.0.

Fungi are more readily observed without staining than are bacteria, and cultures that form fruiting bodies are more distinct in appearance. Colonial morphology, pigmentation, and behavior are so distinct that many experts can identify fungi by visual observation. The fruiting bodies of fungi are so characteristic that identification to genus level can often be made from this structure. Yeasts have less variation in colonial features and are more often identified by a combination of structure and metabolic activities. Most yeasts reproduce by budding and some have mycelial stages or can be induced metabolically to form mycelia.

Fungi are very important members of the biosphere. They are of significance in maintaining soil fertility and biodegrading wastes in nature. They are useful in industrial processes; e.g., bread, wine, beer, and cheese production. Cacao beans are rendered useful as food by growth of fungi on the beans and many fermented foods are the products of fungal metabolism. Fungi are useful in the production of organic acids, vitamins, and antibiotics. These microbes are a major agent in biodeterioration. They attack most organic matter such as food, fabric, leather, wood, and nearly all consumer goods.

Among the more important groups of fungi are:

(1) Oomycetes, the water molds, have well-developed mycelium and cause mildew in grapes and potatoes and diseases of fish and fish eggs.

(2) Zygomycetes are saprobes (living on dead matter) or parasites and have sexual reproduction. These microbes are the causative agents of bread mold and of rot in fruits and vegetables. Microbes in this group produce copious quantities of organic acid.

(3) Ascomycetes are fungi that form spores, resulting from meiosis inside a special sac called an ascus. Many of the fungi in this group are cellulytic and are a major cause of cellulose fiber degradation. Ascomycetes cause mildew and brown rot. In this group are the causative agents of corn ear rot, Dutch elm disease, and vascular plant parasites. One microbe in this group can grow on rye and produce alkaloids that are exceedingly dangerous to man and animals. Several ascomycetous yeasts are of benefit to man in the production of bread, wine, and food yeasts, and in the fermentation of cacao beans.

(4) The molds include the black molds that biodeteriorate foodstuffs, leather, and cloth fibers and can impart a musty odor to such materials. The green molds destroy citrus fruits, jellies, and preserves. Others in this group destroy foods and stain lumber as well as cause several diseases in commercial crops.

(5) Basidomycetes form sexual spores that develop on the surface of special structures called basidia. In this group are smuts, rusts, jelly fungi, mushrooms, puffballs, and stinkhorns. The bracket fungi that grow on living trees and lumber are included in this class.

The rusts cause great economic losses in cereal crops, coffee, beans, and other foodstuffs. Many species in this group grow on and destroy lumber. The polypores are the wood rotters for which most preservatives are employed. Among the basidomycetes are the mushrooms, which are utilized as food.

(6) Deuteromycetes are called the imperfect fungi because they reproduce asexually. They resemble the ascomycetes and basidiomycetes and are of economic importance as causative agents of plant disease. Microbes that cause pink rot are found in this group. Many destroy foods that contain lactic acid; e.g., pickles, sauerkraut, summer sausage, cheese, and other dairy products. Several can destroy ripe fruits and vegetables.

The algae are the most important producers in water, carrying out the photosynthesis that gives them color. They are also prolific but less evident on land. The colors of algae provide a basis for subclassification; green, yellow, brown, and red algae are groups of species. Motile algae possess flagella, which are appendages employed for propulsion. Algae provide the basic food for aquatic life and are used for human and animal food, fertilizer, and chemicals. Algae blooms can also clog waterways and destroy aquatic life (Ref. 2). Protozoa are eucaryotes, which include an enormously complex and heterogeneous group of microbes, including the amoeba. Slime molds are a group of eucaryotic microbes whose outstanding characteristic is a unique life cycle that involves the formation of a complex and highly organized structure through the cooperative action of a large number of individual cells. Algae, protozoa, and slime molds are relatively unimportant in materiel deterioration considerations (Ref. 1).

14-2.2 MICROBIAL GROWTH

A great diversity of metabolic types prevail in the microbes present in the environment. Generally, microbes can perform all the metabolic reactions found in higher plants and animals plus many unique ones. The residue of living microbial, plant, or animal cells do not accumulate on earth, due to the ability of the microbe to biodegrade and mineralize all components of living cells. The fact that the biological productivity of the oceans–about 30 billion metric tons per year–is biodegraded without any significant accumulation gives some idea of the numbers and biodegradative capacities of the microbe. An estimated 15 to 20 percent of the protoplasm on earth is animal, 30 to 35 percent is plant, but 50 percent is microbial, giving some idea as to the ubiquity and diversity of microbial types on earth. It also helps explain why anything that can be degraded by the microbe, if left unprotected, is rapidly utilized as a substrate. Every gram of fertile soil contains between 10^6 and 10^9 microbes and these numbers extend down 1 to 3 ft into the soil. Plants and animals are covered with millions of microbes. The rumen of a ruminant (cow, deer, sheep, camel) contains a mass of microbes that degrades the plant diet to a form that can be utilized by the animal. The digestive tract of a warmblooded animal contains great quantities of microbes, and an estimated 70 percent of feces are microbes (Refs. 13,14).

The growth rate of microbes in nature varies to a considerable extent. The major factor is the food supply, which provides carbon building blocks and energy. The generation time (division time) for microbes ranges from 15 to 20 min in some bacteria to several hours in fungi and blue-green algae. Even those microbes with a relatively extended generation time can achieve massive amounts of growth, under favorable conditions, in a few days.

While microbes utilize a wide array of energy and carbon sources, their metabolism is markedly different from animals in one important aspect. Whereas animals utilize food for both growth and energy, microbes often utilize separate sources for carbon and energy. Some microbes resemble green plants in utilizing light for energy and carbon dioxide for carbon.

Bacteria are divided into two groups based on nutrition: (1) autotrophs, which utilize inorganics or light as sources of energy and, generally, carbon dioxide as a source of carbon and (2) heterotrophs, which utilize preformed organic compounds for both carbon and energy. Autotrophs can metabolize hydrogen, reduced sulfur, reduced nitrogen, ferrous iron, and manganese or use light as a source of energy. The nitrifying and sulfur bacteria are exceedingly important in the biological life cycle. These microbes absorb reduced sulfur and nitrogen products from living cells and oxidize them to nitrate and sulfate, which are the forms required by plants. Most mineralization and biodegradation are accomplished by the heterotrophic bacteria.

All microbes, whether heterotrophs or

autotrophs, require various cations and anions including phosphorus, potassium, magnesium, calcium, boron, manganese, iron, zinc, molybdenum, and copper. Since traces of these are available in most of the enviromental niches in which microbes exist, the limiting growth factor for microbes is usually the supply of the three basic components of cells: carbon, nitrogen, and phosphorus.

Temperature has an important influence on the types of microbes that survive in an ecological niche. Microbes can grow over a wide temperature range and are generally classified as follows: psychrophiles, 0° to 15°C; mesophiles, 20° to 45°C; and thermophiles, from 50°C to the temperature of boiling water in hot springs. Some mesophiles will grow at lower or higher temperatures, but, generally, the growth of any of the three types is restricted to the temperatures given.

Microbes will grow in environments over a wide range of acidity or alkalinity. Sulfur bacteria will grow in sulfuric acid at a pH near 0 while urea bacteria will grow at a pH of 12. Most bacteria prefer a pH between 5.5 and 7.5.

Osmotic pressure of the solute is also an important factor in survival of bacteria. Most microbes grow best in a solute that has an osmotic pressure near that of physiological saline solution. However, some microbes are obligate halophiles and grow only in salt concentrations such as are found in the Dead Sea, in Great Salt Lake, or in salt brines. These microbes lack a rigid cell wall and lyse when exposed to lowered osmotic pressures. The ability of microbes to survive in distilled water or water with a low osmotic measure varies greatly, but this is primarily species related.

All microbes require moisture for growth and reproduction and do not grow well if the moisture content of the substrate falls below 12 to 15 percent. However, endospores and other resistant bodies formed by microbes can survive desiccation and remain viable after extended periods of dryness.

Only the fringes of the potential biosynthetic capabilities of fungi are known because: (1) a tremendous number of varieties and strains of fungi exist, (2) thorough biochemical study of a single species usually reveals its ability to synthesize a wide variety of organic compounds, and (3) few fungi have been subjected to exhaustive biochemical study (Ref. 10).

When a microbial cell divides, every one of its components is identically reproduced, and a large number of coordinated chemical reactions are linked together. The living substance is endowed with the potential of self-synthesis; the existing pattern of the present substance serving as a pattern for the new. All the properties of a cell depend upon the molecular pattern of its constituent material (Ref. 15).

For cell growth a highly complex interlocking series of reactions takes place. The cell takes in a variety of simple starting materials and combines them into many complex products. A helpful concept is that of a series of relatively simple unit processes that can easily change from one source of material to another with alternatives at various stages of the manufacturing process. Depending upon the substrate material available and physical environmental conditions, the route followed in the synthesis of cell material may vary. Hence, it can be concluded that the enzymatic constitution of the cell will vary with the conditions of growth. Bioassay largely depends upon the fact that, when growth has been long continued under standardized conditions, a steady state with constant proportions among the various enzymes will be established. It appears that critical levels of certain key substances are formed in the cell before it divides.

Since few microbes have control over their association with digestible materials, some remain dormant or die, while others oftentimes adapt after a lag period and soon grow well. This adaption of microbial growth to new substrates may be for either of two reasons:

(1) The microbe may be heterogeneous and contain cells already able to utilize the new medium. Such adapted cells would multiply selectively and soon make up the entire population.

(2) Mutations may occur continually, giving rise to cells with every conceivable type of characteristic further selected by environment exposure.

Soil is the home or habitat of the great majority (98 percent) of mold fungi. During use or storage, materials are often in contact with soil and its nature will affect the rate of rot. Physically, soils are classified into three phases: a solid, liquid, and gas.

The character of a soil is mostly determined by the solid phase or soil matrix. It is made up of mineral and organic particles whose size determines the soil texture. Soils are classified into textural groups depending upon the fractions of each texture they contain, but aggregation of soil particles must be taken into account. The amount of clay and organic colloids (particles less than 0.002 mm and 0.0002 mm, respectively) present determines the extent and type of particle grouping or aggregation, and, hence, soil structure. The organic matter content is particularly important because it absorbs water internally, breaks down rapidly, and serves as a food/energy source for microbes.

The liquid phase of the soil is spoken of as the soil solution or soil moisture. It determines the suitability of the soil for microbial growth. The soil solution comprises water, soluble salts, and dissolved gases. The amount of water that a soil retains depends on the amount of particle surface area and the quantity and the nature of the porosity of the matrix. Optimal microbe development occurs within certain soil water limits, which are measured as percent of soil or percent of dry weight.

The gas phase or soil air is constantly changing in composition and greatly influences the microbial population. The intake of oxygen used in respiration and the loss of carbon dioxide into the atmosphere are referred to as soil aeration. The composition, the volume per unit of soil, and the rate of movement of air in the soil all affect the life activities of the microbes present and consequent rate of transformation of materials. Oxygen may vary from 0 to 21 percent and carbon dioxide from 0.03 to 21 percent. Thus, microbe populations vary, depending on their oxygen requirements for respiration.

14-3 BIODEGRADATION OF MATERIALS*

The ubiquity of microbes and their metabolic versatility suggest that few materials are resistant to some form of attack or alteration by microbes. Examples of such attack include damage to concrete, bricks, electrical materials, glass, optical equipment, photographic products, fats, oils, waxes, minerals, metals, paints, petroleum fuels, oils, greases, asphalt, plastics, rubber, resins, sewage processing sludges, wool, linen, cotton, synthetic textiles, wood pulp, paper, and cork. For reference purposes, the Biodeterioration Information Center (Ref. 20) has established the subject matter categories for classification purposes given in Table 14-2.

Microbes have the capacity to alter or mineralize any organic molecule that is synthesized by living cells. Any dead plant or animal material, animal waste, or other organic matter is quickly and efficiently assimilated into biological cycles by microbes. The accumulation of carbon-containing compounds in nature is confined to a few materials, e.g., fossil fuels that are products of extreme physical conditions and are inaccessible to the microbes associated with the carbon, oxygen, and nitrogen cycles. When petroleum hydrocarbons are brought to the surface, however, a great variety of microbes present in the biosphere attack them. Although these microbes can be a problem when fuel is held in storage for any period of time, microbes capable of degrading hydrocarbons

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*General references for this paragraph are Refs. 16-19.

TABLE 14-2

CLASSIFICATION OF MATERIALS FOR BIODETERIORATION STUDIES (Ref. 20)

1. Cellulose
2. Fats, oils, and waxes
3. Foodstuffs and drugs
4. Fresh fruit and vegetables
5. Fuels and petrochemicals
6. Keratin and chitin
7. Lignin and organic sewage sludges
8. Metals
9. Paints
10. Paper and pulp
11. Stone and minerals
12. Stored products
13. Textiles; vegetable, animal, and synthetic fibers
14. Wood; trees, timber, and lumber

are an absoulte necessity for the continuation of life on earth.

The general types of microbial damage to materiel are:

(1) Mechanical damage includes corrosion of metal surfaces, destruction of insulation on electrical wires, and deterioration of lubricants.

(2) Assimilation includes eating of cellulosic materials and decomposition of foodstuffs.

(3) Excretory products corrode iron with sulfides produced by sulfate reducers and attack material with organic or inorganic acids produced by bacteria and fungi.

(4) Impairment results from clogging of iron pipes by iron bacteria and blocking of fuel lines by hydrocarbon-utilizing microbes in fuel tanks.

The destructive effects that microbes have on any material is the composite result of a great many environmental factors. Material degradation is more dependent on the accessibility of the material to attack than on the presence of microbes that can attack it since their presence can be assumed. Among the environmental and nutritional factors in microbial growth and survival are:

(1) *Temperature.* The effect of temperature on the growth and survival of microbes varies over a wide range. Although bacterial spores can survive long periods of temperatures greater than 100°C, they will not grow or thrive at such extreme temperatures. Fungi have a narrower growth range than bacteria, ranging from above freezing to 55°C, while bacteria can grow in freezing arctic water as well as in hot springs at 100°C. The major determinations to make regarding temperature are the temperature below which no growth occurs, the temperature above which no growth occurs, and the range of temperature where optimal growth rates are obtained. The temperature for most rapid and abundant growth is difficult to determine with precision because it varies with the length of the growth period used in the determination. Fungi growing at lower than optimal temperatures grow slower but attain about the same total cellular mass. Many microbes will grow faster at a temperature less than optimal if certain growth factors are present. The temperature optima for most saprophytic bacteria and fungi lie in the range 18° to 35°C. Most studies on the effects of microbes on deterioration can be carried out in this range because a multiplicity of microbes grow between these temperatures.

Most bacterial and fungal species will survive long periods of subzero temperature. If stored in a dry state, lyophilized or under glycerol, they will remain viable after years of storage at temperatures below 0°C. When microbes are thawed, considerable damage occurs to cells, and alternate freezing and thawing is lethal to many species. The effectiveness of autoclaving or pressure cooking for killing bacteria is based on the fact that moist heat is more lethal than dry heat.

(2) *Light.* Light has many effects on microbes. The photosynthetic blue-green algae and purple and green photosynthetic bacteria are obligate phototrophs, which will not grow in absence of light. Most photosynthetic microbes have a phototactic response to light. Few of these photosynthetic bacteria can grow heterotrophically, and some are actually inhibited by organic matter. The great majority of bacteria are not photosynthesizers and are adversely affected by ambient light. It is believed by some that the widespread synthesis of pigments in bacteria is a protective mechanism that filters harmful wavelengths of light from the cells. Many of these pigments are synthesized only when the microbe is grown in the light. All microbes are damaged or killed by high intensity light, particularly ultraviolet, which is commonly used as a sterilant.

Most fungi are unaffected by light although some molds fix more carbon dioxide in the light than in dark. The pigment associated with the reaction is not chlorophyll. Spore formation is adversely affected in some species by light although in other species it is stimulated. Sporophore formation in the basidiomycetes is controlled, in many cases, by the presence of light.

(3) *Oxygen.* Most microbes grow better in the presence of oxygen. Fungi generally require oxygen for growth. Some bacteria (facultatives) can grow in the absence or presence of oxygen although they grow more efficiently if oxygen is present. Some obligate anaerobes among the bacteria are killed by atmospheric oxygen. Fungi do not grow well below the surface of still water because of the limited water solubility of oxygen.

(4) *Water.* Biodeterioration by microbes is severely limited in the absence of free water. If the moisture content of a material is less than 10 percent and no moisture is available from other sources, little growth on the material will occur. When the temperature varies and moisture is present in the air, sufficient water will accumulate on surfaces for biodegradation to occur. This is particularly true in tropical areas where the relative humidity is very high during the night. Textiles and other degradable materials can endure for extended periods of time in deserts. Foodstuffs are often lyophilized (freeze

dried) or heat dried for preservation. Many bacterial and fungal spores will survive long periods of desiccation and will not grow if moisture is not available.

(5) *Acidity*. Microbes can grow over a relatively wide range of acidity or alkalinity. Fungi generally thrive at a pH of 5.5 to 6.2 but some species can grow at a pH of 2 to 9. Fungi tend to produce organic acids during growth that lower the pH of the growth medium. Bacteria grow over a wider pH range, from near 0 to 11 or more. The *Thiobacilli* that utilize reduced sulfur compounds as a source of energy produce sulfuric acid and can survive in exceedingly high levels of acid. The urea-decomposing bacilli produce copious quantities of ammonia and survive under very alkaline conditions. Rarely are conditions encountered in nature that are so extreme in either acidity or alkalinity that microbes will not grow.

(6) *Nutritional factors*. The elements necessary for the growth of microbes are carbon, hydrogen, oxygen, nitrogen, sulfur, potassium, magnesium, and phosphorus, plus small amounts of the trace elements: iron, zinc, copper, cobalt, manganese, molybdenum, and boron. Calcium is essential for bacteria and some fungi, and sodium is necessary for many microbes, including the marine forms.

All types of living cells are believed to require vitamin B group substances (folic acid, *p*-aminobenzoic acid, and cyanocobalamin whose function appears to be as components of catalytic systems) since many are part of the structure of coenzymes or precursors of enzyme systems. This reflects a fundamental similarity in basic cell processes. Presumably, they are involved in the biosynthesis of nucleic acid derivatives, which seem to govern the activities of the living cell. Studies have shown that cellulose-decomposing fungi require the biotin, even though only 0.004 μg is present per 100 ml of liquid medium.

(7) *Solute concentration*. The cells of living organisms have differentially permeable membranes through which materials in solution move at different rates. Impairment of this tendency to attain an equilibrium of dissolved substances on either side of a living cell membrane may result in osmotic pressure. As the concentration of soluble materials digested from the substrate increases (i.e., specific gravity), the rate of biodegradation diminishes. Some microbes are very sensitive to the effect of osmotic concentration (i.e., inhibited at low soluble salt content), while others (e.g., yeasts) are osmophilic and can grow in or on substrates of extremely high salt or sugar concentration. In fact, repeated culturing on a medium of high specific gravity may cause a permanent change in the water content of the cells.

14-3.1 METALS*

Metal corrosion can be defined as deterioration of metallic substances that results from chemical or electrochemical environmental influences. Generally, corrosion results when a metal passes from the elemental to a compound state.

A metal in contact with moisture results in a dissolution of metal at the surface and an equilibrium with the fluid medium. Two fundamental principles are involved in metal corrosion: (1) a given system (metal or products) tends to react in a way that carries the material to a lower energy level, and (2) the resulting compounds tend to dissolve and are transported from the surface. As dissolved material is removed, the solution of the surface metal continues and corrosion is the result. Because the compounds of gold are at a higher energy level than the pure metal, gold is not corroded. Other metals, however, tend to revert to a more stable state that more closely resembles that of the ore from which the metal was refined.

The corrosion of metal is an electrochemical reaction, for the most part, and ionic and electron transport processes are involved.

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*General references for this paragraph are Refs. 17, 18, 19, 21, and 22.

Several conditions must exist to have an electrochemical corrosion cell:

(1) Two sites of electrochemical reaction: one, an electron donor and the other an electron acceptor

(2) An electrical conducting path between the two corroding sites

(3) Continuous reaction between the metal and the electrolyte

(4) Metal in a higher energy state than in a dissolved form. (Most metals used in construction of materiel meet this condition.)

If the four conditions are met, the resultant spontaneous process will continue until blocked by any one or a combination of three conditions:

(1) Electrical polarization at the anodic or cathodic area

(2) Concentration of polarized material at the anodic or cathodic end

(3) Accumulation of a dense insulating product.

Microbes affect the electrochemical corrosion process and cause metal deterioration by a number of mechanisms, namely:

(1) *Excretion of corrosive materials.* The metabolic activities of microbes growing on metal coatings may convert the inert material to corrosive substances. Bacteria can produce acids, molecular oxygen, molecular hydrogen, or corrosive enzymes. Algae can grow on metal surfaces, particularly in tropical areas of high humidity. When the algae mass dies, it provides a substrate for bacterial or fungal growth. These bacteria or fungi produce substances that cause corrosion of steel, copper, aluminum, and other metals. Reduced sulfur compounds are oxidized by autotrophic bacteria with the concomitant production of sulfuric acid, which will degrade almost any metallic surface.

(2) *Surface changes on metal due to microbial growth.* The metal surface may be altered due to covering of the metal by microbial growth. Blue-green algae, which can utilize atmospheric carbon dioxide and nitrogen for cell synthesis and light as a source of energy, can grow profusely in areas where moisture accumulates on the surface of material. The surface growth affects the electrochemical potential of the metal surface while the algae form a semipermeable, semiconducting layer. The layer acts as an electrolyte, thereby producing a corrosion cell on the metal surface.

(3) *Localized blistering.* Encapsulation by microbial growth can isolate an area of the metal surface. This process can be initiated by the accumulation of a layer of inorganic or organic material on the surface. The subsequent growth of microbes under this layer creates a blister, under which a local electrochemical corrosion cell is established. This corrosion cell is unaffected by cathodic protection methods. When outside conditions are favorable, the metal surface under the blister may also become active, becoming one electrode in an electrochemical cell with the metal surface outside the blister acting as the other electrode. An example of this type of corrosion is found in an iron water pipe that is clogged by bacteria. The bacteria convert soluble ferrous salts to insoluble ferric oxide, which shields the metal surface from oxygen. Once this type of corrosion attack begins, it becomes vigorous.

(4) *Action on the metal surface by an expanding biomass.* Rapid growth of microbes underneath or within a polarizing layer can result in an expanding biomass, which produces pressure or force, in turn causing cracks, loosening, or blisters, depending on the particular structure. Microbes grow under protective coatings such as paint, rust preventives, grease, or other material. This form of metal corrosion is demonstrated by fungi that corrode aluminum coatings. Hydrocarbon-utilizing bacteria on painted pipes cause expansion, which raises the paint coating and allows corrosion.

(5) *Corrosion by microbial depolarization.* When an electrochemical corrosion cell ceases its activity, it is usually due to the formation of an electrically insulating or polarization layer on one of the electrodes. The corrosion cell will continue to operate if the insulating layer is removed. It can be removed by microbial consumption. Microbes consume the nitrates and sulfur that accumulate on corroding iron as well as gaseous products such as hydrogen or oxygen that form on the electrodes under various conditions, thus sustaining the corrosive process.

Over 80 percent of the badly pitted areas of corrosion of buried metal gas pipes has been found to result from microbial depolarization by anaerobic bacteria. Low alloy and stainless steel are corroded by depolarization due to sulfate-reducing bacteria. The casings used in oil wells are often destroyed by the action of anaerobic bacteria.

It is not now possible to predetermine the condition of metal relative to microbial depolarization. If it were, it would reduce the hazards of gas leaks and explosions that are due to corrosion of gas mains.

The microbes primarily responsible for biodeterioration of metals are the (1) aerobic microbes, (2) fungi and algae, and (3) anaerobic bacteria. Some of the general effects of microbes on metals are:

(1) *Aerobes.* The iron, sulfur, nitrogen, and heterotrophic bacteria develop conditions favorable for metal corrosion. These conditions result from either oxidation or reduction of organic or inorganic materials, producing acids or chemicals that react with metal, thus causing it to corrode.

Iron bacteria utilize reduced iron as a source of energy and, during the process of oxidation, produce insoluble iron compounds. Such reactions are typified by the chemical equation

$$4FeCO_3 + O_2 + 6H_2O \rightarrow 4Fe(OH)_3 + 4CO_2$$

Nitrogen bacteria utilize reduced nitrogen compounds as a source of energy as described by the reaction

$$2NH_4 + 5O_2 \rightarrow 2NO_3 + 4H_2O$$

All of these microbes are autotrophs, which utilize the reduced inorganic compound (Fe, S, or HN_4) as a source of energy and atmospheric carbon dioxide as a source of carbon. Generally, materials exposed to the natural environment are covered with enough dust and other airborne material to provide the remaining minerals necessary for microbial growth.

(2) *Fungi and algae.* Fungi grow on the organic contaminants present on exposed metallic surfaces. Their metabolic activities during growth result in the production of organic acids that cause metal corrosion. Often, the wood products that are used in conjunction with metals provide a growth substrate for the fungal growth.

Fungi can grow on electrical contact points causing breakdown of communication equipment. The hyphal strands contain moisture that causes degradation of electrical properties of insulators by introducing leakage paths that lower insulation resistance. When these strands bridge two dissimilar metals, they also promote galvanic corrosion.

Algae grow on any surface exposed to the air if sufficient moisture is available. They split water molecules, produce oxygen, and fix carbon dioxide to make byproducts that are utilized by bacteria and fungi.

(3) *Anaerobes.* These microbes use cathodic hydrogen for the reduction of sulfates to sulfides and the precipitation of iron from solution as ferrous sulfide. These reactions are typically summarized by

$$4Fe + 2H_2O + Na_2SO_4 + 2H_2CO_3 \rightarrow 3Fe(OH)_2 + FeS + 2NaHCO_3$$

Whenever anaerobic conditions exist, as

with buried metals, and sulfate or sulfide derivatives are present, corrosion can occur. The following metals are corroded and destroyed by such reactions: iron, cast iron, steel, stainless steel, aluminum, lead, zinc, brass, bronze, magnesium, and manganese.

Bacteria can utilize the energy gained from the oxidation of simple atoms to form a more complex chemical compound. This ability has had a great influence on the geological evolution of the earth by promoting the erosion of igneous rock and the formation of sedimentary deposits such as calcium carbonate in the sea. Microbes also play an indispensable role in the sulfur, carbon, and nitrogen cycles on the surface of the earth. The activities of microbes have resulted in the accumulation of coal, petroleum, and ore deposits.

The role of microbes in the conversion and deposition of iron ore deposits is well illustrated by the great ore fields in the Mesabi Range. These deposits in the Lake Superior region cover 5,000 to 10,000 mi^2 and are over 500 ft thick. Algae, iron bacteria, and bacilli are present in dust specimens in the ore deposits, some of which are estimated to be 0.5 to 1.5 billion yr old. Algae and bacteria were responsible for the original weathering of the rocks and solution of the iron. The utilization of this iron in solution by iron bacteria as a source of energy resulted in the eventual reprecipitation of the iron ore as it exists today.

Many present day problems are associated with solubilization of iron by microbes that are unrelated to corrosion. This occurs in acid mine drainage with a high sulfur content. Aerobic organisms that utilize reduced sulfur compounds as an energy source also can use reduced iron. The resultant oxidized iron causes fouling of streams. A similar situation occurs in pipes and water mains that are not made of cast iron. Many microbes grow in both nonmetallic and metallic pipes on the small amounts of organic matter present in the water. These microbes oxidize manganese and clog such pipes with the resulting precipitates. This is of particular significance in areas of the world that have water containing relatively high levels of manganese.

14-3.2 PETROLEUM PRODUCTS*

Hydrocarbons, in general, are naturally occurring compounds and are readily utilized by bacteria and fungi as sources of carbon and energy. Various hydrocarbons are constituent parts of plant, animal, and microbial cells with the content ranging as high as 0.1 percent of the cellular dry weight in some species of bacteria. The average in plant and animal tissue is about 0.01 percent. The bulk of the biological productivity of the ocean is calculated to be 30 billion metric tons of organic matter per year. These numbers provide an estimate that about 3 million metric tons of natural hydrocarbon are released into the ocean annually. This hydrocarbon, as well as that lost into the ocean from oil seepage and disposal, is biodegraded quickly and efficiently. This suggests that microbes that utilize hydrocarbon substrates are abundant in the environment.

In biodegradation, the hydrocarbon molecule is usually utilized completely as a source of carbon and energy. None of the original carbon skeleton remains. All of the constituent carbon molecules are bioconverted to cellular material or carbon dioxide. In some cases the hydrocarbon molecule may be partially degraded or altered in a minor way. This alteration may consist of the addition of an oxygen molecule or unsaturation of a carbon-to-carbon bond. This relatively minor attack on a hydrocarbon molecule is referred to as cooxidation.

At the present time all evidence suggests that a molecular oxygenase is involved in the initial oxidative attack on hydrocarbon substrates. One anaerobic bacterium, *Desulfovibrio desulfuricans,* has been identified in hydrocarbon degradation, but it has not been proved that the hydrocarbon is used as a source of carbon and energy. This microbe causes problems at oil well drilling sites and

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*General references for this paragraph are Refs. 23 and 24.

has been found in considerable numbers in the area of oil spills. It is possible that these bacteria can utilize hydrocarbons as a source of energy.

Hydrocarbons are classified in two broad chemical groups, aliphatics and aromatics. Among the aliphatic hydrocarbon molecules readily biodegraded are the normal alkanes, alkenes, branched alkanes and alkenes, and cycloparaffins. The gaseous alkanes–methane, ethane, propylene, propane, butane, and isobutane–are readily degraded by many microbial species. The *n*-alkanes, from pentane to the longest straight chain compounds yet synthesized, are readily utilized by microbes. The ability to grow on these substrates falls into a series of patterns. The C_{12} to C_{18} *n*-alkanes most readily serve as substrates. The gaseous alkanes–ethane, propane and *n*-butane–are utilized by most microbes that grow on C_{12} to C_{18} *n*-alkanes. The C_5 to C_{11} *n*-alkanes are not readily degraded by microbes unless they are added at very low levels. This is probably due to the fact that the hydrocarbons of this structure, being excellent lipid solvents, destroy the cellular membranes.

Alkenes are readily attacked by many microbes present in the soil. The C_4 to C_{10} alkenes are relatively more toxic than the alkanes. Alkenes are not often found in natural materials.

Cycloparaffins–cyclopentane, cyclohexane, cycloheptane, etc.–are not degraded by many microbes present in nature. On the other hand, the aromatic hydrocarbons, which are a constituent part of crude oil and many structures in living cells, are readily degraded by microbes. Some aromatics, however, are highly resistant to microbial attack and are often used as preservatives in wood and other materials. Examples are creosote, cresol, and phenol.

Branched chain hydrocarbons (isooctane) are not as readily degraded as straight chain substrates. The more branching present in a compound, the less likely that it will be degraded by microbes. This resistance to degradation can cause problems in many cases, e.g., soaps, because it is essential that such manmade products are mineralized quickly in a disposal system. Some years ago the widespread use of soft detergents with a branched alkyl chain caused problems with water supplies. The low degradability resulted in the passage of the detergent through the sewage treatment process. Upon reuse, the water foamed and had a distinct detergent taste. Substitution of *n*-alklyl chains on the hydrophic part of the detergent molecule eliminated the problem.

As previously mentioned the hydrocarbon and petrochemical degrading microbes are primarily aerobic and are present in most environments. Bacteria, fungi, and yeasts, are instrumental in degrading hydrocarbons in nature. The higher bacterial form–*Mycobacteria,* nocardial types, coryneform types, Actinomycetes, etc.–have many representative types that will actively grow on hydrocarbon substrates. Several other genera, e.g., *Pseudomonas* and *Moraxella,* can utilize these reduced compounds as a source of carbon and energy. Many yeasts are efficient utilizers of petroleum products. This is especially so for members of the genus *Candida.* The capacity to utilize hydrocarbons is also widespread in the filamentous fungi and has been demonstrated in *Penicillium, Asperigillus, Cladosporium, Cunninghanella,* and other genera.

The microbial attack on alkanes and alkenes usually occurs by one of two basic mechanisms: terminal attack, the incorporation of oxygen into the end carbon atom; and subterminal attack, the incorporation of the oxygen into the carbon atom adjacent to the end carbon. Terminal oxidation has been demonstrated in long chain ($> C_{10}$) hydrocarbons and proceeds as follows:

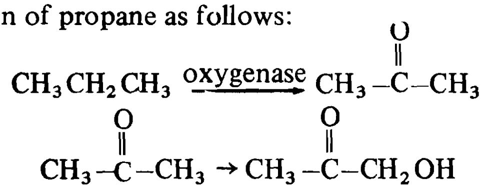
$$CH_3(CH_2)\text{–}n\text{–}CH_3 \xrightarrow{\text{oxygenase}} CH_3(CH_2)\text{–}n\text{–}CH_2OH$$

$$CH_3(CH_2)\text{–}n\text{–}CH_2OH \xrightarrow{\text{dehydrogenase}} CH_3(CH_2)\text{–}n\text{–}CHO$$

$$CH_3(CH_2)\text{–}n\text{–}CHO \xrightarrow{\text{dehydrogenase}} CH_3(CH_2)\text{–}n\text{–}COOH$$

These organic acids are further metabolized in the cell via betaoxidation whereby two carbon units (acetate) are removed at each step.

An example of subterminal oxidation in shorter chain hydrocarbons involved utilization of propane as follows:



$$CH_3CH_2CH_3 \xrightarrow{\text{oxygenase}} CH_3\text{–}\overset{\overset{O}{\|}}{C}\text{–}CH_3$$

$$CH_3\text{–}\overset{\overset{O}{\|}}{C}\text{–}CH_3 \rightarrow CH_3\text{–}\overset{\overset{O}{\|}}{C}\text{–}CH_2OH$$

The product is further metabolized to acetate and a one-carbon unit. These basic reactions for the oxidation of branched and unsaturated hydrocarbons are modified somewhat.

Numerous mechanisms have been described for the biodegradation of the vast array of aromatic petrochemicals manufactured each year. Microbial attacks on aromatic compounds are of two types. In the first, the reactions lead to ring cleavage or reactions of carbons in the ring, and the second requires attack on the side chains of the molecule. This may lead to shortening or removal of the side chain. No attempt will be made to cover the various modes of attack on aromatic compounds.

An important reaction with many hydrocarbons is cooxidation. Many petrochemical-utilizing microbes will cause alterations of substrates that they cannot use as a source of carbon or energy. It has been demonstrated that *Mycobacterium vaccae,* a microbe that will grow on a wide variety of hydrocarbons, will oxidize cyclic alkanes to cycloketones. This microbe cannot utilize cycloalkanes or cycloketones as sources of carbon or energy. The number of cycloketone utilizers in nature is much greater than the number of cycloalkane utilizers. Cooxidation may be one pathway that has evolved for the mineralization of molecules that are resistant to biodegradation. *Pseudomonas methanica* cannot utilize any source of carbon or energy except methane or methanol. However, if *n*-butane is added to a growing culture of this genus, the butane is oxidized to *n*-butanol, methyl-ethyl ketone, and *n*-butyric acid.

Bacteria and fungal spores are always present in fuel oils and other petroleum products. If temperature and humidity are favorable for microbial growth, the microbes grow quickly and cause a number of difficulties, namely:

(1) Corrosion of metal fuel tanks can be caused by thin films of microbes that grow in them and produce acidic material that corrodes the metal. Both paint corrosion and pit corrosion can occur, and the chemical reaction develops into an electrochemical corrosion process. A potential develops between the metal under the film of microbes not exposed to oxygen and the surrounding metal exposed to oxygen. This metal corrosion can cause damage to fuel tanks as well as structural damage to wings of planes. Sulfate-reducing bacteria are often introduced into the tanks of ships by the flushing and washing of tanks. If these tanks do not drain sufficiently, the microbes grow and corrode the tank metal. Often microbes grow on the plastic liner of fuel tanks. Much cooxidation by these microbes can be expected, thus changing the properties of the fuel. Also, the cooxidation by hydrocarbon utilizers in the fuel could be expected to attack the plastic material.

(2) Clogging of fuel lines can result from microbes growing at the water-fuel interface. The products of microbial growth and the cells themselves can block fuel lines and fuel pumps. Some grades of jet fuel are excellent substrates for microbial growth. Both *Mycobacteria* and *Pseudonomas* grow in kerosene but not as well in gasoline. Kerosene can absorb great quantities of moisture and hold it for a long time. When water is mixed with kerosene, the surface tension at the interface is less than with gasoline. Accordingly, colonies of bacteria and fungi can produce a biomass at this boundary more readily.

(3) Microbes can cause mechanical failure of fuel gages and of mechanical parts of fuel lines. Filters are plugged quickly by growth of microbes in petroleum.

(4) Lubricating grease in sensitive instruments is attacked by microbes, resulting in excessive wear of the mechanical parts and corrosion of the metal. The antioxidants that are added to grease usually provide a better substrate for growth of microbes than does the grease itself. There is a tremendous array of fungi (*Penicillium, Aspergillus, Chaetomium, Fusarium, Cladosporium,* etc.) that grow on grease and cause breakdown and corrosion of the machinery on which the grease is used. Cutting oils used with lathes and other shop tools have a short span of use because of fungal growth in the oil. Breakdown of the grease occurs, and odor from the growth products can be a problem.

14-3.3 PLASTICS AND SYNTHETICS*

Plastics have many uses in the production of coatings, packaging materials, water repellant and nonbiodegradable textiles, insulation, containers, and building materials. Most plastics are polymers or copolymers containing a wide assortment of benzene, toluene, and other aromatic compounds polymerized with reactive molecules like propylene, ethylene glycol, urea, formaldehyde, diisocyanate, and epichlorohydrin. In many cases the raw plastic has undesirable properties, e.g., brittleness, until a plasticizer is incorporated into the material. Among the more effective plasticizers are high boiling esters such as octyl phthalate.

Examples of widely used plastics include the bakelite resins, which are condensation products of phenol and formaldehyde; the nylons, which are polymeric products of the reaction of hexamethylenediamine and adipic acid; and polyurethanes, which are a polymer synthesized from 2,4-toluene diisocyanate and ethylene glycol. Although some plastics are synthesized from and contain some natural materials, for the most part they are synthesized by the chemical industry. These synthetic polymers have few constituents that occur in nature as part of living cells, and only a few microbes have enzyme systems capable of biodegrading plastics. This is a benefit in use but causes many disposal problems. These problems of waste disposal have become so severe, in many cases, that Federal regulation of the production of many nonbiodegradable plastics is under consideration.

The component of many plastics that is more subject to attack by microbes is the plasticizer added to the molten plastic to give it desirable qualities. When these substances are removed by microbial growth, the plastic becomes brittle. Insulation of both wire and electrical components is of little use after plasticizers are destroyed by microbes.

Nylon, Orlon*, and Dacron* are reported to lose tensile strength after attack by microbes. Although the loss in strength may be insignificant, the staining and odor problems created by microbial growth are not desirable. Many insulating materials, e.g., polyurethane and plastics, can be biodeteriorated by microbes. Synthetic textiles that are rendered water or wind resistant by coating of the fabric are also subject to microbial attack. Usually, the microbe utilizes the plasticizer and renders the material brittle and subject to cracking.

Despite the relative resistance of plastic materials to microbial attack, the effectiveness of plastics is greatly diminished by biodegradation in a number of areas. Protective packaging can be penetrated by microbes. This entry into sensitive materials is particularly rapid if the coating is composed of chloroprene or tetrafluoroethylene. Some plastic coatings, such as Mylar† and polyisophylene, are subject to penetration, particularly if pin holes are present in the material.

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*General references for this paragraph are Refs. 17, 18, and 25.

*Orlon and Dacron are trademarks of E. I. du Pont de Nemours and Co.

†Mylar is a trademark of E. I. du Pont de Nemours and Co.

Bacteria can penetrate films much more rapidly than fungi.

All unprotected plasticized vinyl systems are susceptible to microbiological attack, and none can resist deterioration by bacteria or fungi indefinitely. Fungal attack on vinyl systems can affect the material esthetically by discoloring and spotting and can destroy cellulosic components adjacent to or part of the overall system. When electrical systems are insulated with various plastics, including vinyl, fungal attack can completely destroy the dielectric properties of the material. Bacterial attack, being less spectacular, can go unobserved, although it can affect the physical properties of a system and can also create foul odors.

Often bacteria and fungi combine to cause staining of films or plastic coatings. These microbes can grow on the small amounts of organic matter that accumulate on material in tropical areas of the world. This is most prevalent when brief periods of hot and cold temperatures occur in a climate of high humidity. The water that accumulates in material provides a ready source of nutrient for the growth of microbes.

14-3.4 CELLULOSIC MATERIALS*

Some authorities estimate that cellulose makes up over 50 percent of the total organic carbon in the plant and animal biosphere. Cellulose is the simplest and most abundant cell wall polysaccharide in the plant world. Cotton is almost pure cellulose, and wood contains an average of about 50 percent of this polysaccharide. Native cotton that has not been treated mechanically or chemically is composed of long chains of linked sugars that have little cross-linkage between chains. Advanced methods have demonstrated that these chains are organized into parallel fibrils and are held together by hydrogen bonding.

Cellulose is composed entirely of the simple hexose D-glucose structure joined by other atomic groups. The molecular weight can vary from 50,000 to 500,000, corresponding to a polymer of 300 to 3,000 glucose residues. Complete hydrolysis of cellulose yields only D-glucose but partial hydrolysis will produce cellobiose.

Since glucose is probably the most abundant sugar in the environment, it is obvious that microbes capable of attacking it are abundant in nature. Indeed, glucose plays a central role in the metabolism of sugars and is a precursor for pentose, hexose, and heptulose sugars.

The basic problem in the destruction of cellulosic materials is not in the utilization of the component parts but in the breakdown of cellulose to D-glucose molecules. When unprotected cellulosic textiles are exposed to conditions favoring bacterial or fungal growth, varied resistance is encountered. It is essential for degradation that noncellulosic nutrient substances be present as impurities. This is usually true in natural fibers, but well scoured or bleached materials, not treated with microbial nutrients, are more resistant to decay. If cellulosic materials contact soil, they decay rapidly.

Cellulose degradation is caused by bacteria and fungi. Among the aerobic spore-forming microbes in soil is a group of unusually slender, flexible microbes called *Cytophaga.* These bacteria can completely destroy cellulose, such as filter paper, and convert it to a slimy pigmented mass. A feature of the growth of these bacteria on cellulose is the way in which the rod-shaped cells align themselves on the fibers; they are oriented parallel to the fibrillar substructure of the cellulose filaments. The only substrate that they can use as a carbon and energy source is cellulose. The *Cytophaga* do not secrete an extracellular hydrolase for the initial attack on cellulose; they must be in direct physical contact with cellulose to decompose it. The cellulose is probably attacked by an exocellular enzyme that is associated with the cell surface but cannot diffuse away from it as

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*General references for this paragraph are Refs. 5, 22, and 26-28.

does a true extracellular hydrolytic enzyme.

Fungi produce a complex of extracellular enzymes that degrade cotton to the basic glucose units. The combined effect of the enzyme complex is much greater than the additive effect of each.

The useful life of cellulose-containing products can be extended by a number of means. For example, keeping cellulose-containing products dry can have a considerable effect on the serviceable life of products. This is particularly true for textiles and paper.

Since most textile fibers containing cotton are exposed to moisture, it is necessary to provide other means of protection. Usually, this is done by bleaching the fabrics or otherwise treating them so as to eliminate impurities that support the growth of microbes. Chemical modification of cellulosic fibers by oxidation or acetylation leads to a fiber with a longer life. Treatment of fibers with bactericides or fungicides such as copper-8-quinolinate are effective, although many antimicrobials that remain in fabrics are so water insoluble that it is difficult to get them distributed throughout the material. Methylamine resins bind to cellulose by covalent bonding to the anhydrous glucose units of cellulose. This treatment and graft polymerization by irradiation of material with polyacrylonitrate and other monomers may extend the life of cellulose-containing materials.

The mechanisms of cellulose degradation lead to wood decay, although many cellulolytic microbes have a very limited ability to utilize the cellulose in a lignified cell wall of wood. Most must have a precellulolytic system to open up complex cell wall structures so that the cellulose is exposed to the enzymes.

The three major components of wood are cellulose, lignin, and hemicellulose. The cellulose in all plants is a polymer of D-glucose units. Hemicellulose is not structurally related to cellulose, being made up of D-xylans and other sugars. Lignin makes up approximately 25 percent of the dry weight of wood. This structural material is composed of polymerized aromatic alcohols. These three principal components of wood are degraded by many different microbes and, in general, any single microbe will attack only one of the three.

The major types of wood rot are classified as white, brown, and soft rot and can be described as follows:

(1) White rot is caused by certain Basidiomycete fungi that consume carbohydrates and lignin more or less simultaneously.

(2) Brown rot is caused by Basidiomycete fungi, which consume only the carbohydrate fraction of the wood.

(3) Soft rot is caused by Ascomycete fungi and Fungi Imperfecti, which also decompose the carbohydrate constituents of the wood.

In both brown rot and soft rot, lignin is modified and, in some cases, may be degraded. The chemical changes involved in these two types of rotting are similar but the morphological changes are quite different. The brown rot fungal hyphae grow in contact with the cell wall. The secreted enzymes diffuse into the cell and hydrolyze the carbohydrate components. The products are metabolized by the fungi. After brown rot decay, a skeleton of the wood remains that consists mostly of lignin material. In soft rot, many of the fungi penetrate inside the cell wall and develop there.

Bacteria and fungi are the major organisms that attack wood and wood products. The bacteria are relatively unimportant in terms of destruction of buildings and materials although they cause weakening of structural material. This is particularly true for pilings and other wood products that are buried in the ground.

The fungi that attack wood are sometimes divided into three groups: (1) the surface molds that cause superficial blemishes, (2) the blue-stain fungi that cause deeply penetrating stains, and (3) the wood-rotting fungi that are the major cause of damage of economic importance. The distinctions among these fungi are not significant since blue-stain fungi and surface molds can also attack solid wood and bring about soft rot.

14-3.5 PAINTS AND COATINGS

The biodegradation of paint and paint films is a major economical problem leading to the failure of materials. Both bacteria and fungi are involved in the attack on painted surfaces. Fungi are of greater importance because they are more adaptable to conditions of low moisture, sharp temperature variations, minimal nutrition, and a low pH. Paint can be disfigured by products of microbial growth and, when conditions are suitable, the painted surface will become coated with algae.

Water-based paints contain many naturally occurring compounds, e.g., cellulose and proteins, that can serve as a nutrient source for microbes. Usually, the storage conditions and the pH for paint are conducive to microbial attack, particularly in containers that have been opened and in which oxygen is available. Many forms of biological attack on water-thinned emulsion paints depend on the stabilizer used in manufacture.

Microbial contamination of paint can occur from the pigment pastes, tinting colors, wetting agents, and other additives used in the formulation of water-based emulsion paints. Usually, these ingredients are produced by different manufacturers so that the bacterial contaminants can originate in any of a number of sources. In some cases, cellulase-producing bacteria may be transferred to the paint with the additives. If the compounded paint uses methyl cellulose or carboxy methyl cellulose as a viscosity stabilizer, the cellulase can break the glycosidic bonds of the cellulolytic structure and markedly alter the viscosity of the paint.

A number of surveys have been made of the microbes present on paint films. Many are there by chance but others are present in such numbers that they obviously thrive on the film. Many of these are fungi that have been implicated in the deterioration and disfigurement of painted surfaces. The microbe found most often, *Pullularia pullulans,* is an agent for much deterioration.

Some general observations concerning the growth of fungi on paint can be made:

(1) Fungal growth is most profuse when associated with fissures in the paint films.

(2) The addition of fungal preservatives to paint reduces the growth of the fungi. Mycelial growth is more pronounced on unprotected paint films. Growth on preserved paint takes on the appearance of spore cluster.

(3) The presence of fungal growth on paint films results in a greater retention of dirt particles and organic matter. This results in more rapid growth of the fungi with accelerated deterioration and discoloration.

Biodegradation of oil or alkyd primers by bacteria has been related to the lack of adhesion between paint films and the surface. The most undesirable failure of paint is peeling, which occurs upon the loss of adhesion between the paint film and the substrate to which it has been applied. Peeling is related to several factors, including the nature of the substrate, the amount of moisture that accumulates behind and within the film, and the stress caused by several layers of paint. Large populations of bacteria are routinely found at the paint-substrate interface when peeling occurs, suggesting that biodegradation of the resinous binders of the paint film plays an important role in the loss of adhesion. The importance of insuring that paint primers are fully protected against microbial attack is suggested by studies that show that the bacterial population at paint-substrate interface of unprotected paints is up to 10,000 times that found at the interface where biocide-treated paint was used.

The resistance of paint films to the growth of microbes depends on several factors, such as the antimicrobial agent added to the paint and the nature of the raw materials used in its formulation. The more naturally occurring compounds (protein, cellulose, etc.) present in the paint, the more likely that it will be biodegraded. The antimicrobials added to paint can be placed in two categories:

(1) The microbiocides or static inorganic pigments, when added in significant concentration, can fulfill the need for pigment and antimicrobial agent at the same time. Added to the paint during manufacture, these include barium metaborate, zinc oxide, cuprous oxide, cadmium sulfate, or other materials.

(2) Organic additives, which are the larger of the two categories, are usually added at concentrations not exceeding 2 percent of the total weight and do not affect other properties of the paint.

The most frequently used organic preservatives have been the organometallic compounds such as phenyl mercury compounds, which will inhibit bacteria, fungi, and algae. One of the difficulties with these preservatives is the leaching that occurs rapidly in the hot humid climates where protection is needed most. Chlorinated phenols are also used for protecting paint films. Among these are tetrachlorophenols and pentachlorophenol. Some captans, e.g., *N*-(trichloromethylthio) phthalimide, have also been incorporated into paint. Bis(tributyltin) oxide and tributyltin linoleate are effective in preserving paints that are used in marine environments.

14-3.6 ANIMAL PRODUCTS*

Animal fibers are frequently used in the manufacture of clothing and other material. Leather has many uses—boots, shoes, straps, etc.—for which no effective substitute has yet been found. Woolen goods are particularly suited for use in colder climates. Since all animal products are composed of proteins and lipids, they are subject to rapid biodegradation if they are exposed to microbes under suitable conditions of pH, temperature, and moisture.

Both proteins and lipids serve as excellent substrates for microbial growth. The major constituents of lipids are fatty acid moieties, which are readily utilized as sources of carbon and energy. The rancidity associated with many lipid-containing materials is associated with the partial degradation by microbes of the fatty acids in lipids to shorter chain, volatile, fatty acids such as butyric acid. Lipids fall into two general overall classifications—phospholipids and the neutral lipids or glycerides. Both contain long chain fatty acids esterified to a glycerol molecule. These fatty acids are a ready source of carbon and energy for the growth of fungi and bacteria. Fatty acids are generally degraded by beta-oxidation to acetate, and those microbes utilizing these long chain substrates are growing, basically, on acetate.

Proteins are of numerous types and some are more resistant to degradation than others. Microbial proteinases range from those that attack only a few bonds of complex proteins to those with wide specificity. One proteolytic enzyme of an Actinomycete can hydrolyze over 80 percent of the peptide bonds in some protein molecules. All of the proteinases in microbes are extracellular in nature.

Proteinases cause the breakdown of large protein molecules to small peptides and free amino acids. Although these enzymes have many degradative capacities, not all proteins are readily attacked. The insoluble fibrous proteins, such as keratin, are relatively resistant to digestion. The prevalent proteins in animal fibers are keratin and collagen. Keratin makes up the outer impenetrable and tough layer while collagen makes up the inside layer which has criss-crossed peptide chains that form a feltlike mat. The keratins are high in cystine residues and are bound together into the compact hard materials of wool, hair, and skin. Collagen is high in glycine and proline residues.

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*General references for this paragraph are Refs. 17 and 29.

Most animal fibers are resistant to biodeterioration if good housekeeping practices are followed. In many cases material constructed of animal fibers is subject to biodegradation because of the exposure it has during active use. This is particularly true of leather. Major damage to leather products is caused by a wide variety of fungi. Biocides of various types have been incorporated into leather products. Among the fungicides and biocides that have been employed are copper-8-quinolinate. This compound is effective in low concentration, is relatively nontoxic, and is resistant to leaching. Among the other effective agents are *p*-nitrophenol, sodium pentachlorophenate, zinc dimethyldithiocarbamate, and lauryl pentachlorophenate.

The incorporation of biocides in the thread that contains animal fiber is also of utmost importance in the life of the product.

14-3.7 FOODSTUFFS AND DRUGS*

The materials most susceptible to biodeterioration are the foodstuffs. Virtually all food used for human consumption is a natural product; i.e., it is composed completely of chemical components that are produced in nature. Biodecomposition of all living matter, after it has attained full growth, is nature's way of replenishing the atmosphere with carbon dioxide and the soil with nitrate, sulfate, and phosphate. All foodstuff contains lipids, proteins, and carbohydrates. The amounts of these basic components in living cells differ in various foods. Meat is consumed for its lipids and proteins, many vegetables for roughage and carbohydrates, fruit for carbohydrates, and cheese for proteins. All of these provide the body with various levels of vitamins, nucleic acids, and other essential factors.

Meat, fruit, vegetables, milk, and cheese are exposed to large numbers of microbes during growth or handling. Although fresh meat is relatively sterile after slaughter, further processing into products such as hamburger results in the contamination of the product with millions of microbes per gram. Fruits and vegetables are covered with microbes at the time of harvest. Fresh milk contains billions of bacteria in every quart. If conditions are favorable, any of these foodstuffs will be destroyed by microbes in a matter of hours or days.

Some products have a natural resistance to microbial attack if they are undamaged during harvest and handling. Fruit, e.g., apples and oranges, can last a long time without decomposition, but even longer if maintained at a lower temperature. None are resistant indefinitely, however, since microbes produce pectinase that causes soft rot of the tissue. Once soft rot begins, other microbes invade and destroy the product. This also occurs with peanuts, potatoes, peaches, and other foods.

Most food products become inedible after any significant amount of biodegradation. The products of microbial metabolism on meat, fruit, and vegetables, as well as the odors of the organic acids and amines produced, are such that decomposed foodstuffs are generally unfit for human consumption. Many partially decomposed foods are unappealing but are otherwise harmless to the consumer. Some foods are potentially hazardous to health if they are contaminated with bacteria that produce toxins.

Botulism is a disease caused by a toxin produced by an anaerobic bacillus. The symptoms of botulism poisoning are difficulties in swallowing, speech, and respiration. This form of poisoning can lead to death caused by paralysis of the muscles of respiration. Botulism is caused primarily by poorly canned foods that contain little acid and are preserved in an anaerobic condition.

Another such pathogen is salmonellosis, which is caused by microbes of the genus *Salmonella*. This is usually associated with fecal contamination resulting from inadequate hand washing among food handlers. Food handlers who have chronic low level infec-

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*General references for this paragraph are Refs. 29-31.

tions should not be allowed to work with food products until they are cured. Salmonellosis is marked by abdominal pains, diarrhea, chills, fever, frequent vomiting, and prostration. The contaminated foods that cause this illness are usually inadequately cooked egg products, poultry, or similar foods.

Streptococcal food poisoning is caused by an enterococcal bacteria. The symptoms are nausea, sometimes vomiting, colicky pains, and diarrhea. This form of food poisoning is caused by inadequately refrigerated foods that are contaminated with enterococci. Carelessness by food handlers who have infected sores or pimples is most often the cause of outbreaks.

Clostridium perfringens food poisoning is caused by a gram-positive anaerobic bacillus. The symptoms are nausea, sometimes vomiting, colicky pains, and diarrhea. Poultry and meat products cooked and left unrefrigerated at a warm temperature for several hours are generally the cause of this illness.

Bacillus cereus food poisoning, which is caused by an aerobic bacillus, has symptoms resembling *Clostridium perfringens* food poisoning and is caused by inadequately refrigerated starchy foods.

Brucellosis (undulant fever) is caused by a microbe associated with a disease of cattle, goats, or swine and results from milk products or direct contact with infected animals. The disease is characterized by a long incubation period of 5 to 30 or more days, and at the onset the patient has generalized aches and pains of the muscles and joints, headaches, chills, and light fever. The disease can be controlled by insuring that products are made from pasteurized milk.

Bacillary dysentery is a bacterial disease characterized by severe dysentery, often with blood and mucus. This disease can be food borne and is one of the commonest illnesses of man. Dysentery was a major cause of sickness and loss of fighting effectiveness among troops of all nations in World War II. It is particularly prevalent in tropical countries and wherever men are crowded together in unhygienic conditions.

Other illnesses are caused by microbes in food. Many diseases not usually considered to be foodborne can be carried in this manner if proper sanitary conditions are not maintained. Among these are infectious hepatitis and similar viral diseases that are caused by contamination of food with fecal material.

Other than diseases caused by eating food that contains hazardous microbes, other potential danagers exist in eating contaminated food. Grain, peanuts, and other foods can become contaminated with aflatoxins that are produced by fungi during growth. Ergot poisoning has also been caused by production of this compound by the fungi on grain.

Some food products are more resistant to infection and biodeterioration than others. Ripe apples can be stored for long periods of time at cool temperatures while bananas deteriorate rapidly under the best of conditions. Vegetables and salad greens have little resistance to deterioration unless they are kept at a low temperature or in an atmosphere devoid of oxygen.

Many methods can be used for preserving foodstuff, and most of these involve a means for making the physical conditions unfavorable for microbial growth. Among these are:

(1) *Canning.* This method was discovered by Nicolas Appert, a Frenchman who was awarded a prize in the early part of the 19th century by the French government for discovering a means of preserving food for Napolean's army. Basically, canning is accomplished by heating the foodstuff under pressure to a temperature that is sufficient to kill most living microbes. The sterilized material is then sealed so that further deterioration by microbes is prevented by the inaccessibility of the food.

(2) *Refrigeration.* Foodstuff is kept at a temperature that is too low for the rapid

growth of microbes. This is effective for relatively short periods of time. Over long periods of time, fungi and bacteria, which continue to grow slowly, will cause considerable damage to many materials even at low temperatures.

(3) *Freezing.* This is more effective than refrigeration, since virtually no microbes grow in ice crystals. This is an effective method but is impractical under field conditions.

(4) *Gassing.* Vegetables, fresh fruits, and salad greens can be preserved for much longer times (1 to 2 weeks) by keeping them in a controlled atmosphere. Oxygen is added to the system only at the rate that it is respired, and the carbon dioxide produced by metabolic reactions is removed. Generally, the atmosphere consists of controlled levels of carbon monoxide, oxygen, carbon dioxide, and nitrogen.

(5) *Drying.* Extending the shelf life of food by removal of moisture is an ancient practice. The American Indians preserved meat by sun drying. Many goods are freeze-dried today, an effective practice because microbes require moisture for growth and reproduction. Among the foods protected by moisture removal are dry sausage, cheese, and cured pork products. Many of these foods contain spices and other preservatives but are resistant to biodeterioration primarily because of their low moisture content. Fungi can thrive on material with lower moisture content than can bacteria, so fungal attack is often associated with cheese deterioration (mold).

(6) *Brining.* Many foods are preserved by fermentation that results in an acid or alcoholic medium that is unfavorable for microbial growth. In some cases, the salt concentration is too high for most microbes to thrive although halophilic bacteria are known. Some products of brining are pickles, sauerkraut, and olives. The low pH of vinegar renders it an effective preserving agent.

(7) *Osmotic pressure.* Some foodstuffs are resistant to microbial growth due to an unfavorable osmotic pressure of the product. Honey is an excellent example of a natural food that is resistant to microbial attack for this reason. Jellies, jams, and other sugar-containing preserves are not readily biodeteriorated because few microbes can withstand such conditions. Some cheese products resist microbial attack because of osmotic conditions.

Some foods that have little microbial contamination, e.g., finished cheese, can be coated with paraffin or plastic to prevent contamination of the product. Other coatings have been used to prevent access to the foodstuff during storage and handling. The incorporation of antimicrobials into poultry products and other foodstuff has been attempted but has generally been discouraged.

14-4 MEASUREMENTS AND INSTRUMENTATION*

The first recorded observations of microbes were made by Van Leeuwenhoek (1632-1723) of Delft, Holland. The primitive lenses made by Van Leeuwenhoek enabled him to observe living entities never before seen by man. Despite considerable refinement since this pioneering work, the microscope remains the major instrument for observing and studying microbes. A variety of microscopes are now used, the most common of which being the transmission optical microscope, which has a light source under the specimen. With it, objects less than one-half the wavelength of light do not block enough light to give a discernible image. This limits the optical microscope to the observation of objects with dimensions greater than 0.2 μm since the wavelengths of light visible to the human eye are between 0.4 and 0.7 μm. A typical light microscope has an ocular, or eyepiece, lens that magnifies 10 times and has three or more objective lenses. The low-power objectives magnify 10 times; the high-power 45 times; and the oil-immersion objective magnifies about 100 times. The maximum

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*General references for this paragraph are Refs. 32 and 33.

magnification using these three objectives would be 100X, 450X, and 1,000X, respectively. Optical microscopes are employed for routine examination of all microbes.

The dark-field microscope is useful for observing structures somewhat smaller than those seen in the light microscope. A special condenser in the microscope prevents direct rays from the light source from passing through the objective lens. In this microscope, sufficient light is reflected to allow bacterial flagella and very slender Spirochetes to be observed. An added advantage of dark-field illumination is that staining of the cells is not necessary.

The phase-contrast microscope and the fluorescent microscope are other modifications of the basic microscope that are of importance in the observation and examination of microbes. The fluorescent microscope is particularly useful in diagnostic microbiology.

The electron microscope is similar to the light microscope in many respects. A beam of electrons rather than a beam of light passes through the object being examined. The electron density of the specimen determines the nature of the image. Direct magnifications of 80,000 times are possible and additional magnification is obtained by enlargement of the photographic plate that is obtained. This instrument allows the observation of smaller microbes, such as viruses, and the internal structure of cells that are 10 nm or less in size.

An indispensable tool for the isolation and manipulation of microbes is an autoclave. All media and glassware are presterilized to avoid the ubiquitous microbes that would interfere with the particular one being studied. An autoclave is similar to a pressure cooker. The material placed in it is exposed to live steam under 15 psi pressure. The temperature, under these conditions, is 121°C, which effectively kills living cells.

Often in studying biodeterioration, it is necessary to isolate the microbe associated with the problem under investigation. Microbes can be isolated by use of liquid-solid media. Agar is the solidifying agent most often used in microbiology laboratories. Such media can be obtained commercially. Synthetic media containing the minerals required by microbes supplemented with nutrients are also available. Microbes associated with the biodeterioration of a specific material may be isolated by adding the material to the medium.

An important procedure in studies of biodeterioration is the estimation of the number of microbes of a specific type growing in or on a material. The number of microbes is generally directly correlated with the amount of available substrate and is of considerable significance. This enumeration is accomplished by counting colonies that develop on solid media prepared from the material being studied or on other substrates. Direct counts of cells in a sample of known volume can also be employed. A Petroff-Hauser counting chamber or a Breed count are used most often for counting. The Petroff-Hauser count is accomplished by placing a liquid containing microbes on a grid and counting the number of microbes per square. Since the square is of a known area, the total number of microbes can be estimated by applying a constant multiplier to the count obtained. The Breed count is done by placing a measured volume of cell suspension over a prescribed area on a microscope slide; after drying, the cells are stained and the microbes in several fields of the microscope are counted.

Microbiological laboratory procedures, measurements, and techniques are much more diverse than is indicated in this paragraph.

14-5 AVOIDING BIODEGRADATION*

The design of materiel that will be resistant to biodeterioration should be undertaken with all aspects of potential use under consideration. The many reasons why particular

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*General references for this paragraph are 22, 28, and 34-37.

products are resistant to biodeterioration have been studied by scientists and much progress has been made. The methods used in manufacturing or designing biodeterioration resistant materials or components are discussed in this paragraph.

Rendering a material inaccessible to microbes is one method for preventing biodeterioration. This can be accomplished by (1) hermetically sealing in an enclosure as is done with canned foods, (2) coating with a layer of paint or grease that is impervious to microbial decomposition, (3) coating with a biocidal compound, and (4) aseptic packaging of sensitive instrumenta and other materiel, after sterilization, in synthetic films that are impervious to microbial attack.

Using and storing material under conditions where essential factors for the growth of microbes are not available will also help prevent biodeterioration. In many cases this can be considered good housekeeping. A prime requisite for biodeterioration is moisture. If material is kept dry, little deterioration occurs. This is particularly true in gasoline tanks in which hydrocarbon-utilizing microbes cause problems that can be avoided by periodic draining. Often material can be coated with paraffin, rubber, or grease to prevent moisture accumulation. Although all of these coatings are subject to microbial attack, they are not affected unless moisture accumulates. Moisture does not accumulate readily on such hydrophobic materials. Foodstuffs can be preserved by drying and, provided that moisture is unavailable, the food will remain edible.

Stored water supplies are readily destroyed by algae growth. However, since algae require light as a source of energy, the storage of water in opaque containers is an effective control. This applies equally to the control of algae growth in water containing instruments or equipment.

Clean textiles are resistant to biodeterioration because the attacking microbe needs the minerals that are available only in soiled material. Moisture also accumulates on soiled cloth. High quality leather goods are free of lipids and soluble proteins; thus they are resistant to biodeterioration unless they become soiled.

A major factor in the growth of microbes is temperature. Storage of foodstuffs and other material at low temperatures can preserve them indefinitely. Heat is often used to destroy microbes.

Biocidal protection of material may be used to prevent biotic attack. Some woods, e.g., locust, possess inhibitors against bacterial or fungal attack and, consequently, are not readily susceptible to biodegradation. Some materials can be transformed chemically in a manner that will render them less subject to deterioration. For example, textiles that are woven from cotton, a relatively biodegradable material, are made much more resistant to microbial attack if the cellulose in the cotton is acetylated.

Thick asphalt coatings can be used to protect metal from iron and sulfur bacteria. Surrounding buried metals with neutral clay or loam that is free of sulfates can also be of benefit. Pipes can be protected by clorinating the water that passes through them or by adjusting the pH of the water to the alkaline side. Insulating and providing protective coatings for pipes, as well as cathodic protection, can retard the corrosion caused by microbe-accelerated electrochemical reactions.

Bactericides are used in water systems to prevent the growth of microbes. Some examples are chlorine, chloramine, perchlorate, potassium permanganate, copper sulfate, zinc chloride, and phenols. These prevent the growth of sulfide oxidizers and producers, iron bacteria, manganese oxidizers, and other detrimental microbes.

Fungicides are used to protect material. The addition of these inhibitors to vinyl plastics not only protects against fungi but also aids the material in retaining its strength when exposed to deteriorating temperature and humidity conditions. Many compounds have been used to protect plastic materials. Among these are benzophenone, phosphite, and heavy metal combinations (barium, cadmium, and zinc) but none is completely satisfactory.

For a biocide to be effective, it must have the following qualities:

(1) The compound must be highly effective against a wide variety of microbes, both bacteria and fungi. This is a particularly difficult assignment since most agents that inhibit bacteria do not affect fungi and vice versa. If an agent is effective against both, it is generally highly toxic and, as such, is of limited applicability.

(2) The material must be economical.

(3) The biocide should endure high temperatures and weathering.

(4) The material should be colorless and nontoxic.

(5) The physical characteristics of the finished product should not be affected.

Wood can be protected from biodegradation in several ways:

(1) Preventing moisture and other impurities from accumulating on the wood

(2) Coating the wood with paint to prevent access by fungi and to keep out moisture

(3) Treating the wood with preservatives.

The most important of these overall for wood above ground are preservatives and painting, or, painting alone. Many wood preservatives are effective when wood is in contact with soil and exposed to moisture. These are applied either by the dip method or by high pressure impregnation. In some cases the preservative effectively inhibits the growth of both microbes and termites. In more modern methods the inhibitors used for control of fungi are different from those used to prevent termite invasion. Compounds such as tributyltin oxide and pentachlorophenol that have been used for termite proofing of wood have been ineffective in preventing the growth of wood-rotting microbes. Biocidal inhibitors that are used include creosote, copper naphthenate, and copper-8-quinolinate.

Protection of fuels can be achieved by good housekeeping. Much older equipment was so designed that the fuel tanks could not be completely drained. During periods when the equipment is inactive, water accumulates in the tank. This water contains dust so that, when fuel is added to the tank, rapid growth of hydrocarbon-utilizing microbes can occur. All fuel tanks should be constructed so that they can be completely drained. When stored in areas where moisture can accumulate, either drying agents should be added or the water should be removed from the tank periodically.

The anti-icing additives in fuel are usually effective biocides and can keep gasoline and kerosene relatively free of microbial growth. These include MB 55*, which has been shown to be effective in controlling the growth of a fungus that causes problems in stored fuel, and Biobor*, which is effective in controlling microbial growth. Chromate is used in washing tanks to control the growth of sulfate-reducing bacteria. Antifungal agents are added to greases and cutting oils to control the growth of fungi. Despite all of these measures, biodegradation of petroleum products remains a problem.

Chemical methods of preventing biodeterioration require that the microbe must either be killed, or directly or indirectly prevented from exercising its degrading action. Control measures are directed at the microbe or at the material. The measure can inactivate or kill the microbe, neutralize the acids or enzymes it produces, interpose a physical or toxic chemical barrier, or modify the chemical

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*MB 55 is a trademark of Phillips Petroleum Co.; Biobor is a trademark of Standard Oil Co. (Sohio).

structure of the material. Protective or prophylactic measures are used to prevent the microbe from becoming established on the substrate, and eradicants or disinfectants are used to eliminate the microbe from the material to which it has gained access.

Over 6,000 pesticides are in use and more are being added. Fortunately, D.E.H. Frear has compiled information on their composition and has listed manufacturers in *The Pesticide Handbook* (Ref. 34). The same biotoxic compound may have three or more names; the chemical name, the common or generic name, and one or more trade names. The chemical name is based on the composition and structure of the molecule (e.g., ferric dimethyl-dithiocarbamate). The common or generic name is assigned by a national committee to a biocide containing the same active chemical ingredient (e.g., ferbam). A trade or trademarked name is given the same product (with additives) by each of the companies that manufactures it (e.g., Fermate, Ferradow, etc.).

Chemicals in use to inhibit microbes were once thought of as either inorganic (e.g., copper) or organic (e.g., quinones). When copper or sulfur ions are synthesized into "organic" compounds, their effectiveness is greatly increased and such a dichotomous separation is no longer possible. Sulfur, copper, cadmium, mercury, silver salts, and their derivatives are commonly used to check the growth of bacteria and fungi. Phenol is representative of the closed "aromatic" carbon chain group and ethanol of the open "aliphatic" carbon chain group of biocidal hydrocarbons with an –OH (hydroxyl) radical added. Formaldehyde is a well-known disinfectant representative of fungitoxic chemicals that contain a C=O (carbonyl) radical. Potent antimildew agents have been found with the quinone, carbamate, phthalimide, glyoxalidine, guanidine, and morpholine moiety as the active or toxophoric part. Chlorination greatly increases the antibiotic activity of diphenyl methanes, phenols, benzenes, and naphthalenes. Quaternary and heterocyclic nitrogen compounds have proved useful for inhibiting bacteria and fungi.

Although one is prone to think first of chemical toxic agents for antimicrobial use, physical agents such as heat, ultraviolet light, ionizing radiation, and ultrasonic vibration are effective. The action of heat, either as dry heat or as steam (water vapor), is well known as an agent of coagulation of microbial protoplasm. The use of ultraviolet light is limited to surface contaminants because of the inability of the short wavelengths to penetrate materials. The energy of ionizing radiation is believed to be transmitted to living organisms and substrates in two ways. One is the actual transduction of energy from the photon of radiation to the molecule with which it comes in direct contact. Alternatively, the energy may be transmitted indirectly through the medium of water. Structurally, protoplasm is a colloidal suspension with a high water content; hence, the inactivating mechanism of radiation is believed to be due to its formation of hydrogen (oxidizing) and hydroxyl (reducing) radicals. Sporulating microbes and enzymes *in situ* require high radiation levels that may be harmful to the material being sterilized. The use of sonifiers is still limited in scope because of the limited volume capable of treatment and frequent failure to obtain 100-percent kill.

14-6 TESTING

Some form of testing is indispensable in determining whether materials will withstand the attack of microbes. Since it is difficult to simulate the complex factors inducing biodegradation with any accuracy, it is necessary that all material and equipment be tested under field conditions. However, many materials that are used for protection against biodegradation are tested in the laboratory during development. The methods used in testing must be specified closely and should be designed to simulate the actual operating conditions. Usually, the tests are designed to cover the more harsh operating conditions and to provide a valid evaluation for comparing one method of protection with another.

Many cases require that tests be designed that will determine whether the growth of microbes on a substrate other than the material being tested has a deleterious effect on the test material. For example, bacteria living on a soiled metal surface may produce a byproduct, such as an acid, that attacks the metal. Petri dishes with a rich medium are prepared, the microbes (whose products might attack the material) are spread over the surface of the dish, and a sample of the material in question placed on the surface. Incubation should be carried out in a moist chamber. After a suitable test period, the material in question can be examined for deterioration.

14-6.1 TEST LEVELS

When a protective product is developed, at least three graded levels of testing are applied: screening, end-use, and field tests, in order to determine the effectiveness of the product in preventing degradation of the materiel to which it is applied. These testing levels have different tasks, ranges of application, and goals.

(1) *Screening tests.* These are employed during development of products and primary assessment of the material. They are indispensable in the industrial laboratory. The screening tests must be simple to administer and must give results in a short period of time. This allows testing of many different materials. It must be possible to assess whether a given substance exerts any influence on various types of microbes and whether the materiel is protected against microbial attack. A few microbes from a wide range of different types are used in most tests. In screening tests, it is not essential that the substance in question have promise of practical use. When a substance yields results that indicate usefulness, it is subsequently tested under a wider range of conditions and on a variety of materials.

(2) *End-use tests.* These are the next step in the evaluation of biocides. These procedures assess the practical suitability of the product. End-use tests determine whether a specific material gives protection or is protected against attack by specific microbes. The developed product is applied to and tested on a specific material to evaluate the protection it gives against conditions that will be encounterd during later use. It is important to select microbes for the tests that correspond to those encountered in practical use. End-use tests are important–the sooner one obtains valid results, the more desirable the test. Typical end-use tests include the Petri dish test and the soil burial method for evaluation of textile, plastic, or wood preservatives. To obtain reproducible results, the testing procedures are carefully prescribed and followed.

(3) *Field tests.* These are the third level of testing. These are necessary regardless of the results obtained in end-use tests and are carried out under actual conditions of use. Examples of field tests are exposure of exterior paints on fences, placing of utility posts in the ground, and exposure of tenting materials to the environment. The conditions are not well controlled under this testing condition since climatic conditions change from year to year. Field tests are expensive, require much time, but allow valid judgments of biocide efficacy under real working conditions. Results from field tests also allow assessment of the validity of laboratory tests.

Ideally, any end-use or field test will yield results that can be applied to the material tested, with the exception that results should be forthcoming in as short a period of time as is practical. Consequently, to save time, more tests of relatively stable material are carried out under more severe conditions than are expected in use.

14-6.2 SOIL BURIAL TESTS

Soil burial testing can be used with any material used in construction in order to determine whether microbes that can utilize that specific material are present in the biosphere. Conditions are obtained to approximate those encountered during normal use of the material. From such experiments, microbes are isolated that are capable of attacking almost any material. Further experiments with these microbes relative to their mode of attack, their susceptibility or resistance to biocide, and their relative activity under various environmental conditions can then be performed (Ref. 32).

Material utilization is one of the parameters used to measure the extent of biodegradation and to ascertain the types of microbes that are active. In conjunction with this, it is essential to learn whether the material is modified to a significant extent.

When microbes are isolated in soil burial tests, the substrate for isolation can be one of two types:

(1) A rich medium containing a source of carbon (carbohydrate), vitamins (B complex), and some form of fixed nitrogen (amino acids). The medium can be used either in the liquid form by adding water, or as a semisolid medium by adding agar (1.5 to 2.0 percent) These medium constituents are added in quantities specified in method manuals for microbiology.

(2) A medium composed of mineral salts to which a single source of carbon and energy can be added. The source of carbon and energy can be any material under consideration; wood, cellulose, leather, plastics, or paint constituents, at concentrations of 1 to 3 percent. Microbes that grow on these materials can be utilized in experiments designed to find biocides that control biodeterioration.

To achieve a standard set of conditions for soil burial tests, the procedures used are rigorously controlled. Temperature is set at a prescribed level, usually 24°, 30°, or 37°C, with a relative humidity of 86 percent. The moisture level in the soil is maintained at 40 percent or some other selected level. These conditions are best achieved in a greenhouse or other room with a controlled environment. The specific temperature and soil moisture are selected to approximate those that will be encountered during use of the material under test.

Textiles are tested in soil burial by placing 1- by 5-in. swatches of treated or untreated material in the soil. One end of each swatch remains above ground level. The soil should be rich fertile topsoil taken from an area that is relatively free of pesticides. At intervals, test samples are removed from the soil and tested for tensile strength, weight loss after washing, or other parameters that measure the degree of biodeterioration.

Wood blocks or plies of wood can be tested in a similar manner. Strength tests and visual examination are used to evaluate samples removed from the soil at intervals.

Metal rods or sheets are also tested by soil burial. The weight loss of the metal is determined after exposure to the corrosive conditions. The metal is cleansed of rust or other corrosive products by washing or ultrasonic cleaning prior to weighing.

Plastics can also be tested by soil burial and subsequent examination to determine changes in physical, chemical, or electrical properties.

14-6.3 RESPIROMETRY

Respirometry is another effective method used to determine whether a material is subject to microbial attack (Ref. 38). Comparative studies between various microbes that attack a given material or a number of material samples treated with different biocides can be tested in a short period of time using this method. Essentially the respirometer consists of the following:

(1) A water bath that has an accurate temperature control.

(2) Manometers that are connected to flasks. These manometers are of small bore, contain a standardized liquid, and are so constructed that they are sensitive to small changes in pressure.

(3) Flasks (14 to 20 milliliter capacity) with a centerwell into which an absorbent (20 percent NaOH) can be placed for the trapping of any carbon dioxide that is generated.

To carry out the tests, 2 to 3 milliliters of suspending medium containing the microbe is put into the flasks, which are then placed in the temperature-controlled bath. The flasks have a small sidearm constructed in such a way that the contents (0.2 to 0.3 milliliter of liquid) can be kept separate from the main compartment of the vessel. The substrate (test material) is placed in the sidearm. After the flasks adjust to the bath temperature (equilibrate), a manometer reading is taken on each flask. The material (substrate) is added to the suspending medium from the sidearm (by tilting the flask) and any changes in gas content (oxygen uptake) are measured by the changes in the height of the liquid in the manometer. A separate flask without either substrate or cells is present (thermobar) to measure pressure changes due to changing atmospheric conditions.

The respirometer is used to observe material metabolism and to give a relative activity rate. The rate is generally referred to as a Q_{O_2} for a growth substrate and, with nonproliferating microbial cells, is constant.

14-6.4 BIOCIDAL EFFICACY

Tests of biocides to determine their usefulness as an antimicrobial that can be incorporated in or on a product are important in industry and the military. Usually a sterile medium containing agar and nutrients is added to a Petri dish. The candidate biocide is added at a selected concentration to the melted agar medium prior to or during preparation of test plates. Generally, a dilution series containing the biocide under test is prepared—levels might be 1,000, 500, 100, 50, 10 ppm of the biocide agent. The test microbe is placed in a streak across the center of the prepared plate by diluting spores, mycelium, or cells in sterile water and passing a loopful across the plate. The inoculated plates are incubated at a temperature favorable for optimal growth of the test microbe. At intervals the extent of mycelial or cellular growth is measured. The percent inhibition is determined by comparing the amount of growth attained with that on plates prepared in a similar manner except with no biocide. The dosage of biocide that is necessary for total inhibition can thus be determined.

The "Spore Germination Inhibition" technique is a sensitive indicator of fungicidal efficacy (Ref. 32). Chemically clean 1- by 3-in. glass slides are prepared and the test fungicide is applied in solution at four points on each slide. The drops are allowed to dry. Meanwhile, an aqueous spore suspension of the desired fungus is prepared. The suspension is standardized to about 25 spores per microscope field at 100X magnification. By placing one drop of the spore suspension over each of the four areas on the slide where the toxic agent was applied, the spores are exposed to a known concentration of fungitoxic material. Control slides with drops of water without toxic agent are also prepared. After incubation at an optimal temperature for 4 to 24 hr in a container that prevents drying of the water drops, the slides are examined. At least 80 percent or more of the spores on the control slide should germinate. The number of spores germinating when exposed to the fungicide is determined and compared to the control. With these data, the effectiveness of the fungicide is quantitatively determined. By using various concentrations and types of fungicide, the optimal dosage can be determined and the relative effectiveness of different formulations can be compared.

14-6.5 FOOD TESTING

Demonstration of foodstuff deterioration, in most cases, is not a difficult task (Refs. 29, 39). The aroma and consistency of decomposed food is familiar to most people and such products should not be consumed by human beings. Food is tested for microbial contamination if contamination is suspected. The presence of microbes, both bacteria and fungi, on or in food is not an indication that the food is spoiled or is inedible. Milk contains large numbers of microbes. All fruits and vegetables are coated with bacteria, fungi, and yeasts that are either incompletely removed by washing or are recolonized after washing. Foods that are a complete medium for microbes—e.g., salad dressing, puddings, and starch fillings—will support the growth of tremendous numbers of microbes in a short period of time (4 to 6 hr) at favorable temperatures. Determining the numbers and types of microbes present on foodstuffs is important in tracing the origins of food poisoning outbreaks.

The tests that indicate food spoilage and identify the type of microbe present are varied. For example, if a can containing food swells due to internal pressure, it indicates that the heat treatment used in canning was insufficient to kill the microbes. If the food is acid, e.g., canned tomatoes, little or no danger of botulism food poisoning exists but all such foodstuffs should be destroyed on the chance that botulism would result upon ingestion. Tests can be run to determine whether lethal levels of botulinus toxin are present by feeding the material to monkeys or by injecting it into the intraperitoneal cavity of mice. If a possibility exists that foodstuff, e.g., smoked fish, contains botulinus toxin, it should be tested in animals by extracting the food with water and injecting an aliquot into mice or by using it in animal feeding experiments. Botulinus toxin is one of the most potent toxins known and is fatal at exceedingly low concentrations.

When it is necessary to examine foodstuff for microbial contamination or to determine whether a method of preservation is successful, the microbes present should be isolated and characterized. An estimate of the total number of microbes present should be made. This is accomplished in the following manner:

(1) The material to be examined should be so collected that it is not exposed to more microbes than are already present. At the time the foodstuff is sampled, it should be placed in a container and stored so that further microbial growth cannot occur. This is difficult if a significant length of time elapses between the sampling and the testing of the material. The samples are usually packed in ice. Freezing can destroy some microbes and some thawed products are in a physical state that renders them more difficult to test. The most important factor is time; the samples should be tested as quickly as possible.

(2) Uniform samples of the foodstuff should be aseptically removed and subsequent contamination should be prevented. Usually a 1-g sample of material is employed. A more reliable test can be made if the sample is homogenized in a blender. Enough sterile water should be added to the sample in the sterilized blender cup to get thorough mixing and to obtain 100 milliliters of blend. Further dilutions of this blend are made for Petri plate counting and isolation. For counting purposes, either no dilutions or dilutions up to 10^9 are sometimes required.

(3) After agar-coated glass plates are innoculated with the blend, they are incubated at 30° to 37°C for 72 hr and the number of microbe colonies present are determined. Plates with 50 to 200 colonies give the most reliable count. Multiplication of this colony number by the dilution factor used gives the number of microbes (colony forming units) in the original gram of sample. The medium used in plating can be any of the many available although a rich medium like plate count agar or bacto-tryptone, are preferred.

(4) Microbes can be isolated from the above plates and examined for properties that would be significant in diagnosis. If the food caused food poisoning, one would look for *Salmonella, Shigella,* or hemolytic coagulase-positive *Staphylococcus aureus.* An examination for food-destroying organisms would utilize tests for pectinase production, or growth on the product.

(5) The above sequence (1 to 4) can be utilized for isolating and characterizing microbes that are a causative agent in most problems of microbial biodeterioration.

14-6.6 OTHER TEST TECHNIQUES

The extractable material method for determining whether a material contains substrates that support microbial growth is an effective test. Test materials such as coatings, leather, plastics, and metals are extracted with water or other solvents (Ref. 32). If solvents are used, the extract is dried and resuspended in water. This water extract is added to a mineral salts medium that contains no other nutrient source. The mixture is inoculated with microbes and incubated at a suitable temperature for 3 to 5 days. The microbial mass attained after incubation gives a relative measure of the amount of carbonaceous material present in the test material that will support microbial growth.

Fuels and oils sometimes contain additives than can be utilized by growing microbes. The antioxidants added to grease are often excellent substrates for microbial growth. The proliferation of microbes on this constituent can set off a sequence of attack by various microbes that effectively destroys the grease. The resistance of grease to attack and, hence, its protective properties can be determined by coating 5- X 5-in. tin plates with the lubricant. Fungal spores are added to some of the plates. Controls are coated with lubricant only. The plates are incubated in a desiccator at 100 percent relative humidity and 28° to 30°C. The control plates should not show any signs of corrosion. Those to which spores were added may have various amounts of corrosion depending on the ability of the fungal spores to grow in the grease. Among the fungi recommended by the International Electrochemical Commission in testing for resistant materials for use in the tropics are: *Aspergillus niger, Paecilomyces varioti, Stachybotrys atra, Penicillium brevicompactum, Chaetomium compactum,* and *Cladosporium resinae.**

The presence of microbes in fuel can best be determined by ascertaining whether water is present in the fuel tank (Refs. 17, 24). If water is present, a sample should be taken at the water-fuel interface and the number of microbes present determined. Whether these microbes can grow on hydrocarbon substrates must be determined. For this purpose a flask of mineral salts medium (without added carbonaceous substrate) is prepared and 0.5 to 1.0 percent of an *n*-alkane, preferably *n*-tetradecane, and a drop of the sample from the fuel tank are added. The inoculated flask is either placed on a rotary shaker or incubated in stationary culture for 4 to 7 days. Significant microbial growth would indicate that hydrocarbon-utilizing microbes were present in the fuel tank. If fuel was stored in the tank for any significant period of time, the metallic surfaces should be checked for corrosion. The fuel should also be filtered prior to being used in an internal combustion engine.

The resistance of fuels to microbial attack after treatment with deicers or antimicrobials should also be determined. Since most fuel contains fungal spores and hydrocarbon-utilizing microbes, the effectiveness of biocides can be tested by adding water to the treated fuel and incubating for a suitable period. For better and more reproducible results, the treated fuel can be inoculated with a standardized inoculum of hydrocarbon-utilizing microbes.

Paints and coatings are tested in a number of ways (Ref. 18). Panels of painted or coated wood, plastic, or metal are placed in the environment such that they will be exposed to more severe conditions than will be encountered in use. They can also be tested by carefully painting metal rods or wood dowels with the material. The samples are cured without undue exposure to microbes in the air. After curing, the coated samples are tested by one of the methods listed:

(1) *Extract studies.* The coated rods are soaked in sterile water and the extract inoculated with microbes. Recommended microbial types include *Pseudomonas aeruginosa, Aspergillus niger, Cladosporium resinae,* and *Bacillus subtilis.* The relative amount of growth of the microbe is a measure

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*See Table 14-3 for sources of cultures.

TABLE 14-3

CULTURE COLLECTIONS

Sources	Cultures supplied
American Type Culture Collection 12301 Parklawn Drive Rockville, Md. 20852	Bacteria Fungi Viruses
The U.S. Army Natick Laboratories Natick, Mass.	Deterioration fungi
Northern Utilization Research and Development Division U.S. Department of Agriculture Peoria, Ill.	Bacteria, yeasts, and molds useful in fermentations
Forest Products Research Laboratory Princess Risborough Aylesbury Buckinghamshire, England	Wood-rotting fungi
Forest Disease Laboratory RFD 2 Box 263 Laurel, Md.	Wood-rotting fungi
Centraalbureau voor Schimmel-cultures Oosterstraat 1 Baarn, The Netherlands	Bacteria, fungi, and viruses

of the biodegradability of the coating or paint.

(2) *Petri dish studies.* The coated or painted samples are placed on the surface of agar in a 150-mm Petri dish. The agar, either nutrient or mineral salts agar, is sprayed with a mixture of *Aspergillus niger, Aspergillus flavus, Penicillium funiculosum,* and *Trichoderma.* The relative amount of growth and corrosion of the metal should be followed for up to 30 days.

(3) *High humidity evaluation.* The samples are sprayed with a calibrated fungal spore suspension at a concentration of about 10^4 per milliliter. Various species of fungi can be used in this test (*Penicillia, Aspergilli, Myrothecium*). The coated or painted materials should be incubated at a high humidity for 21 to 28 days and examined for fungal growth.

(4) *Soil burial exposure.* The coated samples are buried in soil and maintained at a

favorable humidity, temperature, and soil moisture condition. The samples are recovered in 1 to 6 mo and examined by one of the following methods:

(a) Pencil hardness test. Pencils of varying hardness are used to determine which will/will not penetrate the surface.

(b) Electrical resistance test. A loss of electrical resistance suggests a deterioration of the coating or paint.

(c) Scanning electron microscope. Examination for breakdown of the coating and penetration of the barrier. Frequently, pitting or degradation of the underlying material is also observed.

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APPENDIX A

UNITS AND UNIT CONVERSION FACTORS

TABLE A-1

BASIC UNITS*

Physical quantity	Name of unit	Symbol	Definition
length	meter	m	The meter is the length equal to 1,650,763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels 2 p_{10} and 5 d_5 of the krypton-86 atom.
mass	kilogram	kg	The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram. (The international prototype of the kilogram is a particular cylinder of platinum-iridium alloy that is preserved in a vault at Sèvres, France, by the International Bureau of Weights and Measures.)
time	second	s	The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.
electric current	ampere	A	The ampere is the constant current that, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2 X 10^{-7} newtons per meter of length.
temperature	kelvin	K	The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
luminous intensity	candela	cd	The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600,000 square meters of a blackbody at the temperature of freezing platinum under a pressure of 101,325 newtons per square meter.

*Obtained from E. A. Mechtly, The International System of Units, NASA SP-7012, National Aeronautics and Space Administration, Washington, D.C., 1973.

TABLE A-2

IMPORTANT DERIVED UNITS

Physical quantity	Name	Symbol	Definition of unit
Force	newton	N	The newton is the force that gives to a mass of 1 kilogram an acceleration of 1 meter per second per second.
Work	joule	J	The joule is the work done when the point of application of 1 newton is displaced a distance of 1 meter in the direction of the force.
Power	watt	W	The watt is the power that gives rise to the production of energy at the rate of 1 joule per second.
Electric potential	volt	V	The volt is the difference of electric potential between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.
Electric resistance	ohm	Ω	The ohm is the electric resistance between two points of a conductor when a constant difference of potential of 1 volt, applied between these two points, produces in this conductor a current of 1 ampere, this conductor not being the source of any electromotive force.
Quantity of electricity	coulomb	C	The coulomb is the quantity of electricity transported in 1 second by a current of 1 ampere.
Capacitance	farad	F	The farad is the capacitance of a capacitor between the plates of which there appears a difference of potential of 1 volt when it is charged by a quantity of electricity equal to 1 coulomb.
Inductance	henry	H	The henry is the inductance of a closed circuit in which an electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at a rate of 1 ampere per second.
Magnetic flux	weber	Wb	The weber is the magnetic flux that, linking a circuit of one turn, produces in it an electromotive force of 1 volt as it is reduced to zero at a uniform rate in 1 second.
Luminous flux	lumen	lm	The lumen is the luminous flux emitted in a solid angle of 1 steradian by a uniform point source having an intensity of 1 candela.

TABLE A-3

CONVERSION FACTORS FREQUENTLY USED TO OBTAIN SI UNITS

Physical quantity	Miscellaneous unit	Multiplier	SI Unit
Acceleration	1 ft s^{-2}	= 4.047 X 10^{3}	m s^{-2}
	1 G (free fall)	= 9.807	m s^{-2}
Area	1 acre	= 4.047 X 10^{3}	m^{2}
	1 ft^{2}	= 9.290 X 10^{-2}	m^{2}
	1 $in.^{2}$	= 6.452 X 10^{-4}	m^{2}
	1 $mile^{2}$	= 2.590 X 10^{6}	m^{2}
	1 $yard^{2}$	= 8.361 X 10^{-1}	m^{2}
Density	1 g cm^{-3}	= 1 X 10^{3}	kg m^{-3}
	1 pound mass ft^{-3}	= 1.602 X 10	kg m^{-3}
Energy	1 Btu*	= 1.055 X 10^{3}	J
	1 calorie (thermo-chemical)	= 4.184	J
	1 electron volt	= 1.602 X 10^{-19}	J
	1 erg	= 1 X 10^{-7}	J
	1 foot pound force	= 1.356	J
	1 kilowatt hour	= 3.6 X 10^{6}	J
Force	1 dyne	= 1 X 10^{-5}	N
	1 pound force	= 4.448	N
	1 poundal	= 1.383 X 10^{-1}	N
Length	1 angstrom	= 1 X 10^{-10}	m
	1 astronomical unit	= 1.496 X 10^{11}	m
	1 ft	= 3.048 X 10^{-1}	m
	1 in.	= 2.540 X 10^{-2}	m
	1 micron	= 1 X 10^{-6}	m
	1 mil	= 2.54 X 10^{-5}	m
	1 mile (statute)	= 1.609 X 10^{3}	m
	1 nautical mile	= 1.852 X 10^{3}	m

*Conversion factor holds for Btu of International Standards Organization and International Steam Table and is within 10.001 for mean Btu and thermochemical Btu.

TABLE A-3 (Continued)

CONVERSION FACTORS FREQUENTLY USED TO OBTAIN SI UNITS

Physical quantity	Miscellaneous unit		Multiplier	SI Unit
Mass	1 grain	=	6.480×10^{-5}	kg
	1 gram	=	1×10^{-3}	kg
	1 pound mass	=	4.536×10^{-1}	kg
	1 ton (short)	=	9.072×10^{2}	kg
Power	1 horsepower	=	7.457×10^{2}	W
Pressure	1 atmosphere	=	1.013×10^{5}	$\mathrm{Nm^{-2}}$
	1 cm of Hg (0°C)	=	1.333×10^{3}	$\mathrm{Nm^{-2}}$
	1 dyne $\mathrm{cm^{-2}}$	=	1.0×10^{-1}	$\mathrm{Nm^{-2}}$
	1 millibar	=	1.0×10^{2}	$\mathrm{Nm^{-2}}$
	1 torr	=	1.333×10^{2}	$\mathrm{Nm^{-2}}$
Speed	1 ft $\mathrm{s^{-1}}$	=	3.048×10^{-1}	$\mathrm{m\ s^{-1}}$
	1 km $\mathrm{hr^{-1}}$	=	2.778×10^{-1}	$\mathrm{m\ s^{-1}}$
	1 knot	=	5.144×10^{-1}	$\mathrm{m\ s^{-1}}$
	1 mile $\mathrm{hr^{-1}}$	=	4.470×10^{-1}	$\mathrm{m\ s^{-1}}$
Time	1 day	=	8.640×10^{4}	s
	1 hr	=	3.600×10^{3}	s
	1 year (calendar)	=	3.154×10^{7}	s
Viscosity	1 centistoke	=	1×10^{-6}	$\mathrm{m^{2}\ s^{-1}}$
	1 centipoise	=	1×10^{-3}	$\mathrm{Ns\ m^{-2}}$
Volume	1 $\mathrm{ft^{3}}$	=	2.832×10^{-2}	$\mathrm{m^{3}}$
	1 $\mathrm{in.^{3}}$	=	1.639×10^{-5}	$\mathrm{m^{3}}$
	1 liter	=	1×10^{-3}	$\mathrm{m^{3}}$
	1 ounce (U.S. fluid)	=	2.957×10^{-5}	$\mathrm{m^{3}}$
	1 quart (U.S. liquid)	=	9.464×10^{-4}	$\mathrm{m^{3}}$
	1 $\mathrm{yard^{3}}$	=	7.646×10^{-1}	$\mathrm{m^{3}}$

APPENDIX B

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

TABLE B-1

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
								NORTH AMERICA																				
United States (Conterminous):																												
Albuquerque, N. Mex.	35 03N	106 37W	5,311	30	46	24	69	42	91	66	71	45	104	-16	30	0.4	0.4	0.5	0.5	0.8	0.6	1.2	1.3	1.0	0.8	0.4	0.5	8.4
Asheville, N.C.	35 26N	82 32W	2,140	30	48	28	67	42	84	61	68	45	99	- 7	30	4.2	4.0	4.8	4.0	3.7	3.5	5.9	4.9	3.6	3.1	2.8	3.6	48.1
Atlanta, Ga.	33 39N	84 26W	1,010	30	52	37	70	50	87	71	72	52	103	- 9	30	4.4	4.5	5.4	4.5	3.2	3.8	4.7	3.6	3.3	2.4	3.0	4.4	47.2
Austin, Tex.	30 18N	97 42W	597	30	60	41	78	57	95	74	82	60	109	- 2	30	2.4	2.6	2.1	3.6	3.7	3.2	2.2	1.9	3.4	2.8	2.1	2.5	32.5
Birmingham, Ala.	33 34N	86 45W	620	30	57	36	76	50	93	71	79	52	107	-10	30	5.0	5.3	6.0	4.5	3.4	4.0	5.2	4.9	3.3	3.0	3.5	5.0	53.1
Bismark, N. Dak.	46 46N	100 45W	1,647	30	20	0	55	32	86	58	59	34	114	-45	30	0.4	0.4	0.8	1.2	2.0	3.4	2.2	1.7	1.2	0.9	0.6	0.4	15.2
Boise, Idaho	43 34N	116 13W	2,838	30	36	22	63	37	91	59	65	38	112	-28	30	1.3	1.3	1.3	1.2	1.3	0.9	0.2	0.2	0.4	0.8	1.2	1.3	11.4
Brownsville, Tex.	25 54N	97 26W	16	30	71	52	82	66	93	76	85	67	104	12	30	1.4	1.5	1.0	1.6	2.4	3.0	1.7	2.8	5.0	3.5	1.3	1.7	26.9
Buffalo, N.Y.	42 56N	78 44W	705	30	31	18	53	34	80	59	60	41	99	-21	30	2.8	2.7	3.2	3.0	3.0	2.5	2.6	3.1	3.1	3.0	3.6	3.0	35.6
Cheyenne, Wyo.	41 09N	104 49W	6,126	30	37	14	56	30	85	55	63	32	100	-38	30	0.5	0.6	1.2	1.9	2.5	2.1	1.8	1.4	1.1	0.8	0.6	0.5	15.0
Chicago, Ill.	41 47N	87 45W	607	30	33	19	57	41	84	67	63	47	105	-23	30	1.9	1.6	2.7	3.0	3.7	4.1	3.4	3.2	2.7	2.8	2.2	1.9	33.2
Des Moines, Iowa	41 32N	93 39W	938	30	29	11	59	38	87	65	66	43	110	-30	30	1.3	1.1	2.1	2.5	4.1	4.7	3.1	3.7	2.9	2.1	1.8	1.1	30.5
Dodge City, Kans.	37 46N	99 58W	2,582	30	42	20	66	41	93	68	71	46	109	-26	30	0.6	0.7	1.2	1.8	3.2	3.0	2.3	2.4	1.5	1.4	0.6	0.5	19.2
El Paso, Tex.	31 48N	106 24W	3,918	30	56	30	78	49	95	69	79	50	109	- 8	30	0.5	0.4	0.4	0.3	0.4	0.7	1.3	1.2	1.1	0.9	0.3	0.5	8.0
Indianapolis, Ind.	39 44N	86 17W	792	30	37	21	61	40	86	64	67	44	107	-25	30	3.1	2.3	3.4	3.7	4.0	4.6	3.5	3.0	3.2	2.6	3.1	2.7	39.2
Jacksonville, Fla.	30 25N	81 39W	20	30	67	45	80	58	92	73	80	62	105	10	30	2.5	2.9	3.5	3.6	3.5	6.3	7.7	6.9	7.6	5.2	1.7	2.2	53.6
Kansas City, Mo.	39 07N	94 36W	742	30	40	23	66	46	92	71	72	49	113	-22	30	1.4	1.2	2.5	3.6	4.4	4.6	3.2	3.8	3.3	2.9	1.8	1.5	34.2
Las Vegas, Nev.	36 05N	115 10W	2,162	30	54	32	78	51	104	76	80	53	117	8	30	0.5	0.4	0.4	0.2	0.1	*	0.5	0.5	0.3	0.2	0.3	0.4	3.8
Los Angeles, Calif.	33 56N	118 23W	97	30	64	45	67	52	76	62	73	57	110	23	30	2.7	2.9	1.8	1.1	0.1	0.1	*	*	0.2	0.4	1.1	2.4	12.8
Louisville, Ky.	38 11N	85 44W	477	30	44	27	66	43	89	67	70	46	107	-20	30	4.1	3.3	4.6	3.8	3.9	4.0	3.4	3.0	2.6	2.3	3.2	3.2	41.4
Miami, Fla.	25 48N	80 16W	7	30	76	58	83	66	89	75	85	71	100	28	30	2.0	1.9	2.3	3.9	6.4	7.4	6.8	7.0	9.5	8.2	2.8	1.7	59.9
Minneapolis, Minn.	44 53N	93 13W	834	30	22	2	56	33	84	61	61	37	108	-34	30	0.7	0.8	1.5	1.9	3.2	4.0	3.3	3.2	2.4	1.6	1.4	0.9	24.9
Missoula, Mont.	46 55N	114 05W	3,190	30	28	10	57	31	85	49	58	30	105	-33	30	0.9	0.9	0.7	1.0	1.9	1.9	0.9	0.7	1.0	1.0	0.9	1.1	12.9
Nasheville, Tenn.	36 07N	86 41W	590	30	49	31	71	48	91	70	74	49	107	-15	30	5.5	4.5	5.2	3.7	3.7	3.3	3.7	2.9	2.9	2.3	3.3	4.2	45.2
New Orleans, La.	29 59N	90 15W	3	30	64	45	78	58	91	73	80	61	102	7	30	3.8	4.0	5.3	4.6	4.4	4.4	6.7	5.3	5.0	2.8	3.3	4.1	53.7
New York, N.Y.	40 47N	73 58W	132	30	40	27	60	43	85	68	66	50	106	-15	30	3.3	2.8	4.0	3.4	3.7	3.3	3.7	4.4	3.9	3.1	3.4	3.3	42.3
Oklahoma City, Okla.	35 24N	97 36W	1,285	30	46	28	71	49	93	72	74	52	113	-17	30	1.3	1.4	2.0	3.1	5.2	4.5	2.4	2.5	3.0	2.5	1.6	1.4	30.9
Phoenix, Ariz.	33 26N	112 01W	1,117	30	64	35	84	50	105	75	87	55	118	16	30	0.7	0.9	0.7	0.3	0.1	0.1	0.8	1.1	0.7	0.5	0.5	0.9	7.3
Pittsburgh, Pa.	40 27N	80 00W	747	30	40	25	63	42	85	65	65	45	103	-20	30	2.8	2.3	3.5	3.4	3.8	4.0	3.6	3.5	2.7	2.5	2.3	2.5	36.9
Portland, Maine	43 39N	70 19W	47	30	32	12	53	32	80	57	60	37	103	-39	30	4.4	3.8	4.3	3.7	3.4	3.2	2.9	2.4	3.5	3.2	4.2	3.9	42.9
Portland, Oreg.	45 36N	122 36W	21	30	44	33	62	42	79	56	63	45	107	- 3	30	5.4	4.2	3.8	2.1	2.0	1.7	0.4	0.7	1.6	3.6	5.3	6.4	37.2
Reno, Nev.	39 30N	119 47W	4,404	30	45	16	65	31	89	46	69	29	106	-19	30	1.2	1.0	0.7	0.5	0.5	0.4	0.3	0.2	0.2	0.5	0.6	1.1	7.2
Salt Lake City, Utah	40 46N	111 58W	4,220	30	37	18	63	36	94	60	65	38	107	-30	30	1.4	1.2	1.6	1.8	1.4	1.0	0.6	0.9	0.5	1.2	1.3	1.2	14.1
San Francisco, Calif.	37 37N	122 23W	8	30	55	42	64	47	72	54	71	51	106	20	30	4.0	3.5	2.7	1.3	0.5	0.1	*	*	0.2	0.7	1.6	4.1	18.7
Sault Ste. Marie, Mich.	46 28N	84 22W	721	30	23	8	46	30	76	54	55	38	98	-37	30	2.1	1.5	1.8	2.2	2.8	3.3	2.5	2.9	3.8	2.8	3.3	2.3	31.3
Seattle, Wash.	47 27N	122 18W	400	30	44	33	58	40	76	54	60	44	100	0	30	5.7	4.2	3.8	2.4	1.7	1.6	0.8	1.0	2.1	4.0	5.4	6.3	39.0
Sheridan, Wyo.	44 46N	106 58W	3,964	30	34	9	56	31	87	56	62	33	106	-41	30	0.6	0.7	1.4	2.2	2.6	2.6	1.2	0.9	1.2	1.1	0.8	0.6	15.9
Spokane, Wash.	47 38N	117 32W	2,356	30	31	19	59	36	86	55	60	38	108	-30	30	2.4	1.9	1.5	0.9	1.2	1.5	0.4	0.4	0.8	1.6	2.2	2.4	17.2
Washington, D.C.	38 51N	77 03W	14	30	44	30	66	46	87	69	68	50	106	-15	30	3.0	2.5	3.2	3.2	4.1	3.2	4.2	4.9	3.8	3.1	2.8	2.8	40.8
Wilmington, N.C.	34 16N	77 55W	28	30	58	37	74	51	89	71	76	55	104	5	30	2.9	3.4	4.0	2.9	3.5	4.3	7.7	6.9	6.3	3.0	3.1	3.4	51.4

See footnotes at end of table.

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
United States, Alaska:																												
Anchorage	61 13N	149 52W	85	30	21	4	44	28	65	50	42	28	86	-38	30	0.8	0.7	0.5	0.4	0.5	1.0	1.9	2.6	2.5	1.9	1.0	0.9	14.7
Annette	55 02N	131 34W	110	30	38	30	50	37	63	51	51	42	90	- 4	30	11.4	8.5	9.6	9.1	7.1	5.7	6.0	7.5	9.9	16.9	14.7	12.1	118.5
Barrow	71 18N	156 47W	31	30	- 9	-23	7	- 7	45	33	21	12	78	-56	30	0.2	0.2	0.1	0.1	0.1	0.4	0.8	0.9	0.6	0.5	0.2	0.2	4.3
Bethel	60 47N	161 48W	125	30	11	- 4	34	18	62	48	38	25	90	-52	30	1.1	1.1	1.0	0.6	1.0	1.2	2.0	4.2	2.6	1.5	1.1	1.0	18.4
Cold Bay	55 12N	162 43W	96	30	33	23	38	28	54	45	45	36	78	- 9	30	2.3	3.2	1.8	1.5	2.3	2.0	1.8	4.3	4.3	4.6	3.8	2.6	34.5
Fairbanks	64 49N	147 52W	436	30	- 1	-21	42	17	72	48	35	17	99	-66	30	0.9	0.5	0.4	0.3	0.7	1.4	1.8	2.2	1.1	0.9	0.6	0.5	11.3
Juneau	58 22N	134 35W	12	30	30	20	45	31	63	48	47	37	89	-21	30	4.0	3.1	3.3	2.9	3.2	3.4	4.5	5.0	6.7	8.3	6.1	4.2	54.7
King Salmon	58 41N	156 39W	49	30	21	6	41	25	63	47	43	29	88	-40	30	1.1	1.0	1.0	0.6	1.0	1.4	2.1	3.4	3.1	2.2	1.5	1.0	19.4
Nome	64 30N	165 26W	13	30	12	- 3	28	14	55	44	35	24	84	-47	30	1.0	0.9	0.9	0.8	0.7	0.9	2.3	3.8	2.7	1.7	1.2	1.0	17.9
St. Paul Island	57 09N	170 13W	22	30	30	21	33	24	49	42	41	33	64	-26	30	1.8	1.2	1.1	1.0	1.3	1.2	2.3	3.3	3.1	3.2	2.5	1.8	23.8
Shemya	52 43N	174 06E	122	30	34	29	38	33	49	44	42	38	63	16	30	2.5	2.3	2.6	2.1	2.4	1.3	2.2	2.1	2.3	2.8	2.7	2.1	27.4
Yakutat	59 31N	139 40W	28	30	34	20	45	29	61	48	49	35	86	-24	30	10.9	8.2	8.7	7.2	8.0	5.1	8.4	10.9	16.6	19.6	16.1	12.3	132.0
Canada:																												
Aklavik, N.W.T.	68 14N	135 00W	30	22	-10	-26	19	- 2	66	47	25	15	93	-62	22	0.5	0.5	0.4	0.5	0.5	0.8	1.4	1.4	0.9	0.9	0.8	0.4	9.0
Alert, N.W.T.	82 31N	62 20W	95	9	-19	-29	- 8	-18	44	36	2	- 7	67	-53	10	0.2	0.3	0.3	0.3	0.5	0.6	0.5	1.1	1.0	0.9	0.2	0.4	6.3
Calgary, Alta.	51 06N	114 01W	3,540	55	24	2	53	27	76	47	54	29	97	-49	55	0.5	0.5	0.8	1.0	2.3	3.1	2.5	2.3	1.5	0.7	0.7	0.6	16.7
Charlottetown, P.E.I.	46 17N	63 08W	181	65	26	10	43	30	73	58	54	41	98	-27	65	3.8	3.0	3.2	2.8	2.7	2.6	3.0	3.4	3.4	4.1	3.8	4.0	39.8
Chatham, N.B.	47 00N	65 27W	109	50	23	2	47	28	77	56	55	37	102	-43	50	3.4	2.7	3.3	3.0	3.2	3.6	3.9	4.0	3.1	4.0	3.4	3.2	40.8
Churchhill, Man.	58 45N	94 04W	94	30	-11	-27	24	4	64	43	34	20	96	-57	30	0.5	0.6	0.9	0.9	0.9	1.9	2.2	2.7	2.3	1.4	1.0	0.7	16.0
Edmonton, Alta.	53 34N	113 31W	2,219	71	16	- 3	52	28	74	50	51	30	99	-57	71	0.9	0.7	0.7	1.0	1.9	3.2	3.3	2.4	1.3	0.8	0.9	0.9	18.0
Fort Nelson, B.C.	58 50N	122 35W	1,253	12	1	-15	47	25	74	51	43	25	98	-61	13	0.9	1.2	0.7	0.8	1.4	2.5	2.4	1.5	1.3	1.0	1.4	1.2	16.3
Fort Simpson, N.W.T.	61 45N	121 14W	554	42	-10	-27	38	14	74	50	36	21	97	-70	42	0.7	0.7	0.5	0.7	1.4	1.5	2.0	1.5	1.3	1.1	0.9	0.8	13.1
Frobisher Bay, N.W.T.	63 45N	68 33W	110	18	- 9	-23	16	- 1	53	39	29	18	76	-49	10	0.7	0.9	0.8	0.8	0.7	0.9	1.5	2.0	1.8	1.1	1.1	1.0	13.3
Gander, Nfld.	48 57N	54 34W	496	14	27	13	40	27	71	52	51	37	96	-17	14	2.6	3.3	2.8	2.6	2.6	2.8	3.6	3.6	3.7	4.1	4.2	3.7	39.6
Halifax, N.S.	44 39N	63 34W	83	75	32	15	47	31	74	55	57	41	99	-21	71	5.4	4.4	4.9	4.5	4.1	4.0	3.8	4.4	4.1	5.4	5.3	5.4	55.7
Kapuskasing, Ont.	49 25N	82 28W	743	19	10	-14	43	19	75	50	47	31	101	-53	19	2.0	1.1	1.6	1.8	2.1	2.3	3.4	2.9	3.5	2.5	2.4	1.9	27.5
Knob Lake, Que.	54 48N	66 49W	1,712	30	- 3	-21	30	12	64	46	37	25	88	-59	10	1.9	1.9	1.4	1.6	1.7	3.3	3.3	4.4	3.4	2.9	2.4	1.5	29.7
Montreal, Que.	45 30N	73 34W	187	67	21	6	50	33	78	61	54	40	97	-35	77	3.8	3.0	3.5	2.6	3.1	3.4	3.7	3.5	3.7	3.4	3.5	3.6	40.8
North Bay, Ont.	46 21N	79 25W	1,216	17	22	2	48	28	78	56	49	36	99	-46	23	2.0	1.5	1.8	2.2	2.5	3.2	3.2	2.7	3.7	3.2	2.7	2.1	30.8
Ottowa, Ont.	45 19N	75 40W	374	65	21	3	51	31	81	58	54	37	102	-38	65	2.9	2.2	2.8	2.7	2.5	3.5	3.4	2.6	3.2	2.9	3.0	2.6	34.3
Penticton, B.C.	49 28N	119 36W	1,129	32	32	21	61	35	84	53	59	38	105	-16	32	1.0	0.7	0.7	0.7	1.1	1.2	0.8	0.8	1.0	0.8	0.9	1.1	10.8
Port Arthur, Ont.	48 22N	89 19W	644	62	17	- 4	44	26	74	52	50	34	104	-42	59	0.9	0.8	1.0	1.5	2.1	2.8	3.6	2.8	3.4	2.5	1.5	0.9	23.8
Prince George, B.C.	53 53N	122 41W	2,218	27	23	3	54	27	75	44	52	30	102	-58	27	1.8	1.2	1.4	0.8	1.3	2.1	1.6	1.9	2.0	2.0	1.9	1.9	19.9
Prince Rupert, B.C.	54 17N	130 23W	170	26	39	30	50	37	62	49	53	42	90	- 3	26	9.8	7.6	8.4	6.7	5.3	4.1	4.8	5.1	7.7	12.2	12.3	11.3	95.3
Quebec, Que.	46 48N	71 23W	239	72	18	2	44	29	76	57	51	37	97	-34	72	3.5	2.7	3.0	2.4	3.1	3.7	4.0	4.0	3.6	3.4	3.2	3.2	39.8
Regina, Sask.	50 26N	104 40W	1,884	55	10	-11	50	26	79	51	52	27	110	-56	49	0.5	0.3	0.7	0.7	1.8	3.3	2.4	1.8	1.3	0.9	0.6	0.4	14.7
Resolute, N.W.T.	74 43N	94 59W	220	13	-20	-33	- 1	-16	45	35	11	0	61	-61	7	0.1	0.1	0.2	0.2	0.5	0.8	0.9	1.1	0.8	0.5	0.2	0.1	5.5
St. John, N.B.	45 17N	66 04W	119	61	28	11	43	32	69	54	54	41	93	-24	61	4.1	3.1	3.7	3.2	3.1	3.2	3.1	3.6	3.7	4.1	3.9	3.8	42.6
St. Johns, Nfld.	47 32N	52 44W	211	68	30	18	41	29	69	51	53	40	93	-21	58	5.3	5.1	4.6	3.8	3.9	3.1	3.1	4.0	3.7	4.8	5.7	6.0	53.1
Saskatoon, Sask.	52 08N	106 38W	1,690	38	9	-11	49	26	77	52	51	27	104	-55	38	0.9	0.5	0.7	0.7	1.4	2.6	2.4	1.9	1.5	0.9	0.5	0.6	14.6
The Pas, Man.	53 49N	101 15W	890	27	1	-18	45	21	75	54	45	26	100	-54	27	0.6	0.5	0.7	0.8	1.4	2.2	2.2	2.1	2.0	1.2	1.0	0.8	15.5
Toronto, Ont.	43 40N	79 24W	379	105	30	16	50	34	79	59	56	40	105	-26	105	2.7	2.4	2.6	2.5	2.9	2.7	3.0	2.7	2.9	2.4	2.8	2.6	32.2
Vancouver, B.C.	49 17N	123 05W	127	43	41	32	58	40	74	54	57	44	92	2	41	8.6	5.8	5.0	3.3	2.8	2.5	1.2	1.7	3.6	5.8	8.3	8.8	57.4

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Whitehorse, Y.T.	60 43N	135 04W	2,303	10	13	-3	41	22	67	45	41	28	91	-62	10	0.6	0.5	0.6	0.4	0.6	1.0	1.6	1.5	1.3	0.7	1.0	0.8	10.6
Winnipeg, Man.	49 54N	97 14W	783	66	7	-13	48	27	79	55	51	31	108	-54	66	0.9	0.9	1.2	1.4	2.3	3.1	3.1	2.5	2.3	1.5	1.1	0.9	21.2
Yellow Knife, N.W.T.	62 28N	114 27W	674	13	-8	-23	29	9	69	52	36	26	90	-60	13	0.8	0.6	0.7	0.4	0.7	0.6	1.5	1.4	1.0	1.3	1.0	0.8	10.8
Greenland:																												
Angmagssalik	65 36N	37 33W	95	30	23	10	35	16	54	37	35	25	77	-26	38	2.9	2.4	2.6	2.1	2.0	1.8	1.5	2.1	3.3	4.7	3.0	2.7	31.1
Danmarkshaven	76 46N	19 00W	7	2	-1	-15	6	-13	47	34	13	2	63	-42	2	1.2	0.7	0.7	0.1	0.2	0.2	0.5	0.6	0.3	0.3	1.0	0.7	6.0
Eismitte	70 53N	40 42W	9,843	1	-33	-53	-14	-37	19	1	-23	-42	27	-85	1	0.6	0.2	0.3	0.2	0.1	0.1	0.1	0.4	0.3	0.5	0.5	1.0	4.3
Godthaab	64 10N	51 43W	66	40	19	10	31	20	52	38	35	26	76	-20	45	1.4	1.7	1.6	1.2	1.7	1.4	2.2	3.1	3.3	2.5	1.9	1.5	23.5
Ivigtut	61 12N	48 10W	98	48	24	12	38	24	57	42	40	29	86	-20	50	3.3	2.6	3.4	2.5	3.5	3.2	3.1	3.7	5.9	5.7	4.6	3.1	44.6
Jacobshavn	69 13N	51 02W	104	32	8	-7	24	6	51	40	31	20	71	-46	52	0.4	0.4	0.5	0.5	0.6	0.8	1.2	1.4	1.3	0.9	0.7	0.5	9.2
Nord	81 36N	16 40W	118	8	-15	-28	-5	-18	44	35	3	-6	61	-60	8	0.8	0.8	0.5	0.3	0.1	0.3	1.0	1.4	1.2	0.6	1.4	0.5	8.9
Scoresbysund	70 29N	21 58W	56	12	12	-3	22	6	49	36	25	15	63	-42	12	1.8	1.4	0.9	1.4	0.4	0.8	1.5	0.7	1.7	1.4	1.1	1.9	15.0
Thule	76 31N	68 44W	251	12	-4	-17	10	-7	46	38	19	8	63	-44	12	0.4	0.3	0.2	0.2	0.3	0.2	0.7	0.6	0.6	0.7	0.5	0.2	4.9
Upernivik	72 47N	56 07W	59	40	-1	-13	15	-1	48	35	29	21	69	-44	50	0.4	0.5	0.7	0.6	0.6	0.5	0.9	1.1	1.1	1.1	1.1	0.6	9.2
Mexico:																												
Acapulco	16 50N	99 56W	10	8	85	70	87	71	89	75	88	74	97	60	40	0.3	*	0.0	*	1.4	12.8	9.1	9.3	13.9	6.7	1.2	0.4	55.1
Chihuahua	28 42N	105 57W	4,429	9	65	36	81	51	89	66	79	51	102	12	22	0.2	0.4	0.3	0.2	0.2	1.7	3.6	3.7	3.3	0.9	0.5	0.4	15.4
Guadalajara	20 41N	103 20W	5,194	26	73	45	85	53	79	60	78	56	101	26	33	0.4	0.2	0.2	0.2	1.1	8.8	9.4	8.5	7.2	2.2	0.8	0.7	39.7
Guaymas	27 57N	110 55W	58	9	74	57	84	65	96	82	91	75	117	41	41	0.5	0.2	0.2	0.1	*	0.1	1.7	2.7	2.1	0.7	0.3	0.8	9.4
La Paz	24 07N	110 17W	85	9	74	54	86	58	96	73	90	68	108	31	12	0.2	0.1	0.0	0.0	0.0	0.2	0.4	1.2	1.4	0.6	0.5	1.1	5.7
Lerdo	25 30N	103 32W	3,740	10	72	45	86	57	90	68	82	58	105	23	14	0.4	0.1	0.2	0.3	0.8	1.5	1.5	1.3	2.0	0.8	0.8	0.5	10.2
Manzanillo	19 04N	104 20W	26	17	86	68	87	67	93	76	91	76	103	54	17	0.1	0.2	*	0.0	0.1	4.7	5.7	6.4	14.5	5.1	0.9	1.8	39.5
Mazatlan	23 11N	106 25W	256	10	71	61	76	65	86	77	85	76	93	52	46	0.8	0.5	0.2	0.1	0.1	1.5	5.9	8.3	8.0	2.6	0.9	1.3	30.2
Merida	20 58N	89 38W	72	22	83	62	92	69	92	73	87	71	106	51	40	1.2	0.9	0.7	0.8	3.2	5.6	5.2	5.6	6.8	3.8	1.3	1.3	36.5
Mexico City	19 26N	99 04W	7,340	42	66	42	78	52	74	54	70	50	92	24	48	0.2	0.3	0.5	0.7	1.9	4.1	4.5	4.3	4.1	1.6	0.5	0.3	23.0
Monterrey	25 40N	100 18W	1,732	11	68	48	84	62	90	71	80	64	107	25	33	0.6	0.7	0.8	1.3	1.3	3.0	2.3	2.4	5.2	3.0	1.5	0.8	22.9
Salina Cruz	16 12N	95 12W	184	10	85	72	88	76	89	76	87	75	98	62	22	*	0.4	0.6	0.5	3.3	11.6	4.5	5.5	7.1	4.0	0.9	0.1	38.5
Tampico	22 16N	97 51W	78	12	75	59	83	69	89	75	85	71	104	34	12	1.5	1.2	1.0	1.5	1.9	8.7	4.9	4.8	10.8	5.0	2.0	1.6	44.9
Vera Cruz	19 12N	96 08W	52	10	77	66	83	72	87	74	85	73	98	53	40	0.9	0.6	0.6	0.8	2.6	10.4	4.1	11.1	13.9	6.9	3.0	1.0	65.7
CENTRAL AMERICA																												
British Honduras:																												
Belize	17 31N	88 11W	17	27	81	67	86	74	87	75	86	72	97	49	33	5.4	2.4	1.5	2.2	4.3	7.7	6.4	6.7	9.6	12.0	8.9	7.3	74.4
Canal Zone:																												
Balboa Heights	08 57N	79 33W	118	34	88	71	90	74	87	74	85	73	97	63	46	1.0	0.4	0.7	2.9	8.0	8.4	7.1	7.9	8.2	10.1	10.2	4.8	69.7
Cristobal	09 21N	79 54W	35	36	84	76	86	77	85	76	86	75	97	66	73	3.4	1.5	1.5	4.1	12.5	13.9	15.6	15.3	12.7	15.8	22.3	11.7	130.3
Costa Rica:																												
San Jose	09 56N	84 08W	3,760	8	75	58	79	62	77	62	77	60	92	49	34	0.6	0.2	0.8	1.8	9.0	9.5	8.3	9.5	12.0	11.8	5.7	1.6	70.8
El Salvador:																												
San Salvador	13 42N	89 13W	2,238	39	90	60	93	65	89	65	87	65	105	45	39	0.3	0.2	0.4	1.7	7.7	12.9	11.5	11.7	12.1	9.5	1.6	0.4	70.0
Guatemala:																												
Guatemala City	14 37N	90 31W	4,855	6	73	53	82	58	78	60	76	60	90	41	29	0.3	0.1	0.5	1.2	6.0	10.8	8.0	7.8	9.1	6.8	0.9	0.3	51.8
Honduras:																												
Tela	15 46N	87 27W	41	4	82	67	87	72	88	73	86	71	96	58	20	8.9	5.1	2.6	3.3	4.3	5.0	6.4	9.4	7.7	13.5	15.9	14.0	96.1

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
WEST INDIES																												
Bridgetown, Barbados	13 08N	59 36W	181	35	83	70	86	72	86	74	86	73	95	61	22	2.6	1.1	1.3	1.4	2.3	4.4	5.8	5.8	6.7	7.0	8.1	3.8	50.3
Camp Jacob, Guadaloupe	16 01N	61 42W	1,750	19	77	64	79	65	81	68	81	68	92	54	21	9.2	6.1	8.1	7.3	11.5	14.1	17.6	15.3	16.4	12.4	12.3	10.1	140.4
Ciudad Trujillo, Dominican Rep.	18 29N	69 54W	57	26	84	66	85	69	88	72	87	72	98	59	25	2.4	1.4	1.9	3.9	6.8	6.2	6.4	6.3	7.3	6.0	4.8	2.4	55.8
Fort-de-France, Martinique	14 37N	61 05W	13	22	83	69	86	71	86	74	87	73	96	56	31	4.7	4.3	2.9	3.9	4.7	7.4	9.4	10.3	9.3	9.7	7.9	5.9	80.4
Hamilton, Bermuda	32 17N	64 46W	151	59	68	58	71	59	85	73	79	69	99	40	62	4.4	4.7	4.8	4.1	4.6	4.4	4.5	5.4	5.2	5.8	5.0	4.7	57.6
Havana, Cuba	23 08N	82 21W	80	25	79	65	84	69	89	75	85	73	104	43	72	2.8	1.8	1.8	2.3	4.7	6.5	4.9	5.3	5.9	6.8	3.1	2.3	48.2
Kingston, Jamaica	17 58N	76 48W	110	33	86	67	87	70	90	73	88	73	97	56	59	0.9	0.6	0.9	1.2	4.0	3.5	1.5	3.6	3.9	7.1	2.9	1.4	31.5
La Guerite, St. Christopher (St. Kitts)	17 20N	62 45W	157	19	80	71	83	73	86	76	85	75	91	61	21	4.1	2.0	2.3	2.3	3.8	3.6	4.4	5.2	6.0	5.4	7.3	4.5	50.9
Nassau, Bahamas	25 05N	77 21W	12	35	77	65	81	69	88	75	85	73	94	41	57	1.4	1.5	1.4	2.5	4.6	6.4	5.8	5.3	6.9	6.5	2.8	1.3	46.4
Port-au-Prince, Haiti	18 33N	72 20W	121	42	87	68	89	71	94	74	90	72	101	58	70	1.3	2.3	3.4	6.3	9.1	4.0	2.9	5.7	6.9	6.7	3.4	1.3	53.3
Saint Clair, Trinidad	10 40N	61 31W	67	49	87	69	90	69	88	71	89	71	101	52	97	2.7	1.6	1.8	2.1	3.7	7.6	8.6	9.7	7.6	6.7	7.2	4.9	64.2
Saint Thomas, Virgin Is.	18 20N	64 58W	11	9	82	71	85	74	88	77	87	76	92	63	9	2.5	1.9	1.7	2.2	4.6	3.2	3.2	4.1	6.9	5.6	3.9	3.9	43.7
San Juan, Puerto Rico	18 26N	66 00W	13	30	81	67	84	69	87	74	87	73	94	60	30	4.7	2.9	2.2	3.7	7.1	5.7	6.3	7.1	6.8	5.8	6.5	5.4	64.2
SOUTH AMERICA																												
Argentina:																												
Bahia Blanca	38 43S	62 16W	95	33	88	62	71	51	57	39	71	48	109	18	46	1.7	2.2	2.5	2.3	1.2	0.9	1.0	1.0	1.6	2.2	2.1	1.9	20.6
Buenos Aires	34 35S	58 29W	89	23	85	63	72	53	57	42	69	50	104	22	70	3.1	2.8	4.3	3.5	3.0	2.4	2.2	2.4	3.1	3.4	3.3	3.9	37.4
Cipolletti	38 57S	67 59W	889	9	89	56	72	40	55	29	72	43	107	9	24	0.4	0.4	0.7	0.4	0.6	0.6	0.5	0.3	0.6	0.9	0.5	0.5	6.4
Corrientes	27 28S	58 50W	177	39	93	71	81	63	71	53	82	60	112	30	40	4.7	4.5	5.3	5.6	3.3	1.9	1.7	1.5	2.8	4.7	5.2	5.2	46.4
La Quiaca	22 06S	65 36W	11,345	23	70	41	69	32	60	16	71	32	95	0	25	3.5	2.6	1.8	0.3	*	0.0	*	*	0.1	0.3	1.0	2.7	12.3
Mendoza	32 53S	68 49W	2,625	23	90	60	73	47	59	35	76	50	109	15	46	0.9	1.2	1.1	0.5	0.4	0.3	0.2	0.3	0.5	0.7	0.7	0.7	7.5
Parana	31 44S	60 31W	210	12	91	67	77	58	62	45	75	54	113	21	23	3.1	3.1	3.9	4.9	2.6	1.2	1.2	1.6	2.4	2.8	3.7	4.5	35.0
Puerto Madryn	42 47S	65 01W	26	50	81	57	70	46	55	36	68	45	104	10	50	0.4	0.6	0.7	0.5	0.9	0.6	0.6	0.4	0.6	0.7	0.4	0.6	7.0
Santa Cruz	50 01S	68 32W	39	12	70	48	57	39	41	28	58	39	94	1	20	0.6	0.3	0.3	0.6	0.4	0.5	0.4	0.5	0.3	0.3	0.4	0.7	5.3
Santiago del Estero	27 46S	64 18W	653	28	97	69	82	59	70	44	87	59	116	19	20	3.4	3.0	3.0	1.3	0.6	0.3	0.2	0.2	0.5	1.4	2.5	4.1	20.4
Ushuaia	54 50S	68 20W	26	16	57	41	48	33	39	25	52	35	85	- 6	21	2.0	2.6	1.9	2.1	1.5	1.2	1.2	1.1	1.3	1.6	1.5	1.9	19.9
Bolivia:																												
Concepcion	16 15S	62 03W	1,607	5	85	66	86	62	81	54	88	62	101	32	16	7.2	4.7	4.4	1.8	2.0	1.5	1.1	0.9	1.2	2.9	5.0	5.9	38.6
La Paz	16 30S	68 08W	12,001	31	63	43	65	40	62	33	66	40	80	26	50	4.5	4.2	2.6	1.3	0.5	0.3	0.4	0.5	1.1	1.6	1.9	3.7	22.6
Sucre	19 03S	65 17W	9,344	5	63	48	63	45	61	37	65	46	88	25	52	7.3	4.9	3.7	1.6	0.2	0.1	0.2	0.3	1.0	1.6	2.6	4.3	27.8
Brazil:																												
Barra do Corda	05 35S	45 28W	266	9	89	71	89	71	92	64	94	72	103	45	9	6.7	8.7	8.0	6.1	2.3	1.0	0.7	0.7	1.0	2.5	3.9	5.7	47.2
Bela Vista	22 06S	56 22W	525	13	91	67	85	61	77	49	87	61	108	20	20	6.6	4.9	4.4	4.3	5.0	2.8	1.3	1.8	2.9	5.4	5.8	7.0	52.2
Belem	01 27S	48 29W	42	16	87	72	87	73	88	71	89	71	98	61	20	12.5	14.1	14.1	12.6	10.2	6.7	5.9	4.4	3.5	3.3	2.6	6.1	96.0
Brasilia	15 51S	47 56W	3,481	3	80	65	82	62	78	51	82	64	93	46	3	9.0	7.8	4.8	3.4	1.4	*	0.0	*	1.3	4.9	9.7	11.7	54.0
Conceicao do Araguaia	08 15S	49 12W	53	5	88	70	91	68	95	63	93	68	102	55	5	14.9	12.1	10.8	4.1	1.9	0.4	*	0.5	1.5	6.6	4.9	8.6	66.2
Corumba	19 00S	57 39W	381	8	94	73	92	73	84	64	93	70	106	33	11	7.3	5.9	5.1	4.6	2.9	1.9	0.3	1.2	2.6	4.0	5.6	7.1	48.5
Florianopolis	27 35S	48 33W	96	17	83	72	74	64	68	57	73	63	102	32	25	7.6	5.6	6.3	4.1	3.6	3.5	2.2	3.7	4.3	5.1	3.5	4.3	53.1
Goias	15 58S	50 04W	1,706	11	86	63	91	63	89	56	94	63	104	41	11	12.5	9.9	10.2	4.6	0.4	0.3	0.0	0.3	2.3	5.3	9.4	9.5	64.8
Guarapuava	25 16S	51 30W	3,592	10	79	61	73	55	66	47	74	53	94	23	5	8.7	5.8	5.4	4.5	4.6	6.5	2.7	3.6	4.6	6.9	6.6	6.1	65.8
Manaus	03 08S	60 01W	144	11	88	75	87	75	89	75	92	76	101	63	25	9.8	9.1	10.3	8.7	6.7	3.3	2.3	1.5	1.8	4.2	5.6	8.0	71.3

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Natal	05 46S	35 12W	52	18	87	76	86	73	82	69	85	75	100	61	18	1.9	4.8	7.0	9.2	7.1	8.7	7.7	3.8	1.4	0.8	0.7	1.1	54.2
Parana	12 26S	48 06W	853	19	90	58	90	58	91	48	94	58	105	37	19	11.3	9.3	9.4	4.0	0.5	*	0.1	0.2	1.1	5.0	9.1	12.2	62.3
Porto Alegre	30 02S	51 13W	33	22	87	67	78	60	66	49	74	57	105	25	22	3.5	3.2	3.9	4.1	4.5	5.1	4.5	5.0	5.2	3.4	3.1	3.5	49.1
Quixeramobim	05 12S	39 18W	653	9	92	79	86	76	88	74	93	77	100	63	13	0.7	5.0	6.6	5.0	7.0	1.7	0.7	0.6	0.4	0.6	0.7	0.6	29.6
Recife	08 04S	34 53W	97	27	86	77	85	75	80	71	84	75	94	50	56	2.1	3.3	6.3	8.7	10.5	10.9	10.0	6.0	2.5	1.0	1.0	1.1	63.4
Rio de Janeiro	22 55S	43 12W	201	38	84	73	80	69	75	63	77	66	102	46	84	4.9	4.8	5.1	4.2	3.1	2.1	1.6	1.7	2.6	3.1	4.1	5.4	42.6
Salvador (Bahia)	13 00S	38 30W	154	25	86	74	84	74	79	69	83	71	100	50	20	2.6	5.3	6.1	11.2	10.8	9.4	7.2	4.8	3.3	4.0	4.5	5.6	74.8
Santarem	02 30S	54 42W	66	22	86	73	85	73	87	71	91	73	99	65	22	6.8	10.9	13.2	12.9	11.3	6.9	4.1	1.7	1.5	1.9	2.3	4.1	77.9
Sao Paulo	23 37S	46 39W	2,628	44	77	63	73	59	66	53	68	57	100	32	24	8.8	7.8	6.0	2.2	3.0	2.4	1.5	2.1	3.5	4.6	6.0	9.4	57.3
Sena Madureira	09 04S	68 39W	443	12	92	69	91	68	91	63	93	69	100	41	17	11.2	11.3	10.2	9.4	4.1	2.2	1.1	1.5	4.0	7.0	7.5	11.7	81.2
Uaupes	00 08S	67 05W	272	15	88	72	88	72	85	70	89	71	100	52	10	10.3	7.7	10.0	10.6	12.0	9.2	8.8	7.2	5.1	6.9	7.2	10.4	105.4
Uruguaiana	29 46S	57 07W	246	15	91	69	78	59	66	48	77	55	108	27	12	3.6	3.6	5.6	5.1	3.7	4.2	3.2	2.8	3.6	4.1	2.9	4.1	46.6
Chile:																												
Ancud	41 47S	73 52W	184	30	62	51	57	47	50	42	55	45	82	30	46	3.1	3.7	5.3	7.4	9.9	11.0	10.3	9.4	6.5	4.2	4.7	4.6	80.1
Antofagasta	23 42S	70 24W	308	22	76	63	70	58	63	51	66	55	86	37	32	0.0	0.0	0.0	*	*	0.1	0.2	0.1	*	0.1	*	0.0	0.5
Arica	18 28S	70 20W	95	15	78	64	74	60	66	54	69	58	93	39	25	*	-0.0	0.0	0.0	0.0	0.0	0.0	*	0.0	0.0	0.0	*	*
Cabo Raper	46 50S	75 38W	131	8	58	46	54	44	47	38	51	40	72	28	10	7.8	5.8	7.1	7.7	7.5	7.9	9.5	7.5	5.6	7.0	6.7	7.0	87.1
Los Evangelistas	52 23S	75 07W	190	16	50	44	48	41	43	36	45	39	66	19	27	11.7	10.0	11.3	11.4	9.6	9.4	9.4	8.6	9.2	8.8	9.9	10.1	119.4
Potrerillos	26 30S	69 27W	9,350	7	65	49	63	47	57	40	61	44	75	20	7	*	*	0.3	*	0.7	*	0.5	0.3	0.2	0.2	0.0	*	2.2
Puerto Aisen	42 24S	72 42W	33	8	63	50	55	43	45	37	55	42	93	18	11	7.8	7.8	8.3	7.5	14.7	10.4	11.1	11.1	6.5	7.8	7.0	7.9	107.9
Punta Arenas	53 10S	70 54W	26	15	58	45	50	39	40	31	51	38	86	11	15	1.5	0.9	1.3	1.4	1.3	1.6	1.1	1.2	0.9	1.1	0.7	1.4	14.4
Santiago	33 27S	70 42W	1,706	14	85	53	74	45	59	37	72	45	99	24	58	0.1	0.1	0.2	0.5	2.5	3.3	3.0	2.2	1.2	0.6	0.3	0.2	14.2
Valdivia	39 48S	73 14W	16	29	73	52	62	46	52	41	63	44	97	19	60	2.6	2.9	5.2	9.2	14.2	17.7	15.5	12.9	8.2	5.0	4.9	4.1	102.4
Valparaiso	33 01S	71 38W	135	30	72	56	67	52	60	47	65	50	94	32	41	0.1	*	0.3	0.6	4.1	5.9	3.9	2.9	1.3	0.4	0.2	0.2	19.9
Colombia:																												
Andagoya	05 06N	76 40W	197	8	90	75	90	75	89	74	90	74	97	62	15	25.0	21.4	19.5	26.1	25.5	25.8	23.3	25.3	24.6	22.7	22.4	19.5	281.1
Bogota	04 42N	74 08W	8,355	10	67	48	67	51	64	50	66	50	75	30	49	2.3	2.6	4.0	5.8	4.5	2.4	2.0	2.2	2.4	6.3	4.7	2.6	41.8
Cartagena	10 28N	75 30W	39	6	84	73	87	76	88	78	87	77	98	61	10	0.4	0.0	0.4	0.9	3.4	3.4	3.0	0.6	0.5	10.8	8.9	4.5	36.8
Ipiales	00 50N	77 42W	9,680	9	61	50	60	49	57	42	62	49	77	32	13	3.1	2.3	3.5	3.5	2.8	1.9	1.3	1.1	1.4	3.1	3.3	2.6	29.9
Tumaco	01 49N	78 45W	7	10	82	75	84	76	82	75	82	75	90	64	10	16.9	11.7	9.6	14.6	17.4	12.0	7.7	7.3	7.3	5.9	4.9	7.0	122.3
Ecuador:																												
Cuenca	02 53S	78 39W	8,301	7	69	50	69	50	65	47	70	49	81	29	10	2.0	1.8	3.2	4.3	4.3	1.7	0.9	1.1	1.6	3.1	1.8	2.5	28.3
Guayaquil	02 10S	79 53W	20	5	87	72	88	72	84	67	86	68	98	52	10	8.3	11.4	11.5	8.1	2.1	0.4	0.2	*	*	*	0.1	1.1	43.2
Quito	00 08S	78 29W	9,222	54	67	46	69	47	71	44	71	46	86	25	33	3.9	4.4	5.6	6.9	5.4	1.7	0.8	1.2	2.7	4.4	3.8	3.1	43.9
French Guiana:																												
Cayenne	04 56N	52 27W	20	38	84	74	86	75	88	73	91	74	97	65	51	14.4	12.3	15.8	18.9	21.7	15.5	6.9	2.8	1.2	1.3	4.6	10.7	126.1
Guyana:																												
Georgetown	06 50N	58 12W	6	54	84	74	85	76	85	75	87	76	93	68	35	8.0	4.5	6.9	5.5	11.4	11.9	10.0	6.9	3.2	3.0	6.1	11.3	88.7
Lethem	03 24N	59 38W	270	3	91	73	91	74	87	73	92	76	97	63	9	1.2	1.4	1.3	5.7	11.5	11.9	14.8	9.4	3.4	2.3	4.3	1.3	68.5
Paraguay:																												
Asuncion	25 17S	57 30W	456	15	95	71	84	65	74	53	86	62	110	29	30	5.5	5.1	4.3	5.2	4.6	2.7	2.2	1.5	3.1	5.5	5.9	6.2	51.8
Bahia Negra	20 14S	58 10W	318	20	92	74	87	68	79	61	90	69	106	35	20	5.4	5.3	4.9	2.9	2.3	1.6	1.5	0.6	2.3	4.2	5.3	4.3	40.6

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Peru:																												
Arequipa	16 21S	71 34W	8,460	13	67	49	67	48	67	47	68	47	82	25	37	1.3	1.8	0.7	0.2	*	*	*	*	0.0	*	*	0.4	4.4
Cajamarca	07 09S	78 30W	8,662	9	71	48	70	47	70	41	71	47	79	25	9	3.6	4.2	4.6	3.4	1.7	9.5	9.2	9.3	2.3	2.3	1.9	3.2	28.2
Cusco	13 33S	71 59W	10,866	13	68	45	71	40	70	31	72	43	86	16	12	6.4	5.9	4.3	2.0	0.6	0.2	0.2	0.4	1.0	2.6	3.0	5.4	32.0
Iquitos	03 45S	73 13W	384	5	90	71	87	71	88	68	90	70	100	54	5	9.1	10.4	9.4	13.6	10.7	5.7	6.4	5.2	10.5	7.3	9.1	10.3	107.7
Lima	12 05S	77 03W	394	15	82	66	80	63	67	57	71	58	93	49	15	0.1	*	*	*	0.2	0.2	0.3	0.3	0.3	0.1	0.1	*	1.6
Mollendo	17 00S	72 07W	80	10	79	66	76	63	67	57	70	59	90	50	10	*	0.1	*	*	0.1	0.1	*	0.2	0.2	0.1	0.1	*	0.9
Surinam:																												
Paramaribo	05 49N	55 09W	12	35	85	72	86	73	87	73	91	73	99	62	75	8.4	6.5	7.9	9.0	12.2	11.9	9.1	6.2	3.1	3.0	4.9	8.8	91.0
Uruguay:																												
Artigas	30 24S	56 23W	384	13	91	65	77	55	65	45	75	54	107	24	50	4.3	3.9	4.7	5.1	4.1	4.1	2.8	3.0	4.0	4.7	3.8	4.1	48.6
Montevideo	34 52S	56 12W	72	56	83	62	71	53	58	43	68	49	109	25	56	2.9	2.6	3.9	3.9	3.3	3.2	2.9	3.1	3.0	2.6	2.9	3.1	37.4
Venezuela:																												
Caracas	10 30N	66 56W	3,418	30	75	56	81	60	78	61	79	61	91	45	46	0.9	0.4	0.6	1.3	3.1	4.0	4.3	4.3	4.2	4.3	3.7	1.8	32.9
Ciudad Bolivar	08 07N	63 32W	197	10	90	72	93	75	90	75	93	75	100	64	10	1.4	0.8	0.7	1.0	3.8	5.5	6.3	7.1	3.6	4.0	2.8	1.3	38.3
Maracaibo	10 39N	71 36W	20	12	90	73	92	76	94	76	92	76	102	66	36	0.1	*	0.3	0.8	2.7	2.2	1.8	2.2	2.8	5.9	3.3	0.6	22.7
Merida	08 36N	71 10W	5,293	14	73	56	75	60	76	59	75	60	90	48	14	2.5	1.5	3.6	6.7	9.8	7.3	4.7	5.7	6.7	9.5	8.2	3.4	69.7
Santa Elena	04 36N	61 07W	2,976	10	82	61	82	63	81	61	84	61	95	48	10	3.2	3.2	3.2	5.7	9.6	9.5	9.1	7.6	5.3	4.9	4.9	4.5	70.7
PACIFIC ISLANDS																												
Easter Is. (Isla de Pascua)	27 10S	109 26W	98	4	77	64	78	63	70	58	73	58	88	46	10	4.8	3.7	4.6	4.2	4.6	4.3	3.5	3.0	2.7	3.7	4.6	4.9	48.6
Mas a Tierra (Juan Fernandez)	33 37S	78 52W	20	25	72	60	68	57	60	50	61	51	86	39	29	0.8	1.2	1.6	3.4	5.9	6.4	5.8	4.4	2.9	1.9	1.6	1.0	36.9
Seymour Is. (Galapagos Is.)	00 28S	90 18W	36	3	86	72	87	75	81	69	81	67	93	58	3	0.8	1.4	1.1	0.7	*	*	*	*	*	*	*	*	4.0
ATLANTIC ISLANDS																												
Fernando de Noronha	03 50S	32 25W	148	32	84	75	82	75	81	73	82	75	93	63	32	1.7	4.7	7.4	10.5	10.5	7.3	5.4	1.9	0.7	0.3	0.4	0.5	51.3
Cumberland Bay, South Georgia	54 16S	36 30W	8	23	48	35	42	29	34	23	41	28	84	- 3	24	3.3	4.3	5.3	5.4	5.2	4.9	5.5	5.3	3.5	2.6	3.4	3.0	51.7
Laurie Is., South Orkneys	60 44S	44 44W	13	48	35	29	31	21	20	4	30	19	54	-40	46	1.4	1.5	1.9	1.6	1.2	1.0	1.3	1.3	1.1	1.1	1.3	1.0	15.7
Stanley, Falkland Isles	51 42S	57 51W	6	25	56	42	49	37	40	31	48	35	76	12	41	2.8	2.3	2.5	2.6	2.6	2.1	2.0	2.0	1.5	1.6	2.0	2.8	26.8
									EUROPE																			
Albania:																												
Durres	41 19N	19 28E	23	10	51	42	63	55	83	74	68	58	95	21	10	3.0	3.3	3.9	2.2	1.6	1.9	0.5	1.9	1.7	7.1	8.5	7.3	42.9
Andorra:																												
Les Escaldes	42 30N	01 31E	3,543	5	43	29	59	39	78	55	61	42	91	0	9	1.5	1.7	2.9	2.4	4.7	3.1	2.2	3.4	3.1	3.5	3.3	2.5	34.3
Austria:																												
Innsbruck	47 16N	11 24E	1,909	34	34	20	60	39	78	55	58	40	97	-16	35	2.1	1.8	1.5	2.2	2.9	4.1	5.1	4.5	3.1	2.4	2.2	1.9	33.8
Vienna (Wien)	48 15N	16 22E	664	50	34	26	57	41	75	59	55	44	98	-14	100	1.5	1.4	1.8	2.0	2.8	2.7	3.0	2.7	2.0	2.0	1.9	1.8	25.6
Bulgaria:																												
Sofiya (Sofia)	42 42N	23 20E	1,805	30	34	22	62	41	82	57	63	42	99	-17	27	1.3	1.1	1.7	2.3	3.3	3.2	2.4	2.0	2.3	2.1	1.9	1.4	25.0
Varna	43 12N	27 55E	115	30	40	30	59	43	84	63	67	50	107	-12	20	1.5	0.9	1.2	1.2	1.8	2.6	1.9	1.2	1.5	1.9	1.9	2.0	19.6
Cyprus:																												
Nicosia	35 09N	33 17E	716	40	58	42	74	50	97	69	81	58	116	23	64	2.9	2.0	1.3	0.8	1.1	0.4	*	*	0.2	0.9	1.7	3.0	14.6

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
					Average daily								Extreme															
					Jan		Apr		July		Oct																	
				Length of record	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Czechoslovakia:																												
Praha (Prague)	50 05N	14 25E	662	40	34	25	55	40	74	58	54	44	98	-16	70	0.9	0.8	1.1	1.5	2.4	2.8	2.6	2.2	1.7	1.2	1.2	0.9	19.3
Prerov	49 27N	17 27E	702	20	34	25	57	38	77	55	56	40	100	-23	21	1.3	1.1	1.1	2.0	2.4	2.9	3.5	3.2	2.0	2.4	1.5	1.4	24.8
Denmark:																												
Copenhagen (Kobenhavn)	55 41N	12 33E	43	30	36	29	50	37	72	55	53	42	91	- 3	30	1.6	1.3	1.2	1.7	1.7	2.1	2.2	3.2	1.9	2.1	2.2	2.1	23.3
Aarhus	56 08N	10 12E	161	21	35	27	51	37	70	54	53	42	87	-12	21	2.3	1.5	1.4	1.8	1.2	2.2	2.5	3.3	3.2	2.6	2.5	2.1	26.6
Finland:																												
Helsinki	60 10N	24 57E	30	20	27	17	43	31	71	57	45	37	89	-23	50	2.2	1.7	1.7	1.7	1.9	2.0	2.3	3.3	2.8	2.9	2.7	2.4	27.6
Kuusamo	65 57N	29 12E	843	20	17	2	35	18	68	50	36	27	90	-40	20	1.1	1.1	1.1	1.1	1.4	2.3	2.8	3.0	2.1	2.1	1.6	1.1	20.8
Vaasa	63 05N	21 36E	13	18	26	16	41	28	69	55	44	36	89	-29	19	1.1	0.8	0.8	1.0	1.4	1.8	2.4	2.5	2.7	2.3	1.7	1.1	19.6
France:																												
Ajaccio (Corsica)	41 52N	08 35E	243	46	56	40	66	48	85	64	72	55	103	23	86	3.0	2.3	2.6	2.2	1.6	0.9	2.8	0.7	1.7	3.8	4.4	3.1	29.1
Bordeaux	44 50N	00 43W	157	51	48	35	63	44	80	58	66	47	102	9	47	2.7	2.8	2.9	2.6	2.5	2.3	2.0	1.9	2.2	3.0	3.9	3.9	32.7
Brest	48 19N	04 47W	56	56	49	40	57	44	70	56	61	49	95	7	56	3.5	3.0	2.5	2.5	1.9	2.0	2.0	2.2	2.3	3.6	4.2	4.4	34.1
Cherbourg	49 39N	01 38W	30	47	47	40	54	43	67	57	59	50	91	14	47	3.3	2.9	2.7	2.0	1.9	1.8	1.9	3.0	2.9	4.6	5.1	5.2	37.3
Lille	50 35N	03 05W	141	40	42	33	58	40	75	55	59	45	96	0	40	2.5	1.9	2.5	2.0	2.4	2.2	2.8	2.3	2.6	3.0	3.0	3.2	30.3
Lyon	45 42N	04 47E	938	70	41	30	61	42	80	58	61	45	105	-13	70	1.4	1.4	1.8	2.1	2.8	2.9	2.8	2.9	3.1	3.1	2.6	1.9	28.8
Marseille	43 18N	05 23E	246	72	53	38	59	41	78	58	76	57	101	9	102	1.9	1.5	1.8	2.0	1.9	1.0	0.6	0.9	2.6	3.7	3.1	2.2	23.2
Paris	48 49N	02 29E	164	66	42	32	60	41	76	55	59	44	105	1	118	1.5	1.3	1.5	1.7	2.0	2.1	2.1	2.0	2.0	2.2	2.0	1.9	22.3
Strasbourg	48 35N	07 46E	465	20	40	31	59	41	78	57	58	43	101	- 8	20	1.6	1.4	1.7	2.6	2.6	3.1	3.4	3.4	3.1	2.7	2.0	1.9	29.5
Toulouse	43 33N	01 23E	538	47	47	35	62	43	82	59	66	48	111	1	47	1.9	1.7	2.3	2.7	2.9	2.4	1.5	2.1	2.3	2.2	2.4	2.3	26.7
Germany:																												
Berlin	52 27N	13 18E	187	50	35	26	55	38	74	55	55	41	96	-15	40	1.9	1.3	1.5	1.7	1.9	2.3	3.1	2.2	1.9	1.7	1.7	1.9	23.1
Bremen	53 05N	08 47E	52	50	37	30	53	38	71	55	54	43	94	- 7	80	1.9	1.6	1.8	1.5	2.1	2.6	3.2	2.8	2.1	2.2	2.0	2.2	26.0
Frankfurt A/M	50 07N	08 40E	338	50	37	29	58	41	75	56	56	43	100	- 7	80	1.7	1.3	1.6	1.5	2.0	2.5	2.8	2.6	1.9	2.2	2.0	2.0	24.1
Hamburg	53 33N	09 58E	66	50	35	28	51	39	69	56	53	44	92	- 4	80	2.1	1.9	2.0	1.8	2.1	2.7	3.4	3.2	2.5	2.6	2.1	2.5	28.9
Munchen (Munich)	48 09N	11 34E	1,739	50	33	23	54	37	72	54	53	40	92	-14	80	1.7	1.4	1.9	2.7	3.7	4.6	4.7	4.2	3.2	2.2	1.9	1.9	34.1
Munster	51 58N	07 38E	207	50	39	29	56	38	73	54	56	42	96	-17	40	2.6	1.9	2.2	2.0	2.2	2.7	3.3	3.1	2.5	2.7	2.4	2.9	30.5
Nurnberg	49 27N	11 03E	1,050	50	35	26	56	38	74	55	55	41	99	-18	80	1.5	1.2	1.3	1.7	2.2	2.5	3.1	3.1	2.1	2.1	1.9	1.7	24.4
Gibraltar:																												
Windmill Hill	36 06N	05 21W	400	12	58	50	64	55	77	66	70	61	97	35	12	4.6	3.4	3.7	2.5	1.4	0.2	*	0.1	0.8	3.5	4.1	5.4	29.7
Greece:																												
Athinai (Athens)	37 58N	23 43E	351	72	54	42	67	52	90	72	74	60	109	20	80	2.2	1.6	1.4	0.8	0.8	0.6	0.2	0.4	0.6	1.7	2.8	2.8	15.8
Iraklion (Crete)	35 20N	25 08E	98	21	60	48	70	54	85	72	77	62	114	32	22	3.7	3.0	1.6	0.9	0.7	0.1	*	0.1	0.7	1.7	2.7	4.0	19.2
Rodhos (Rhodes)	36 26N	28 15E	289	10	59	51	67	59	83	74	76	68	104	30	6	5.7	3.9	2.6	1.7	0.5	0.3	0.0	*	0.4	1.7	5.2	6.7	28.5
Thessaloniki (Salonika)	40 37N	22 57E	78	9	49	37	66	49	90	70	73	56	107	15	26	1.5	1.5	1.6	1.9	2.0	1.2	1.0	0.7	1.2	2.4	2.1	1.9	19.0
Hungary:																												
Budapest	47 31N	19 02E	394	50	35	26	62	44	82	61	61	45	103	-10	50	1.5	1.5	1.7	2.0	2.7	2.6	2.0	1.9	1.8	2.1	2.4	2.0	24.2
Debrecen	47 36N	21 39E	430	50	33	21	61	39	81	57	60	41	102	-22	80	1.2	1.1	1.4	1.8	2.4	2.8	2.5	2.3	1.8	2.2	2.0	1.6	23.1
Iceland:																												
Akureyri	65 41N	18 05W	16	23	34	26	40	30	57	47	43	34	83	- 8	26	1.7	1.5	1.7	1.3	0.6	0.9	1.3	1.6	1.9	2.3	1.9	1.9	18.6
Reykjavik	64 09N	21 56W	92	25	36	28	43	33	58	48	44	36	74	4	30	4.0	3.1	3.0	2.1	1.6	1.7	2.0	2.6	3.1	3.4	3.6	3.7	33.9
Ireland:																												
Cork	51 54N	08 29W	56	27	48	38	55	41	68	53	58	44	85	15	35	4.9	3.6	3.3	2.6	2.9	2.0	2.9	3.1	2.9	3.9	4.5	4.7	41.3
Dublin	53 22N	06 21W	155	30	47	35	54	38	67	51	57	43	86	8	35	2.7	2.2	2.0	1.9	2.3	2.0	2.8	3.0	2.8	2.7	2.7	2.6	29.7
Shannon Airport	52 41N	08 55W	8	9	46	36	55	41	66	53	58	45	87	12	12	3.8	3.0	2.0	2.2	2.4	2.1	3.1	3.0	3.0	3.4	4.2	4.3	36.5

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Italy:																												
Ancona	43 37N	13 32E	52	30	46	36	62	50	83	68	67	55	102	18	30	2.6	1.7	1.6	2.3	2.1	1.9	1.5	1.5	3.5	3.7	2.5	3.0	28.0
Cagliari (Sardinia)	39 15N	09 03E	3	30	56	43	66	50	86	67	72	58	102	25	25	2.2	1.5	1.5	1.2	1.5	0.5	0.1	0.4	1.0	3.0	1.8	2.3	17.0
Genova (Genoa)	44 24N	08 55E	318	10	50	41	65	53	82	70	73	58	100	18	10	3.9	4.0	3.3	3.4	4.6	1.4	1.6	2.3	4.7	6.1	7.2	4.1	46.6
Napoli (Naples)	40 51N	14 15E	82	30	54	40	65	52	84	70	71	60	101	24	30	3.7	3.2	3.0	2.6	1.8	1.8	0.6	0.7	2.8	5.1	4.5	5.4	35.2
Palermo (Sicily)	38 07N	13 19E	354	10	58	47	67	53	86	71	75	62	113	31	30	3.8	3.4	2.4	1.9	1.1	0.6	0.2	0.6	2.0	3.7	4.1	4.5	28.3
Rome	41 48N	12 36E	377	10	54	39	68	46	88	64	73	53	104	20	30	3.3	2.9	2.0	2.0	1.9	0.7	0.4	0.7	2.8	4.3	4.4	4.1	29.5
Taranto	40 28N	17 17E	56	10	55	43	59	50	89	70	73	58	108	26	10	1.6	0.9	1.3	0.8	1.0	0.6	0.4	0.7	1.0	2.2	1.8	1.9	14.2
Venezia (Venice)	45 26N	12 23E	82	10	43	33	63	49	82	67	65	52	97	14	30	2.0	2.1	2.4	2.8	3.2	3.3	2.6	2.6	2.6	3.7	3.5	2.6	33.4
Luxembourg:																												
Luxembourg	49 37N	06 03E	1,096	7	36	29	58	40	74	55	56	43	99	-10	100	2.3	2.0	1.9	2.1	2.4	2.5	2.8	2.6	2.4	2.7	2.7	2.8	29.2
Malta:																												
Valletta	35 54N	14 31E	233	90	59	51	66	56	84	72	76	66	105	34	90	3.3	2.3	1.5	0.8	0.4	0.1	*	0.2	1.3	2.7	3.6	3.9	20.3
Monaco:																												
Monaco	43 44N	07 25E	180	60	54	46	61	53	77	70	67	60	93	27	60	2.4	2.3	3.1	2.2	2.1	1.4	0.7	1.1	2.3	4.7	4.3	3.5	30.1
Netherlands:																												
Amsterdam	52 23N	04 55E	5	29	40	34	52	43	69	59	56	48	95	3	29	2.0	1.4	1.3	1.6	1.8	1.8	2.6	2.7	2.8	2.8	2.6	2.2	25.6
Norway:																												
Bergen	60 24N	05 19E	141	49	43	27	55	34	72	51	57	38	89	3	75	7.9	6.0	5.4	4.4	3.9	4.2	5.2	7.3	9.2	9.2	8.0	8.1	78.8
Kristiansand	58 10N	07 59E	175	11	32	25	50	35	71	53	53	39	90	-14	56	5.0	3.6	3.6	2.7	2.5	2.8	3.5	5.3	4.7	6.2	5.7	6.4	52.0
Oslo	59 56N	10 44E	308	44	30	20	50	34	73	56	49	37	93	-21	56	1.7	1.3	1.4	1.6	1.8	2.4	2.9	3.8	2.5	2.9	2.3	2.3	26.9
Tromso	69 39N	18 57E	335	47	30	22	37	27	59	48	40	33	83	- 1	75	4.1	3.8	3.3	2.4	2.1	2.1	2.3	2.9	4.7	4.5	4.0	3.9	40.1
Trondheim	63 25N	10 27E	417	44	31	22	45	32	66	51	46	36	95	-22	65	3.1	2.7	2.6	2.0	1.7	1.9	2.4	3.0	3.4	3.7	2.8	2.8	32.1
Vardo	70 22N	31 06E	43	40	27	19	34	26	53	44	38	32	80	-11	56	2.5	2.5	2.3	1.5	1.3	1.3	1.5	1.7	1.9	2.5	2.1	2.4	23.5
Poland:																												
Gdansk (Danzig)	54 24N	18 40E	36	36	33	25	49	37	70	56	53	42	94	-16	35	1.2	1.0	1.3	1.5	1.8	2.3	2.8	2.6	2.1	1.8	1.8	1.5	21.7
Krakow	50 04N	19 57E	723	35	32	22	55	38	76	57	56	41	97	-28	35	1.1	1.3	1.4	1.8	2.8	4.0	4.5	3.8	2.7	2.2	1.7	1.3	28.6
Warsaw	52 13N	21 02E	294	25	30	21	54	38	75	56	54	41	98	-22	113	1.2	1.1	1.3	1.5	1.9	2.6	3.0	3.0	1.9	1.7	1.4	1.4	22.0
Wroclaw (Breslau)	51 07N	17 05E	482	50	35	25	55	39	74	57	55	42	98	-26	40	1.5	1.1	1.5	1.7	2.4	2.4	3.4	2.7	1.8	1.7	1.5	1.5	23.2
Portugal:																												
Braganca	41 49N	06 47W	2,395	11	46	31	59	39	80	54	62	42	103	10	11	11.9	6.9	7.7	3.7	3.0	1.6	0.5	0.6	1.5	3.0	6.3	7.1	53.8
Lagos	37 06N	08 38W	46	21	61	47	67	52	83	64	73	58	107	28	17	3.2	2.6	2.8	1.4	0.8	0.2	*	*	0.4	1.5	2.6	2.8	18.3
Lisbon	38 43N	09 08W	313	75	56	46	64	52	79	63	69	57	103	29	75	3.3	3.2	3.1	2.4	1.7	0.7	0.2	0.2	1.4	3.1	4.2	3.6	27.0
Romania:																												
Bucuresti (Bucharest)	44 25N	26 06E	269	41	33	20	63	41	86	61	65	44	105	-18	41	1.5	1.1	1.7	1.6	2.5	3.8	2.3	1.8	1.5	1.6	1.9	1.5	22.8
Cluj	46 47N	23 40E	1,286	15	31	18	58	38	79	56	60	41	100	-26	16	1.3	1.2	1.0	2.1	3.3	3.3	2.6	3.3	2.0	1.7	1.0	1.2	24.0
Constanta	44 11N	28 39E	13	20	37	25	55	42	79	63	62	49	101	-13	39	1.2	1.2	1.1	1.1	1.3	1.7	1.3	1.1	1.1	1.4	1.2	1.4	15.1
Spain:																												
Almeria	36 51N	02 28W	213	20	61	47	69	54	85	69	76	62	108	34	20	0.9	1.0	0.7	0.9	0.7	0.2	*	0.1	0.6	0.9	1.5	1.1	8.6
Barcelona	41 24N	02 09E	312	20	56	42	64	51	81	69	71	58	98	24	30	1.2	2.1	1.9	1.8	1.8	1.3	1.2	1.7	2.6	3.4	2.7	1.8	23.5
Burgos	42 20N	03 42W	2,825	29	42	30	57	38	77	53	61	43	99	0	29	1.5	1.5	2.1	1.9	2.4	1.7	0.8	0.7	1.4	2.0	2.2	2.0	20.2
Madrid	40 25N	03 41W	2,188	30	47	33	64	44	87	62	66	48	102	14	30	1.1	1.7	1.7	1.7	1.5	1.2	0.4	0.3	1.2	1.9	2.2	1.6	16.5
Sevilla	37 29N	05 59W	98	26	59	41	73	51	96	67	78	57	117	27	26	2.2	2.9	3.3	2.3	1.3	0.9	0.1	0.1	1.1	2.6	3.7	2.8	23.3
Valencia	39 28N	00 23W	79	26	58	41	67	51	83	68	73	57	107	20	29	0.9	1.5	0.9	1.2	1.1	1.3	0.4	0.5	2.2	1.6	2.5	1.3	15.4
Sweden:																												
Abisko	68 21N	18 49E	1,273	11	20	6	33	19	61	45	35	24	82	-30	11	0.7	0.6	0.5	0.5	0.7	1.8	1.6	1.8	1.2	1.0	0.6	0.6	11.7

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Sweden cont'd:																												
Goteberg	57 42N	11 58E	55	39	35	27	48	36	69	56	51	42	88	-13	61	2.5	2.0	2.0	1.7	1.9	2.2	2.8	3.7	3.1	3.1	2.7	2.8	30.5
Haparanda	65 50N	24 09E	30	20	22	10	38	23	71	53	39	30	89	-34	20	2.2	1.6	1.2	1.5	1.4	1.7	2.1	2.8	2.6	2.8	2.5	2.0	24.4
Karlstad	59 23N	13 30E	164	30	30	20	49	32	73	56	49	38	93	-21	30	1.9	1.2	1.2	1.4	1.9	1.9	2.6	3.1	2.9	2.4	2.4	1.9	24.8
Sarna	61 41N	13 07E	1,504	20	19	4	42	23	69	46	42	28	91	-51	20	1.6	0.8	0.9	1.2	1.6	2.8	3.6	3.3	2.6	2.3	1.8	1.8	24.3
Stockholm	59 21N	18 04E	146	30	31	23	45	32	70	55	48	39	97	-26	30	1.5	1.1	1.1	1.5	1.6	1.9	2.8	3.1	2.1	2.1	1.9	1.9	22.4
Visby (Gotland)	57 39N	18 18E	36	30	35	28	44	33	67	55	50	41	88	1	30	1.7	1.1	1.2	1.4	1.1	1.4	2.0	2.7	1.7	1.9	2.1	2.0	20.3
Switzerland:																												
Berne	46 57N	07 26E	1,877	30	35	26	56	39	74	56	55	42	96	- 9	77	1.9	2.0	2.6	3.0	3.7	4.4	4.4	4.3	3.5	3.5	2.7	2.5	38.5
Geneve (Geneva)	46 12N	06 09E	1,329	30	39	29	58	41	77	58	58	44	101	- 1	125	1.9	1.8	2.2	2.5	3.0	3.1	2.9	3.6	3.6	3.8	3.1	2.4	33.9
Zurich	47 23N	08 33E	1,617	23	38	28	57	39	76	55	57	42	98	-12	23	2.3	1.9	2.9	3.4	4.0	4.9	5.0	4.6	3.3	3.2	2.5	2.9	40.9
Turkey:																												
Edirne (Adrianople)	41 39N	26 34E	154	18	41	28	66	44	88	63	70	49	107	- 8	18	2.2	1.9	1.7	1.9	1.7	2.1	1.5	1.1	1.1	2.1	2.9	3.0	23.2
Istanbul (Constantinople)	40 58N	28 50E	59	18	45	36	61	45	81	65	67	54	100	17	18	3.7	2.3	2.6	1.9	1.4	1.3	1.7	1.5	2.3	3.8	4.1	4.9	31.5
United Kingdom:																												
Belfast	54 35N	05 56W	57	7	42	34	53	38	65	52	55	44	82	14	30	4.2	2.8	2.3	2.4	2.3	2.5	3.5	3.5	3.4	3.8	3.6	3.9	38.2
Birmingham	52 29N	01 56W	535	30	42	35	53	40	69	54	55	45	92	11	30	2.9	2.1	1.7	2.2	2.5	1.8	2.8	2.7	2.3	2.9	3.2	2.6	29.7
Cardiff	51 28N	03 10W	203	30	45	36	55	41	69	54	57	45	91	2	30	4.6	3.0	2.3	2.5	3.0	2.2	3.4	3.9	3.6	4.5	4.6	4.3	41.9
Dublin	53 22N	06 21W	155	30	47	35	54	38	67	51	57	43	86	8	35	2.7	2.2	2.0	1.9	2.3	2.0	2.8	3.0	2.8	2.7	2.7	2.6	29.7
Edinburgh	55 55N	03 11W	441	30	43	35	50	39	65	52	53	44	83	15	30	2.5	1.6	1.6	1.6	2.2	1.9	3.1	3.1	2.6	2.9	2.4	2.1	27.6
London	51 29N	00 00	149	30	44	35	56	40	73	55	58	44	99	9	30	2.0	1.5	1.4	1.8	1.8	1.6	2.0	2.2	1.8	2.3	2.5	2.0	22.9
Liverpool	53 24N	03 04W	198	30	44	36	52	41	66	55	55	46	87	15	30	2.7	1.9	1.5	1.6	2.2	2.0	2.8	3.1	2.6	3.0	3.0	2.5	28.9
Perth	56 24N	03 27W	77	30	43	32	53	38	68	51	55	41	89	0	30	3.1	2.2	1.9	1.7	2.3	2.0	3.1	2.9	2.8	3.3	2.7	2.7	30.7
Plymouth	50 21N	04 07W	87	30	47	40	54	43	66	55	58	49	88	16	30	4.3	3.0	2.6	2.3	2.5	2.0	2.6	2.9	2.8	3.8	4.6	4.4	37.8
Wick	58 26N	03 05W	119	30	42	35	48	38	59	50	52	43	80	8	30	2.9	2.1	1.8	2.1	1.8	2.0	2.6	2.6	2.9	3.2	3.1	2.9	30.0
U.S.S.R.:																												
Arkhangelsk	64 33N	40 32E	22	23	9	2	36	23	64	51	36	30	91	-49	25	1.2	1.1	1.1	0.7	1.3	1.9	2.6	2.7	2.2	1.9	1.6	1.3	19.8
Astrakhan	46 21N	48 02E	45	10	23	14	57	40	85	69	56	40	99	-22	25	0.5	0.5	0.4	0.6	0.6	0.7	0.5	0.4	0.6	0.4	0.6	0.6	6.4
Dnepropetrovsk	48 27N	35 04E	259	18	25	16	53	39	80	62	56	40	101	-25	17	1.4	1.1	1.2	1.4	1.8	3.0	1.9	1.6	1.0	1.8	1.6	1.6	19.4
Kaunas	54 54N	23 53E	118	19	26	18	49	34	72	53	50	38	96	-23	19	1.6	1.3	1.3	1.8	2.0	3.2	3.3	3.5	1.9	1.9	1.6	1.6	25.0
Kirov	58 36N	49 41E	594	20	6	- 2	41	27	72	55	37	29	92	-43	29	1.2	1.0	0.9	0.9	1.9	2.5	2.1	2.9	2.3	2.0	1.6	1.3	20.6
Kursk	51 45N	36 12E	773	15	19	11	47	35	74	58	48	36	91	-23	20	1.5	1.3	1.2	1.5	2.2	2.5	3.2	2.3	1.6	1.8	1.5	1.7	22.3
Leningrad	59 56N	30 16E	16	26	23	12	45	31	71	57	45	37	91	-36	95	1.0	0.9	0.9	1.0	1.6	2.0	2.5	2.8	2.1	1.8	1.4	1.2	19.2
Lvov	49 50N	24 01E	978	9	31	22	53	38	77	59	55	43	97	-29	35	1.3	1.5	1.8	2.0	2.8	3.7	4.1	3.1	2.4	2.1	0.8	1.6	28.2
Minsk	53 54N	27 33E	738	12	22	13	47	33	70	54	47	36	92	-27	20	1.4	1.5	1.3	1.5	2.0	2.8	3.0	3.1	1.6	1.5	1.5	1.7	22.9
Moskva (Moscow)	55 46N	37 40E	505	15	21	9	47	31	76	55	46	34	96	-27	11	1.5	1.4	1.1	1.9	2.2	2.9	3.0	2.9	1.9	2.7	1.7	1.6	24.8
Odessa	46 29N	30 44E	214	20	28	22	52	41	79	65	57	47	99	-13	15	1.0	0.7	0.7	1.1	1.1	1.9	1.6	1.4	1.1	1.4	1.1	1.1	14.3
Riga	56 57N	24 06E	67	30	29	20	48	35	72	56	49	39	93	-20	57	1.3	1.0	1.1	1.2	1.7	2.4	3.0	3.0	2.1	2.0	1.9	1.5	22.2
Saratov	51 32N	46 03E	197	14	15	7	50	35	82	64	48	36	102	-27	15	1.0	1.0	0.8	1.0	1.3	1.8	1.2	1.3	1.1	1.4	1.4	1.2	14.5
Sevastopol	44 37N	33 31E	75	20	39	30	55	42	79	65	63	50	97	- 4	30	1.1	1.1	1.1	0.9	0.6	1.1	0.8	0.6	1.1	1.5	1.2	1.1	12.2
Stalingrad	48 42N	44 31E	136	8	15	4	52	36	84	65	53	37	106	-30	12	0.9	1.0	0.6	0.6	1.0	1.9	0.9	0.8	0.7	1.0	1.5	1.3	12.2
Stavropol	45 02N	41 58E	1,886	18	26	17	50	37	76	60	55	42	95	-22	41	1.4	1.1	1.5	2.4	3.0	4.1	3.0	2.0	2.5	2.3	1.8	1.8	26.9
Tallin	59 26N	24 48E	146	15	27	18	42	31	70	55	47	38	89	-19	63	1.1	1.0	0.9	1.1	1.7	1.9	2.1	2.7	2.3	2.1	1.9	1.5	20.2
Tbilisi	41 43N	44 48E	1,325	10	39	26	61	44	83	65	64	48	95	6	10	0.7	0.8	1.3	1.6	3.6	3.1	2.2	1.7	1.9	1.3	2.0	1.2	21.4
Ust'Shchugor	64 16N	57 34E	279	15	4	-14	35	17	65	49	33	23	90	-67	15	1.1	0.8	0.8	0.7	1.4	2.2	3.0	3.2	2.4	2.2	1.5	1.3	20.6
Ufy	54 43N	55 56E	571	20	6	- 3	44	30	75	58	41	31	99	-42	23	1.6	1.3	1.2	0.9	1.6	2.4	2.6	2.2	1.8	2.3	2.2	2.3	22.5

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Yugoslavia:																												
Beograd (Belgrade)	44 48N	20 28E	453	16	37	27	64	45	84	61	65	47	107	-14	16	1.6	1.3	1.6	2.2	2.6	2.8	1.9	2.5	1.7	2.7	1.8	1.9	24.6
Skopje	41 59N	21 28E	787	10	40	26	67	42	88	60	65	43	105	-11	10	1.5	1.2	1.3	1.5	1.9	1.9	1.3	1.1	1.1	2.6	2.3	1.8	19.5
Split	43 31N	16 26E	420	14	51	29	65	50	87	68	69	55	100	17	51	3.1	2.5	3.2	3.0	2.5	2.1	1.2	1.6	2.9	4.4	4.2	4.4	35.1
OCEAN ISLANDS																												
Bjornoya, Bear Island	74 31N	19 01E	49	10	26	17	27	16	44	36	36	29	71	-25	25	1.6	1.3	1.3	0.9	0.8	0.7	0.8	1.2	1.8	1.7	1.4	1.6	15.1
Gronfjorden, Spitzbergen	78 02N	14 15E	23	19	10	- 4	15	- 3	46	38	25	17	60	-57	15	1.4	1.3	1.1	0.9	0.5	0.4	0.6	0.9	1.0	1.2	0.9	1.5	11.7
Horta, Azores	38 32N	28 38W	200	30	62	54	64	55	76	65	71	62	88	38	30	4.5	4.1	4.2	3.0	2.9	2.0	1.5	1.9	3.2	4.4	4.1	4.5	40.3
Jan Mayen	71 01N	08 28W	131	5	31	21	31	22	46	38	39	29	60	-18	29	2.1	1.7	1.6	1.4	0.9	0.9	1.4	1.8	2.5	2.5	2.2	2.2	21.2
Lerwick, Shetland Island	60 08N	01 11W	269	30	42	35	46	37	58	49	50	42	71	17	30	4.5	3.4	2.9	2.7	2.2	2.2	2.7	2.9	3.7	4.3	4.5	4.5	40.5
Matochkin Shar, Novaya Zemlya	73 16N	56 24E	61	9	8	- 6	13	- 1	47	36	30	21	68	-41	9	0.6	0.6	0.6	0.4	0.3	0.4	1.4	1.5	1.5	0.6	0.6	0.4	8.9
Ponta Delgada, Azores	37 45N	25 40W	118	30	62	54	64	55	76	64	71	61	85	37	30	4.0	3.5	3.5	2.5	2.3	1.4	1.0	1.2	2.9	3.6	3.7	3.0	32.6
Stornoway, Hebrides	58 11N	06 21W	34	30	44	37	49	39	61	51	53	44	78	11	15	6.4	3.2	3.2	3.1	2.5	2.4	3.0	4.3	4.7	6.2	4.6	5.5	49.1
Thorshavn, Faeroes	62 02N	06 45W	82	50	42	33	45	36	56	47	58	40	70	8	50	6.6	5.2	4.8	3.6	3.4	2.5	3.1	3.5	4.7	5.9	6.3	6.6	56.2
AFRICA																												
Algeria:																												
Adrar	27 52N	00 17W	938	15	69	39	92	60	115	82	92	63	124	25	15	*	*	0.1	*	*	*	*	*	*	0.2	0.2	*	0.6
Alger (Algiers)	36 46N	03 03E	194	25	59	49	68	55	83	70	74	63	107	32	25	4.4	3.3	2.9	1.6	1.8	0.6	*	0.2	1.6	3.1	5.1	5.4	30.0
Bone	36 54N	07 46E	66	26	59	46	67	52	85	69	75	61	115	32	26	5.6	4.1	2.9	2.2	1.5	0.6	0.1	0.3	1.2	3.0	4.3	5.2	31.0
El Golea	30 35N	02 53E	1,247	15	63	37	84	56	107	79	87	60	120	23	15	0.1	0.3	0.5	*	*	*	*	*	*	0.3	0.4	0.3	1.9
Fort Flatters	28 06N	06 42E	1,224	15	67	38	90	59	110	78	92	63	124	19	15	0.3	0.1	0.1	0.2	*	*	0.0	*	*	*	0.2	0.2	1.1
Tamanrasset	22 42N	05 31E	4,593	15	67	39	86	56	95	71	85	59	102	20	15	0.2	*	*	0.2	0.4	0.1	0.1	0.4	0.1	*	*	*	1.5
Touggourt	33 07N	06 04E	226	26	62	38	83	55	107	77	84	59	122	26	26	0.2	0.4	0.5	0.2	0.2	0.2	*	*	0.1	0.3	0.5	0.3	2.9
Angola:																												
Cangamba	13 41S	19 52E	4,331	6	84	62	89	58	82	46	87	59	109	20	7	8.9	7.4	6.8	1.8	0.1	0.0	0.0	0.2	0.2	1.6	5.1	8.5	40.6
Luanda	08 49S	13 13E	194	27	83	74	85	75	74	65	79	71	98	58	59	1.0	1.4	3.0	4.6	0.5	*	*	*	0.1	0.2	1.1	0.8	12.7
Mocamedes	15 12S	12 09E	10	15	79	65	82	66	68	56	74	61	102	44	21	0.3	0.4	0.7	0.5	*	*	*	*	*	*	0.1	0.1	2.1
Nova Lisboa	12 48S	15 45E	5,577	14	78	58	78	57	77	47	81	58	90	36	14	8.7	7.8	9.8	5.7	0.4	0.0	*	*	0.6	5.5	9.6	8.9	57.0
Botswana:																												
Francistown	21 13S	27 30E	3,294	20	88	65	83	56	75	41	90	61	107	24	28	4.2	3.1	2.8	0.7	0.2	0.1	*	*	*	0.9	2.3	3.4	17.7
Maun	19 59S	23 25E	3,091	20	90	66	87	58	77	42	95	64	110	24	20	4.3	3.8	3.5	1.1	0.2	*	0.0	0.0	*	0.5	1.9	2.8	18.2
Tsabong	26 03S	22 27E	3,156	10	94	65	83	51	71	34	88	54	107	15	14	2.0	1.9	1.9	1.3	0.4	0.4	0.1	*	0.2	0.7	1.1	1.5	11.5
Cameroon:																												
Ngaoundere	07 17N	13 19E	3,601	9	87	55	87	64	82	63	82	61	102	46	10	*	*	1.1	5.5	7.0	8.4	10.6	9.6	9.2	5.3	0.5	*	57.2
Yaounde	03 53N	11 32E	2,526	11	85	67	85	66	80	66	81	65	96	57	11	0.9	2.6	5.8	6.7	7.7	6.0	2.9	3.1	8.4	11.6	4.6	0.9	61.2
Central African Republic:																												
Bangui	04 22N	18 34E	1,270	5	90	68	91	71	85	69	87	69	101	57	5	1.0	1.7	5.0	5.3	7.4	4.5	8.9	8.1	5.9	7.9	4.9	0.2	60.8
Ndele	08 24N	20 39E	1,939	3	99	67	98	73	86	69	90	68	109	58	3	0.2	1.3	0.6	1.7	8.4	6.1	8.3	10.1	10.7	7.8	0.6	0.0	55.8
Chad:																												
Am Timan	11 02N	20 17E	1,430	3	98	56	105	68	89	70	96	67	113	43	3	0.0	0.0	0.1	1.2	4.3	5.0	7.3	12.3	5.8	1.2	0.0	0.0	37.2
Fort Lamy	12 07N	15 02E	968	5	93	57	107	74	92	72	97	70	114	47	5	0.0	0.0	0.0	0.1	1.2	2.6	6.7	12.6	4.7	1.4	0.0	0.0	29.3
Largeau (Faya)	18 00N	19 10E	837	5	84	54	104	69	109	76	103	72	121	37	5	0.0	0.0	0.0	0.0	*	0.0	*	0.7	*	0.0	0.0	0.0	0.7

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Congo, Democratic Republic of the:																												
Albertville	05 54S	29 12E	2,493	5	85	66	83	67	82	58	87	67	92	50	20	4.2	4.7	6.3	8.4	3.3	0.3	0.1	0.3	0.8	2.8	7.9	6.3	45.4
Kinspasa (Leopoldville)	04 20S	15 18E	1,066	8	87	70	89	71	81	64	88	70	97	58	12	5.3	5.7	7.7	7.7	6.2	0.3	0.1	0.1	1.2	4.7	8.7	5.6	53.3
Luluabourg	05 54S	22 25E	2,198	3	85	68	86	68	85	63	85	68	94	57	14	5.4	5.6	7.7	7.6	3.3	0.8	0.5	2.3	4.6	6.5	9.1	8.9	62.3
Stanleyville	00 26N	25 14E	1,370	8	88	69	88	70	84	67	86	68	97	61	14	2.1	3.3	7.0	6.2	5.4	4.5	5.2	6.5	7.2	8.6	7.8	3.3	67.1
Congo, Republic of:																												
Brazzaville	04 15S	15 15E	1,043	15	88	69	91	71	82	63	89	70	98	54	18	6.3	4.9	7.4	7.0	4.3	0.6	*	*	2.2	5.4	11.5	8.4	58.0
Ouesso	01 37N	16 04E	1,132	4	88	69	91	71	85	69	87	69	106	60	4	2.4	3.6	6.4	3.2	5.8	4.6	2.9	3.7	7.9	10.0	5.7	2.4	58.6
Pointe Noire (Loango)	04 39S	11 48E	164	7	85	73	87	74	78	66	83	72	93	59	7	5.4	6.7	6.4	8.0	3.9	0.0	0.0	0.0	0.4	4.1	6.6	6.6	48.1
Dahomey:																												
Cotonou	06 21N	02 26E	23	5	80	74	83	78	78	74	80	75	95	65	10	1.3	1.3	4.6	4.9	10.0	14.4	3.5	1.5	2.6	5.3	2.3	0.5	52.4
Ethiopia:																												
Addis Ababa	09 20N	38 45E	8,038	15	75	43	77	50	69	50	75	45	94	32	37	0.5	1.5	2.6	3.4	3.4	5.4	11.0	11.8	7.5	0.8	0.6	0.2	48.7
Asmara	15 17N	38 55E	7,628	9	74	44	78	51	71	53	72	53	88	31	17	*	*	0.4	1.5	1.5	1.3	6.7	5.0	1.3	0.3	0.4	*	18.4
Ethiopia cont'd:																												
Diredawa	09 02N	41 45E	3,937	8	81	58	91	69	90	68	89	67	100	49	8	0.8	0.8	3.3	3.0	2.8	1.5	4.3	3.8	2.2	0.5	0.3	0.8	24.1
Gambela	08 15N	34 35E	1,345	26	98	64	98	71	87	69	92	67	111	48	30	0.2	0.4	1.4	3.2	5.9	6.7	8.5	9.5	7.3	3.5	1.8	0.4	48.8
French Territory of Afars and Issas (F.T.A.I.):																												
Djibouti	11 36N	43 09E	23	16	84	73	90	79	106	87	92	80	117	63	46	0.4	0.5	1.0	0.5	0.2	*	0.1	0.3	0.3	0.4	0.9	0.5	5.1
Gabon:																												
Libreville	00 23N	09 26E	115	11	87	73	89	73	83	68	86	71	99	62	21	9.8	9.3	13.2	13.4	9.6	0.5	0.1	0.7	4.1	13.6	14.7	9.8	98.8
Mayoumba	03 25S	10 38E	200	8	84	73	86	73	78	68	82	72	91	60	8	6.5	9.3	6.2	10.2	2.3	0.1	0.0	0.2	2.6	9.3	10.7	4.6	62.0
Gambia:																												
Bathurst	13 21N	16 40W	90	9	88	59	91	65	86	74	89	72	106	45	9	0.1	0.1	*	*	0.4	2.3	11.1	19.7	12.2	4.3	0.7	0.1	51.0
Ghana:																												
Accra	05 33N	00 12W	88	17	87	73	88	76	81	73	85	74	100	59	65	0.6	1.3	2.2	3.2	5.6	7.0	1.8	0.6	1.4	2.5	1.4	0.9	28.5
Kumasi	06 40N	01 37W	942	10	88	66	89	71	82	70	86	70	100	51	10	0.8	2.3	5.7	5.1	7.5	7.9	4.3	3.1	6.8	7.1	3.7	0.8	55.2
Guinea:																												
Conakry	09 31N	13 43W	23	-7	88	72	90	73	83	72	87	73	96	63	10	0.1	0.1	0.4	0.9	6.2	22.0	51.1	41.5	26.9	14.6	4.8	0.4	169.0
Kouroussa	10 39N	09 53W	1,217	9	93	60	99	73	87	69	90	69	109	39	10	0.4	0.3	0.9	2.8	5.3	9.7	11.7	13.6	13.4	6.6	1.3	0.4	66.4
Ifni (now in Morocco):																												
Sidi Ifni	29 27N	10 11W	148	14	66	52	71	59	75	64	75	62	124	40	14	1.0	0.6	0.5	0.6	0.1	0.1	*	*	0.4	0.1	0.9	1.8	6.1
Ivory Coast:																												
Abidjan	05 19N	04 01W	65	13	88	73	90	75	83	73	85	74	96	59	10	1.6	2.1	3.9	4.9	14.2	19.5	8.4	2.1	2.8	6.6	7.9	3.1	77.1
Bouake	07 42N	05 00W	1,194	12	91	68	92	70	85	68	89	68	104	57	10	0.4	1.5	4.1	5.8	5.3	6.0	3.1	4.6	8.2	5.2	1.5	1.0	46.7
Kenya:																												
Mombasa	04 03S	39 39E	52	45	87	75	86	76	81	71	84	74	96	61	54	1.0	0.7	2.5	7.7	12.6	4.7	3.5	2.5	2.5	3.4	3.8	2.4	47.3
Nairobi	01 16S	36 48E	5,971	15	77	54	75	58	69	51	76	55	87	41	17	1.5	2.5	4.9	8.3	6.2	1.8	0.6	0.9	1.2	2.1	4.3	3.4	37.7
Liberia:																												
Monrovia	06 18N	10 48W	75	6	89	71	90	72	80	72	86	72	97	62	4	0.2	0.1	4.4	11.7	13.4	36.1	24.2	18.6	29.9	25.2	8.2	2.9	174.9

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Libya:																												
Banghazi (Benghazi)	32 06N	20 04E	82	46	63	50	74	58	84	71	80	66	109	37	46	2.6	1.6	0.8	0.2	0.1	*	*	*	0.1	0.7	1.8	2.6	10.5
Cufra	24 12N	23 21E	1,276	7	69	43	90	62	101	75	90	64	122	26	7	*	0.0	0.0	0.0	*	0.0	0.0	0.0	0.0	0.0	0.0	*	*
Sabhah	27 01N	14 26E	1,457	3	64	41	89	60	102	74	91	64	120	24	10	*	*	*	*	0.1	0.1	0.0	0.0	0.0	*	*	*	0.3
Tarabulus (Triopoli)	32 54N	13 11E	72	47	61	47	72	57	85	71	80	65	114	33	56	3.2	1.8	1.1	0.4	0.2	0.1	*	*	0.4	1.6	2.6	3.7	15.1
Malagasy Republic:																												
Diego Suarez	12 17S	49 17E	100	11	88	75	88	75	84	69	86	72	98	63	31	10.6	9.5	7.6	2.2	0.3	0.2	0.2	0.3	0.3	0.7	1.1	5.8	38.7
Tananarive	18 55S	47 33E	4,500	44	79	61	76	58	68	48	80	54	95	34	62	11.8	11.0	7.0	2.1	0.7	0.3	0.3	0.4	0.7	2.4	5.3	11.3	53.4
Tulear	23 20S	43 41E	20	27	92	72	89	64	81	58	86	65	108	43	15	3.1	3.2	1.4	0.3	0.7	0.4	0.1	0.2	0.3	0.7	1.4	1.7	13.5
Malawi:																												
Karonga	09 57S	33 56E	1,596	8	86	71	85	70	81	59	91	66	99	51	8	7.1	7.0	10.8	6.2	1.7	0.1	*	*	0.0	0.3	0.3	4.7	38.3
Zomba	15 23S	35 19E	3,141	27	80	65	78	62	72	53	85	64	95	41	29	12.1	9.9	10.1	2.7	0.7	0.4	0.3	0.3	0.2	1.0	4.3	10.9	52.9
Mali:																												
Araouane	18 54N	03 33W	935	8	81	48	110	67	111	79	103	70	130	37	10	*	*	0.0	0.0	0.0	0.2	0.2	0.5	0.6	0.1	0.1	*	1.7
Bamako	12 39N	07 58W	1,116	11	91	61	103	76	89	71	93	71	117	47	10	*	*	0.1	0.6	2.9	5.4	11.0	13.7	8.1	1.7	0.6	*	44.1
Gao	16 16N	00 03W	902	15	83	58	105	77	97	80	100	78	116	44	19	*	0.0	*	0.1	0.4	1.0	2.9	5.4	1.5	0.2	*	0.0	11.5
Mauritania:																												
Atar	20 31N	13 04W	761	7	84	54	97	67	106	81	98	72	117	39	10	*	0.0	*	*	*	0.1	0.3	1.2	1.1	0.1	*	*	2.8
Nema	16 36N	07 16W	883	9	86	62	105	79	99	78	101	79	120	47	10	0.1	*	*	*	0.7	1.1	2.3	4.7	2.1	0.7	*	0.1	11.6
Nouakchott	18 07N	15 36W	69	5	85	57	90	64	89	74	91	71	115	44	10	*	0.1	*	*	*	0.1	0.5	4.1	0.9	0.4	0.1	*	6.2
Morocco:																												
Casablanca	33 35N	07 39W	164	48	63	45	69	52	79	65	76	58	110	31	40	2.1	1.9	2.2	1.4	0.9	0.2	0.0	*	0.3	1.5	2.6	2.8	15.9
Marrakech	31 36N	08 01W	1,509	35	65	40	79	52	101	67	83	57	120	27	31	1.0	1.1	1.3	1.2	0.6	0.3	0.1	0.1	0.4	0.9	1.2	1.2	9.4
Rabat	34 00N	06 50W	213	35	63	46	71	52	82	63	77	58	118	32	29	2.6	2.5	2.6	1.7	1.1	0.3	*	*	0.4	1.9	3.3	3.4	19.8
Tangier	35 48N	05 49W	239	35	60	47	65	51	80	64	72	59	106	28	35	4.5	4.2	4.8	3.5	1.7	0.6	*	*	0.9	3.9	5.8	5.4	35.3
Mozambique:																												
Beira	19 50S	34 51E	28	37	89	75	86	71	77	61	87	71	109	48	39	10.9	8.4	10.1	4.2	2.2	1.3	1.2	1.1	0.8	5.2	5.3	9.2	59.9
Chicoa	15 36S	32 21E	899	8	96	65	93	63	86	55	101	68	117	32	8	7.8	5.7	4.4	0.6	*	*	*	*	*	1.1	2.6	5.2	27.4
Lourenco Marques	25 58S	32 36E	194	42	86	71	83	66	76	55	82	64	114	45	42	5.1	4.9	4.9	2.1	1.1	0.8	0.5	0.5	1.1	1.9	3.2	3.8	29.9
Niger:																												
Agades	16 59N	07 59E	1,706	8	86	50	105	70	104	75	101	68	115	40	10	0.0	0.0	*	*	0.2	0.3	1.9	3.7	0.7	0.0	0.0	0.0	6.8
Bilma	18 41N	12 55E	1,171	9	81	45	101	63	108	75	101	62	116	29	10	0.0	0.0	0.0	*	*	0.0	0.1	0.5	0.3	0.0	0.0	0.0	0.9
Niamey	13 31N	02 06E	709	10	93	58	108	77	94	74	101	74	114	47	10	*	*	0.2	0.3	1.3	3.2	5.2	7.4	3.7	0.5	*	0.0	21.6
Nigeria:																												
Enugu	06 27N	07 29E	763	11	90	72	91	74	83	71	87	71	99	55	33	0.7	1.1	2.6	5.9	10.4	11.4	7.6	6.7	12.8	9.8	2.1	0.5	71.5
Kaduna	10 35N	06 26E	2,113	18	89	59	95	72	83	68	89	66	105	46	34	*	0.1	0.5	2.5	5.9	7.1	8.5	11.9	10.6	2.9	0.1	*	50.1
Lagos	06 27N	03 24E	10	32	88	74	89	77	83	74	85	74	104	60	47	1.1	1.8	4.0	5.9	10.6	18.1	11.0	2.5	5.5	8.1	2.7	1.0	72.3
Maiduguri	11 51N	13 05E	1,162	15	90	54	104	72	90	73	96	68	112	43	40	*	*	*	0.3	1.6	2.7	7.1	8.7	4.2	0.7	*	0.0	25.3
Portuguese Guinea:																												
Bolama	11 34N	15 26W	62	31	88	67	91	73	84	74	87	74	106	59	37	*	*	*	*	0.8	7.8	23.1	27.6	16.9	8.0	1.6	0.1	85.9
Rhodesia:																												
Bulawayo	20 09S	28 37E	4,405	15	81	61	79	56	70	45	85	59	99	28	50	5.6	4.3	3.3	0.7	0.4	0.1	*	*	0.2	0.8	3.2	4.8	23.4
Salisbury	17 50S	31 08E	4,831	15	78	60	78	55	70	44	83	58	95	32	50	7.7	7.0	4.6	1.1	0.5	0.1	*	0.1	0.2	1.1	3.8	6.4	32.6

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Senegal:																												
Dakar	14 42N	17 29W	131	25	79	64	81	65	88	76	89	76	109	53	26	*	*	*	*	*	0.7	3.5	10.0	5.2	1.5	0.1	0.3	21.3
Kaolack	14 08N	16 04W	20	9	93	60	103	68	91	75	93	74	114	48	10	*	0.0	*	*	0.3	2.6	6.9	10.7	7.0	2.7	0.1	*	30.3
Sierra Leone:																												
Freetown/Lungi	08 37N	13 12W	92	8	87	73	88	76	82	73	85	72	98	62	8	0.4	0.2	1.2	3.1	9.5	14.3	29.2	36.5	22.3	14.2	5.5	1.2	137.6
Somalia:																												
Berbera	10 26N	45 02E	45	30	84	68	89	77	107	88	92	76	117	58	30	0.3	0.1	0.2	0.5	0.3	*	*	0.1	*	0.1	0.2	0.2	2.0
Mogadishu (Mogadiscio)	02 02N	45 21E	39	13	86	73	90	78	83	73	86	76	97	59	21	*	*	*	2.3	2.3	3.8	2.5	1.9	1.0	0.9	1.6	0.5	16.9
South Africa, Republic of:																												
Capetown	33 54S	18 32E	56	19	78	60	72	53	63	45	70	52	103	28	18	0.6	0.3	0.7	1.9	3.1	3.3	3.5	2.6	1.7	1.2	0.7	0.4	20.0
Durban	29 50S	31 02E	16	15	81	69	78	64	72	52	75	62	107	39	78	4.3	4.8	5.1	3.0	2.0	1.3	1.1	1.5	2.8	4.3	4.8	4.7	39.7
Kimberley	28 48S	24 46E	3,927	19	91	64	77	52	65	36	83	54	103	20	57	2.4	2.5	3.1	1.5	0.7	0.2	0.2	0.3	0.6	1.0	1.6	2.0	16.1
Port Elizabeth	33 59S	25 36E	190	14	78	61	73	55	67	45	70	54	104	31	84	1.2	1.3	1.9	1.8	2.4	1.8	1.9	2.0	2.3	2.2	2.2	1.7	22.7
Port Nolloth	29 14S	16 52E	23	20	67	53	66	50	62	45	64	49	107	31	64	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.1	0.1	0.1	2.3
Pretoria	25 45S	28 14E	4,491	13	81	60	75	50	66	37	80	55	96	24	12	5.0	4.3	4.5	1.7	0.9	0.6	0.3	0.2	0.8	2.2	5.2	5.2	30.9
Walvis Bay	22 56S	14 30E	24	20	73	59	75	55	70	47	67	51	104	25	20	*	0.2	0.3	0.1	0.1	*	*	0.1	*	*	*	*	0.9
Southwest Africa:																												
Keetmanshoop	26 35S	18 08E	3,295	17	95	65	85	57	70	42	87	55	108	26	45	0.8	1.1	1.4	0.6	0.2	*	*	*	0.1	0.2	0.3	0.4	5.2
Windhoek	22 34S	17 06E	5,669	30	85	63	77	55	68	43	84	59	97	25	60	3.0	2.9	3.1	1.6	0.3	*	*	*	0.1	0.4	0.9	1.9	14.3
Spanish Sahara:																												
Semara	26 46N	11 31W	1,509	6	73	47	88	58	99	66	88	61	121	37	6	0.1	*	0.0	*	*	0.0	0.0	*	1.0	*	0.4	0.0	1.5
Villa Cisneros	23 42N	15 52W	35	12	71	56	74	60	78	65	80	65	107	48	14	*	*	*	*	0.1	0.0	*	0.2	1.4	0.1	0.2	1.0	3.0
Sudan:																												
El Fasher	13 38N	25 21E	2,395	17	88	50	102	64	96	70	99	64	113	33	17	*	0.0	*	*	0.3	0.7	4.5	5.3	1.2	0.2	0.0	0.0	12.2
Khartoum	15 37N	32 33E	1,279	46	90	59	105	72	101	77	104	75	118	41	46	*	*	*	*	0.1	0.3	2.1	2.8	0.7	0.2	*	0.0	6.2
Port Sudan	19 37N	37 13E	18	30	81	68	89	71	106	83	93	76	117	50	40	0.2	0.1	*	*	*	*	0.3	0.1	*	0.4	1.7	0.9	3.7
Wadi Halfa	21 55N	31 20E	410	39	75	46	98	62	106	74	98	67	127	28	39	*	*	*	*	*	0.0	*	*	*	*	*	0.0	*
Wau	07 42N	28 03E	1,443	38	96	64	99	72	89	69	93	69	115	50	38	*	0.2	0.9	2.6	5.3	6.5	7.5	8.2	6.6	4.9	0.6	*	43.3
Tanzania:																												
Dares Salaam	06 50S	39 18E	47	44	83	77	86	73	83	66	85	69	96	59	49	2.6	2.6	5.1	11.4	7.4	1.3	1.2	1.0	1.2	1.6	2.9	3.6	41.9
Iringa	07 47S	35 42E	5,330	14	76	59	75	59	72	52	80	57	90	42	24	6.8	5.1	7.1	3.5	0.5	*	*	*	0.1	0.2	1.5	4.5	29.3
Kigoma	04 53S	29 38E	2,903	26	80	67	81	67	83	63	84	69	100	53	18	4.8	5.0	5.9	5.1	1.7	0.2	0.1	0.2	0.7	1.9	5.6	5.3	36.5
Togo:																												
Lome	06 10N	01 15E	72	5	85	72	86	74	80	71	83	72	94	58	15	0.6	0.9	1.9	4.6	5.7	8.8	2.8	0.4	1.4	2.4	1.1	0.4	31.0
Tunisia:																												
Gabes	33 53N	10 07E	7	50	61	43	74	54	89	71	81	62	122	27	50	0.9	0.7	0.8	0.4	0.3	*	*	0.1	0.5	1.2	1.2	0.6	6.7
Tunis	36 47N	10 12E	217	50	58	43	70	51	90	68	77	59	118	30	50	2.5	2.0	1.6	1.4	0.7	0.3	0.1	0.3	1.3	2.0	1.9	2.4	16.5
Uganda:																												
Kampala	00 20N	32 36E	4,304	15	83	65	79	64	77	62	81	63	97	53	15	1.8	2.4	5.1	6.9	5.8	2.9	1.8	3.4	3.6	3.8	4.8	3.9	46.2
Lira	02 15N	32 54E	3,560	14	91	61	86	64	81	61	86	61	100	50	14	0.7	1.0	3.5	6.9	7.9	4.9	6.4	10.0	8.3	6.1	3.2	1.8	60.7
United Arab Republic:																												
Alexandria	31 12N	29 53E	105	45	65	51	74	59	85	73	83	68	111	37	61	1.9	0.9	0.4	0.1	*	*	*	*	*	0.2	1.3	2.2	7.0
Aswan	24 02N	32 53E	366	46	74	50	96	66	106	79	98	71	124	35	11	*	*	*	*	*	*	0.0	0.0	0.0	*	*	*	*
Cairo	29 52N	31 20E	381	42	65	47	83	57	96	70	86	65	117	34	42	0.2	0.2	0.2	0.1	0.1	*	0.0	0.0	*	*	0.1	0.2	1.1

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Upper Volta:																												
Bobo Dioulasso	11 10N	04 15W	1,411	11	92	58	99	71	87	69	90	70	115	46	10	0.1	0.2	1.1	2.1	4.6	4.8	9.8	12.0	8.5	2.5	0.7	0.0	46.4
Ouagadougou	12 22N	01 31W	991	10	92	60	103	79	91	74	95	74	118	48	15	*	0.1	0.5	0.6	3.3	4.8	8.0	10.9	5.7	1.3	*	0.0	35.2
Zambia:																												
Balovale	13 34S	23 06E	3,577	8	82	65	84	61	81	47	91	64	108	38	9	8.5	6.9	5.8	1.2	*	0.0	0.0	*	0.3	2.3	4.4	8.9	38.3
Kasama	10 12S	31 11E	4,544	10	79	61	79	60	76	50	87	62	95	39	10	10.7	9.9	10.9	2.8	0.5	*	*	*	*	0.8	6.4	9.5	51.5
Lusaka	15 25S	28 19E	4,191	10	78	63	79	59	73	49	88	64	100	39	10	9.1	7.5	5.6	0.7	0.1	*	*	0.0	*	0.4	3.6	5.9	32.9
ATLANTIC ISLANDS:																												
Funchal, Madeira Island	32 38N	16 55W	82	30	66	56	67	58	75	66	74	65	103	40	30	2.5	2.9	3.1	1.3	0.7	0.2	*	*	1.0	3.0	3.5	3.3	21.5
Georgetown, Ascension Island	07 56S	14 25W	55	29	85	73	88	75	84	72	83	71	95	65	45	0.2	0.4	0.7	1.1	0.5	0.5	0.5	0.4	0.3	0.3	0.2	0.1	5.2
Hutts Gate, St. Helena	15 57S	05 40W	2,062	30	68	60	69	61	62	55	61	54	82	50	30	2.1	3.1	4.2	3.1	2.8	3.2	4.3	2.6	2.2	1.7	1.2	1.6	32.1
Las Palmas, Canary Islands	28 11N	15 28W	20	45	70	58	71	61	77	67	79	67	99	46	48	1.4	0.9	0.9	0.5	0.2	*	*	*	0.2	1.1	2.1	1.6	8.6
Porto da Praia, Cape Verde Is.	14 54N	23 31W	112	25	77	68	79	69	83	75	85	76	94	56	25	0.1	*	*	*	0.0	*	0.2	3.8	4.5	1.2	0.3	0.1	10.2
Santa Isabel, Fernando Po	03 46N	08 46E	-----	2	87	67	89	70	84	69	86	70	102	61	16	1.3	2.5	4.2	7.2	9.4	11.1	7.4	6.6	9.6	10.4	3.5	1.7	74.9
Sao Tome, Sao Tome	00 20N	06 43E	16	10	86	73	86	73	82	69	84	71	91	56	10	3.2	4.2	5.9	5.0	5.3	1.1	*	*	0.9	4.3	4.6	3.5	38.0
Tristan da Cunha	37 03S	12 19W	75	5	66	59	64	57	57	50	59	51	75	38	5	3.5	3.5	6.4	4.7	7.1	5.9	6.1	6.9	7.9	5.8	4.3	4.0	66.1
INDIAN OCEAN ISLANDS:																												
Agalega Island	10 26S	56 40E	10	3	86	77	87	77	83	75	84	75	91	69	2	5.9	10.1	4.9	6.9	13.2	8.9	8.7	3.2	1.8	4.2	7.0	10.0	84.7
Cocos (Keeling) Island	12 05S	96 53E	15	36	86	77	85	78	82	76	84	76	94	68	38	5.4	7.7	8.5	10.4	7.9	9.0	8.7	4.8	3.7	3.3	4.2	4.6	78.2
Heard Island	53 01S	73 23E	16	5	41	35	39	33	34	27	35	28	58	13	5	5.8	5.8	5.7	6.1	5.8	3.9	3.6	2.2	2.5	3.7	4.0	5.1	54.3
Hellburg, Reunion Island	21 04S	55 22E	3,070	5	74	59	73	56	65	48	69	51	84	40	11	22.4	8.0	16.4	7.2	5.3	4.4	3.1	3.0	2.0	2.3	3.5	12.9	90.5
Port Victoria, Seychelles	04 37S	55 27E	15	60	83	76	86	77	81	75	83	75	92	67	64	15.2	10.5	9.2	7.2	6.7	4.0	3.3	2.7	5.1	6.1	9.1	13.4	92.5
Royal Alfred Observatory, Mauritius	20 06S	57 32E	181	40	86	73	82	70	75	62	80	64	95	50	43	8.5	7.8	8.7	5.0	3.8	2.6	2.3	2.5	1.4	1.6	1.8	4.6	50.6
ASIA – FAR EAST																												
China																												
Canton	23 10N	113 20E	59	26	65	49	77	65	91	77	85	67	101	31	36	0.9	1.9	4.2	6.8	10.6	10.6	8.1	8.5	6.5	3.4	1.2	0.9	63.6
Chanasha	28 15	112 58E	161	14	45	35	70	56	94	78	75	59	109	16	26	1.9	3.7	5.3	5.7	8.2	8.7	4.4	4.3	2.7	3.0	2.7	1.5	52.1
Chungking	29 30N	106 33E	855	27	51	42	73	59	93	76	71	61	111	28	60	0.7	0.8	1.5	3.8	5.7	7.1	5.6	4.7	5.8	4.3	1.9	0.8	42.9
China cont'd:																												
Hankow	30 35N	114 17E	75	29	46	34	69	55	93	78	74	60	108	9	55	1.8	1.9	3.6	5.8	7.0	9.0	7.0	4.1	3.0	3.1	1.9	1.2	49.4
Harbin (Ha-erh-pin)	45 45N	126 38E	476	35	7	-14	54	31	84	65	54	31	102	-43	38	0.2	0.2	0.4	0.9	1.7	3.7	6.6	4.7	2.3	1.2	0.5	0.2	22.6
Kashgar	39 24N	76 07E	4,296	27	33	12	71	48	92	68	71	43	106	-15	18	0.6	0.1	0.5	0.2	0.3	0.2	0.4	0.3	0.1	0.1	0.2	0.3	3.2
Kunming	25 02N	102 43E	6,211	32	61	37	76	51	77	62	70	53	91	22	31	0.4	0.5	0.7	0.8	4.3	6.3	8.8	8.6	5.0	3.0	1.7	0.4	40.5
Lanchow	36 06N	103 55E	5,105	8	33	7	65	40	84	61	62	39	100	- 3	4	0.2	0.2	0.2	0.5	0.8	0.7	3.3	5.1	2.2	0.6	0.0	0.3	14.1
Mukden (Shen-yang)	41 47N	123 24E	138	40	20	- 2	60	36	87	69	62	39	103	-28	42	0.2	0.2	0.7	1.2	2.6	3.8	7.0	6.3	2.9	1.7	0.9	0.4	28.2
Shanghai	31 12N	121 26E	16	56	47	32	67	49	91	75	75	56	104	10	81	1.9	2.4	3.3	3.6	3.8	7.0	5.8	5.5	5.2	2.9	2.1	1.5	45.0
Tientsin	39 10N	117 10E	13	24	33	16	68	45	90	73	68	48	109	- 3	25	0.2	0.1	0.4	0.5	1.1	2.4	7.6	6.0	1.7	0.6	0.4	0.2	21.0
Urumchi	43 45N	87 40E	2,972	6	13	-7	60	36	82	58	50	31	112	-30	6	0.6	0.3	0.5	1.5	1.1	1.5	0.7	1.0	0.6	1.7	1.6	0.4	11.5
Hong Kong:	22 18N	114 10E	109	50	64	56	75	67	87	78	81	73	97	32	50	1.3	1.8	2.9	5.4	11.5	15.5	15.0	14.2	10.1	4.5	1.7	1.2	85.1

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Japan:																												
Kushiro	43 02N	144 12E	315	41	30	8	44	31	66	55	58	40	87	-19	41	1.8	1.4	2.8	3.6	3.8	4.1	4.4	4.9	6.6	4.0	3.1	2.0	42.9
Miyako	39 38N	141 59E	98	30	43	23	58	37	77	62	66	46	99	1	30	2.9	3.0	3.2	3.5	4.5	5.0	5.0	7.2	9.5	6.8	3.0	2.6	56.2
Nagasaki	32 44N	129 53E	436	59	49	36	66	50	85	73	72	58	98	22	59	2.8	3.3	4.9	7.3	6.7	12.3	10.1	6.9	9.8	4.5	3.7	3.2	75.5
Osaka	34 47N	135 26E	49	60	47	32	65	47	87	73	72	55	102	19	60	1.7	2.3	3.8	5.2	4.9	7.4	5.9	4.4	7.0	5.1	3.0	1.9	52.6
Tokyo	35 41N	139 46E	19	60	47	29	63	46	83	70	69	55	101	17	60	1.9	2.9	4.2	5.3	5.8	6.5	5.6	6.0	9.2	8.2	3.8	2.2	61.6
Korea:																												
Pusan	35 10N	129 07E	6	36	43	29	62	47	81	71	70	54	97	7	36	1.7	1.4	2.7	5.5	5.2	7.9	11.6	5.1	6.8	2.9	1.6	1.2	53.6
P'yongyang	39 01N	125 49E	94	43	27	8	61	38	84	69	65	43	100	-19	43	0.6	0.4	1.0	1.8	2.6	3.0	9.3	9.0	4.4	1.8	1.6	0.8	36.4
Seoul	37 31N	126 55E	34	22	32	15	62	41	84	70	67	45	99	-12	22	1.2	0.8	1.5	3.0	3.2	5.1	14.8	10.5	4.7	1.6	1.8	1.0	49.2
Mongolia:																												
Ulan Bator	47 54N	106 56E	4,287	13	- 2	-27	45	18	71	50	44	17	97	-48	15	*	*	0.1	0.2	0.3	1.0	2.9	1.9	0.8	0.2	0.2	0.1	7.7
Taiwan:																												
Tainan	22 57N	120 12E	53	13	72	55	82	67	89	77	86	70	95	39	13	0.7	0.7	1.1	3.2	6.3	15.6	16.0	15.8	8.4	1.2	0.9	0.6	70.5
Taipei	25 04N	121 32E	21	12	66	53	77	64	92	76	80	68	101	32	12	3.8	5.3	4.3	5.3	6.9	8.8	8.8	8.7	8.2	5.5	4.2	2.9	72.7
Union of Soviet Socialist Republics:																												
Alma-Ata	43 16N	76 53E	2,543	19	23	7	56	38	81	60	55	35	100	-30	27	1.3	0.9	2.2	4.0	3.7	2.6	1.4	1.2	1.0	2.0	1.9	1.3	23.5
Chita (Tchita)	52 02N	113 30E	2,218	10	-10	-27	42	19	75	51	38	18	99	-52	24	0.1	0.1	0.1	0.4	1.1	1.8	3.3	3.3	1.2	0.5	0.2	0.2	12.3
Dubinka	69 07N	87 00E	141	5	-23	-31	6	-10	59	47	19	11	84	-62	5	0.3	0.4	0.2	0.3	0.6	1.9	1.5	2.1	1.8	0.9	0.4	0.3	10.7
Irkutsk	52 16N	104 19E	1,532	10	3	-15	42	20	70	50	41	21	98	-58	38	0.5	0.4	0.3	0.6	1.3	2.2	3.1	2.8	1.7	0.7	0.6	0.6	14.9
Kazalinsk	45 46N	62 06E	207	10	16	5	58	27	90	65	57	35	108	-27	19	0.4	0.4	0.5	0.5	0.6	0.2	0.2	0.3	0.3	0.4	0.5	0.6	4.9
Khabarovsk	48 28N	135 03E	165	7	- 2	-13	41	28	75	63	48	34	91	-46	8	0.3	0.2	0.3	0.7	2.0	3.5	4.1	3.3	3.0	0.7	0.6	0.5	19.2
Kirensk	57 47N	108 07E	938	18	-14	-28	38	15	74	51	10	- 4	95	-71	19	0.8	0.5	0.5	0.5	1.0	1.8	2.1	2.1	1.7	1.0	1.0	1.0	14.0
Krasnoyarsk	56 01N	92 52E	498	10	3	-10	34	23	67	55	34	26	103	-47	8	0.1	0.2	0.1	0.2	1.0	1.4	1.2	2.1	1.7	0.9	0.5	0.4	9.8
Markovo	64 45N	170 50E	85	15	-19	-29	5	- 8	59	47	16	9	84	-72	16	0.2	0.2	0.3	0.1	0.3	0.8	1.0	1.9	1.1	0.4	0.4	0.3	7.0
Narym	58 50N	81 39E	197	13	- 7	-18	35	19	71	56	35	25	94	-61	14	0.8	0.5	0.8	0.5	1.3	2.6	2.4	2.7	1.7	1.4	1.1	0.9	16.8
Okhotsk	59 21N	143 17E	18	19	- 6	-17	29	10	57	48	33	21	78	-50	25	0.1	0.1	0.2	0.4	0.9	1.6	2.2	2.6	2.4	1.0	0.2	0.1	11.8
Omsk	54 58N	73 20E	279	19	- 1	-14	39	21	74	56	40	27	102	-56	22	0.6	0.3	0.3	0.5	1.2	2.0	2.0	2.0	1.1	1.0	0.7	0.8	12.5
Petropavlovsk	52 53N	158 42E	286	7	23	11	35	25	56	47	46	34	84	-29	35	3.0	2.2	3.4	2.5	2.2	2.0	3.1	3.2	3.8	3.9	3.6	3.0	35.9
Salehkard	66 31N	66 35E	60	18	-13	-21	18	4	61	49	26	20	85	-65	27	0.3	0.3	0.3	0.3	0.7	1.3	1.9	2.0	1.5	0.7	0.5	0.4	10.2
Semipalatinsk	50 24N	80 13E	709	10	8	- 7	45	26	81	57	46	30	101	-47	10	0.9	0.5	0.5	0.6	1.2	1.5	1.1	1.3	0.7	1.2	1.1	1.0	11.6
Sverdlovsk	56 49N	60 38E	894	21	6	- 5	42	26	70	54	37	28	94	-45	29	0.5	0.4	0.5	0.7	1.9	2.7	2.6	2.7	1.6	1.2	1.1	0.8	16.7
Tashkent	41 20N	69 18E	1,569	19	37	21	65	47	92	64	65	41	106	-19	19	2.1	1.1	2.6	2.3	1.4	0.5	0.2	0.1	0.1	1.2	1.5	1.6	14.7
Verkhoyansk	67 34N	133 51E	328	24	-54	-63	19	-10	66	47	12	- 3	98	-90	44	0.2	0.2	0.1	0.2	0.3	0.9	1.1	1.0	0.5	0.3	0.3	0.2	5.3
Vladivostok	43 07N	131 55E	94	14	13	0	46	34	71	60	55	41	92	-22	53	0.3	0.4	0.7	1.2	2.1	2.9	3.3	4.7	4.3	1.9	1.2	0.6	23.6
Yakutsk	62 01N	129 43E	535	19	-45	-53	27	6	73	54	23	11	97	-84	22	0.3	0.2	0.1	0.3	0.4	1.1	1.6	1.3	1.1	0.5	0.4	0.3	7.4
ASIA – SOUTHEAST																												
Brunei:																												
Brunei	04 55N	114 55E	10	5	85	76	87	77	87	76	86	77	99	70	12	14.6	7.6	7.8	9.8	10.9	9.5	9.0	7.3	11.8	14.5	15.2	13.0	131.0
Burma:																												
Mandalay	21 59N	96 06E	252	20	82	55	101	77	93	78	89	73	111	44	20	0.1	0.1	0.2	1.2	5.8	6.3	2.7	4.1	5.4	4.3	2.0	0.4	32.6
Moulmein	16 26N	97 39E	150	43	89	65	95	77	83	74	88	75	103	52	60	0.2	0.2	0.5	3.0	19.9	37.1	47.5	44.2	27.1	8.5	1.7	0.3	190.2

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Cambodia:																												
Phnom Penh	11 33N	104 51E	39	37	88	71	95	76	90	76	87	76	105	55	49	0.3	0.4	1.4	3.1	5.7	5.8	6.0	6.1	8.9	9.9	5.5	1.7	54.8
Indonesia:																												
Batavia (Jakarta)	06 11S	106 50E	26	80	84	74	87	75	87	73	87	74	98	66	78	11.8	11.8	8.3	5.8	4.5	3.8	2.5	1.7	2.6	4.4	5.6	8.0	70.8
Manokwari	00 53S	134 03E	10	5	86	73	86	74	86	74	87	74	93	68	40	12.0	9.4	13.2	11.1	7.8	7.2	5.4	5.6	4.9	4.7	6.5	10.3	98.1
Mapanget	01 32N	124 55E	264	21	85	73	86	73	87	73	89	72	97	65	63	18.6	13.8	12.2	8.0	6.4	6.5	4.8	4.0	3.3	4.9	8.9	14.7	106.1
Penfui	10 10S	123 39E	335	21	87	75	89	72	88	70	92	72	101	58	63	15.2	13.7	9.2	2.6	1.2	0.4	0.2	0.0	0.0	0.7	3.3	9.1	55.7
Pontianak	00 00N	109 20E	13	20	87	74	89	75	89	74	89	75	96	68	63	10.8	8.2	9.5	10.9	11.1	8.7	6.5	8.0	9.0	14.4	15.3	12.7	125.1
Tabing	00 52S	100 21E	19	21	87	74	87	75	87	74	86	74	94	68	63	13.9	10.1	12.2	14.5	12.8	11.7	10.5	13.7	16.2	20.1	20.5	19.2	175.4
Tarakan	03 19N	117 33E	20	19	85	73	86	75	87	74	87	74	94	67	31	10.9	10.2	14.0	13.9	13.5	12.6	10.3	12.4	11.6	14.3	15.2	13.4	152.3
Laos:																												
Vientiane	17 58N	102 34E	559	13	83	58	95	73	89	75	88	71	108	32	27	0.2	0.6	1.5	3.9	10.5	11.9	10.5	11.5	11.9	4.3	0.6	0.1	67.5
Malaya, Fed.:																												
Kuala Lumpur	03 06N	101 42E	111	19	90	72	91	74	90	72	89	73	99	64	19	6.2	7.9	10.2	11.5	8.8	5.1	3.9	6.4	8.6	9.8	10.2	7.5	96.1
Singapore	01 18N	103 50E	33	39	86	73	88	75	88	75	87	74	97	66	64	9.9	6.8	7.6	7.4	6.8	6.8	6.7	7.7	7.0	8.2	10.0	10.1	95.0
North Borneo:																												
Sanda Kan	05 54N	118 03E	38	45	85	74	89	76	89	75	88	75	99	70	46	19.0	10.9	8.6	4.5	6.2	7.4	6.7	7.9	9.3	10.2	14.5	18.5	123.7
Philippine Islands:																												
Davao	07 07N	125 38E	88	15	87	72	91	73	88	73	89	73	97	65	34	4.8	4.5	5.2	5.8	9.2	9.1	6.5	6.5	6.7	7.9	5.3	6.1	77.6
Manila	14 31N	121 00E	49	61	86	69	93	73	88	75	88	74	101	58	75	0.9	0.5	0.7	1.3	5.1	10.0	17.0	16.6	14.0	7.6	5.7	2.6	82.0
Sarawak:																												
Kuching	01 29N	110 20E	85	5	85	72	90	73	90	72	89	73	98	64	19	24.0	20.1	12.9	11.0	10.3	7.1	7.7	9.2	8.6	10.5	14.1	18.2	153.7
Thailand:																												
Bangkok	13 44N	100 30E	53	10	89	67	95	78	90	76	88	76	104	50	10	0.2	1.1	1.1	2.3	5.2	6.0	6.9	9.2	14.0	9.9	1.8	0.1	57.8
Viet Nam																												
Hanoi	21 03N	105 52E	20	12	68	58	80	70	92	79	84	72	108	41	12	0.8	1.2	2.5	3.6	4.1	11.2	11.9	15.2	10.0	3.5	2.6	2.8	69.4
Saigon	10 49N	106 39E	33	31	89	70	95	76	88	75	88	74	104	57	33	0.6	0.1	0.5	1.7	8.7	13.0	12.4	10.6	13.2	10.6	4.5	2.2	78.1
ASIA – MIDDLE EAST																												
Aden:																												
Riyan	14 39N	49 19E	83	13	82	67	88	74	92	77	88	72	111	57	13	0.3	0.1	0.6	0.2	*	0.1	0.1	0.1	*	*	0.7	0.3	2.5
Afghanistan:																												
Kabul	34 30N	69 13E	5,955	9	36	18	66	43	92	61	73	42	104	- 6	45	1.3	1.5	3.6	3.3	0.9	0.2	0.1	0.1	*	0.4	0.6	0.6	12.6
Kandhar	31 36N	65 40E	3,462	7	56	31	83	50	102	66	85	44	111	14	7	3.1	1.7	0.8	0.3	0.2	*	0.1	*	0.0	*	*	0.8	7.0
Ceylon:																												
Colombo	06 54N	79 52E	22	25	86	72	88	76	85	77	85	75	99	59	40	3.5	2.7	5.8	9.1	14.6	8.8	5.3	4.3	6.3	13.7	12.4	5.8	92.3
East Pakistan:																												
Dacca	23 46N	90 23E	24	60	77	56	92	74	88	79	88	75	108	43	61	0.3	1.2	2.4	5.4	9.6	12.4	13.0	13.3	9.8	5.3	1.0	0.2	73.9

See footnotes at end of table.

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
India:																												
Ahmadabad	23 03N	72 37E	180	45	85	58	104	75	93	79	97	73	118	36	45	*	0.1	0.1	*	0.4	3.7	12.2	8.1	4.2	0.4	0.1	*	29.3
Bangalore	12 57N	77 40E	2,937	60	80	57	93	69	81	66	82	65	102	46	60	0.2	0.3	0.4	1.6	4.2	2.9	3.9	5.0	6.7	5.9	2.7	0.4	34.2
Bombay	19 06N	72 51E	27	60	88	62	93	74	88	75	93	73	110	46	60	0.1	0.1	0.1	*	0.7	19.1	24.3	13.4	10.4	2.5	0.5	0.1	71.2
Calcutta	22 32N	88 20E	21	60	80	55	97	76	90	79	89	74	111	44	60	0.4	1.2	1.4	1.7	5.5	11.7	12.8	12.9	9.9	4.5	0.8	0.2	63.0
Cherrapunji	25 15N	91 44E	4,309	35	60	46	71	59	72	65	72	61	87	33	35	0.7	2.1	7.3	26.2	50.4	106.1	96.3	70.1	43.3	19.4	2.7	0.5	425.1
Hyderabad	17 27N	78 28E	1,741	50	85	59	101	75	87	73	88	68	112	43	45	0.3	0.4	0.5	1.2	1.1	4.4	6.0	5.3	6.5	2.5	1.1	0.3	29.6
Jalpaiguri	26 32N	88 43E	272	50	74	50	90	68	89	77	87	70	104	36	55	0.3	0.7	1.3	3.7	11.8	25.9	32.2	25.3	21.2	5.6	0.5	0.2	128.7
Lucknow	26 45N	80 52E	400	60	74	47	101	71	92	80	91	67	119	34	60	0.8	0.7	0.3	0.3	0.8	4.5	12.0	11.5	7.4	1.3	0.2	0.3	40.1
Madras	13 04N	80 15E	51	60	85	67	95	78	96	79	90	75	113	57	60	1.4	0.4	0.3	0.6	1.0	1.9	3.6	4.6	4.7	12.0	14.0	5.5	50.0
Mormugao	15 22N	73 49E	157	10	86	70	88	79	83	75	86	75	98	59	30	*	*	*	0.7	2.6	29.6	31.2	15.9	9.5	3.8	1.3	0.2	94.8
New Delhi	28 35N	77 12E	695	10	71	43	97	68	95	80	93	64	115	31	75	0.9	0.7	0.5	0.3	0.5	2.9	7.1	6.8	4.6	0.4	0.1	0.4	25.2
Silchar	24 49N	92 48E	95	60	78	52	88	69	90	77	88	72	103	41	53	0.8	2.1	7.9	14.3	15.6	21.7	19.7	19.7	14.4	6.5	1.4	0.4	124.5
Indian Ocean Islands:																												
Port Blair, Andaman Is.	11 40N	92 43E	261	60	84	72	89	75	84	75	84	74	97	62	60	1.8	1.1	1.1	2.4	15.1	21.7	15.4	16.3	17.4	12.5	10.5	7.9	123.2
Amini Divi, Laccadive Is.	11 07N	72 44E	13	29	86	74	92	80	86	77	86	77	99	65	30	0.7	*	*	1.5	3.7	14.3	12.0	7.7	6.3	5.8	2.6	1.3	56.0
Minicoy, Maldive Is.	08 18N	73 00E	9	20	85	73	87	80	85	76	85	76	98	63	50	1.8	0.7	0.9	2.3	7.0	11.6	8.9	7.8	6.3	7.3	5.5	3.4	63.5
Car Nicobar, Nicobar Is.	09 09N	92 49E	47	13	86	77	90	77	86	77	85	75	95	66	30	3.9	1.2	2.1	3.5	12.5	12.4	9.3	10.2	12.9	11.6	11.4	7.8	98.8
Iran:																												
Abadan	30 21N	48 13E	10	12	64	44	90	62	112	81	98	63	127	24	10	1.5	1.7	0.6	0.8	0.1	0.0	0.0	0.0	0.0	0.1	1.0	1.8	7.6
Esfahan (Isfahan)	32 37N	51 41E	5,238	45	47	25	72	46	98	67	78	47	108	- 4	45	0.7	0.6	0.8	0.6	0.3	*	0.1	*	*	0.1	0.4	0.7	4.4
Kermanshah	34 19N	47 07E	4,331	15	45	23	68	38	99	56	79	38	108	-13	15	2.6	2.3	2.8	2.2	1.6	*	*	*	*	0.4	2.0	2.4	16.4
Rezaiyeh	37 32N	45 05E	4,364	3	32	17	67	45	91	64	67	47	99	-11	3	1.9	2.3	2.0	1.7	1.2	0.5	*	0.1	0.2	1.5	0.8	1.6	13.8
Tehran	35 41N	51 19E	3,937	24	45	27	71	49	99	72	76	53	109	- 5	33	1.8	1.5	1.8	1.4	0.5	0.1	0.1	0.1	0.1	0.3	0.8	1.2	9.7
Iraq:																												
Baghdad	33 20N	44 24E	111	15	60	39	85	57	110	76	92	61	121	18	15	0.9	1.0	1.1	0.5	0.1	*	*	*	*	0.1	0.8	1.0	5.5
Basra	30 34N	47 47E	8	10	64	45	85	63	104	81	94	64	123	24	10	1.4	1.1	1.2	1.2	0.2	0.0	*	*	*	*	1.4	0.8	7.3
Mosul	36 19N	43 09E	730	26	54	35	77	49	109	72	88	51	124	12	29	2.8	3.1	2.1	1.9	0.7	*	*	*	*	0.2	1.9	2.4	15.2
Israel:																												
Haifa	32 48N	35 02E	23	16	65	49	77	58	88	75	85	68	112	27	30	6.9	4.3	1.6	1.0	0.2	*	*	*	0.1	1.0	3.7	7.3	26.2
Jerusalem	31 47N	35 13E	2,654	19	55	41	73	50	87	63	81	59	107	26	50	5.1	4.7	2.9	0.9	0.1	*	0.0	0.0	*	0.3	2.2	3.5	19.7
Tel Aviv	32 06N	34 46E	33	10	64	50	70	57	82	72	79	65	102	34	10	4.9	2.7	2.0	0.7	0.1	0.0	0.0	0.0	0.1	0.4	4.1	6.1	21.1
Jammu/Kashmir:																												
Srinagar	33 58N	74 46E	5,458	50	41	24	67	45	88	64	74	41	106	- 4	50	2.9	2.8	3.6	3.7	2.4	1.4	2.3	2.4	1.5	1.2	0.4	1.3	25.9
Jordan:																												
Amman	31 58N	35 59E	2,547	25	54	39	73	49	89	65	81	57	109	21	25	2.7	2.9	1.2	0.6	0.2	0.0	0.0	0.0	*	0.2	1.3	1.8	10.9
Kuwait:																												
Kuwait	29 21N	48 00E	16	14	61	49	83	68	103	86	91	73	119	33	10	0.9	0.9	1.1	0.2	*	0.0	0.0	0.0	0.0	0.1	0.6	1.1	5.1
Lebanon:																												
Beirut	33 54N	35 28E	111	62	62	51	72	58	87	73	81	69	107	30	71	7.5	6.2	3.7	2.2	0.7	0.1	*	*	0.2	2.0	5.2	7.3	35.1
Nepal:																												
Katmandu	27 42N	85 22E	4,423	27	65	36	84	53	84	69	80	56	99	27	9	0.6	1.6	0.9	2.3	4.8	9.7	14.7	13.6	6.1	1.5	0.3	0.1	56.2
Oman and Muscat:																												
Muscat	23 37N	58 35E	15	23	77	66	90	78	97	87	93	80	116	51	38	1.1	0.7	0.4	0.4	*	0.1	*	*	0.0	0.1	0.4	0.7	3.9

TABLE B-1 (Continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
				Length of record	Average daily								Extreme		Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
					Jan		Apr		July		Oct																	
					Max	Min	Max	Min	Max	Min	Max	Min	Max	Min														
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Pakistan (West):																												
Karachi	24 48N	66 59E	13	43	77	55	90	73	91	81	91	72	118	39	59	0.5	0.4	0.3	0.1	0.1	0.7	3.2	1.6	0.5	0.1	0.1	0.2	7.8
Multan	30 11N	71 25E	400	60	68	42	95	68	102	86	94	64	122	29	60	0.4	0.4	0.4	0.3	0.3	0.6	2.0	1.8	0.5	0.1	0.1	0.2	7.1
Rawalpindi	33 35N	73 03E	1,676	60	62	38	86	59	98	77	89	57	118	25	60	2.5	2.5	2.7	1.9	1.3	2.3	8.1	9.2	3.9	0.6	0.3	1.2	36.5
Saudi Arabia:																												
Dhahran	26 16N	50 10E	78	10	69	54	90	69	107	86	95	73	120	40	10	1.1	0.6	0.4	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.2	0.9	3.5
Jidda	21 28N	39 10E	20	5	84	66	91	70	99	79	95	73	117	49	5	0.2	*	*	*	*	0.0	*	*	*	*	1.0	1.2	2.5
Riyadh	24 39N	46 42E	1,938	3	70	46	89	64	107	78	94	61	113	19	3	0.1	0.8	0.9	1.0	0.4	*	0.0	*	0.0	0.0	*	*	3.2
Syria:																												
Deir Ez Zor	35 21N	40 09E	699	5	53	35	80	52	105	78	86	56	114	16	8	1.6	0.8	0.3	0.8	0.1	*	0.0	0.0	0.0	0.2	1.5	0.9	6.2
Dimashq (Damascus)	33 30N	36 20E	2,362	13	53	36	75	49	96	64	81	54	113	21	7	1.7	1.7	0.3	0.5	0.1	*	*	0.0	0.7	0.4	1.6	1.6	8.6
Halab (Aleppo)	36 14N	37 08E	1,280	8	50	34	75	48	97	69	81	54	117	9	10	3.5	2.5	1.5	1.1	0.3	0.1	0.0	*	*	1.0	2.2	3.3	15.5
Trucial Kingdoms:																												
Sharjah	25 20N	55 24E	18	11	74	54	86	65	100	82	92	71	118	37	12	0.9	0.9	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.4	4.2
Turkey:																												
Adana	36 59N	35 18E	82	21	57	39	74	51	93	71	84	58	109	19	31	4.3	4.0	2.5	1.6	2.0	0.7	0.2	0.2	0.7	1.9	2.4	3.8	24.3
Ankara	39 57N	32 53E	2,825	26	39	24	63	40	86	59	69	44	104	-13	24	1.3	1.2	1.3	1.3	1.9	1.0	0.5	0.4	0.7	0.9	1.2	1.9	13.6
Erzurum	39 54N	41 16E	6,402	16	24	8	50	32	78	53	59	37	93	-22	16	1.4	1.6	2.0	2.5	3.1	2.1	1.3	0.9	1.1	2.3	1.8	1.1	21.2
Izmir (Smyrna)	38 27N	27 15E	92	39	55	39	70	49	92	69	76	55	108	12	58	4.4	3.3	3.0	1.7	1.3	0.6	0.2	0.2	0.8	2.1	3.3	4.8	25.5
Samsun	41 17N	36 19E	131	24	50	38	59	45	79	65	69	56	103	20	27	2.9	2.6	2.7	2.3	1.8	1.5	1.5	1.3	2.4	3.2	3.5	2.4	29.1
Yemen:																												
Kamaran I.	15 20N	42 37E	20	26	82	74	89	79	98	85	93	82	105	66	21	0.2	0.2	0.1	0.1	0.1	*	0.5	0.7	0.1	0.1	0.4	0.9	3.4
AUSTRALIA & PACIFIC ISLANDS																												
Australia:																												
Adelaide	34 57S	138 32E	20	86	86	61	73	55	59	45	73	51	118	32	104	0.8	0.7	1.0	1.8	2.7	3.0	2.6	2.6	2.1	1.7	1.1	1.0	21.1
Alice Springs	23 48S	133 53E	1,791	62	97	70	81	54	67	39	88	58	111	19	30	1.7	1.3	1.1	0.4	0.6	0.5	0.3	0.3	0.3	0.7	1.2	1.5	9.9
Bourke	30 05S	145 58E	361	63	99	70	82	55	65	40	85	56	125	25	72	1.4	1.5	1.1	1.1	1.0	1.1	0.9	0.8	0.8	0.9	1.2	1.4	13.2
Brisbane	27 25S	153 05E	17	53	85	69	79	61	68	49	80	60	110	35	91	6.4	6.3	5.7	3.7	2.8	2.6	2.2	1.9	1.9	2.5	3.7	5.0	44.7
Broome	17 57S	122 13E	56	41	92	79	93	72	82	58	91	72	113	40	50	6.3	5.8	3.9	1.2	0.6	0.9	0.2	0.1	*	*	0.6	3.3	22.9
Burketown	17 45S	139 33E	30	31	93	77	91	69	82	55	93	70	110	40	53	8.2	6.3	5.2	1.0	0.2	0.3	*	*	*	0.4	1.5	4.4	27.5
Canberra	35 18S	149 11E	1,886	23	82	55	67	44	52	33	68	43	109	14	25	1.9	1.7	2.2	1.6	1.8	2.1	1.8	2.2	1.6	2.2	1.9	2.0	23.0
Carnarvon	24 53S	113 40E	13	43	88	72	84	66	71	51	78	61	118	37	57	0.4	0.7	0.7	0.6	1.5	2.4	1.6	0.7	0.2	0.1	*	0.2	9.1
Cloncurry	20 40S	140 30E	622	32	99	77	90	67	77	51	95	68	127	35	59	4.4	4.2	2.4	0.7	0.5	0.6	0.3	0.1	0.3	0.5	1.3	2.7	18.0
Esperance	33 50S	121 55E	14	44	77	60	72	54	62	45	68	50	117	31	60	0.7	0.7	1.2	1.8	3.3	4.1	4.0	3.8	2.7	2.2	1.0	0.9	26.4
Laverton	28 40S	122 23E	1,510	30	96	69	81	57	64	41	82	55	115	25	30	0.8	0.8	1.6	0.8	0.9	0.7	0.6	0.5	0.2	0.3	0.8	0.8	8.8
Melbourne	37 49S	144 58E	115	88	78	57	68	51	56	42	67	48	114	27	88	1.9	1.8	2.2	2.3	2.1	2.1	1.9	1.9	2.3	2.6	2.3	2.3	25.7
Mundiwindi	23 52S	120 10E	1,840	15	101	64	87	61	70	41	89	58	112	22	15	1.0	1.9	2.0	0.8	0.6	0.9	0.1	0.3	0.3	0.5	0.5	1.2	10.1
Perth	31 56S	115 58E	64	44	85	63	76	57	63	48	70	53	112	31	63	0.3	0.4	0.8	1.7	5.1	7.1	6.7	5.7	3.4	2.2	0.8	0.5	34.7
Port Darwin	12 25S	130 52E	104	58	90	77	92	76	87	67	93	77	105	55	70	15.2	12.3	10.0	3.8	0.6	0.1	*	0.1	0.5	2.0	4.7	9.4	58.7
Sydney	33 52S	151 02E	62	87	78	65	71	58	60	46	71	56	114	35	87	3.5	4.0	5.0	5.3	5.0	4.6	4.6	3.0	2.9	2.8	2.9	2.9	46.5
Thursday Island	10 35S	142 13E	200	31	87	77	86	77	82	73	86	76	98	64	49	18.2	15.8	13.9	8.0	1.6	0.5	0.4	0.2	0.1	0.3	1.5	7.0	67.5
Townsville	19 15S	146 46E	18	31	87	76	84	70	75	59	83	71	110	39	67	10.9	11.2	7.2	3.3	1.3	1.4	0.6	0.5	0.7	1.3	1.9	5.4	45.7
William Creek	28 55S	136 21E	247	39	96	69	80	55	65	41	84	56	119	25	30	0.5	0.6	0.3	0.3	0.3	0.5	0.2	0.3	0.3	0.5	0.5	0.7	5.0
Windorah	25 26S	142 36E	390	29	101	74	86	59	70	43	91	61	116	26	50	1.4	1.6	1.6	0.9	0.8	0.8	0.5	0.4	0.5	0.6	0.9	1.4	11.4

TABLE B-1 (continued)

TEMPERATURE AND PRECIPITATION DATA FOR REPRESENTATIVE WORLDWIDE STATIONS

Country and station	Latitude	Longitude	Elevation	Temperature											Average precipitation													
					Average daily								Extreme															
					Jan		Apr		July		Oct																	
				Length of record	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Length of record	January	February	March	April	May	June	July	August	September	October	November	December	yr
	° '	° '	ft	yr	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	yr	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Tasmania:																												
Hobart	42 53S	147 20E	177	70	71	53	63	48	52	40	63	46	105	28	100	1.9	1.5	1.8	1.9	1.8	2.2	2.1	1.9	2.1	2.3	2.4	2.1	24.0
New Zealand:																												
Auckland	37 00S	174 47E	23	36	73	60	67	56	56	46	63	52	90	33	92	3.1	3.7	3.2	3.8	5.0	5.4	5.7	4.6	4.0	4.0	3.5	3.1	49.1
Christchurch	43 29S	172 32E	118	52	70	53	62	45	50	35	62	44	96	21	64	2.2	1.7	1.9	1.9	2.6	2.6	2.7	1.9	1.8	1.7	1.9	2.2	25.1
Dunedin	45 55S	170 12E	4	77	66	50	59	45	48	37	59	42	94	23	77	3.4	2.8	3.0	2.8	3.2	3.2	3.1	3.0	2.7	3.0	3.2	3.5	36.9
Wellington	41 17S	174 46E	415	66	69	56	63	51	53	42	60	48	88	29	79	3.2	3.2	3.2	3.8	4.6	4.6	5.4	4.6	3.8	4.0	3.5	3.5	47.4
PACIFIC ISLANDS:																												
Canton, Phoenix Is.	02 46S	171 43W	9	12	88	78	89	78	89	78	90	78	98	70	30	2.6	2.2	2.5	3.6	4.3	2.6	2.6	2.5	1.2	1.1	1.6	2.6	29.4
Guam, Marianas Is.	13 33N	144 50E	361	30	84	72	86	73	87	72	86	73	95	54	30	4.6	3.5	2.6	3.0	4.2	5.9	9.0	12.8	13.4	13.1	10.3	6.1	88.5
Honolulu, Hawaii	21 20N	157 55W	7	30	79	66	80	68	85	73	84	72	93	56	30	3.8	3.3	2.9	1.3	1.0	0.3	0.4	0.9	1.0	1.8	2.2	3.0	21.9
Iwo Jima, Bonin Is.	24 47N	141 19E	353	15	71	64	77	69	86	78	84	76	95	46	17	3.2	2.5	2.1	3.7	4.9	4.0	6.4	6.5	4.6	5.9	4.8	4.3	52.8
Madang, New Guinea	05 12S	145 47E	19	12	87	75	88	74	88	74	88	75	98	62	20	12.1	11.9	14.9	16.9	15.1	10.8	7.6	4.8	5.3	10.0	13.3	14.5	137.2
Midway Is.	28 13N	177 23W	29	21	69	62	71	64	81	74	79	72	92	46	20	4.6	3.7	3.1	2.5	1.9	1.3	2.9	3.9	3.7	3.7	3.6	4.2	40.7
Naha, Okinawa	26 12N	127 39E	96	30	67	56	76	64	89	77	81	69	96	41	30	5.3	5.4	6.1	6.1	8.9	10.0	7.1	10.0	7.1	6.6	5.9	4.3	82.8
Noumea, New Caledonia	22 16S	166 27E	246	24	86	72	83	70	76	62	80	65	99	52	52	3.7	5.1	5.7	5.2	4.4	3.7	3.6	2.6	2.5	2.0	2.4	2.6	43.5
Pago Pago, Samoa	14 19S	170 43W	29	2	87	75	87	76	83	74	85	75	98	67	41	24.5	20.5	19.2	16.5	15.4	12.3	10.0	8.2	13.1	14.9	19.2	19.8	193.6
Ponape, Caroline Is.	06 58N	158 13E	123	30	86	75	86	75	87	73	87	72	96	67	30	11.1	9.7	14.6	20.0	20.3	16.7	16.2	16.3	15.8	16.0	16.9	18.3	191.9
Port Moresby, New Guinea	09 29S	147 09E	126	20	89	76	87	75	83	73	86	75	98	64	38	7.0	7.6	6.7	4.2	2.5	1.3	1.1	0.7	1.0	1.4	1.9	4.4	39.8
Rabaul, New Guinea	04 13S	152 11E	28	19	90	73	90	73	89	73	92	73	100	65	24	14.8	10.4	10.2	10.0	5.2	3.3	5.4	3.7	3.5	5.1	7.1	10.1	88.8
Suva, Fiji Is.	18 08S	178 26E	20	43	86	74	84	73	79	68	81	70	98	55	43	11.4	10.7	14.5	12.2	10.1	6.7	4.9	8.3	7.7	8.3	9.8	12.5	117.1
Tahiti, Society Is.	17 33S	149 36W	7	23	89	72	89	72	86	68	87	70	93	61	27	13.2	11.5	6.5	6.8	4.9	3.2	2.6	1.9	2.3	3.4	6.5	11.9	74.7
Tulagi, Solomon Is.	09 05S	160 10E	8	20	88	76	88	76	86	76	87	76	96	68	37	14.3	15.8	15.0	10.0	8.1	6.8	7.6	8.7	8.0	8.7	10.0	10.4	123.4
Wake Is.	19 17N	166 39E	11	30	82	73	83	74	87	77	86	77	92	64	30	1.1	1.4	1.5	1.9	2.0	1.9	4.6	7.1	5.2	5.3	3.1	1.8	36.9
Yap, Caroline Is.	9 31N	138 08E	62	30	85	76	87	77	88	75	88	75	97	69	30	7.9	4.6	5.4	6.4	9.5	10.7	13.8	14.7	14.0	13.2	11.2	10.2	121.6
ANTARCTICA																												
Byrd Station	80 01S	119 32W	5,095	6	10	- 2	-11	-30	-25	-45	-15	-33	31	-82	6	0.4	0.4	0.2	0.3	0.4	0.5	0.7	0.7	0.3	0.7	0.0	0.3	4.9
Ellsworth	77 44S	41 07W	139	6	22	12	-10	-25	-21	-35	- 2	-15	36	-70	6	0.3	0.2	0.3	0.6	0.2	0.2	0.2	0.2	0.3	0.4	0.5	0.2	3.6
McMurdo Station	77 53S	166 48W	8	10	30	21	- 1	-13	- 9	-24	2	-12	42	-59	10	0.5	0.7	0.4	0.4	0.4	0.3	0.2	0.3	0.4	0.2	0.2	0.3	4.3
South Pole Station	89 59S	000 00W	9,186	5	-16	-23	-66	-79	-67	-81	-55	-64	6	-107	5	*	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*	0.0	*	0.1
Wilkes	66 16S	110 31E	31	7	34	28	17	9	8	- 3	16	6	46	-35	7	0.5	0.4	1.7	1.1	1.4	1.2	1.3	0.8	1.5	1.2	0.8	0.3	12.2

1. "Length of Record" refers to average daily maximum and minimum temperatures and precipitation. A standard period of the 30 years from 1931-1960 had been used for locations in the United States and some other countries. The length of record of extreme maximum and minimum temperatures includes all available years of data for a given location and is usually for a longer period.

2. * - Less than 0.05"

3. Except for Antarctica, amounts of solid precipitation such as snow or hail have been converted to their water equivalent. Because of the frequent occurrence of blowing snow, it has not been possible to determine the precise amount of precipitation actually falling in Antarctica. The values shown are the average amounts of solid snow accumulating in a given period as determined by snow markers. The liquid content of the accumulation is undetermined.

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(1) Boundary classifications: Soils possessing characteristics of two groups are designated by combinations of group symbols. For example GW-GC, well-graded gravel-sand mixture with clay binder. (2) All sieve sizes on this chart are U. S. standard.

FIELD IDENTIFICATION PROCEDURES FOR FINE-GRAINED SOILS OR FRACTIONS

These procedures are to be performed on the minus No. 40 sieve size particles, approximately 1/64 in. For field classification purposes, screening is not intended, simply remove by hand the coarse particles that interfere with the tests.

Dilatancy (reaction to shaking)

After removing particles larger than No. 40 sieve size, prepare a pat of moist soil with a volume of about one-half cubic inch. Add enough water if necessary to make the soil soft but not sticky.

Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil.

Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

Dry Strength (crushing characteristics)

After removing particles larger than No. 40 sieve size, mold a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun, or air-drying, and then test its strength by breaking and crumbling between the fingers. This strength is a measure of the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.

High dry strength is characteristic for clays of the CH group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when powdering the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

Toughness (consistency near plastic limit)

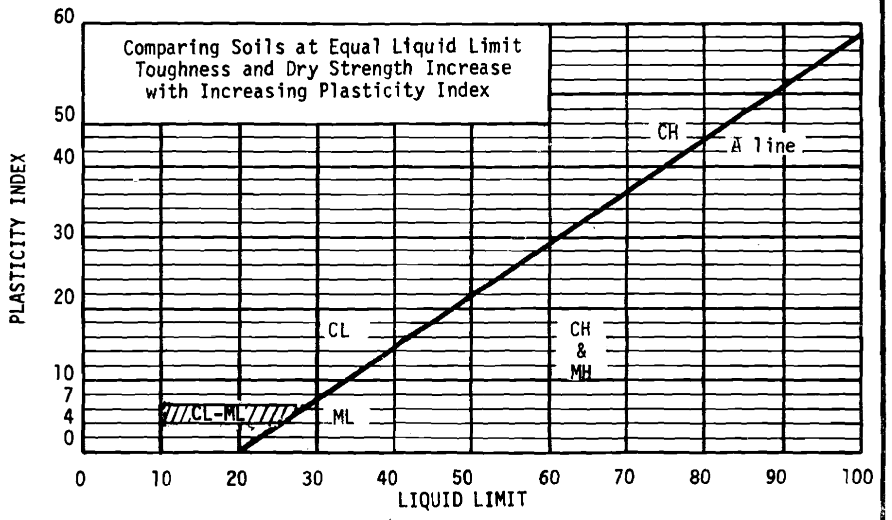
After particles larger than the No. 40 sieve are removed, a specimen of soil about one-half inch cube in size, is molded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about one-eighth inch in diameter. The thread is then folded and rerolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and they stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line.

Highly organic clays have a very weak and spongy feel at the plastic limit.

Major divisions			Group symbols	Typical names	Field identification procedures (Excluding particles larger than 3 in. and basing fractions on estimated weights)			I
1	2		3	4	5			
Coarse-grained soils More than half of material is larger than No. 200 sieve size. The No. 200 sieve size is about the smallest particle visible to the naked eye.	Gravels More than half of coarse fraction is larger than No. 4 sieve size. (For visual classification, the 1/4-in. size may be used as equivalent to the No. 4 sieve size)	Clean gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines.	Wide range in grain sizes and substantial amounts of all intermediate particle sizes.			For undis on stra ness, c and dra
			GP	Poorly graded gravels or gravel-sand mixtures, little or no fines	Predominantly one size or a range of sizes with some intermediate sizes missing.			
		Gravels with fines (Appreciable amount of fines)	GM	Silty gravels, gravel-sand-silt mixture.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).			Give typi percenta mum siz tion, a grains; other p tion; a
			GC	Clayey gravels, gravel-sand-clay mixtures.	Plastic fines (for identification procedures see CL below).			
	Sands More than half of coarse fraction is smaller than No. 4 sieve size.	Clean sands (little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines.	Wide range in grain size and substantial amounts of all intermediate particle sizes.			
			SP	Poorly graded sands or gravelly sands, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.			Example: Silty sa angular maximum sand gra nonplast well com luvial s
		Sands with fines (Appreciable amount of fines)	SM	Silty sands, sand-silt mixtures.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).			
			SC	Clayey sands, sand-clay mixtures.	Plastic fines (for identification procedures see CL below).			
					Identification procedures on fraction smaller than No. 40 sieve size			
					Dry Strength (Crushing characteristics)	Dilatancy (Reaction to shaking)	Toughness (Consistency near PL)	
Fine-grained soils More than half of material is smaller than No. 200 sieve size.	Silts and clays Liquid limit is less than 50		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity.	None to slight	Quick to slow	None	For undist on struc sistency molded s age cond
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.	Medium to high	None to very slow	Medium	
			OL	Organic silts and organic silty clays of low plasticity.	Slight to medium	Slow	Slight	Give typic characte maximum in wet c or geolo descript in paren
	Silts and clays Liquid limit is greater than 50		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.	Slight to medium	Slow to none	Slight to medium	
			CH	Inorganic clays of high plasticity, fat clays.	High to very high	None	High	
			OH	Organic clays of medium to high plasticity, organic silts.	Medium to high	None to very slow	Slight to medium	Example: Clayey s small pe numerous and dry
Highly organic soils			Pt	Peat and other highly organic soils.	Readily identified by color, odor, spongy feel, and frequently by fibrous texture.			

Information required for describing soils	Laboratory classification criteria*			
6	7			
For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions, and drainage characteristics.	Use grain-size curve in identifying the fractions as given under field identification.	Determine percentages of gravel and sand from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse-grained soils are classified as follows: Less than 5% = GW, GP, SW, SP. More than 12% = GM, GC, SM, SC. 5% to 12% = Borderline cases requiring use of dual symbols.	$C_u = \frac{D_{60}}{D_{10}}$ Greater than 4 $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Not meeting all gradation requirements for GW	
Give typical name; indicate approximate percentages of sand and gravel, maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbol in parentheses.			Atterberg limits below "A" line or PI less than 4	Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.
			Atterberg limits above "A" line with PI greater than 7	
			$C_u = \frac{D_{60}}{D_{10}}$ Greater than 6 $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Not meeting all gradation requirements for SW	
Example: Silty sand, gravelly; about 20% hard, angular gravel particles 1/2-in. maximum size; rounded and subangular sand grains, coarse to fine; about 15% nonplastic fines with low dry strength; well compacted and moist in place; alluvial sand; (SM).			Atterberg limits below "A" line or PI less than 4	Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.
			Atterberg limits above "A" line with PI greater than 7	
		*C_u = coefficient of uniformity C_c = coefficient of curvature D_{10}, D_{30}, and D_{60} = grain-size diameters corresponding to 10, 30, and 60 percent, respectively, passing on the cumulative grain-size curves		
For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions. Give typical name; indicate degree and character of plasticity; amount and maximum size of coarse grains; color in wet condition; odor, if any; local or geologic name and other pertinent descriptive information; and symbol in parentheses. Example: Clayey silt, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (ML).		 PLASTICITY CHART For laboratory classification of fine-grained soils		

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