ENGINEERING DESIGN
HANDBOOK

ENVIRONMENTAL SERIES

PART THREE

INDUCED ENVIRONMENTAL FACTORS

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ENGINEERING DESIGN HANDBOOK
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PREFACE

This handbook, ***Induced Environmental Factors,*** is the third in a series on the nature and effects of the environmental phenomena. As the title implies, the handbook addresses a set of induced environmental factors which, for the purpose of this text, comprise:

a. Atmospheric Pollutants
b. Sand and Dust
c. Vibration
d. Shock
e. Acceleration
f. Acoustics
g. Electromagnetic Radiation
h. Nuclear Radiation.

These particular factors were chosen as best representing the needs of the design engineer. It is recognized that this set is arbitrary and that natural forces contribute, sometimes in a major way, to these environmental parameters.

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 the handbooks. Appreciation, however, is extended to the following organizations and through them to the individuals concerned:

a. Frankford Arsenal
b. US Army Engineer Topographic Laboratories
c. US Army Tank-Automotive Command
d. US Army Transportation Engineering Agency
e. 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.

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CHAPTER 1

INTRODUCTION

This handbook, containing information on eight induced environmental factors, is Part Three of the Environmental Series of Engineering Design Handbooks. The complete series includes:

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

Part Two, ***Natural Environmental Factors,*** AMCP **706-116**

Part Three, ***Induced Envimnmental Factors*** (this part), AMCP **706-117**

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

Part Five, ***Envimnmental Glossary,*** AMCP **706-1**19.

The environmental factors included in this handbook—atmospheric pollutants, sand and dust, vibration, shock, acceleration, acoustics, electromagnetic radiation, and nuclear radiation—are those that are derived primarily from human activities. It is apparent, however, that natural forces contribute, sometimes in a major way, to the effects of these environmental parameters. For example, many air pollutants are produced by nature. These include sulfur oxides and dust from volcanic activities, hydrocarbons from decaying vegetation and other organic materials, and the smoke and vapors emanating from naturally occurring, forest fires. Large quantities of sand and dust are also produced naturally but, in this case, it was decided that the sand and dust derived from human activities was more important in its effects on materiel than that of natural origin. Vibration, shock, and acceleration are less influenced by nature although the extremely destructive forces of earthquakes would be classified with these factors, as would forces associated with winds and waves. Natural contributions to the acoustical environmental factor are primarily associated with meteorological disturbances such as thunderstorms or with volcanic activity. The natural background electromagnetic radiation can reach a destructive magnitude in the case of lightning, but otherwise is overshadowed by artificial sources.

Each of these induced environmental factors is also influenced greatly by natural environmental factors. Rain will wash many pollutants from the atmosphere or winds will disperse them; rain or humidity will suppress sand and dust; and the other induced environmental factors are influenced by temperature, humidity, or other natural phenomena.

Because these induced environmental factors are derived from human activities, they are subject to control. Each of them can be eliminated by eliminating its source, but this is not usually desirable. The various mechanical factors associated with transportation of materiel cannot be completely eliminated without also halting transportation. Electromagnetic radiation in the environment cannot be eliminated without sacrificing radio and television broadcasting, many communication links, power-distribution networks, or medical diagnostic equipment. Thus it is with each of the induced environmental factors. The benefits derived from the sources of each factor are such as to outweigh the detrimental effects of that factor; therefore, the emphasis must be on reducing such effects.

The effects of environmental factors may be reduced either by reduction at the source or by protective measures employed in design. Source reduction is particularly obvious in the consideration of air pollutants; hence, it is presently being vigorously attempted in the United States. The magnitude of sand and dust effects can be greatly reduced by paving road surfaces and by encouraging natural ground cover. The reduction of vibration, shock, and acceleration is accomplished by giving attention to the source. Thus, in the transportation system where many of these mechanical forces are found, the use of improved suspensions, roadbeds, and vehicle-operating techniques are effective for reducing these forces. Noise is now recognized as a form of environmental pollution, and noise suppression technology is rapidly advancing. Electromagnetic radiation may be reduced either by proper shielding of radiating sources or by improved broadcasting and detection technology. The nuclear radiation environment is primarily associated with the use of nuclear weapons, nuclear power reactors, and nuclear instrumentation. In all of these applications the nature of the expected radiation is carefully considered, and, when necessary, protection is provided.

Materiel can be protected very adequately from the effects of many induced environmental factors. Thus, the effects of air pollution may be reduced by proper choice of materials, better surface coatings, or by providing hermetic enclosures for sensitive items. Protection against the effects of sand and dust follow much the same procedure, with the sealing of sensitive items from sand and dust being most effective. In other cases it is necessary to provide more resistant surface coatings or operationally to avoid sand and dust exposure. The design of shock mounts, cushioning materials, and packaging techniques allows the protection of many materiel items from.vibration, shock, or acceleration. However, since it is impossible to avoid completely such forces, the mechanical engineer has learned how to compensate or design for such forces. Personnel, on whom the acoustical factor has the most effect, can be protected from such effects with acoustical insulation, ear protectors, or similar devices. Methods to protect materiel from the effects of acoustics are very similar to those employed to protect against vibration. Electromagnetic and nuclear radiation protection of materiel is dependent primarily upon shielding and hardening technology. In the first case the design engineer attempts to prevent such radiation from entering into sensitive regions of the design, while in the second instance the engineer attempts to provide designs that will not be affected by such radiation.

All information on the induced environmental factors is not included in this handbook. A prominent example of such limited treatment is vibration. A variety of texts, journals, and other information sources deal with vibration in all of its many aspects. Only such information on vibration as is deemed of particular importance to the military design engineer is included. Even with this limitation, it is apparent that a number of omissions have occurred. These result primarily from efforts to obtain a coherent presentation within the limitations of time and effort.

The nature of the data presented varies considerably among the various induced environmental factors. The amount of information available on electromagnetic radiation, nuclear radiation, or vibration exceeds that available on sand and dust, acceleration, or acoustics by orders of magnitude. However, a very brief presentation is provided on nuclear radiation because of its classified nature and because of the extensive treatment given to it in other Engineering Design Handbooks—specifically, AMCP 706-235 and AMCP 706-335 through -338.

It is only in the laboratory that the effect of a single environmental factor can be ascertained. In any real situation a large number of environmental factors act in concurrence and often in synergism. However, for the induced environmental factors, the effects of any one or all of them can usually be reduced to a level where they have no detectible effect. Likewise, a number of the natural environmental factors may be controlled to where their effect is minimal. Thus, effects of terrain, solar radiation, rain, solid precipitation, fog, wind, salt, ozone, macrobiological organisms, and microbiological organisms may be eliminated in a controlled environment. However, the effects of temperature and humidity are always present and constitute a controllable factor.

In any field exercise involving materiel, a larger set of environmental factors is always present. The particular factors in the set vary with time, place, and operational modes. The selection of the factors that describe a given environment constitutes a definition of the test or operating environment.

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 units that are not part of this system. In some cases, data may be given in several sets of units in order to relate the less familiar units to those that have been in common usage.

CHAPTER 2

ATMOSPHERIC POLLUTANTS

2-1 INTRODUCTION AND DEFINITIONS

The atmosphere of the earth is a gaseous envelope consisting mostly of nitrogen, oxygen, and water vapor. This blanket of air is finite and is almost completely contained within the troposphere, that layer of the atmosphere extending from the surface of the earth to an altitude of about 10 mi in the tropics and 6 mi in the temperate zone. Approximately one-half of all the air lies within 3.5 mi of the surface of the earth (Ref. 1).

The composition of the atmosphere has undergone great qualitative and quantitative changes since the earth was first formed (Ref. 2) and continues to undergo change; therefore, it is necessary to define or specify 'normal' air in order to discuss atmospheric pollution. Tebbens (Ref. 3) combined recently collected data from various researchers and presented the contents of Table 2-1 as representing good estimates of the concentrations in parts per million (ppm), by volume, of the major and several minor gaseous components of the normal dry atmosphere of the earth at the surface level.

TABLE 2-1. CONCENTRATIONS OF GASES COMPRISING NORMAL DRY AIR

Gas	Concentration, ppm
Nitrogen	780,900
Oxygen	209,400
Argon	9,300
Carbon dioxide	315
Neon	18
Helium	5.2
Methane	1.0-1.2
Krypton	1
Nitrous oxide	0.5
Hydrogen	0.5
Xenon	0.08
Nitrogen dioxide	0.02
Ozone	0.01 -0.04

Normal air contains water vapor in addition to the gases listed in Table 2-1. Water vapor content varies at 100 percent relative humidity from about 100 ppm at −40°F, to about 70,000 ppm at 100°F (Ref. 1).

Air pollution is a complex and diverse problem. It may be defined as the presence of foreign matter suspended in the atmosphere in the form of solid particles, liquid droplets, gases, or in various combinations of these forms in sufficient quantities to produce undesirable changes in the physical, chemical, or biological characteristics of the air (Ref. 4).

Atmospheric pollutants exhibit a variety of undesirable effects on the environment and its inhabitants. Some of the most obvious of these effects are (1) annoyance to the senses, (2) impairment of visibility and darkening of the sky, (3) soiling, (4) impairment to health of human beings and other animals, (5) damage to vegetation, and (6) damage to materials (Ref. 5). A great number of elements and compounds have been identified as atmospheric pollutants but some of them are not distributed widely in the atmosphere. Rather, they are characteristic of a particular area usually because of some specialized industrial process being performed in that area. The Environmental Protection Agency (EPA) now monitors over 40 atmospheric pollutants, recognizing that, in sufficient quantities, any one or combination of these pollutants would prove detrimental to the health and/or welfare of people.

Most discussion of air pollution tends to emphasize one of the first four of the listed effects because they are more readily perceived and understood than are effects on vegetation and materials. However, the increased rate of deterioration of materials resulting from atmospheric pollution is a significant economic factor in any heavily industrialized area. This chapter focuses on those air pollutants to which most of the material damage can be attributed.

Direct damage to structural metals, surface coatings, fabrics, and other materials is related to many types of pollutants. However, the majority of damage is attributable to acid gases (e.g., SO_2, SO_3, and NO_x), oxidants of various kinds, hydrogen sulfide, and particulate matter (Ref. 6).

Table 2-2 (Ref. 7) summarizes the material categories, how they are affected by atmospheric pollutants, and the specific pollutants involved. From this table it can be seen that the majority of damage is done by a relatively few pollutants in synergism with such envi-

TABLE 2-2. AIR POLLUTION DAMAGE TO VARIOUS MATERIALS

Materials	Typical manifestation	Measurement	Principal pollutants	Other environmental factors
Metals	Spoilage of surface, loss of metal, tarnishing	Weight gain of corrosion products, weight loss after removal of corrosion products, reduced physical strength, changed reflectivity or conductivity	SO_2, acid gases	Moisture, temperature
Building materials	Discoloration, leaching	Not usually measured quantitatively	SO_2, acid gases, sticky particulates	Moisture, freezing
Paint	Discoloration, softened finish	Not usually measured	SO_2, H_2S, sticky particulates	Moisture, fungus
Leather	Powdered surface, weakening	Observation, loss of tensile strength	SO_2, acid gases	Physical wear
Paper	Embrittlement	Decreased folding resistance	SO_2, acid gases	Sunlight
Textiles	Reduced tensile strength, spotting	Reduced tensile strength, altered fluidity	SO_2, acid gases	Moisture, sunlight, fungus
Dyes	Fading	Fading by reflectance measurements	NO_2, oxidants, SO_2	Sunlight, moisture
Rubber	Cracking, weakening	Loss in elasticity, increase in depth of cracks when under tension	Oxidants, O_3	Sunlight
Ceramics	Changed surface appearance	Changed reflectance measurements	Acid gases	Moisture

ronmental factors as moisture, temperature, and sunlight.

Design engineers concerned with military materiel must have knowledge Of air pollutants for several reasons. First, materiel is stored and used in a polluted atmosphere. that can adversely affect the performance of certain items of materiel. Second, personnel must sometimes be provided with materiel to negate the effect of atmospheric pollutants. Finally, the military establishment and other Federal agencies have been directed to design, operate, and maintain equipment, vehicles, and other facilities so as to minimize pollutant emissions.[1]

Certain classes of pollutants are listed below with introductory comments about each:

(1) ***Gaseous sulfur pollutants.*** Sulfur pollutants are responsible for a significant fraction of both past and present air pollution problems. As can be seen from Table 2-2, sulfur dioxide (SO_2) is the most frequently listed principal air pollutant causing damage to the different materials. The oxides, sulfur dioxide (SO_2) and sulfur trioxide (SO_3); the corresponding acids, sulfurous acid (H_2SO_3) and sulfuric acid (H_2SO_4); and the salts of these acids are recognized as atmospheric pollutants. By far the most prevalent, and the one that will receive the most attention in this chapter, is sulfur dioxide. The ratio of the atmospheric concentration of sulfur dioxide to sulfur trioxide has been estimated to be about 100 to 1 (Ref. 3). Sulfur trioxide emitted into the atmosphere reacts almost immediately to form sulfuric acid. Therefore, sulfur trioxide in the atmosphere is generally in particulate form as sulfuric acid droplets and is discussed in the paragraph on particulate matter.

Another gaseous sulfur pollutant is hydrogen sulfide (H_2S). An occasional air contaminant, it is almost always associated with some specific incident or isolated source. The importance of hydrogen sulfide as an air pollutant stems from its unpleasant odor even at low concentrations, and its ability to tarnish silver and to darken leadbased paints.

(2) ***Gaseous nitrogen pollutants.*** In the early 1950's, the photochemical smog reaction was identified as a significant air pollution factor in a large number of major urban areas. This has focused attention on the role of nitrogen oxides in urban air pollution. Of the various oxides of nitrogen, the most important as air pollutants are nitric oxide (NO) and nitrogen dioxide (NO_2). Nitrous oxide (N_2O) is the only other oxide of nitrogen present in the atmosphere in measurable concentrations (Ref. 8). It is not generally considered a pollutant because there is no evidence that nitrous oxide is involved in photochemical reactions. The term NO_x is used to represent the composite concentration or emissions of NO and NO_2.

Ammonia gas (NH_3) is normally present in trace amounts. High atmospheric concentrations of ammonia are usually associated with accidental release of the gas from an industrial source. The maximum measured concentration of 3 ppm (before 1956) is below the level known to produce any significant effect (Ref. 3).

Ammonium (NH_4) and nitrate (NO_3) compounds are present as aerosols and are treated as particulate matter.

(3) ***Carbon monoxide.*** Carbon monoxide (CO) is the most abundant and widely distributed air pollutant found in the atmosphere (Ref. 9). Total emissions of carbon monoxide to the atmosphere exceed those of all other pollutants combined. Interest as an air contaminant is focused on its known toxic properties.

The increased use of the internal combustion engine and the development of a number of technological processes wherein carbon monoxide is produced have increased ambient carbon monoxide concentrations in the last several decades. Carbon monoxide pollution no longer is confined to buildings or work environments but includes the ambient air in cities.

(4) ***Gaseous hydrocarbons.*** Hydrocarbon molecules consist of atoms of hydrogen and carbon only. If there are fewer than four carbon atoms per molecule, the hydrocarbons are gaseous at ordinary temperatures. Those with more than four carbon atoms per molecule are liquids or solids in the pure state. Methane (CH_4) usually accounts for at least 50 percent of the total hydrocarbons in the atmosphere. It is the nonmethane hydrocarbon content that is of most interest in air pollution since methane is photochemically inactive. Generally, principal effects are not caused by hydrocarbons directly, but by compounds derived from atmospheric reactions of hydrocarbons and their derivatives with other substances (Ref. 10). Therefore, an appraisal of the effects of atmospheric hydrocarbon pollution is made relative to the damage resulting from the secondary pollutants.

(5) ***Photochemical oxidants.*** Sunlight-induced atmospheric reactions involving hydrocarbons and oxides of nitrogen produce new compounds (secondary pollutants) referred to as oxidants (Ref. 11). The secondary pollutants produced in this manner include ozone,

1. **Executive Order 11507 Prevention, Control, and Abatement of Air and Water Pollution at Federal Facilities.**

formaldehyde, organic hydroperoxides, peroxyacetyl nitrates, and several aldehydes (Ref. 6). The two oxidants of primary concern as air pollutants are ozone and peroxyacetyl nitrate (PAN). A complete chapter (Chap. 12 of Part Two) is devoted to the treatment of ozone because of its importance. PAN is known to have a detrimental effect on vegetation and certain microorganisms but unlike ozone does not affect materials such as natural rubber.

(6) Particulate matter. Aerosols are defined as dispersed, solid, or liquid matter in a gaseous medium, in this case, air. The particle sizes in the atmosphere range from individual aggregates larger than a single small molecule (about 0.002 μm in diameter) up to particles about 500 μm in diameter. Because many of the properties of particles are a function of size, they are usually classified by size intervals. Fig. 2-1 (Ref. 12) relates meteorologic nomenclature for aerosols to the particle sizes. In this chapter, particle size, unless otherwise specified, will refer to particle diameter or Stokes' diameter. This discussion of size classes should not obscure the fact that there is a continuous spectrum of sizes among the particles in the atmosphere and a corresponding continuous graduation of all their size-dependent properties.

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

Particulate matter damages materials by any one of five mechanisms—abrasion, soiling, direct chemical action, indirect chemical action, and electrochemical corrosion.

2-2 PROPERTIES OF ATMOSPHERIC POLLUTANTS

2-2.1 SULFUR DIOXIDE[2]

At standard temperature and pressure sulfur dioxide is a nonflammable, nonexplosive, colorless gas. At concentrations above 0.3 to 1 ppm in air, most people can detect it by taste; in concentrations greater than 3 ppm, it has a pungent, irritating odor. The gas is highly soluble in water: 11.3 g/100 ml at 20°C, as compared to 0.004, 0.006, 0.003, and 0.169 g/100 ml for oxygen, nitric oxide, carbon monoxide, and carbon dioxide, respectively. The physical properties of sulfur dioxide are listed in Table 2-3 (Ref. 13).

Sulfur dioxide at room temperature can act as a reducing agent or as an oxidizing agent. In the atmosphere sulfur dioxide reacts either photochemically or catalytically with various other atmospheric pollutants to form sulfur trioxide, sulfuric acid, and salts of sulfuric acid.

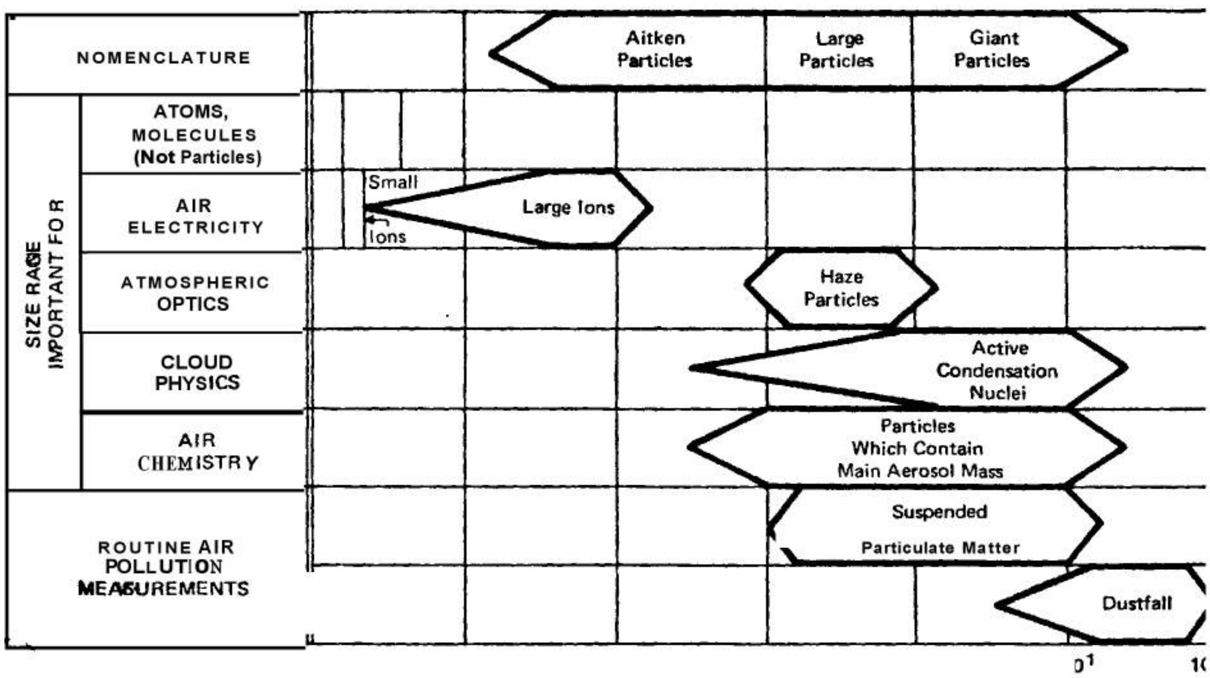


TABLE 2-3. PHYSICAL PROPERTIES OF SULFUR DIOXIDE

Molecular weight	64.06
Density (gas), g/liter	2.927 at 0°C; 1 atm
Specific (liquid) gravity	1.434 at -10°C
Molecular volume (liquid), ml	44
Melting point, °C	-75.5
Boiling point, °C	-10.0
Critical temperature, °C	157.2
Critical pressure, atm	77.7
Heat of fusion, kcal/mole	1.769
Heat of vaporization, kcal/mole	5.96
Dielectric constant (practical units)	13.8 at 14.5°C
Viscosity, dyn s/cm^2	0.0039 at 0°C
Molecular boiling point constant, °C/100 g	1.45
Dipole moment, debye units	1.61

Sulfur dioxide oxidizes hydrogen sulfide to form elemental sulfur and water. This is known as the Claus reaction and generally utilizes a catalyst to increase the rate of reaction.

$$2H_2S + SO_2 \rightarrow 2S + 2H_2O \quad (2\text{-}1)$$

As a reducing agent at room temperature, in the presence of such catalysts as finely divided platinum, charcoal, vanadic oxide, graphite, chromic oxide, ferric oxide, or the nitrogen oxides, the gas will react with oxygen to form sulfur trioxide.

$$SO_2 + 1/2O_2 \xrightarrow[\text{catalyst}]{} SO_3 \quad (2\text{-}2)$$

In the presence of oxygen and moisture, and with ferrous sulfate ($FeSO_4$) as a catalyst, sulfur dioxide is oxidized directly to sulfuric acid.

$$H_2O + SO_2 + 1/2O_2 \xrightarrow[FeSO_4 + \text{moisture}]{} H_2SO_4 \quad (2\text{-}3)$$

Also, some metal oxides will oxidize sulfur dioxide directly to the corresponding sulfate. Magnesium oxide (MgO), ferric oxide (Fe_2O_3), zinc oxide (ZnO), manganic oxide (Mn_2O_3), cerous oxide (Ce_2O_3), and cupric oxide (CuO) are examples.

$$4MgO + 4SO_2 \rightarrow 3MgSO_4 + MgS \quad (2\text{-}4)$$

Four reactions utilized for determining the concentration of atmospheric sulfur dioxide are:

(1) The oxidization of sulfur dioxide by lead peroxide (PbO_2) to form lead sulfate ($PbSO_4$)

$$PbO_2 + SO_2 \rightarrow PbSO_4 \quad (2\text{-}5)$$

(2) The use of hydrogen peroxide (H_2O_2) to oxidize sulfur dioxide to sulfuric acid, the amount of which is determined conductometrically or by titration

$$H_2O_2 + SO_2 - H_2SO_4(\text{aqueous}) \quad (2\text{-}6)$$

(3) The reaction of sulfur dioxide with iodine in an aqueous starch solution to form sulfuric acid and hydrogen iodide (the degree of decolorization of the starch iodine mixture is directly related to the sulfur dioxide concentration)

(4) The reaction of sulfur dioxide with water to form sulfurous acid (H_2SO_3)

$$SO_2 + H_2O \rightleftarrows H_2SO_3 \tag{2-7}$$

Sulfurous acid reacts directly with many organic dyes to change their color, a property that is used by the West-Gaeke method.

2-2.2 HYDROGEN SULFIDE

Hydrogen sulfide has a density of 1.539 g/l and a specific gravity of 1.1895 (*S.G.* of air = 1), a melting point of −82.9°C, and a boiling point of −59.6°C.

Hydrogen sulfide is notorious for its rotten-egg odor. It is as poisonous as hydrogen cyanide and four times as poisonous as carbon monoxide (Ref. 14). Besides its unpleasant odor, at low concentrations it has the ability to darken some paint pigments (Ref. 7). The odor threshold of hydrogen sulfide has been reported to be less than 2 ppb, whereas the toxic level is well above 100 ppb. Because of the low odor threshold, most air pollution agencies have set low tolerance levels. For example, the California Air Resources Board has fixed the maximum tolerable level for hydrogen sulfide at 30 ppb for 1 hr (Ref. 15).

Hydrogen sulfide released to the atmosphere is rapidly oxidized to sulfur dioxide by ozone. It is also oxidized by sulfur dioxide to form elemental sulfur and water (see Eq. 2-1). Hydrogen sulfide burns to produce water and either sulfur or sulfur dioxide, depending on the temperature and the oxygen supply. It is a mild reducing agent and can, for example, reduce the ferric ion to the ferrous ion.

$$2Fe^{+++} + H_2S(g) \rightarrow 2Fe^{++} + S(s) + 2H^+ \tag{2-8}$$

3. A general reference for this paragraph is Ref. 8.

2-2.3 NITRIC OXIDE[3]

Nitric oxide (NO) is a colorless and odorless gas. It is slightly soluble in water (7.34 ml of NO per 100 ml water), has a melting point of −161°C, and a boiling point of −151°C. It is the primary product formed during high-temperature combustion processes when atmospheric oxygen and nitrogen combine according to the following endothermic reaction:

$$N_2 + O_2 \leftrightarrows 2NO \tag{2-9}$$

2-2.4 NITROGEN DIOXIDE

Nitrogen dioxide (NO_2) is a reddish-orange-brown gas with a characteristic pungent odor. It has a specific gravity relative to air of 1.448 at 20°C. The melting and boiling points are −9.3°C and 21.3°C, respectively. The low partial pressure of nitrogen dioxide in the atmosphere restricts it to the gas phase at usual pressures. The nitrogen dioxide molecule contains an odd number of valence electrons (five from the nitrogen and six from each of the oxygens) and is, therefore, paramagnetic. When nitrogen dioxide gas is cooled, the color fades, and the paramagnetism diminishes. This is interpreted to mean that two nitrogen dioxide molecules pair up (dimerize) to form a single molecule of nitrogen tetroxide (N_2O_4). At the dilute concentrations found in the atmosphere, nitrogen tetroxide cannot be present in more than trace amounts; thus, this reaction is probably of minor importance. Nitrogen dioxide is corrosive and highly oxidizing, and may be physiologically irritating and toxic.

Most of the atmospheric nitrogen dioxide occurs as the product of the conversion of nitric oxide to nitrogen dioxide in the atmosphere. A generally accepted mechanism to explain the reaction of nitric oxide with oxygen to form nitrogen dioxide is

$$NO + O_2 \rightleftarrows NO_3, \quad NO_3 + NO \rightarrow 2NO_2 \tag{2-10}$$

The rate constants applicable to these reactions permit significant formation of nitrogen dioxide only when the nitric oxide concentration is in the range of 100 ppm and above.

During daylight hours, atmospheric nitric oxide, nitrogen dioxide, and oxygen undergo a series of reactions resulting in the cyclic formation and decomposi-

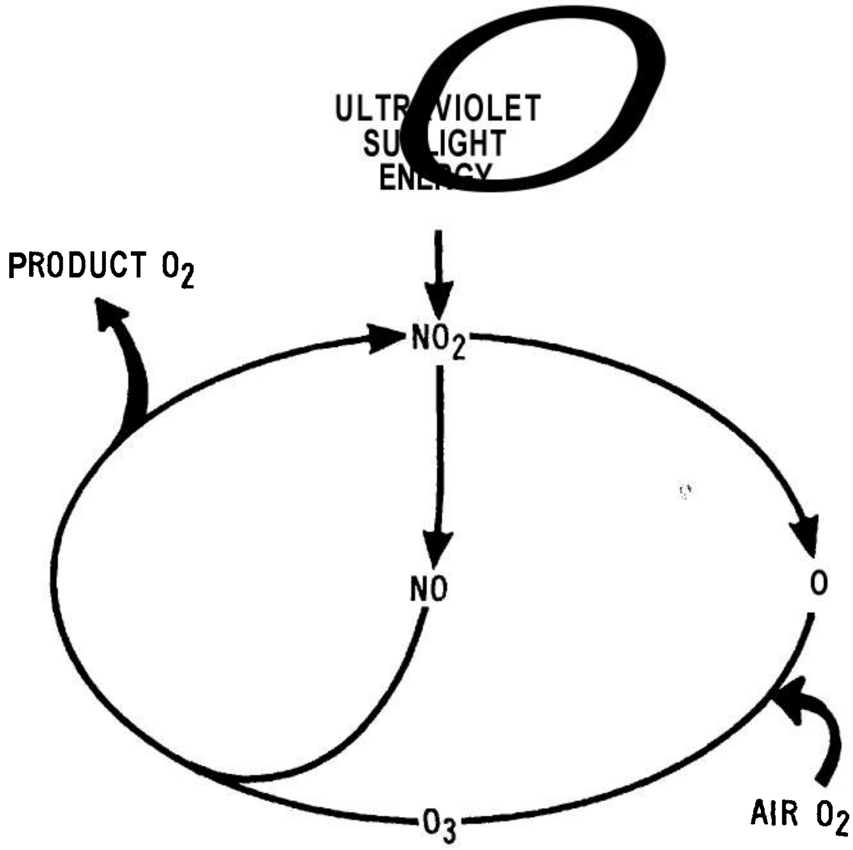


FIGURE 2-2. Atmospheric Nitrogen Dioxide Photolytic Cycle

tion of nitrogen dioxide. This is referred to as the nitrogen dioxide photolytic cycle and is pictured schematically in Fig. 2-2. To initiate the cycle, ultraviolet energy from the sun breaks one of the N-O bonds in a nitrogen dioxide molecule producing nitric oxide and atomic oxygen. The oxygen atom combines with oxygen to form ozone (O_3)that then reacts with the nitric oxide molecule reforming nitrogen dioxide and oxygen. The result, if there were no interfering reactions, would be a rapid cycling of nitrogen dioxide with no overall net effect. However, in the atmosphere the interaction of hydrocarbons with the cycle increases the rate of the nitric oxide to nitrogen dioxide conversion and thereby unbalances the cycle in favor of nitrogen dioxide formation.

2-2.5 CARBON MONOXIDE

There are no known chemical reactions by which atmospheric carbon monoxide is oxidized to carbon dioxide in any appreciable quantities. Two oxidation reactions, although very slow, do occur in the lower atmosphere. These reactions are the oxidation of carbon monoxide by oxygen

$$CO + O_2 \rightarrow CO_2 + O \qquad (2\text{-}11)$$

and, in the presence of moisture,

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (2\text{-}12)$$

These reactions occur more readily on the surfaces of certain catalysts, usually metal oxides.

Carbon monoxide also can be oxidized by ozone and nitrogen dioxide. The rate of reaction is very slow at atmospheric temperatures and concentrations in the case of ozone, and the reaction involving nitrogen dioxide requires such a high activation energy that it probably does not occur at all in the atmosphere.

In the upper atmosphere a small amount of carbon

TABLE 2-4. PHYSICAL PROPERTIES OF CARBON MONOXIDE

Molecular weight	28.01
Melting point	-207°C
Boiling point	-192°C
Specific gravity relative to air	0.968
Density	
At 0°C, 760 mm Hg	1.25 g/l
At 25°C, 760 mm Hg	1.15 g/l
Explosive limits in* air	12.5-74.2% by volume
Solubility in water	
At 0°C	3.54 ml/100 ml
At 25°C	2.14 ml/100 ml
Conversion factors	
At 0°C, 760 mm Hg	1 mg/m^3 = 0.800 ppm
At 25°C, 760 mm Hg	1 mg/m^3 = 0.874 ppm

*Volume of CO indicated is at 0°C, 760 mm Hg.

monoxide is formed by the photo-dissociation of carbon dioxide

$$CO_2 + h\nu(\text{photon}) \rightarrow CO + O \qquad (2\text{-}13)$$

The dissociation of carbon dioxide into carbon monoxide is appreciable only above a height of 100 km due to the rapid decrease in intensity of active ultraviolet radiation below this level. Also, carbon monoxide may be reformed by a three-body collision. Carbon monoxide is a colorless, odorless, tasteless gas that is slightly lighter than air. It does not support combustion but is flammable and bums with a bright blue flame. The physical properties are given in Table 2-4 (Ref. 16).

2-2.6 HYDROCARBONS[4]

From an air pollution point of view, the hydrocarbons are important because of their involvement in photochemical reactions. The secondary contaminants and reaction intermediates account for nearly all the detrimental effects of hydrocarbon air pollution. Methane (CH_4), the simplest and most predominant hydrocarbon, does not react photochemically and is, therefore, usually not considered a pollutant. Fifty-six hydrocarbon compounds have been identified in urban air. Each compound behaves in a different manner rendering an overview of the total atmospheric reaction process very difficult. The chemistry of these reactions and their products are not understood fully. However, the most important features of the observed behavior of photochemical air pollution can be explained.

Sunlight alone has no significant effect on hydrocarbons in the air. Hydrocarbons become involved in photochemical processes because of their reactions with atomic oxygen, excited oxygen, ozone, and free radicals generated by the action of sunlight on other atmospheric components. The speed with which photochemical air pollutants are formed is related directly to the rate of decrease in concentration of hydrocarbons. However, because individual hydrocarbons have different reactivities, the hydrocarbon composition is continuously changing making it difficult to predict accurately the rate of consumption of hydrocarbons in photochemical reactions.

Fig. 2-3 (Ref. 11) indicates a direct relationship between early morning hydrocarbon concentration and the maximum daily oxidant concentration; however, due to the techniques and assumptions used in the analysis of these atmospheric data, a rigorous interpretation is unwarranted.

4. A general reference for this paragraph is Ref. 10.

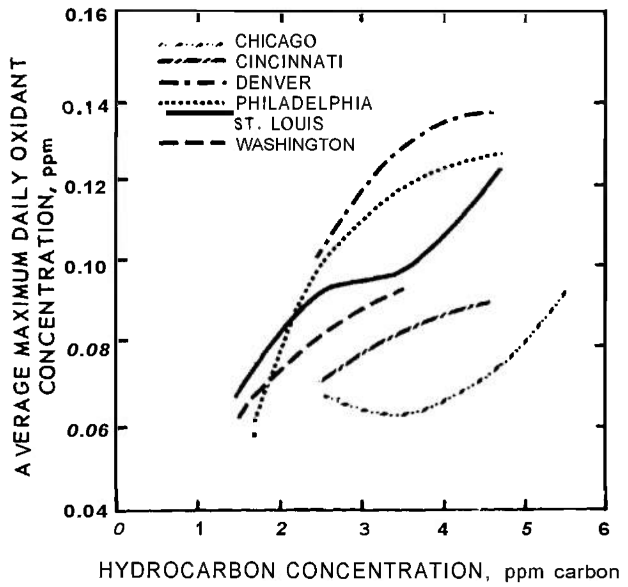


FIGURE 2-3. Effect of 6 a.m. – 9 a.m. Hydrocarbon Concentrations of Maximum Daily Oxidant Concentrations

2-2.7 PEROXYACETYL NITRATE

Peroxyacetyl nitrate (**PAN**) is an unstable compound whose known physical properties are listed in Table 2-5 (Ref. 11).

The exact mechanism of formation of **PAN** in the polluted atmosphere is still somewhat uncertain. Fig. 2-4 (Ref. 17) shows that **PAN** does not appear in the photolysis of polluted air until after the nitric oxide has been reduced to a very low concentration, the nitrogen dioxide has reached its maximum, and the ozone has begun to build up in concentration. The concentration variations of hydrocarbon and aldehyde are also shown. Hydrocarbon is a prerequisite for **PAN** forma-

TABLE 2-5. PHYSICAL PROPERTIES OF PEROXYACETYL NITRATE

Physical state	Colorless liquid
Chemical formula	CH_3COONO_2
Molecular weight	121
Boiling point	No true boiling point, compound decomposes before boiling
Vapor pressure at room temperature	About 15 mm Hg
Conversion factors	
At 0°C, 760 mm Hg	1 ppm = 5398 μg m^{-3}
At 25°C, 760 mm Hg	1 ppm = 4945 μg m^{-3}

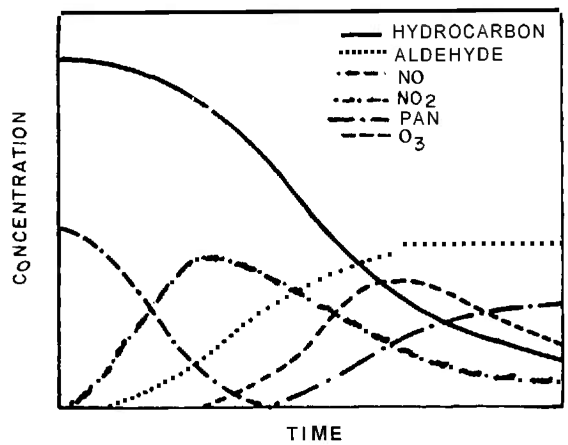


*FIGURE 24. **Concentrations of Various Gases in Photochemically Active Air***

tion and aldehyde is a product of the reactions. The data in Fig. 2-4 show that the quantitative formation of **PAN** does not correlate with nitrogen dioxide or ozone concentrations, but the data in Fig. 2-5 show that it

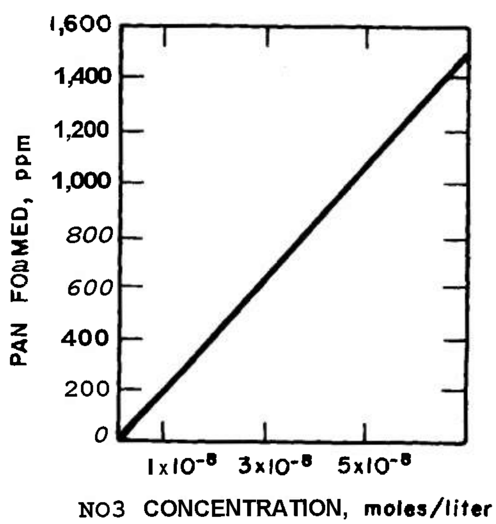


FIGURE 2-5. First-order Dependence of PAN Formation on Nitrogen Trioxide Concentration

does correlate very closely with the nitrogen trioxide concentration.

One reaction that **has** been suggested as the final step in atmospheric **PAN** formation is

$$CH_3\overset{O}{C} - O + NO_2 \rightarrow CH_3\overset{O}{C} - O - NO_3 \quad (2\text{-}14)$$

but this reaction has not been proved by experiment. The mechanism of formation of **PAN,** then, is still uncertain.

2-2.8 PARTICULATE POLLUTANTS

A sample of air from an urban atmosphere may contain particles of fume, dust, soot, fibers, and liquid droplets. Each particle is different in shape, size, and composition, and has an individual history in the atmosphere with relation to mode of origin, growth, interaction, and decay (Ref. 18).

2-2.8.1 Particle Size Distribution

Most of the available experimental and theoretical information on the size distribution of atmospheric aerosols indicates a continuous distribution of the form

$$n(r) = dN/d(\log r) = Ar^{-B}, \text{ cm}^{-3} \quad (2\text{-}15)$$

where

$n(r)$ = log radius-number distribution, cm^{-3}
N = number per unit volume of particles with radius smaller than r, dimensionless
r = radius of particles, μm
$\log r$ = $\log_{10} r$, dimensionless
A = constant that varies with location
B = slope of the curve ($dN/d(\log r)$ vs r) plotted on a log-log scale

The number distribution or number density sometimes requires explanation. Continuous distribution curves are represented such that the number of particles in a size interval, say dr, is represented by the area over this interval and not by the value of the ordinate. For atmospheric particles, because of the wide range of sizes and concentrations, it is necessary to use logarithmic scales. In Eq. 2-15, the number distribution $n(r)$ multiplied by $d(\log r)$, the size interval, gives the number of particles in the size interval, dN.

Fig. 2-6 (Ref. 19) shows a complete size distribution of atmospheric aerosol from 0.01 to 100 μm particle radius. This composite distribution has three different slopes and two transition zones. The slopes are:

0.01 μm — $dN/d(\log r)$ = (Constant) $r^{-2.3}$
2-30 μm — $dN/d(\log r)$ = (Constant) $r^{-2.7}$
50-100 μm — $dN/d(\log r)$ = (Constant) $r^{-6.5}$

This graph was constructed from various sets of measurements made over an extended period of time and in different types of atmospheric environments. It, therefore, does not represent any one type of atmosphere (i.e., urban, rural, ocean, etc.) but should be satisfactory for making a first estimate of the size distribution of an aerosol sample collected by the high-volume method.

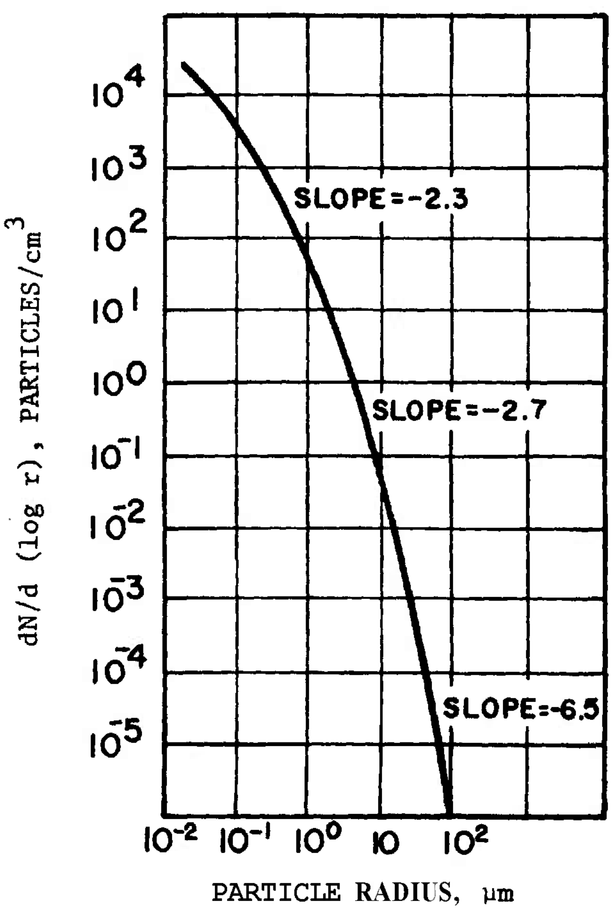


FIGURE 2-6. Complete Atmospheric Aerosol Size Distribution

Fig. 2-7 (Ref. 20) gives particle size distributions for different altitudes. The measurements show a decrease in concentration of particle sizes on both ends of the distribution. This is consistent for higher altitudes (assuming older aerosols at higher altitudes), the theory being that coagulation acts to reduce the concentration of small particles, while sedimentation and rain remove the larger particles.

2-2.8.2 Sorption

Surface properties include sorption, nucleation, and adhesion. Sorption is a general term used to describe the attachment of foreign molecules to a solid surface regardless of whether adsorption, absorption, or some combination of these or other phenomena are involved. Adsorption is a process whereby the molecules are attracted and held to the surface of a solid. There are at least two types of adsorption (Ref. 21). The first type is known as van der Waals' adsorption or physical adsorption. In this case the force of attraction is physical in nature, involving an interaction between dipoles or induced dipoles. Physical adsorption is reversible, so that if the ambient pressure is reduced, the molecules escape from the surface. The second type of adsorption is referred to as chemisorption. This involves forces of interaction between the adsorbent and the molecule that are chemical in nature. These forces are much stronger than those for van der Waals' adsorption, and chemisorption is not reversible. For certain gas and solid combinations, the van der Waals' adsorption may pass over into chemisorption as the temperature is raised.

2-2.8.3 Nucleation

A vapor (i.e., a gas below its critical temperature), present in quantities comparable to its equilibrium vapor pressure, may lead to a deepened sorbed layer on atmospheric particles. This layer, as it thickens, takes on the character of a layer of true liquid. If the vapor is supersaturated, a droplet or crystal may grow by further condensation on the sorbed layer. The net result is heterogeneous nucleation.

A pure vapor, free of particles, must be highly supersaturated before a condensed phase will form from it, because an energy barrier separates the molecular from the particulate state. Such nucleation is called homogeneous.

Two like molecules of gas will not generally stick together, and an aggregate of three molecules is still less likely to retain its identity for any length of time. A small aggregate of molecules is therefore unstable. On

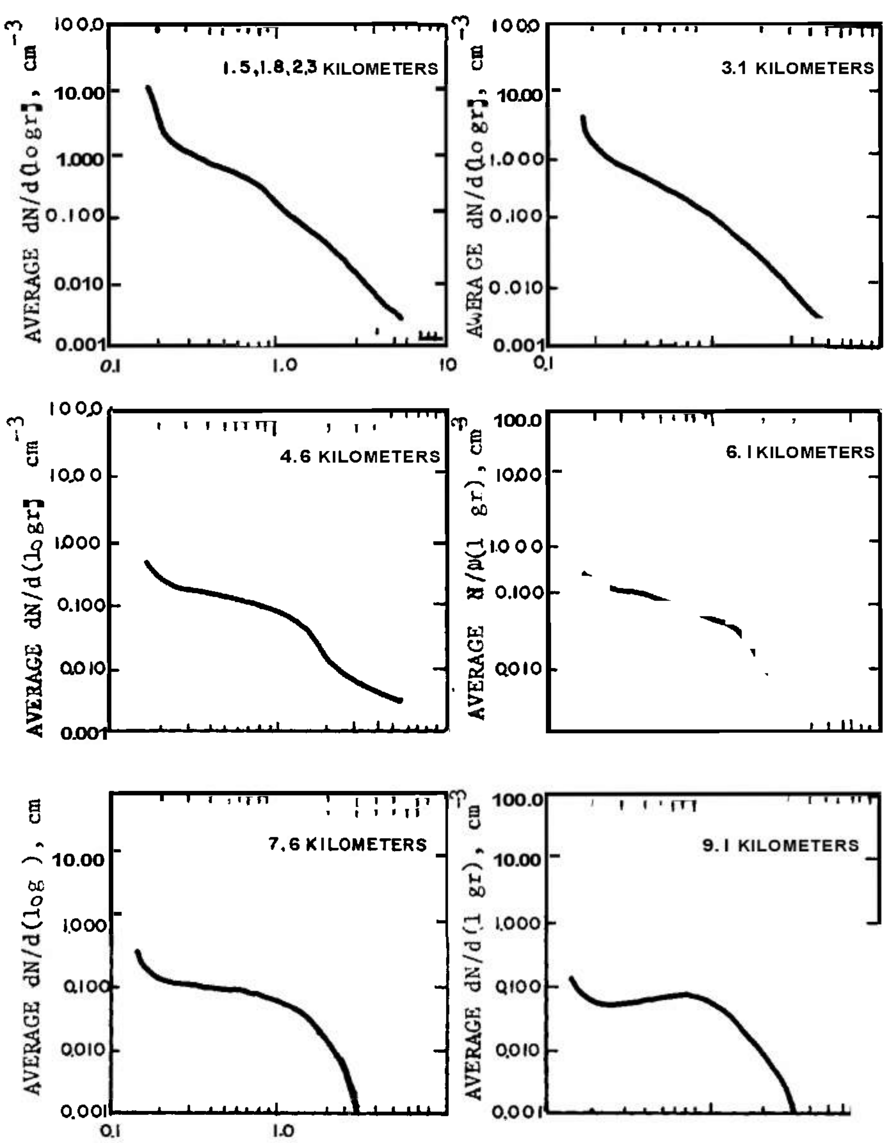


FIGURE 2-7. Altitude Dependence of Particle Size Distribution

the other hand, when a particle is split in two, energy is required to create the new surfaces, since the combined surface area of the two fragments is greater than that of the original particle (surface energy increases with a decrease in size). At some point, these two trends of decreasing stability meet at a maximum that corresponds to a certain particle size, usually referred to as the critical radius (Ref. 22). If a molecular aggregate can reach this critical radius, the addition of a single molecule puts it over the energy barrier and it will become more stable by collecting still more molecules. Conversely, the loss of a single molecule from a nucleus of critical size can destroy its stability with the probable result that it will return to the molecular or gaseous state.

The important point is that the only way by which molecular aggregates for homogeneous nucleation can be formed is by a chance succession of collisions that result in a number of molecules sticking together. Such an event is improbable, except for highly supersaturated conditions, because the total binding force exerted by small aggregates of molecules upon their surface members is too small to counteract the thermal motions tending to carry them away. However, when a suitable surface is present, nucleation (condensation, ice deposition, freezing) will occur on it and the energy barrier to producing a droplet is avoided. Such surfaces may be foreign particles (condensation nuclei, freezing nuclei) or larger surfaces of foreign substances or of the same substance. Since particles are always present in the atmosphere, nucleation on them is of widespread occurrence.

2-2.8.4 Adhesion

The last of the surface properties of consequence is adhesion. All available evidence suggests that solid particles with diameters less than about 1 μm (and liquid particles regardless of size) always adhere when they collide with each other or with a larger surface. Other factors being equal, reentrainment or rebound becomes increasingly probable with increasing particle size. Alternatively, the adhesive property can be considered in terms of the surface energy of small particles or in terms of the more complex shear forces acting to dislodge the larger particles.

2-2.8.5 Motion

Another major class of properties common to all particles, regardless of composition, is the mode motion. The mass of a particle less than about 0.1 μm in diameter is so small that it experiences large random motions due to the buffeting action of individual molecules. This oscillating behavior is known as Brownian motion and increases in magnitude with decreasing particle size.

For particles between 0.1 and 1 μm in diameter, the gravitational settling velocities become larger than molecular impact velocities but are still small compared to 'average air motions. The particle size for which the two velocities are equal is the point of minimum particle activity. It represents the most difficult particle size to remove from the air. Particles larger than 1 μm have significant settling velocities, and their motions can vary greatly from the motion of the ambient air.

Although actual settling times in the atmosphere tend to differ from those computed from Stokes' Law, because turbulence tends to offset gravitational fall, the particles larger than 5 or 10 μm to a large extent are removed by gravity and other inertial processes. The size distribution of a freshly generated aerosol may contain particles as large as 500 μm. These large particles settle rapidly. In the size range of approximately 5 to 10 pm, significant time periods are required to effect

5. A general reference for this paragraph is Ref. 23.

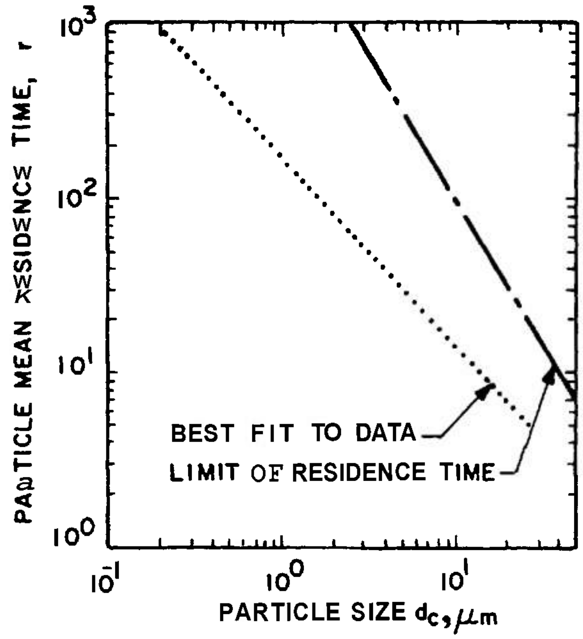


FIGURE 2-8. Particle Size Dependence of Mean Residence Time (Ref. 18)

elimination from the distribution. Fig. 2-8 (Ref. 18) shows a range for the mean time τ that a particle remains in the atmosphere as a function of particle size.

2-2.8.6 Optical Properties[5]

The optical properties of an aerosol vary with the nature of the suspended material, being dependent on its index of refraction and particle shape. However, optical properties are influenced to a greater degree by particle size. There are three light-scattering regimes of interest. They are determined by α, the ratio of the circumference of the particle to the wavelength of the light A ($\alpha = 2\pi r/\lambda$).

Particles less than about 0.1 μm ($\alpha \geq 0.5$) are much smaller than the wavelength of light and scatter light in all directions. This is referred to as Rayleigh scattering in which the intensity of light scattered per unit illumination is proportional to r^6/λ^4. For particles in the intermediate size range (i.e., between 0.1 and 5 pm), the scattering pattern eases its symmetry and becomes a complicated function of α and the angle of observation with respect to the forward direction of illumination. This function, known as the Mie scattering function, requires numerical solutions and is beyond the scope of this discussion. Because the particle dimensions are of the same order of magnitude as the wavelength of light, interference phenomena play a complicating role, and a given scattering behavior may correspond to several particle size distributions. For the largest particles ($r > 5$ μm) geometrical optics

TABLE 2-6. COMPOSITION OF PARTICULATE EMISSIONS
(percent by weight)

Constituent	Source*				
	1	2	3	4	5
Fe_2O_3	89.1	7.1	9.6	3.7	2.0-26.8
SiO_2	0.9	36.3	18.8	9.7	17.3-63.6
Al_2O_3	0.5	25.7	7.1	14.9	9.81-58.4
MnO	0.6		0.2	<1	
P_2O_5	0.5			<1	0.07-47.2
S/SO_2/Sulfates	0.4	8.0		25.0	0.12-24.33
CaO		8.8	40.9	<1	0.12-14.73
MgO	1.4	2.8	2.5		0.06-4.77
Na_2O/K_2O		10.4	8.4	3.0	3.0-3.9
TiO_2		0.9	0.1	<1	0-2.8
V_2O_3				4.7	
C				18.4	0.37-36.2
Carbonate (CO_3)					0-2.6
Ether soluble				4.4	

*Source identification:

1. Open-hearth furnaces
2. Incineration
3. Cement plants
4. Fuel oil combustion
5. Coal combustion

plus diffraction effects apply, with scattering proportional to r^2.

2-2.8.7 Composition

The chemical composition of particulate pollutants depends on the source from which they are derived and is highly variable. Data derived from various emission sources are given in Table 2-6 (Ref. 12).

2-3 SOURCES OF ATMOSPHERIC POLLUTANTS

Natural phenomena such as volcanic eruptions, earthquakes, forest fires, and biological processes contribute to atmospheric pollution. The vast majority of air pollution, however, is derived from man-made sources. Fig. 2-9 (Ref. 4) gives the primary sources of

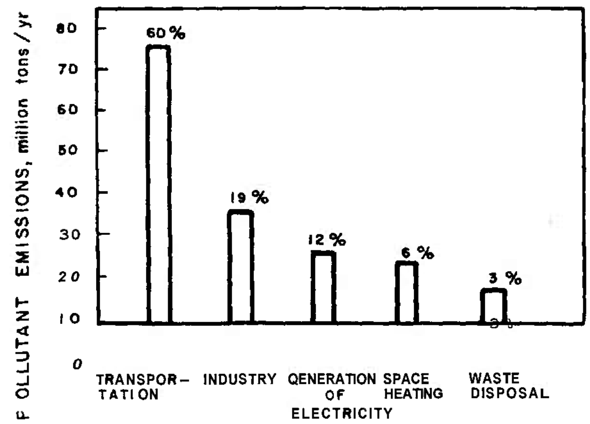


FIGURE 2-9. Sources of Atmospheric Pollutants in the United States

air pollution in the United States, the percentage of total emissions for each source, and the weight of emissions in tons/year for each source. Also, Fig. 2-10 (Ref. 4) gives the yearly weight of emissions over the United States for the five most common pollutants. It should be noted that all other pollutants combined account for only 2 percent by weight of total emissions.

The five major classes of pollutants, with a description of the sources of each, are described in paragraphs that follow.

2-3.1 GASEOUS SULFUR POLLUTANTS

Sulfur compounds in the atmosphere come from both the natural environment and from urban pollution sources. Of the common atmospheric sulfur pollutants, sulfur dioxide (SO_2), sulfur trioxide (SO_3), and hydrogen sulfide (H_2S) originate from pollutant sources while hydrogen sulfide and sulfate compounds are produced in the natural environment (Ref. 24).

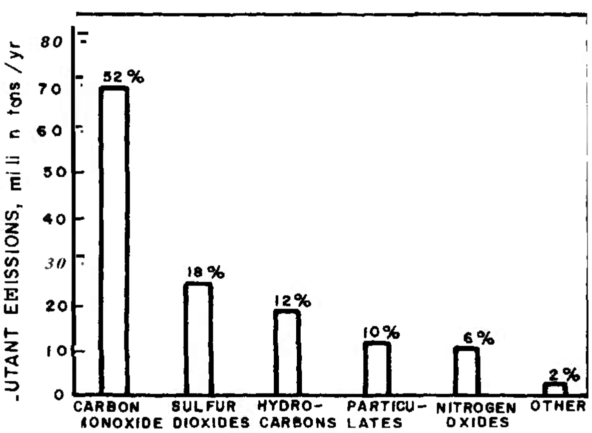


FIGURE 2-10. Volume of Atmospheric Pollutants by Type in the United States

Sulfur dioxide pollution results principally from the combustion of fossil fuels, the refining of petroleum, the smelting of sulfur-containing ores, the manufacturing of sulfuric acid, the burning of refuse, papermaking, and the burning or smoldering of coal refuse banks. In all these processes a small amount of sulfur trioxide or sulfuric acid is also emitted. For example, combustion of the fuel in power plants forms sulfur oxides in the ratio of from 40 to 80 parts of sulfur dioxide to 1 part of sulfur trioxide (Ref. 13). The estimate of worldwide emissions of gaseous sulfur dioxide per year is 80 million tons (Ref. 25).

Naturally occurring sulfur compound emissions include sulfate aerosols produced in sea spray, and hydrogen sulfide from the decomposition of organic matter in swamp areas, bogs, and tidal flats. Volcanic activity and industrial emissions are minor sources of hydrogen sulfide (Ref. 24). The emission rate of hydrogen sulfide from natural sources has been estimated as high as 300 million tons per yr (Ref. 25).

Table 2-7 (Ref. 13) presents the major emission sources and quantities of sulfur dioxide released to the atmosphere for the years 1963 and 1966 in the United States.

Using 1967 U S Statistical Abstracts from the U S Government Printing Office and air pollution emission factors from the U S Public Health Service, the annual worldwide pollution emissions of sulfur dioxide were estimated to be 146 X 10^6 tons in 1965. Also, previous estimates have been quoted as 69 X 10^6 tons in 1937 and 78 X 10^6 tons in 1940 (Ref. 24).

2-3.2 CARBON MONOXIDE

Carbon monoxide emission exceeds that of all other contaminants combined. Worldwide emissions are estimated at 200 million tons per yr (Ref. 25). It is thus regarded as one of the prime indicators of air pollution. Motor-vehicle exhaust emissions are responsible for over 58 percent of the total carbon monoxide emitted into the atmosphere (Ref. 16). Carbon monoxide emissions estimates by source and by weight for the United States in 1968 are given in Table 2-8. The total estimate of 101.6 million tons is considerably more than the yearly discharge rate given in Fig. 2-10 which probably represents a yearly average extending over several years.

TABLE 2-7. ATMOSPHERIC SULFUR DIOXIDE EMISSIONS IN 1963 AND 1966 BY SOURCE (U.S.)

Process	Sulfur dioxide* 1963 Tons	1963 Percent of total emissions	1966 Tons	1966 Percent of total emissions
Burning of coal:				
Power generation (211,189,000 tons, 1963 data)	9,580,000	41.0	11,925,000	41.6
Other combustion (112,630,000 tons-, 1963 data).	4,449,000	19.0	4,700,000	16.6
Subtotal	14,029,000	60.0	16,625,000	58.2
Combustion of petroleum products:				
Residual oil	3,703,000	15.9	4,386,000	15.3
Other products	1,114,000	4.8	1,218,000	4.3
Subtotal	4,817,000	20.7	5,604,000	19.6
Refinery operations	1,583,000	6.8	1,583,000	5.5
Smelting of ores..	1,735,000	7.4	3,500,000	12.2
Coke processing	462,000	2.0	500,000	1.8
Sulfuric acid manufacture..	451,000	1.9	550,000	1.9
Coal refuse banks	183,000	0.8	100,000	0.4
Refuse incineration	100,000	0.4	100,000	0.4
Total Emissions	23,360,000	100.0	28,562,000	100.0

*A small amount of this tonnage is converted to sulfuric acid mist before discharge to the atmosphere. The rest is eventually oxidized and/or washed out. Only under unusual meteorological conditions does accumulation occur.

TABLE 2-8. CARBON MONIXIDE EMISSION ESTIMATES BY SOURCE CATEGORY
(In U.S. - 1968)

Source	Emissions, 10^6 tons/yr			Emissions, Percent		
Transportation	63.8			62.8		
Motor vehicles		59.2			58.2	
Gasoline			59.0			58.0
Diesel			0.2			0.2
Aircraft		2.4			2.4	
Vessels		0.3			0.3	
Railroads		0.1			0.1	
Other nonhighway use of motor fuels		1.8			1.8	
Fuel combustion-stationary	1.9			1.9		
Coal		0.8			0.8	
Fuel oil		0.1			0.1	
Natural gas		N			N	
Wood		1.0			1.0	
Industrial processes	11.2			11.0		
Solid waste disposal	7.8			7.7		
Miscellaneous	16.9			16.6		
Man-made		9.7			9.5	
Forest fires		7.2			7.1	
Total	101.6			100.0		

N = Negligible

2-3.3 NITROGEN OXIDES

The major component of worldwide atmospheric nitrogen oxides (NO_x) is biologically produced nitric oxide (NO) (Ref. 8). Nitrogen dioxide (NO_2) and nitric oxide are the major nitrogen oxides emitted from man-made sources. Combustion processes in which the temperatures are high enough to **fix** the nitrogen in the air and in which the combustion gases are cooled rapidly enough to reduce the subsequent decomposition are the primary cause of technology-associated NO_x emissions (Ref. 26). It is estimated that the ratio between man-made and natural emissions of nitrogen oxides is almost 1 to 15. Table 2-9 (Ref. 8) summarizes the man-made sources and emission levels of nitrogen oxides in the United States for the year 1968. Stationary sources and motor vehicles account for over **83** percent of the total emissions. Global emissions of nitrogen dioxide from combustion processes are estimated at 52.9 X 10^6 tons per yr and nitric oxide produced by biological action at 501 X 10^6 tons per yr (Ref. 26).

2-3.4 HYDROCARBONS (Ref. 10)

Methane is the predominant hydrocarbon emitted to the atmosphere from natural sources. All anaerobic bacterial decomposition of organic matter in swamps, lakes, marshes, and sewage produces hydrocarbons. The production rate of methane from natural sources has been estimated at more than **3** X 10^8 tons per yr. Volatile terpenes and isoprene constitute a separate class of hydrocarbons produced by natural sources. The natural emission rates of these hydrocarbons have been estimated at **4.4** X 10^8 tons per yr. The total

TABLE 2-9. SUMMARY OF NATIONWIDE NITROGEN OXIDES EMISSIONS, 1968

Source	Emissions, 10^6 tons/yr			Emissions, Percent		
Transportation	8.1			39.3		
Motor vehicles		7.2			34.9	
Gasoline			6.6			32.0
Diesel			0.6			2.9
Aircraft[a]		N[b]			N	
Railroads		0.4			1.9	
Vessels		0.2			1.0	
Nonhighway		0.3			1.5	
Fuel combustion - stationary	10.0			48.5		
Coal		4.0			19.4	
Fuel oil		1.0			4.8	
Natural gas[c]		4.8			23.3	
Wood		0.2			1.0	
Industrial processes	0.2			1.0		
Solid waste disposal	0.6			2.9		
Miscellaneous	1.7			8.3		
Forest fires		1.2			5.8	
Structural fires		N			N	
Coal refuse		0.2			1.0	
Agricultural		0.3			1.5	
Total	20.6			100.0		

[a]Emissions below 3,000 ft.

[b]N = Not reported. Estimated less than 0.05 x 106 tons/yr.

‘Includes LPG and kerosene.

nationwide emissions of hydrocarbons and related organic compounds to the atmosphere from technological sources for the year 1968 were estimated to be about 32 X 10^6 tons. Table 2-10 (Ref. 10) lists the technological sources and estimates of their emission rates of hydrocarbons for 1968.

From these data it is clear that natural sources are responsible for most of the atmospheric hydrocarbons and that, of all the technological sources, motor vehicles account for nearly *50* percent of the total emissions.

2-3.5 PARTICULATE MATTER

Natural dust is always present in the atmosphere at varying levels of concentration. These dust particles are made airborne either by high winds or by vehicular action, e.g., a truck traveling along an unsurfaced road or a helicopter hovering over a dusty field. Once airborne, the smaller particles, less than about 10 μm in diameter, may be kept aloft for an extended period of time by turbulent wind conditions arising from, for example, large temperature gradients.

TABLE 2-10. ESTIMATES OF HYDROCARBON EMISSIONS BY SOURCE CATEGORY, 1968 (AP-64)

Source	Emissions					
	10^6 tons/yr			Percent		
Transportation	16.6			51.9		
Motor vehicles		15.6			48.7	
Gasoline			15.2			47.5
Diesel			0.4			1.2
Aircraft		0.3			1.0	
Railroads		0.3			1.0	
Vessels		0.1			0.2	
Nonhighway use, motor		0.3			1.0	
Fuel combustion-stationary	0.7			2.2		
Coal		0.2			0.7	
Fuel oil		0.1			0.3	
Natural gas		N			N	
Wood		0.4			1.2	
Industrial processes	4.6			14.4		
Solid waste disposal	1.6			5.0		
Miscellaneous	8.5			26.5		
Forest fires		2.2			6.9	
Structural fires		0.1			0.2	
Coal refuse		0.2			0.6	
Organic solvent evaporation		3.1			9.7	
Gasoline marketing		1.2			3.8	
Agricultural burning		1.7			5.3	
Total	32.0			100.0		

N = Negligible

Industrial particulate matter consisting of both liquid and solid particles is emitted primarily from combustion processes. Table 2-11 (Ref. 12) shows typical annual emissions of particles from various types of sources in the area of St. Louis, Mo., with a combined population of 2,331,000 and in Ankara, Turkey, with a population of 906,000. Both sets of data were collected using identical procedures.

An estimated 11.5 million tons of particulate matter were emitted to the atmosphere from major sources in the United States in 1966. Fig. 2-11 gives the major sources and the weight of particulate matter emitted by each source.

2-4 ATMOSPHERIC SCAVENGING

Primary pollutants are removed from the atmosphere by (1) deposition and (2) conversion to other atmospheric constituents. In both cases chemical reactions facilitate the process. The atmosphere of the earth has been described as a vast chemical reactor (Ref. 2) where some of the primary pollutants undergo chemical changes thus forming other substances. In some cases the intermediate or final products can be more damaging than the original reactant, but these products may be in a form that is readily removed from the atmosphere.

TABLE 2-11. 1969 EMISSION INVENTORY OF PARTICULATE MATERIAL, METRIC TONS PER YEAR

Source category	City	
	St. Louis, Mo.	Ankara, Turkey
Transportation		
Motor vehicles	5,220	2,090
Other	2,760	240
Subtotal	7,980	2,330
Stationary fuel combustion		
Industry	60,900	4,870
Residential	2,760	7,470
Commercial, institutional, governmental	4,940	4,580
Electric generation	49,400	1,210
Subtotal	118,000	18,130
Refuse disposal		
Incineration	2,180	N
Open burning	3,140	1,200
Subtotal	5,320	1,200
Industrial processes	37,500	3,210
Evaporative losses	--	--
GRAND TOTAL	168,800	24,870

N = Negligible

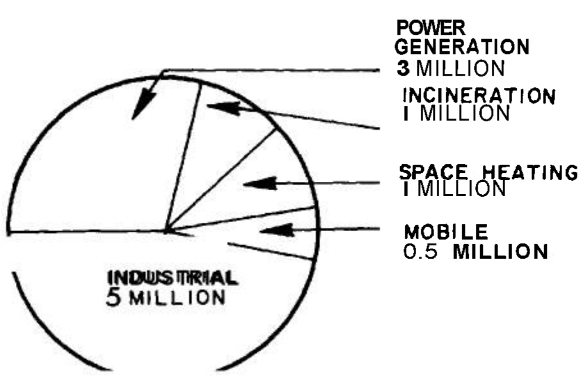


FIGURE 2-77. Sources of Particulate Matter (tons/yr)

In the lower atmosphere, deposition is the primary means of removal; the oxidation and/or combination of pollutants result in solid or liquid particles, or adsorbed phases on such particles, that soon settle out of the atmosphere because of their large size. In the upper atmosphere, conversion to other atmospheric constituents is aided through the breaking down of complex molecules by high energy radiation from the sun.

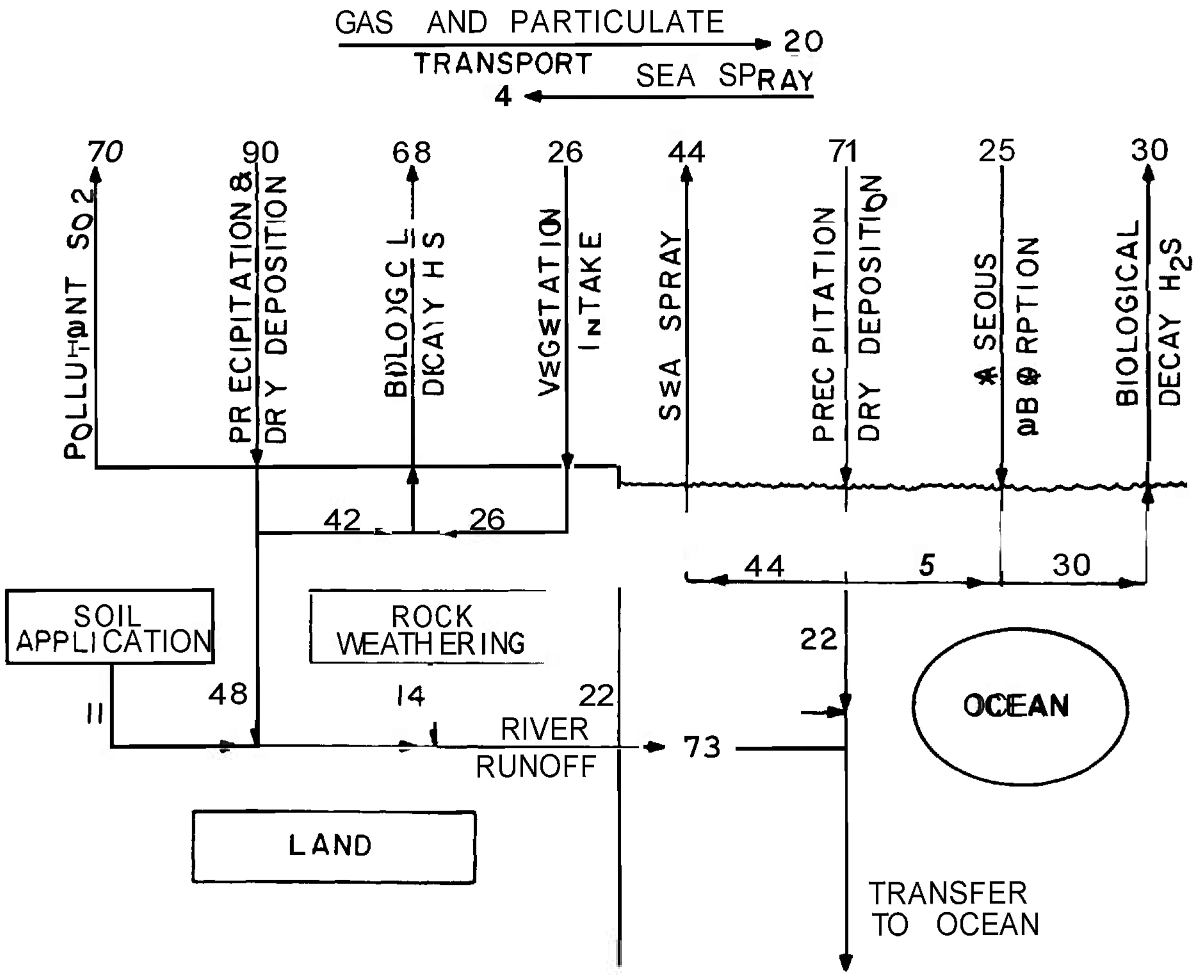
The five major classes of pollutants are listed with descriptions of the natural scavenging processes that tend to exhaust them from the atmosphere.

2-4.1 SULFUR OXIDES AND HYDROGEN SULFIDE

Sulfur oxides in the atmosphere are mostly in the form of sulfur dioxide with small amounts of sulfur trioxide. A large part of the sulfur dioxide in the air is oxidized to sulfur trioxide that reacts with water vapor to form sulfuric acid mist. The transformation of sulfur dioxide to the acid occurs in approximately 4 days (Ref. 24). The acid further reacts with other materials in the air to form sulfates, usually ammonium and calcium sulfates. Also, it has been theorized that a substantial portion of the atmospheric sulfur dioxide is directly neutralized by ammonia, calcite dust, or other airborne alkalies and is then oxidized by the air to the corresponding sulfates. The salts are finally removed from the atmosphere by precipitation. The time from emission to removal of sulfur dioxide is estimated at 43 days or less on the average (Ref. 13). Sulfur dioxide is also scavenged from the atmosphere by vegetation. For a concentration of 1 ppb, a deposition rate of 2.5 μg m^{-2} day^{-1} has been calculated (Ref. 24).

Robinson and Robbins (Ref. 24), using their own calculations along with data from the literature, estimated the mass flow of sulfur in various compound forms through the environment. Fig. 2-12 shows the circulation pattern. Some of the values are reasonably well known, e.g., pollutant emissions and total depositions; however, some such as land and sea emissions of hydrogen sulfide are estimates that were adjusted to balance the cycle. The end result of this cycle shows an accumulation of sulfur in the oceans of 95 X 10^4 tons/yr. This is the sum of pollutant emissions, sulfur applied to the soil, and rock weathering.

The lifetime of hydrogen sulfide in the atmosphere ranges from about 2 hr in urban areas to about 2 days in remote unpolluted areas. The hydrogen sulfide is oxidized to sulfur dioxide in the troposphere by ozone in a heterogeneous reaction usually occurring on the surface of aerosol particles.



2-4.2 CARBON MONOXIDE

There are no identified scavenging processes for carbon monoxide. However, in the absence of removal processes, the estimated worldwide emissions would be sufficient to raise the atmospheric background concentration by 0.03 ppm per yr creating a current background level of 1 ppm. Measurements of the background level indicate an average concentration level much less than 1 ppm with no indication that the level is increasing (Ref. 16). Therefore, it is postulated that some sink or removal process exists. One possibility is that in the upper atmosphere ultraviolet energy from the sun converts the carbon monoxide to carbon dioxide (Ref. 25). Recent research carried out by Inman and Ingersoll (Ref. **27**) to identify and quantify sinks for atmospheric carbon monoxide produced the following results: (l) of the approximately 15 species of green land plants tested, none demonstrated any tendency to take carbon monoxide out of the atmosphere; (2) soil tests showed that the capacity for carbon monoxide uptake by the soil is mediated by a biological mechanism; and **(3)** of the 200 plus species and strains of fungi, yeasts, and bacteria tested, 16 (all were fungi) proved capable of removing atmospheric carbon monoxide. On the basis of these laboratory studies, an estimate of the capacity of the soil to act as a sink of atmospheric carbon monoxide was calculated to be in excess of 500 million metric tons per yr. This is over twice the estimated worldwide production of carbon monoxide by man.

2-4.3 NITROGEN OXIDES[6]

The major portion of oxides of nitrogen released to the atmosphere become involved in photochemical reactions in which nitric oxide and nitrogen dioxide are converted to nitrogen-containing organic compounds. The oxides of nitrogen are usually converted within hours of their exposure to sunlight.

The oxides of nitrogen that are not converted by photochemical processes diffuse throughout the atmosphere and are removed by oxidation of nitric oxide to nitrogen dioxide while, at higher levels in the atmosphere, ozone can react with nitrogen dioxide to form nitrogen pentoxide and trioxide. These then react with alkalies to form nitrates that are removed from the atmosphere by precipitation. Also, nitrogen dioxide may react directly with ammonia giving nitrogen and water vapor. Nitrogen dioxide can be transferred from the lower atmosphere to the ocean as inorganic nitrates and nitrites. Robinson and Robbins (Ref. 26), in deriving an atmospheric nitrogen cycle, arrived at a residence time of **3** days for nitrogen dioxide released to the atmosphere.

6. A general reference for **this** paragraph **is** Ref. 25.

2-4.4 HYDROCARBONS[6]

Hydrocarbons in the atmosphere form radicals when exposed to sunlight. Ozone, nitrogen dioxide, and peroxides serve as light sensitizers or initiators for these reactions. Radicals are subject to further degradation until the end products are carbon dioxide, carbon monoxide, and water. Radicals may also be removed by polymerization and adsorption on suspended particulates that are, in turn, removed from the atmosphere by precipitation.

The rates of reaction of these processes are insufficient to prevent high concentration levels from building up when the right combination of emission and local meteorological conditions exist.

2-4.5 PARTICULATE MATTER[6]

The principal mode of removal of particles larger than **5** to 10 μm in diameter from the atmosphere is gravitational settling. Some of these smaller particles, between about 1 and 10 μm in diameter, settle slowly and may be removed from the lowest atmospheric layer by inertial processes such as impaction on the surfaces of obstacles such as buildings and trees.

Clouds and rain act to cleanse the higher layers of the troposphere of particles larger than about 2 μm. Smaller soluble particles, such as sea salt and nitrates, grow substantially in size by accumulating water from the clouds or rain and are thus brought to the ground by rain.

Smaller particles less than about 0.1 μm coagulate as a result of their high collision rate and form larger particles that are then subject to settling, precipitation, and impaction.

2-5 CONCENTRATION AND DISTRIBUTION OF ATMOSPHERIC POLLUTANTS

Pollutant concentrations vary in time and space as a result of **(1)** variations in the location of pollutant

TABLE 2-12. POLLUTANT CONCENTRATIONS AND COMPOSITION

Particulate pollutants in urban areas*

Pollutant	Typical concentration, $\mu g\ m^{-3}$
Solid particles	110+
Combustible carbon/soot and miscellaneous-organic particles	25
Metal oxides, salts, and non-combustible soot particles	75
Silicates and mineral dusts	10
Liquid particles	10
Total particulates	120
Chemical content of particulates‡	
Chloride	
Nitrate	4**
Phosphate	
Sulfate	13**
Aluminum	5
Calcium	4
Iron	3**
Ammonium	0.7**
Lead	1**
Silicon	4
Zinc	0.5**

Gaseous pollutants

Pollutant	Typical concentration, ppm by volume: Urban	Rural
Organic gases	3.0*	1.0
Hydrocarbons (90% CH_4)	2.8	1.0
Others	0.2	0.05
Total aldehydes	0.05	0.01
Inorganic gases		
Oxides of nitrogen		
Nitric oxide	0.05**	0.01
Nitrogen dioxide	0.05**	0.02
Oxides of sulfur		
Sulfur dioxide	0.05**	0.005
Sulfur trioxide	< 0.001	< 0.001
Oxides of carbon		
Carbon monoxide	7.0**	0.1
Carbon dioxide	350	315
Others		
Ammonia	0.1	0.01
Hydrogen chloride	0.05	0.005
Hydrogen fluoride	0.01	0.003
Hydrogen sulfide	0.003	< 0.001
Ozone	0.05**	0.02

*Rural values are approximately 30% of the urban values.

**From National Air Surveillance Networks.

+Based on the NASN average for suspended particulates of 100 $\mu g\ m^{-3}$ and a dustfall value of 300 tons $mi^{-2}\text{-}mo^{-1}$.

‡Fifteen other elements are known to be present at lower concentration levels.

sources, (2) changes in source activity with time, (3) continually changing meteorological conditions, and (4) transient distributions of chemical reactions in the atmosphere. Patterns of concentration variation are peculiar to the specific locality but usually show distinctive features for certain regions. For example, metropolitan areas on the U S East Coast are characterized by high concentrations of sulfur dioxide, while on the U S West Coast, high concentrations of ozone and nitrogen oxides are the rule.

Concentration data for a particular pollutant are often subject to variations traceable to (1) the different measuring techniques and equipment employed, (2) different sampling times, and (3) in some instances, the location of the sampling site (e.g., on the ground or on a rooftop). The values given in this paragraph are to serve as guides for the concentration levels that one may expect to encounter under various conditions.

Table 2-12 (Ref. 28) presents a list of representative urban and rural values for the concentrations of a majority of the air pollutants. Several of the values, as indicated in the table, are annual averages of data from the National Air Surveillance Networks. The other data were assimilated from a variety of studies as reported in the literature. Concentration characteristics of some of the more important pollutants will be discussed in the paragraphs that follow.

2-5.1 GASEOUS POLLUTANTS

Concentration values for gaseous pollutants are generally reported as parts per million (ppm) by volume. In instances where the concentration level is very low, it is more convenient to give the volumetric concentration as parts per hundred million (pphm) or parts per billion (ppb). Conversions are simple multiples: 100 pphm = 1 ppm and 1000 ppb = 1 ppm. A gravimetric designation, weight of pollutant per unit volume of air ($\mu g/m^3$), is sometimes used in such work areas as toxicology and metal corrosion. To convert from gravimetric to volumetric units, it is necessary to assume some standard conditions of gas temperature and pressure. For 25°C and 760 mm the conversion is approximately

$$\mu g/m^3 = \text{ppm} \times 41.3 \times \text{molecular weight} \quad (2\text{-}16)$$

Concentration data are usually given as maximum or average values, and as distribution plots that show the percentage of time that the pollutant concentration exceeds a certain level. The distribution plots give a more complete insight into the dynamic characteristics of a pollutant for a given site. Most concentration measurements are not real time but represent the average value for the time period over which the sample was collected. The most frequently used averaging or sampling times are 5 min, 1 hr, 8 hr, 1 day, 1 mo, and 1 yr. Therefore, for an exact interpretation and/or comparison of concentration data from different sources, the averaging times employed in collecting the data must be known. Techniques for computing concentrations for averaging times other than the one used in collecting the data are'discussed in Refs. 3 and 29. As an example, the annual expected maximum concentration, C_{max}, for a particular averaging time follows a general law of the type:

$$C_{max} - C't^a \quad (2\text{-}17)$$

where

t = averaging time, hr
a = slope of the line plotted on a logarithmic scale
C' = a constant, the value of which can be determined from the measured data

(1) ***Sulfur dioxide.*** Two monitoring programs sponsored by the U.S. Environmental Protection Agency have produced statistics on atmospheric sulfur dioxide concentrations in and around several U.S. cities. The Continuous Air Monitoring Project (CAMP) has monitored sulfur dioxide concentrations in six large cities since 1961. The National Air Surveillance Networks provide 24-hr-sample data for about 100 locations on a 26 times-per-year basis (Ref. 13).

Fig. 2-13 (Ref. 13) gives the maximum average concentrations for various averaging times for 12 cities. Nearly all cities show an increasing maximum average concentration with a decrease in averaging time right down to the 5-min interval. This indicates short-term variations in the concentration levels giving rise to the possibility of experiencing relatively high levels of sulfur dioxide for short periods of time. The graph shows that the highest concentration value was over 2 ppm and occurred in New York City. All 5-min maxima fall between 0.3 ppm and 2 ppm for this 5-yr period. Fig. 2-14 (Ref. 13) gives the frequency distribution of sulfur dioxide levels for six U S cities over a 5-yr period. These data show higher sulfur dioxide concentrations for cities east of the Mississippi River than for those on the West Coast.

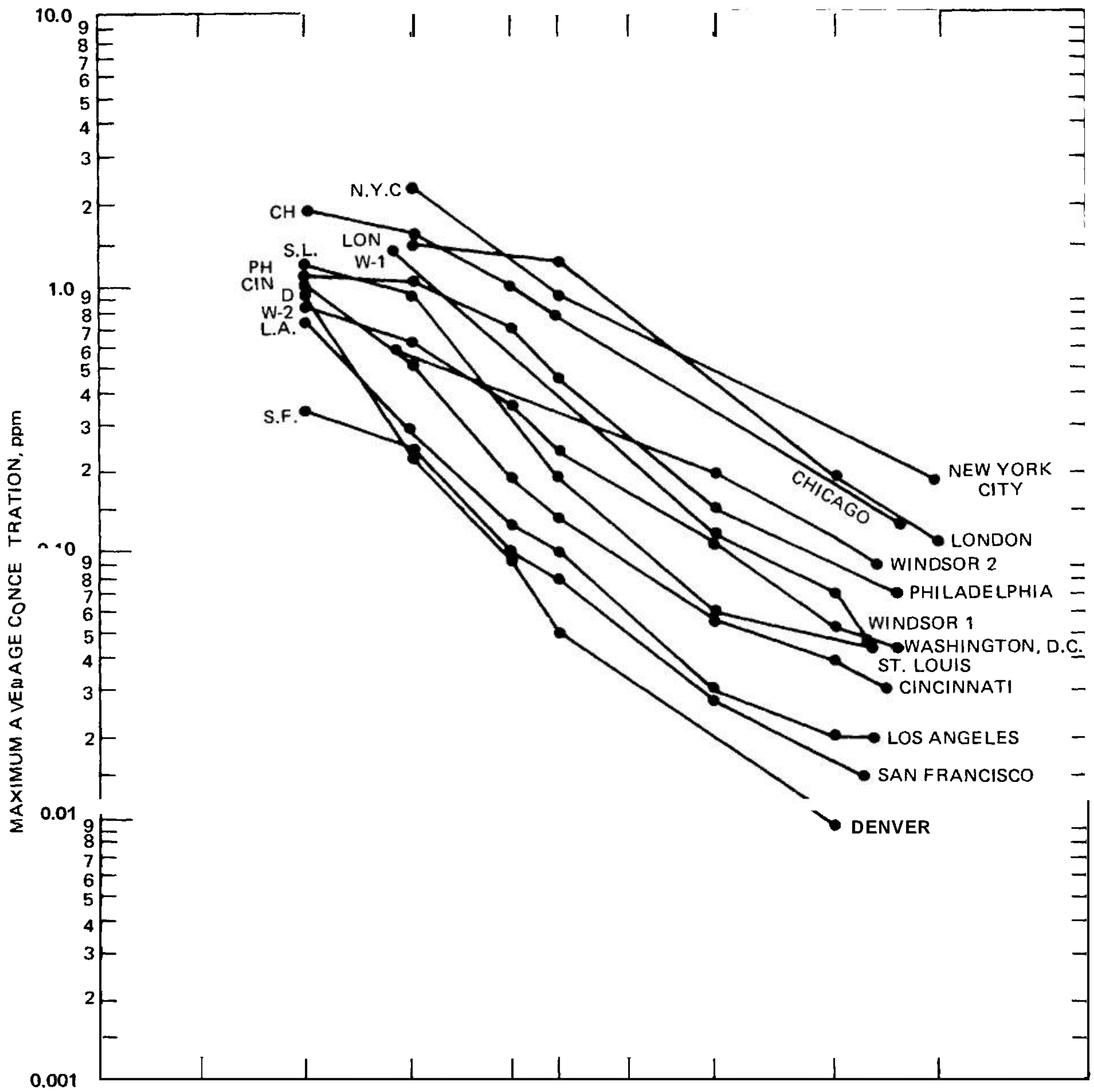


FIGURE 2-13. Maximum Average Sulfur Dioxide Concentrations for Various Averaging Times

Measurements of sulfur dioxide levels in unpolluted areas are, as would be expected, much less plentiful than those for polluted areas. However, Robinson and Robbins (Ref. 24), in an effort to arrive at an estimate for the average tropospheric sulfur dioxide concentration on a global basis, assembled the data in Table 2-13. From the data, an estimate of 0.2 ppb was made for the average global sulfur dioxide concentration.

7. A general reference for this paragraph is Ref. 30.

(2) Hydrogen *sulfide*.[7] There is little data on concentration levels of hydrogen sulfide. A mixture of sulfur dioxide and hydrogen sulfide would be expected in most areas with the hydrogen sulfide concentration higher in areas where sulfur dioxide emissions are small. Measurements made in Bedford, Mass., in 1960 showed a surprisingly constant concentration that was in the range 8 to 9 $\mu g/m^3$ regardless of wind direction. Measurements made in New York City in 1957 showed a low and constant hydrogen sulfide concentration. The maximum

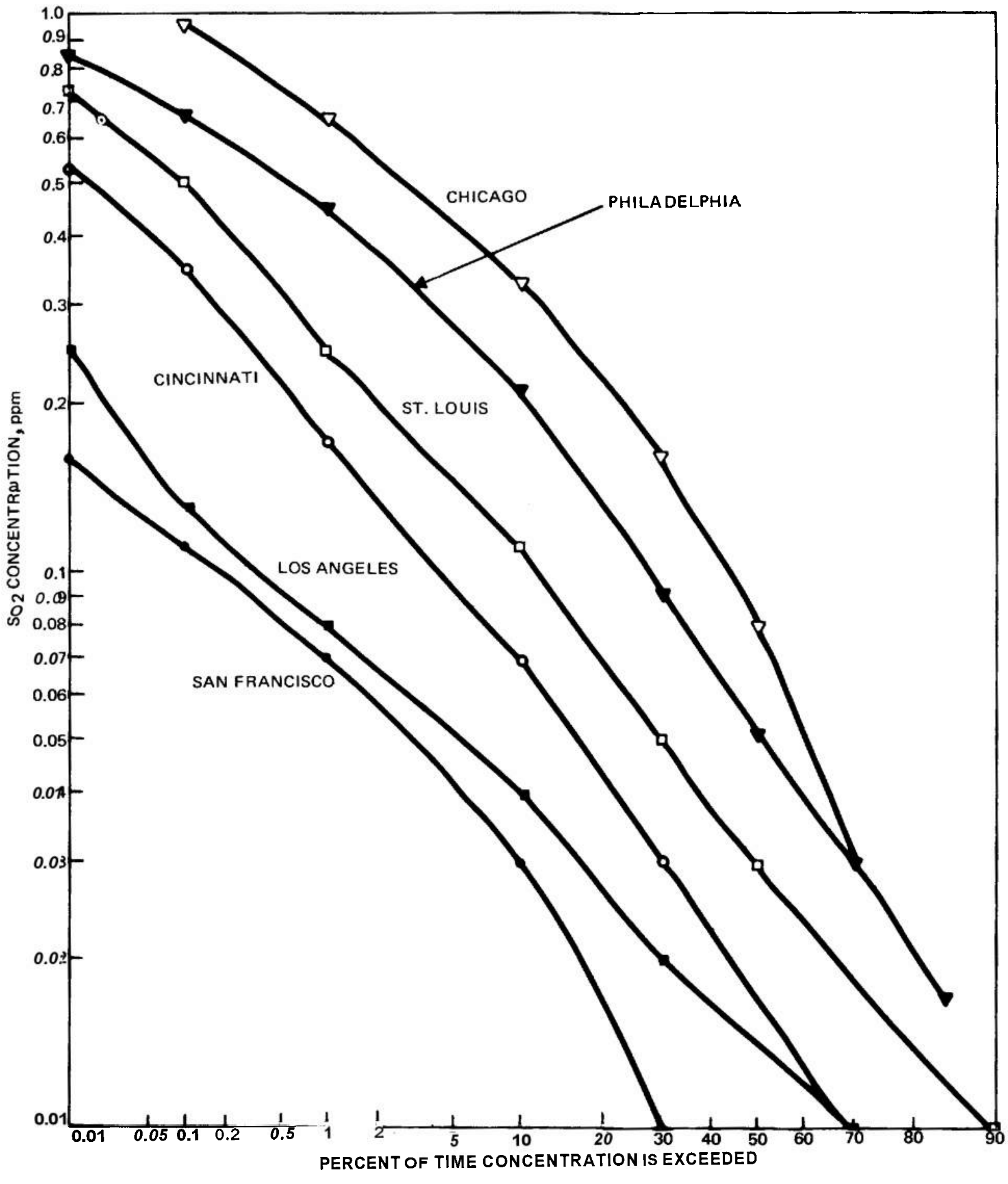


FIGURE 2-14. Frequency Distribution of Sulfur Dioxide Levels, 1962-1967 (1-hr averaging time)

TABLE 2-13. BACKGROUND CONCENTRATIONS OF SULFUR DIOXIDE

Location	Concentration
Nebraska	< 0.3 ppb in upper troposphere
Hawaii	0.3 ppb
Florida (southeast coast)	1.0 ppb
Antarctica	0.3-1 ppb
Panama Canal Zone	0.3-1 ppb
Central Atlantic	< 0.3 ppb

reading from **249** determinations was 7.5 $\mu g/m^3$ with an average value of 3 $\mu g/m^3$.

(3) Carbon monoxide. The average concentration of carbon monoxide for urban areas has been estimated to be 7 ppm and, for rural areas, 0.1 ppm (Ref. 28). Values of 100 ppm for busy streets, 5 ppm for cities, 0.2 ppm for urban areas, and 0.08 ppm for unpolluted areas have been given (Ref. 30). Values as high as 147 ppm have been measured in Los Angeles highway traffic (Ref. 9).

(a) *Diurnal patterns.* Community atmospheric carbon monoxide levels follow a regular diurnal pattern of variation dependent primarily on human activity. Carbon monoxide levels generally correlate well with total traffic volume in urban areas. Fig. 2-15 (Ref. 16) shows the daily variation of carbon monoxide levels on weekdays in Detroit. The two peak levels occur during rush hour traffic, one at approximately 8 a.m. and the other at 6 p.m. This type of variation is probably typical of all urban areas.

(b) *Seasonal patterns.* Community atmospheric carbon monoxide levels reveal seasonal changes that result primarily from changes in the meteorological patterns. Concentrations are generally highest in the fall, followed by the summer, spring, and winter, respectively.

(c) *Annual variations.* Data from continuous measurements at 46 sampling sites (located mainly in California) over a period of years (4 to 12) indicate that no essential change in annual average concentration has occurred during this time period (Ref. 16).

(4) *Nitrogen oxides.* The ambient concentration of nitrogen oxides varies greatly with time and place. The most significant gaseous pollutants in this group are nitric oxide and nitrogen dioxide. Robinson and Robbins (Ref. 26), after studying the data on nitrogen dioxide and nitric oxide concentrations as reported in the literature, estimated the following mean concentrations on a global basis. In land areas between latitudes 65 deg N. and 65 deg S., NO = 2 ppb and NO_2 = 4 ppb. In other land areas and all ocean areas, NO = 0.2 ppb and NO_2 = 0.5 ppb.

(a) *Diurnal patterns.* On a normal day in a city, ambient nitrogen oxide levels follow a regular pattern with the sun and traffic. Fig. 2-16 (Ref. 8) illustrates the diurnal variation of nitrogen oxide concentrations in Los Angeles, Calif. The pattern is probably representative of the daily variation of nitrogen oxides in most cities although the concentration levels may be higher than would be found in other cities. The graph shows that, as human activity, especially automotive traffic, increases in the morning hours between 6 and 8 a.m., the concentration of the primary contaminant, nitric oxide, increases. As the ultraviolet light intensity increases, a rapid and almost quantitative oxidation of nitric oxide to nitrogen dioxide is observed (Ref. 8). By about 9 a.m. the nitric oxide concentration has reached and remains at a minimum until near sundown. The nitrogen dioxide level remains relatively high throughout the daylight hours and drops to a lower level after dark.

(b) *Seasonal patterns.* Concentration data show a

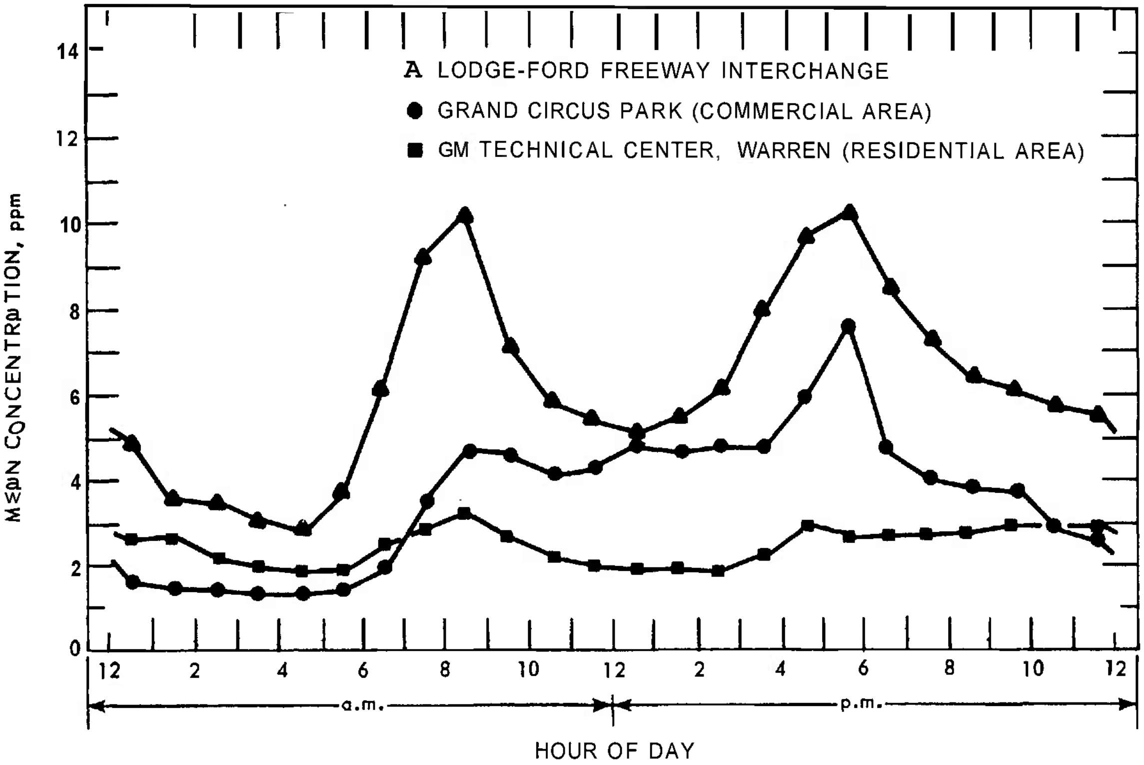


FIGURE 2-15. Diurnal Variation of Carbon Monoxide Levels on Weekdays in Detroit

marked seasonal variation in nitric oxide levels but no set pattern is evident for nitrogen dioxide levels. As Fig. 2-17 (Ref. 8) indicates, the concentration levels of nitric oxide are highest during the late fall and winter. This is a result of less overall atmospheric mixing and generally less ultraviolet energy for converting nitric oxide to nitrogen dioxide during these months. Also, there is probably increased nitric oxide emissions from power and heating sources during the winter months. Fig. 2-18 (Ref. 8) gives the monthly mean nitrogen dioxide concentrations for the same period of time and cities as in Fig. 2-17. As previously stated, there is no recognizable predominant pattern in these data.

(c) ***Annual trends.*** At the present time there are not sufficient long-term data for computing cyclical variations. For example, there is no clear way to separate the effects due to a change in emissions and those due to long-term changes in the meteorological factors that affect ambient concentrations.

(5) ***Hydrocarbons.*** The atmospheric concentration of nonmethane hydrocarbons follows a diurnal pattern similar to that of the traffic density in urban areas. Fig. 2-19 (Ref. 10) shows the diurnal pattern for four U S cities. The patterns, while not exactly the same, all show a fairly sharp rise in concentrations at about 6 a.m. which remain high throughout the daylight hours. The data for Washington, D.C., do not, however, fit this pattern but do show the typical rise at 6 a.m. with a low occurring about 1 p.m. followed by a steady increase from about 1 p.m. to midnight. Instantaneous concentrations of total hydrocarbons have been measured as high as 40 ppm (as carbon) in Los Angeles.

2-5.2 PARTICULATE POLLUTANTS

Particulate pollutants are observed as either suspended particulate matter or as matter that settles from the air, i.e., dustfall. Most of the data on suspended particulate matter were obtained from high-volume filter samples. Average suspended particle mass concentrations range from 60 to 220 $\mu g\ m^{-3}$ for urban areas, depending on the size of the city and on its industrial facilities. In

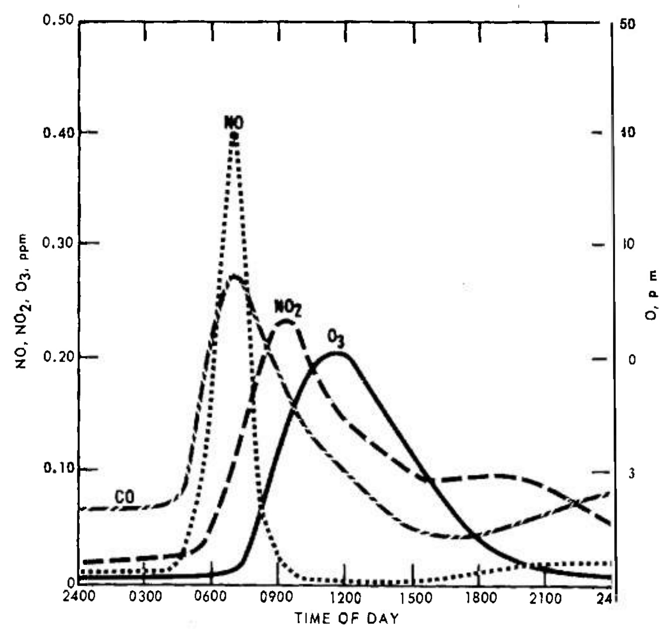


FIGURE 2-16. Diurnal Variation in Concentrations of Selected Pollutants (Los Angeles, 1-hr average concentrations)

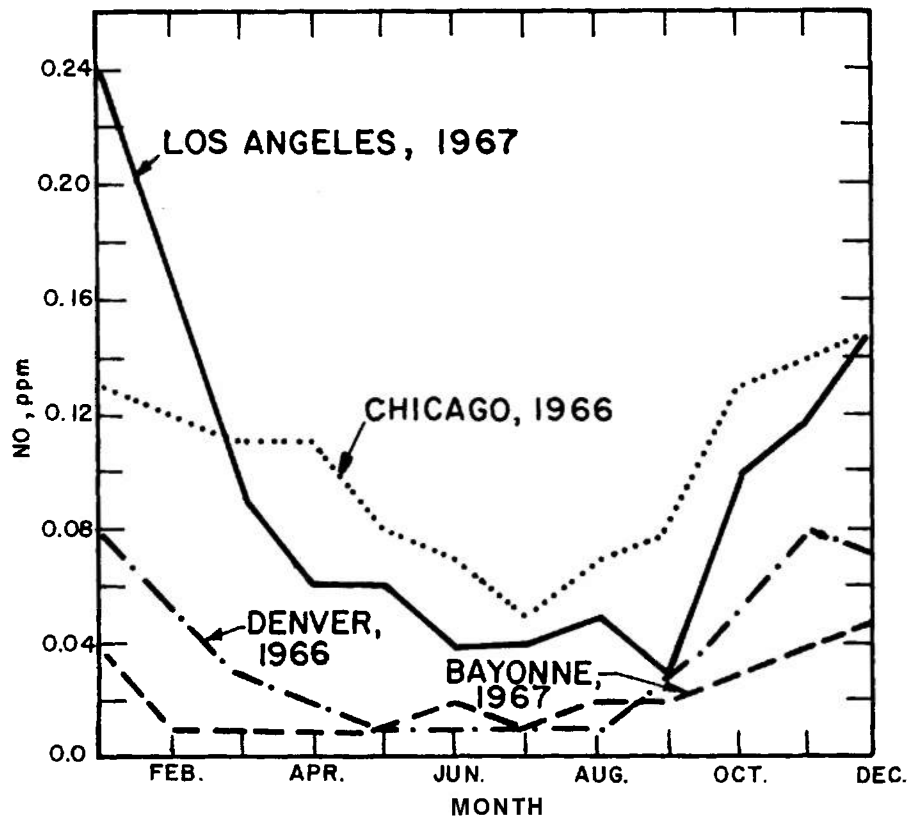


FIGURE 2-17. Monthly Mean Nitric Oxide Concentrations at Four Urban Sites

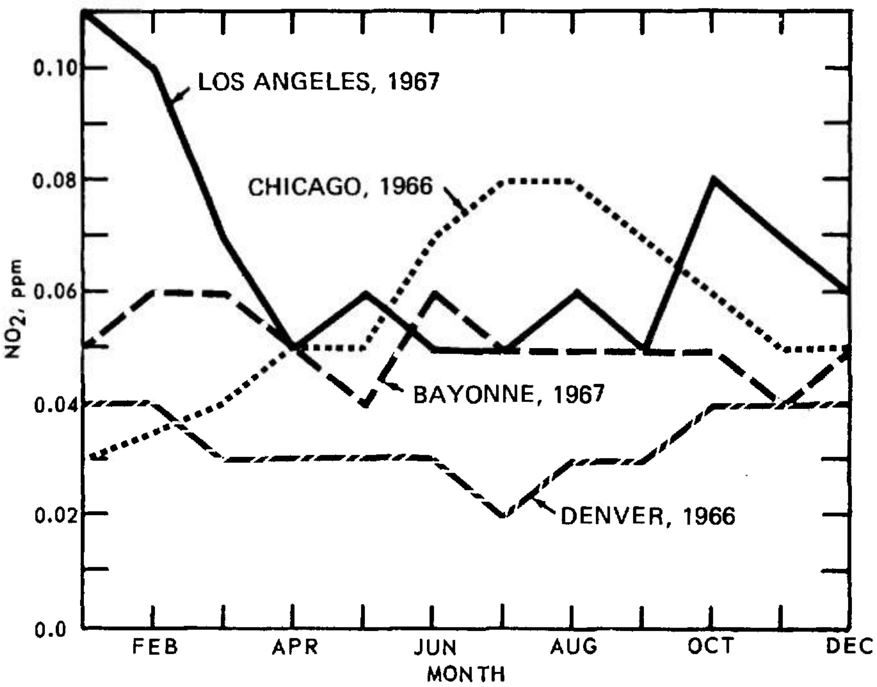


FIGURE 2-18. Monthly Mean Nitrogen Dioxide Concentrations at Four Urban Sites

heavily polluted areas, concentrations as high as 2,000 $\mu g\ m^{-3}$ have been measured over a 24-hr sampling period. Average values range from about 10 $\mu g\ m^{-3}$ for remote nonurban areas to about 60 $\mu g\ m^{-3}$ for near urban environments. Table **2-14** (Ref. **12)** gives the average suspended particle concentrations for 60 cities in the United States. There is a factor of three in particulate matter concentrations between the most polluted atmosphere (Chattanooga) and the least polluted one (Miami).

Particle concentrations have diurnal and seasonal cycles. For most cities these cycles are predictable. In northern cities that experience cold winters, the peak concentrations will occur in midwinter due to the increased emissions from fuel combustion for heating purposes. A daily maximum in the morning between about 6 and 8 a.m. is usually the result of an increase in the strength of sources of particulates, including automobile traffic, and to a combination of meteorological factors.

Dustfall measurements are expressed as dust weight deposited on a unit area in a time unit (usually one month). Dustfall is the usual measurement index for particles in the size range that is separated from the atmosphere by gravitational forces.

Typical dustfall values for urban areas are 0.35 to 3.5 $mg/cm^2/mo$ (10 to 100 $tons/mi^2/mo$). Values approaching 70 $mg/cm^2/mo$ (2,000 $tons/mi^2/mo$) have been measured near especially large sources (Ref. 12).

2-6 MEASUREMENTS

Several methods have been used in measuring air pollutants since the need for monitoring was first recognized in the mid-1950's. The first air pollution instruments were adapted from those in use in the chemical process industry at the time. The majority of these "first generation" instruments operated on chemical principles. In these, the sample air is passed through an aqueous solution in which the pollutant (gas) to be determined reacts (1) to form a colored solution, (2) to form an electrolytic solution, or (3) to oxidize/reduce a compound in the solution. Some of the wet-chemical methods are still being used. In general these methods are not specific for a particular pollutant and lack the sensitivity necessary for continuous ambient air monitoring.

Physical methods employed in air pollution monitor-

TABLE 2-14. SUSPENDED PARTICLE CONCENTRATIONS (GEOMETRIC MEAN OF CENTER CITY STATION) IN URBAN AREAS, 1961 TO 1965

Standard metropolitan statistical area	Total suspended particles	
	$\mu g\ m^{-3}$	Rank
Chattanooga	180	1
Chicago-Gary-Hammond-East Chicago	177	2
Philadelphia	170	3
St. Louis	168	4
Canton	165	5
Pittsburgh	163	6
Indianapolis	158	7
Wilmington	154	8
Louisville	152	9
Youngstown	148	10
Denver	147	11
Los Angeles-Long Beach	145.5	12
Detroit	143	13
Baltimore	141	14.5
Birmingham	141	14.5
Kansas City	140	16.5
York	140	16.5
New York-Jersey City-Newark-Passaic-Paterson	135	18
Akron	134	20
Boston	134	20
Cleveland	134	20
Cincinnati	133	22.5
Milwaukee	133	22.5
Grand Rapids	131	24

TABLE 2-14 (Continued). SUSPENDED PARTICLE CONCENTRATIONS (GEOMETRIC MEAN OF CENTER CITY STATION) IN URBAN AREAS, 1961 TO 1965

Standard metropolitan statistical area	Total suspended particles	
	$\mu g\ m^{-3}$	Rank
Nashville	128	25
Syracuse	127	26
Buffalo	126	27.5
Reading	126	27.5
Dayton	123	29
Allentown-Bethlehem-Easton	120.5	30
Columbus	113	31.5
Memphis	113	31.5
Portland (Oreg.)	108	34
Providence	108	34
Lancaster	108	34
San Jose	105	36.5
Toledo	105	36.5
Hartford	104	38.5
Washington	104	38.5
Rochester	103	40
Utica-Rome	102	41
Houston	101	42
Dallas	99	43
Atlanta	98	44.5
Richmond	98	44.5
New Haven	97	46
Wichita	96	47
Bridgeport	93	50
Flint	93	50
Fort Worth	93	50
New Orleans	93	50
Worcester	93	50

TABLE 2-14 (Continued). SUSPENDED PARTICLE CONCENTRATIONS (GEOMETRIC MEAN OF CENTER CITY STATION) IN URBAN AREAS, 1961 TO 1965

Standard metropolitan statistical area	Total suspended particles	
	$\mu g\ m^{-3}$	Rank
Albany-Schenectady-Troy	91.5	53
Minneapolis-St. Paul	90	54
San Diego	89	55
San Francisco-Oakland	80	56
Seattle	77	57
Springfield-Holyoke	70	58
Greensboro-High Point	60	59
Miami	58	60

TABLE 2-15. MEASUREMENT PRINCIPLES IN AIR QUALITY MONITORING

Classification	Application	Measurement principle	Energy transducer
Infrared absorption	Gases-CO, hydrocarbons	Absorption of IR energy	Thermistors, thermopiles, capacitor microphones
Ultraviolet absorption	Gases-O_3, NO_2	Absorption of UV energy	Phototubes
Light scattering	Aerosols	Scattering of visible light	Phototubes
Reflectance	Filtered particulates	Visible light reflectance	Phototubes
Ionization	Hydrocarbons	Ionization current measurement	Ionization chamber
Colorimetry	Reactive gases-O_3, NO_2, SO_2, HF	Absorption of visible or near UV energy by colored compound	Barrier layer cells, phototubes
Conductometry	Acid gases-SO_2	Electrical conductivity	Conductivity cell
Coulometry	Electroreducible and oxidizable gases-O_3, SO_2	Electrical current measurement	Coulometric or galvanic cell
Fluorescence	Fluorescible materials-fluorides	Emission of UV or near UV energy	Phototubes
Chemiluminescents	Gases-O_3, NO, SO_2	Emission of light energy	Phototubes

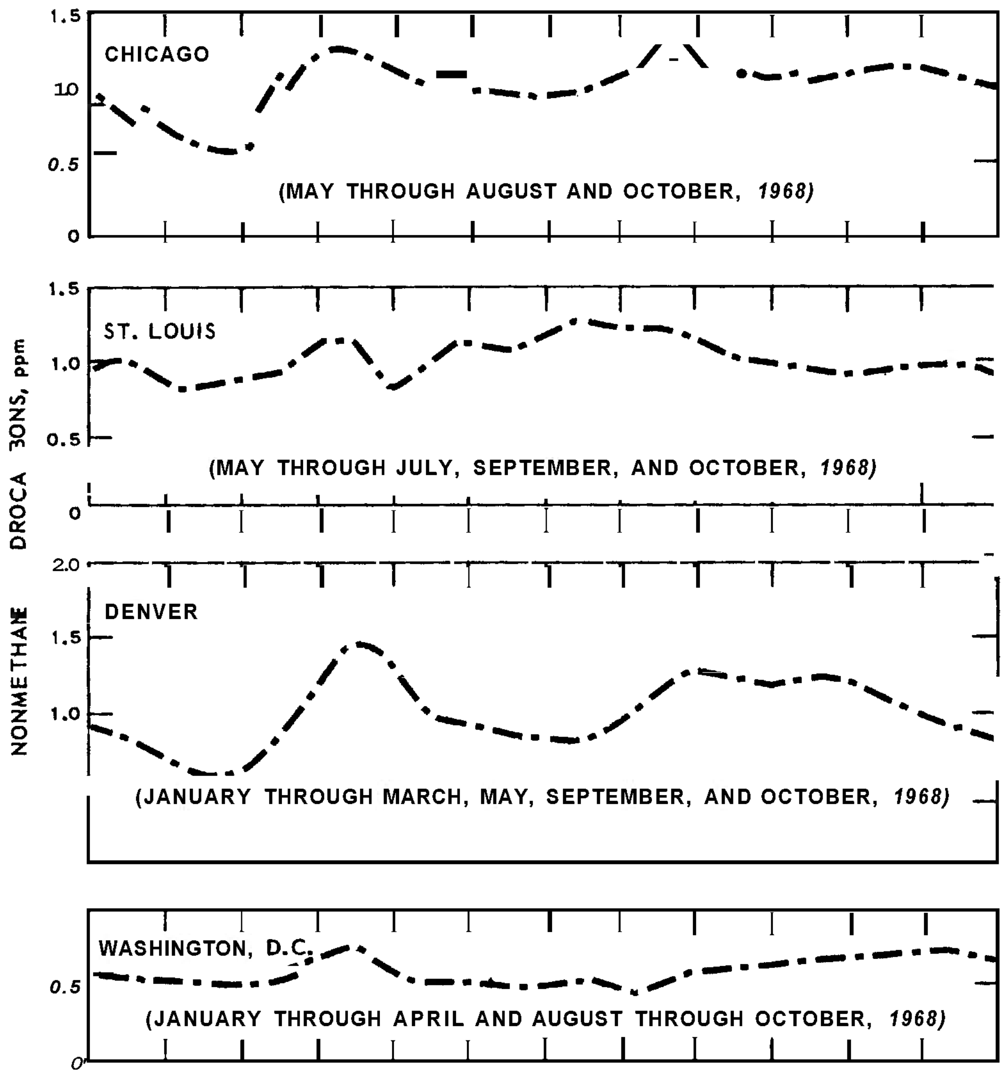


FIGURE 2-19. Diurnal Variation in Concentrations of Nonmethane Hydrocarbons (Hourly averages uwng flame ionization analyzer)

ing include absorption or emission of energy in the electromagnetic spectrum, light scattering, reflectance, and ionization. Some of the most recently developed instruments use a chemiluminescent detection method. This involves the measurement of light energy released when the pollutant gas reacts with certain other gases or reagents.

Table 2-15 (Ref. 31) lists the different measuring methods along with their applications. Table 2-16 (Ref. 32) summarizes the sampling techniques and classifies them according to their use as static, mechanized, or automatic methods.

2-6.1 MEASUREMENT PRINCIPLES[8]

The measuring principles that have found significant application in air pollution monitors are briefly discussed:

(1) *Colorimetry.* Colorimetry involves the absorption of visible or near ultraviolet energy by colored compounds. In colorimetric instruments, sample air is drawn through an aqueous solution in which the pollutant to be determined reacts with a color-forming reagent. The resultant color is proportional to the pollutant concentration and sampling time.

Colorimetric analyzers are available for the continuous measurement of sulfur dioxide, nitrogen dioxide, and oxidants. The colorimetric principle is the reference method for measuring sulfur dioxide and nitrogen dioxide (see par. 2-6.3, "Reference Methods").

Fig. 2-20 is a flow diagram of a typical colorimetric type monitor. This is a dual-flow colorimeter in which the absorbance of the unreacted reagent is measured and used as the zero reference for the sample (reacted) solution. As shown in the diagram, the light source is split with equally intense beams passing through the reference cell and the sample cell where in both cases the transmitted light is detected by photocells. The difference in intensity of the transmitted beams is a function of the pollutant concentration and the length of the light path through the solution. The actual flow of the air sample through the monitor starts with the atmospheric sample passing through the rotameter into the scrubber or absorber. Here, the pollutant reacts with the reagent. From the scrubber the air sample is discharged to the atmosphere and the reacted reagent passes into the sample cell where the absorbance of the solution is measured.

8. General references for this paragraph are Refs. 31 and 33.

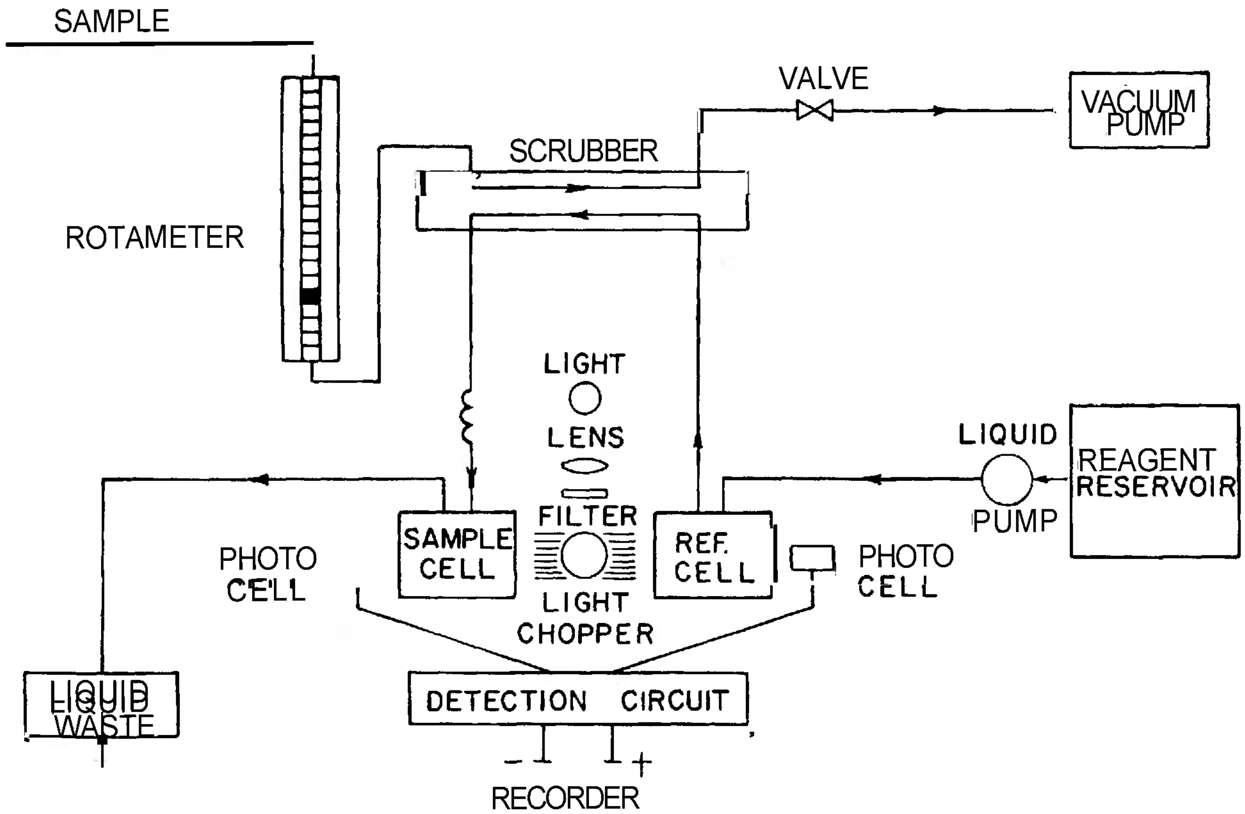


FIGURE 2-20. Schematic Diagram of a Typical Colorimetric Monitor

TABLE 2-16. COMMON AMBIENT AIR POLLUTION SAMPLING? TECHNIQUES

Type	Use	Specificity	Common averaging time	Relative cost	Required training of personnel	Remarks
			STATIC			
Settleable particulates (dustfall)	Mapping and definition of special problem areas	Total settled particulates and general classes of pollutants	1 mo	Collection, low; analysis, high	Collection, low; analysis moderate	Well-equipped laboratory required for analysis only for definition of problem areas where a chemical analysis will pinpoint a particular source. Sensitive to temperature, wind,
Sulfation devices	Mapping and general survey for sulfur dioxide	Responds to oxides of sulfur, hydrogen sulfide, and sulfuric acid	1 mo	Collection, low; analysis, high	Collection, low; analysis moderate to high	
			MECHANIZED			
Hi-vol	Integrated quantification of suspended particulate	Total suspended particulate and multiple specific pollutants	24 hr	Moderate	Moderate	Detailed chemical analysis of Hi-vol and gas samples requires sophisticated laboratory, trained chemists; cost is high
Gas sampler	Integrated quantification of gases	Sulfur dioxide, nitrogen dioxide, mercury, and other gases and vapors	24 hr	Moderate	High	
Gas	Continuous analysis of gaseous pollutants	Single gas or group of related gases	Continuous; sample integration usually 1-15 min	Moderate to high	Moderate to high	Continuous measurements allow use of any desired averaging time by computation. Accuracy is generally much better than other methods. Calibration is simplified. Data are available instantaneously
Particulate: soiling (automatic tape)	Continuous analysis of soiling rate	Unknown	Continuous; sample integration usually 1-15 min	Moderate	Moderate to high	

Cost basis: low, 0 to $500; moderate, $500 to $2000; high, above $2000.
Personnel training: low, maintenance level; moderate, technician; high, experienced technician or professional support staff.

(2) ***Coulometric method.*** Coulometry is a mode of analysis wherein the quantity of electrons or charge required to oxidize or reduce a desired substance is measured. This measured charge, expressed as coulombs, is proportional to the mass of the reacted material according to Faraday's law. Coulometric titration cells for the continuous measurement of sulfur dioxide, oxidants, and nitrogen dioxide have been developed using this principle.

Fig. 2-21 is a schematic diagram of a coulometric sulfur dioxide monitor. The principle of operation of this monitor is based on the stoichiometric reaction of sulfur dioxide with bromine in a titration cell. A redox-potential (originating from Br,) is established between two electrodes and compared to a reference voltage. Sulfur dioxide scrubbed from the sample air stream reduces the bromine to bromide lowering the bromine concentration and the potential of the cell. The charge required to reestablish the original redox-potential is directly proportional to the concentration of sulfur dioxide in the sampled air stream.

The principle of operation is similar to other coulometric instruments, although different reagent systems are used.

(3) ***Conductometry.*** The conductance of electrolytes in solution is proportional to the number of ions present and their mobilities. In dilute sample solutions, the measured conductivity can be directly related to the concentration of ionizable substance present. Sulfur dioxide has been measured by this procedure in continuous recording instrumentation for more than 25 yr. Fig. 2-22 is a schematic diagram of a typical conductivity monitor. Most conductometric analyzers use distilled water reagent modified by the addition of hydrogen peroxide and a small amount of sulfuric acid. This modified reagent forms sulfuric acid when reacted with sulfur dioxide.

(4) ***Flame phorometry.*** Flame photometry is based on the measurement of the intensity of specific spectral lines resulting from quantum excitation and decay of elements in the heat of a flame. Volatile compounds are introduced into the flame by mixing them with the flammable gas or with the air supporting the flame. Nonvolatile compounds are aspirated from a solution into the flame. The specific wavelength of interest is isolated by means of narrowband optical filters, diffraction gratings, or by means of a prism. The intensity of the specific wavelength is measured by means of a

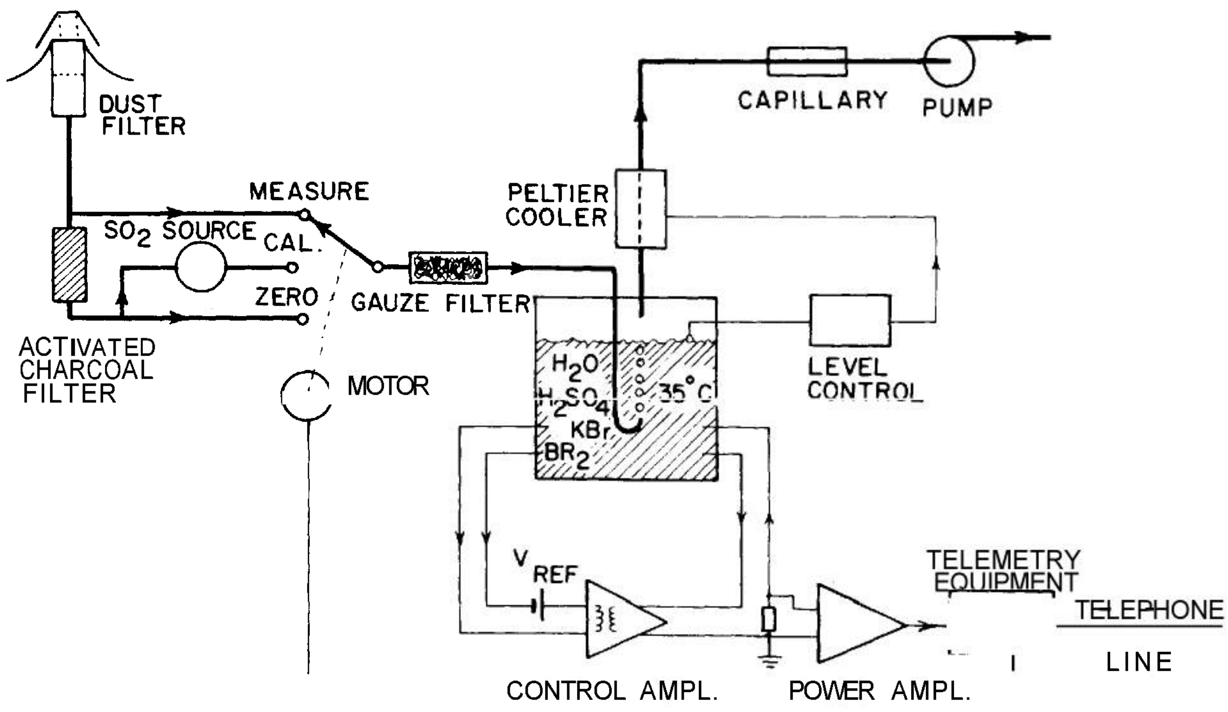


FIGURE 2-21. Schematic Diagram of a Coulometric Sulfur Dioxide Monitor

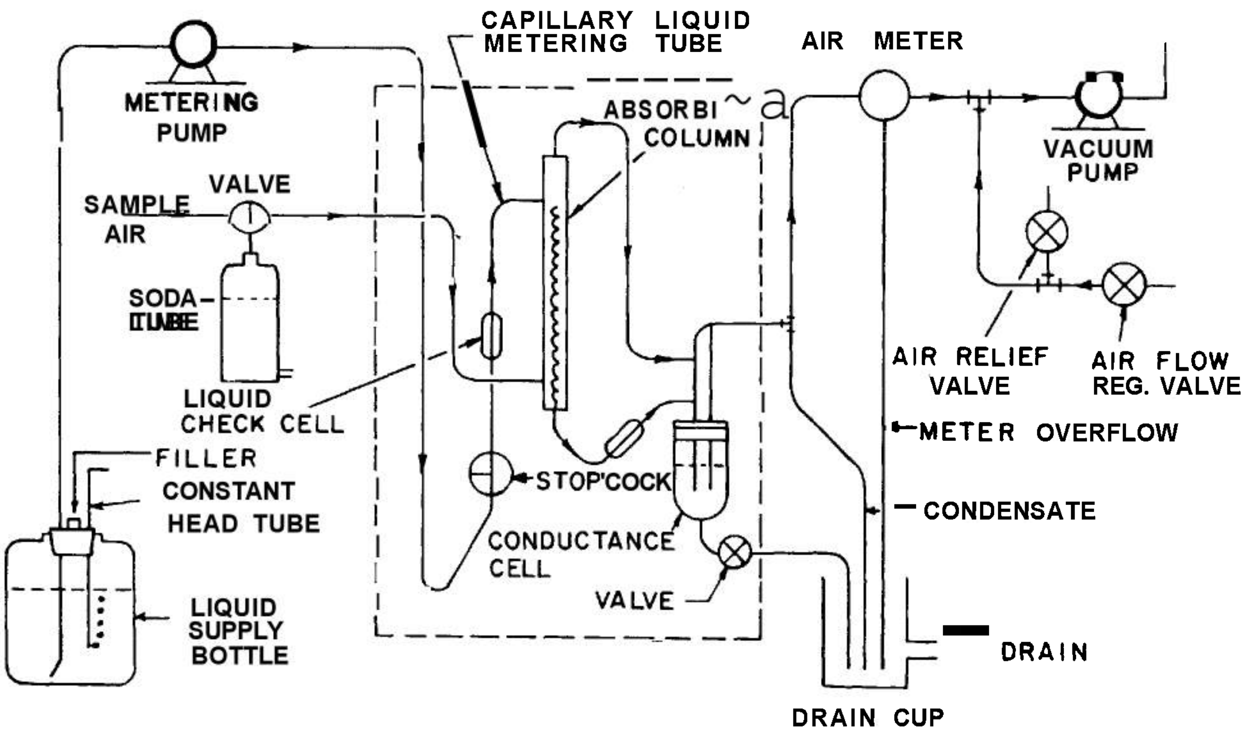


FIGURE 2-22. Schematic Diagram of a Typical Sulfur Dioxide Conductivity Monitor

phototube or photomultiplier tube and associated electronics. A schematic diagram of a typical flame photometric sulfur monitor is given in Fig. **2-23.**

(5) *Flame ionization.* When hydrocarbons are burned in a hydrogen flame, a flow of ions is produced which can be measured electrically. The number of ions produced by a hydrocarbon molecule is proportional to the number of carbon atoms in the molecule. Therefore, this technique is not specific for particular hydrocarbons. The energy from a hydrogen flame is not sufficient to ionize most other gases. Fig. **2-24** is a schematic diagram of a typical flame ionization monitor. A more detailed discussion of this method is given in par. **2-6.3** as the reference method for measuring hydrocarbons.

(6) Chemiluminescence. Small quantities of light energy are produced by certain chemical reactions. Such reactions are being used to measure ozone and nitric oxide. When the pollutant of interest reacts with certain other gases or reagents, the quantity of light released is proportional to the pollutant concentration. This technique is usually highly specific for a given pollutant. It has been designated as the reference method for measuring photochemical oxidants (ozone) and is proving to be, perhaps, the best method for measuring nitrogen oxides. Fig. **2-25** is a schematic diagram of a chemiluminescent nitric oxide analyzer.

In this instrument the phototube is used to detect the light emitted from the chemiluminescent gas phase reaction of nitric oxide and ozone according to the following reaction

$$NO + O_3 \rightarrow NO_2^* + O_2 \rightarrow NO_2 + O_2 + h\nu \qquad (2\text{-}18)$$

where NO_2^* indicates an excited state of nitrogen dioxide that emits a photon (hv) and becomes stable nitrogen dioxide as indicated.

(7) *Infrared absorption.* Certain pollutant molecules have a sufficiently characteristic infrared absorption spectrum that the absorption of infrared energy can be used as a measure of the concentration of a pollutant. Carbon monoxide is uniquely suited to this technique of detection since its absorption characteristics and typical concentrations make possible direct sampling. Nondispersive infrared spectrometry is the reference method for measuring carbon monoxide and is discussed in more detail in par. 2-6.3.

(8) *Suspended particulates.* Suspended particulates

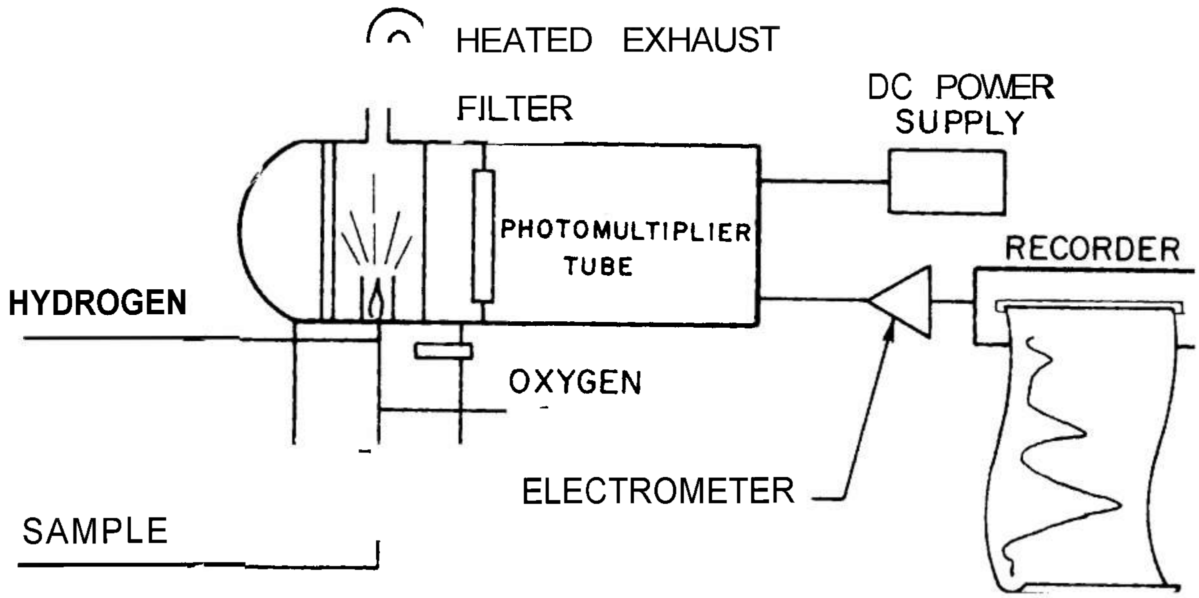


FIGURE 2-23. Schematic Diagram of a Typical Flame Photometric Sulfur Monitor

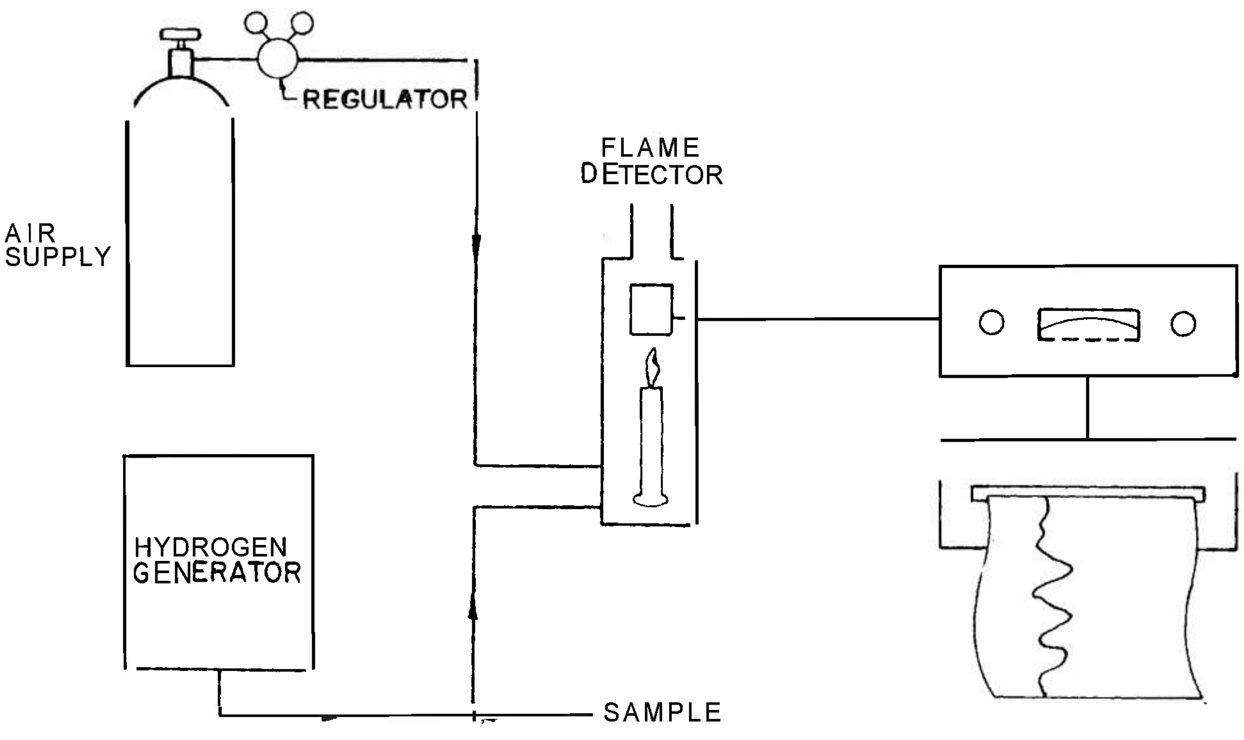


FIGURE 2-24. Schematic Diagram of a Typical Flame Ionization Monitor

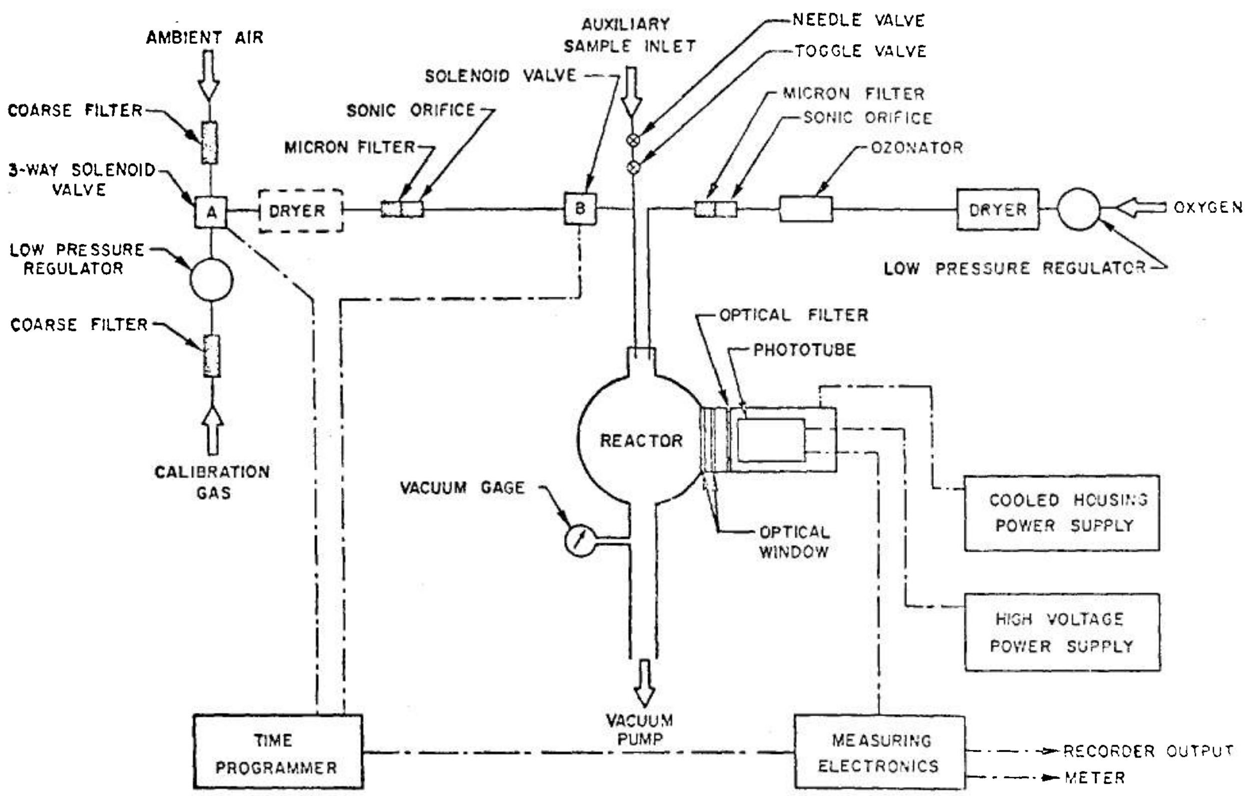


FIGURE 2-25. Schematic Diagram of a Chemiluminescent Nitric Oxide Analyzer

can be measured in a variety of ways. The selection of a particular technique should be determined by the environmental conditions under which the measurements are to be made and the objectives of the measuring program.

Perhaps the most reliable method, and the only one to be discussed here, for determining the mass concentration of suspended particulate matter is filtration. The measurement of suspended particulate matter by filtration is accomplished using a high-volume sampler. Also, for sampling periods less than 24 hr, a tape sampler can be used. Both systems are described in par. 2-6.3.

Equipment and techniques for measuring particle number and size distributions of particulate pollutants are discussed in detail by Giever (Ref. 34).

2-6.2 CALIBRATION TECHNIQUES

The validity of the data derived from air monitoring instrumentation is dependent upon the type and extent of the quality control procedures employed. The first and perhaps most critical element of data quality control is instrument calibration. Calibration determines the relationship between the observed and true values of the variable being measured. Instrument calibration provides maximum quality control in the collection of reliable data (Ref. 31).

Most present-day monitoring instruments are subject to drift and variation in internal parameters; therefore, they do not maintain accurate calibration over long periods of time. It is necessary to check and standardize operating parameters on a periodic basis. These are predetermined by the manufacturer and usually are listed in the operator's manual.

To calibrate an instrument, the method used must deliver a known pollutant quantity to the system. The instrument must be calibrated in the monitoring mode and should sample the calibrating gas at identical settings and flow rates at which the instrument will operate in the field. The calibration involves measuring and adjusting all instrument parameters or subsystems that have a direct bearing on measurement. Typically this includes flow rates, base line, lag and response time, and system response to an input of known standard pollutant concentrations over the entire operating range. Since input levels are varied and instrument parameters are adjusted during this process, it is referred to as dynamic or multipoint calibration. A calibration check, by which a known amount of pollutant is introduced to the system to verify the initial calibration at one point or level, is utilized to simplify the procedure normally required for performing multipoint calibrations.

Static calibrations, sometimes referred to as operational checks, may be carried out using a material having the same effect on the sensor as the pollutant of interest. In this case only the sensor is being calibrated and not the complete system. Permeation tubes are available for use as a source of known concentration in calibration of sulfur dioxide and nitrogen dioxide monitors (Refs. 8,33). A tube made of Teflon[8] containing pure sulfur dioxide or nitrogen dioxide maintained at a constant temperature has a constant permeation rate that can be determined gravimetrically to three significant digits. Calibrated permeation tubes are commercially available. Fig. 2-26 shows a typical permeation tube calibration system.

8. Teflon is a trademark of E. I. du Pont de Nemours and Co.

Standard gases prepared to exact concentrations in pressurized cylinders are available commercially for the calibration of carbon monoxide and hydrocarbon monitors. Mixtures of carbon monoxide in helium or nitrogen and methane in air or nitrogen are stable for periods of several months. Calibration checks can be made by direct introduction of the standard gas to the monitor. A diagram of the apparatus used for calibrating the chemiluminescent nitric oxide (NO) analyzer in Fig. 2-23, using a standard mixture of NO in nitrogen, is given in Fig. 2-27.

2-6.3 REFERENCE METHODS

Reference measurement methods and sample averaging times have been specified for instrumentation to meet national air quality standards for six pollutants (Ref. 35). Other methods for measuring sulfur dioxide, nitrogen dioxide, and suspended particulates have been evaluated by standard test procedures and defined as equiva-

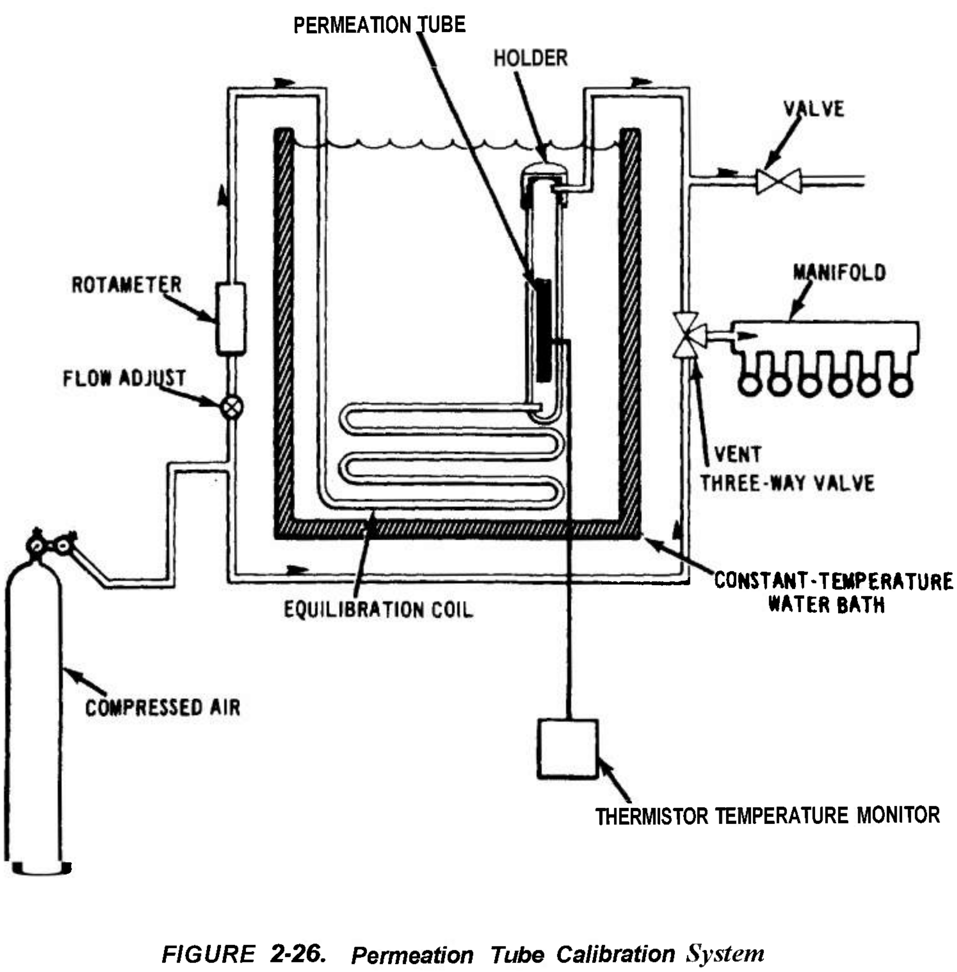


FIGURE 2-26. Permeation Tube Calibration System

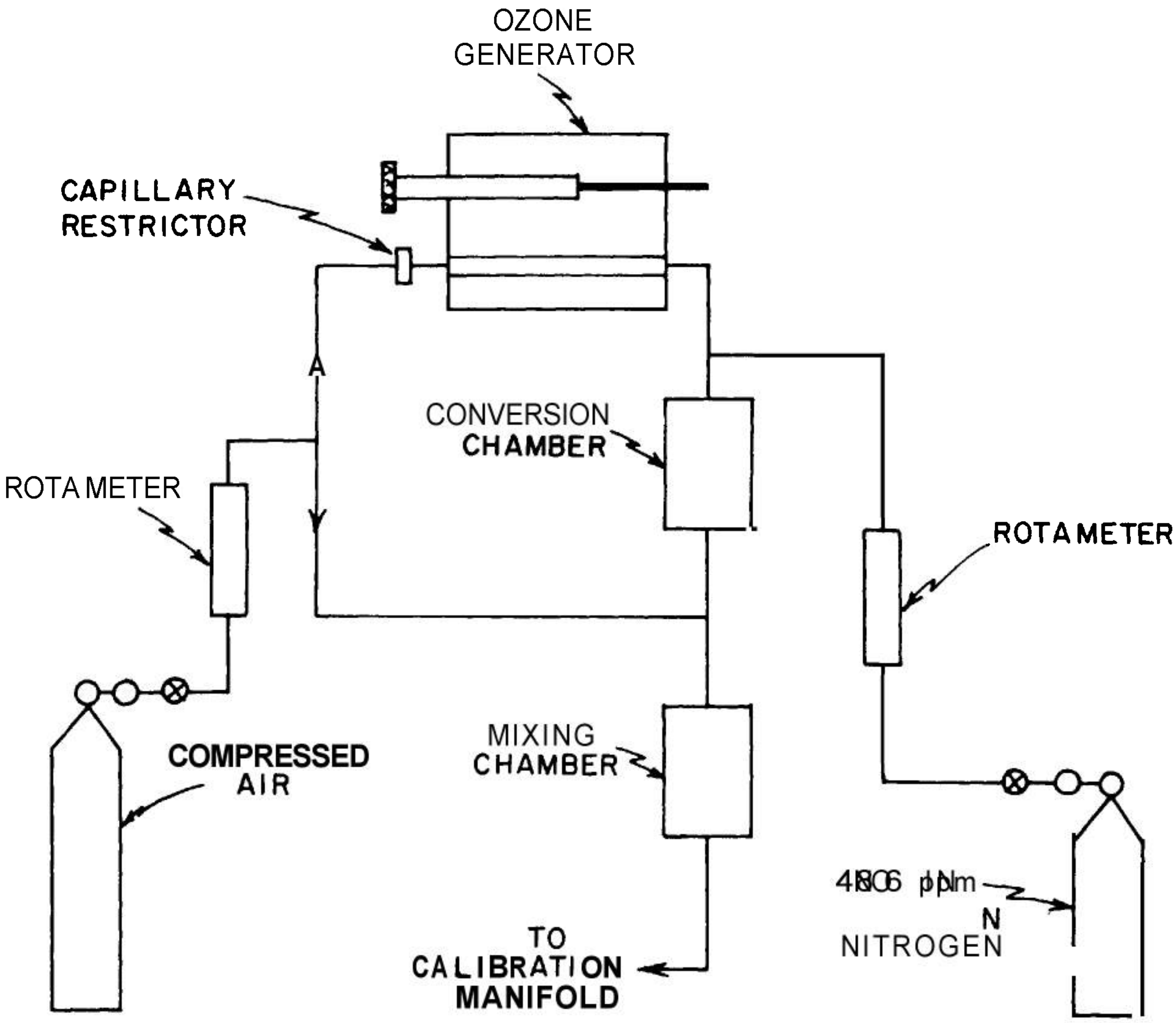


*FIGURE 2-27. **Nitric Oxide and Nitrogen Dioxide Calibration System***

lent to the reference methods (Ref. 36). Table 2-17 lists the reference methods and averaging times as specified.

(1) Sulfur ***dioxide.*** The reference method for the determination of sulfur dioxide in the atmosphere is the pararosaniline method utilizing the calorimetric detection principle.

Sulfur dioxide is absorbed from the air sample in a solution of potassium tetrachloromercurate (TCM) forming a dichlorosulfitomercurate complex. This complex is reacted with pararosaniline and formaldehyde to form the intensely colored pararosaniline methyl sulfonic acid. The absorbance of the solution is measured spectrophotometrically.

This method has serious shortcomings and the validity of the measurements is subject to question unless temperature, pH, and purity of the reagents are carefully controlled. Under controlled conditions, concentrations of sulfur dioxide in the range of 0.01 to 0.40 ppm can be measured.

(2) Particulate matter. The high volume sampler method is the reference method for sampling large volumes of air for suspended particulates. The sampler operates somewhat like a vacuum cleaner. The essential components are a filter and a vacuum pump. Dust-laden ambient air is drawn through the filter where the particulate matter is trapped. The usual procedure is to weigh the filter before and after the sampling period and use the average airflow rate through the filter to give an average concentration in weight per unit volume (units are usually $\mu g\ m^{-3}$). The sample may be used for other analyses such as particle count, particle size, particle shape, or chemical composition.

TABLE 2-17. NATIONAL AIR QUALITY STANDARD REFERENCE METHODS

Pollutant	Averaging time	Reference method	Principle of detection
SO_2	3 hr, 24 hr, annual	Pararosaniline	Colorimetric
Particulate matter	24 hr, annual	Hi-vol sampler	Gravimetric
CO	1 hr, 8 hr	Nondispersive infrared spectrometry	Infrared
Photochemical oxidants (ozone)	1 hr	Gas phase O_3-ethylene reaction (calibrated against neutral buffered KI method)	Chemiluminescence
Hydrocarbons (nonmethane)	3 hr	Gas chromatographic	Flame ionization
NO_2	Annual	24-hr integrated samples collected in alkaline solution	Colorimetric

In actual sampling situations, to insure a high degree of uniformity in filter exposure, the sampler should be operated in a vertically oriented shelter with the filter in a horizontal position. Shelter design may affect the collection characteristics of sampling equipment; therefore, care should be exercised when comparing data from samples collected at sites where different types of shelters have been used.

The standard shelter provides an air opening, slightly larger than the filter area, around the circumference of the sampler. This opening is oriented so that the intake airflow is vertically upward. Therefore, with an average velocity of 64 ft^3 min^{-1} across the horizontal air inlet portal of the shelter, the collection of particles is generally limited to those 100 μm or less in diameter. Particles too large to remain airborne are excluded and variations caused by shifting winds are minimized. Figs. 2-28 and 2-29 give an exploded view and an assembled view, respectively, of a high-volume sampler and standard shelter.

Concentrations of suspended particulates as low as 1 μg m^{-3} can be obtained when the sampler is operated at an average flow rate of approximately 40 ft^3 min^{-1} based on a sampling period of 24 hr. Weight of particulates should be determined to the nearest milligram, air flow rate to the nearest cubic foot per minute, and time to the nearest 2 min.

Although it is not a reference method, the tape sampler method is required for sampling particulates at less than 24-hr intervals (e.g., one sample every 2 hr), as would be necessary under emergency episode conditions. The correlation of the tape-sampler method with the high-volume sample has been found not to be uniform in all areas of the United States; however, this method is the only one available for short-term monitoring of particulates. Fig. 2-30 is the schematic diagram of a typical tape sampler.

Air is drawn through a 1-in.-diameter spot (white filter paper) at a flow rate of 7.0 liters/min (0.25 ft^3 min^{-1}) for periods up to 4 hr. At the end of the sampling period, the tape advances automatically by means of a timing mechanism, placing a clean section of filter paper at the sampling port. The collected spot is positioned under a photoelectric transmittance head that measures the optical density of the spot. The greater the amount of particulate matter filtered out of the air, the darker the spot. The quantity of air sampled is ex-

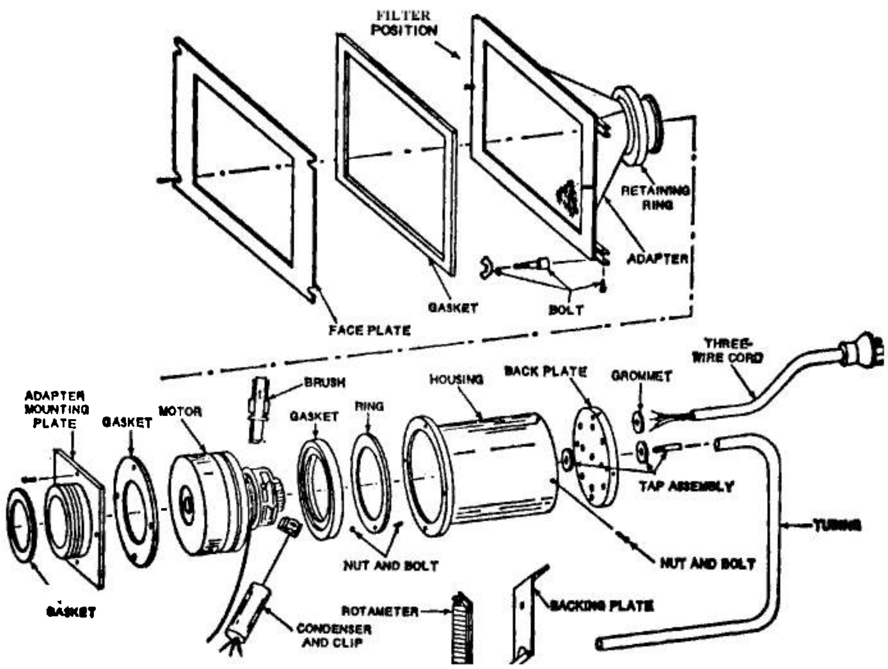


FIGURE 2-28. Exploded View of Typical High-volume Air Sampler Parts

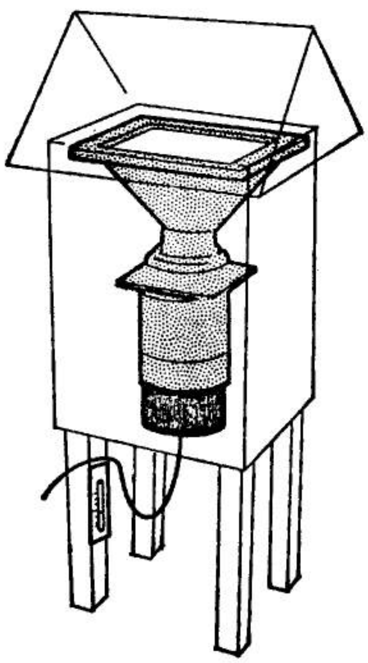


FIGURE 2-29. Assembled High Volume Air Sampler and Shelter

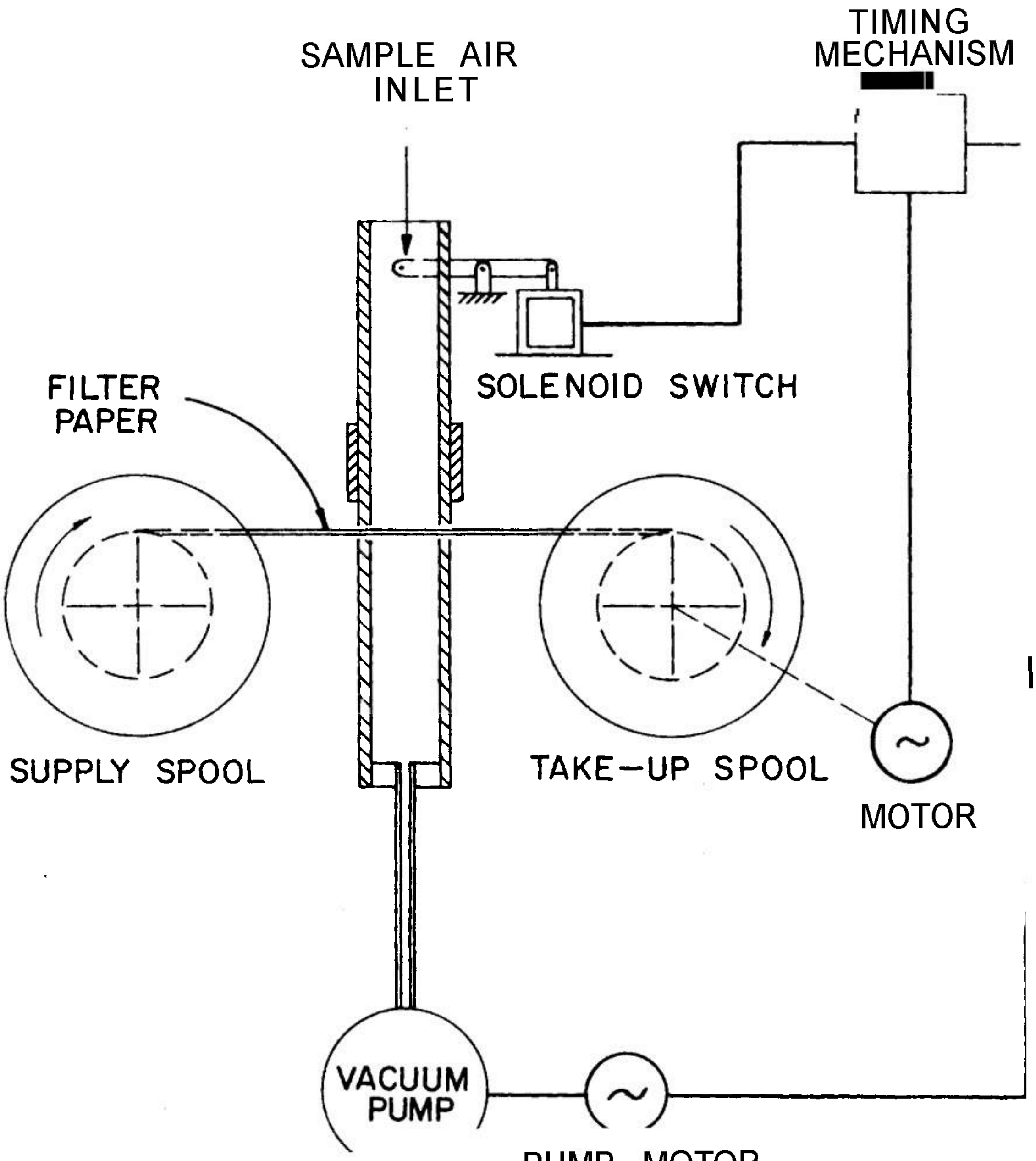


FIGURE 2-30. Schematic Diagram of a Typical Tape Sampler

pressed in linear feet and the results reported as COH (coefficient of haze) per 1,000 linear feet of air. The units of 1,000 linear feet LF are determined as follows:

$$LF \text{ (units of 1000)} = Q \times t/(1000 \times A) \qquad (2\text{-}19)$$

where

LF = linear feet
Q = sample airflow rate, $ft^3\ min^{-1}$
t = sampling time, min
A = cross-sectional areas of sampling spot, ft^2

The COH unit can be defined as the quantity of particulate matter that produces an optical density of 0.01 when measured by light transmittance in the region of 375 to 450 nm. The transmittance of a clean filter is used as a reference and is set at 0.0 density (100 percent transmittance). The light transmitted through the filter tape is expressed as follows:

$$\text{Optical density} = \log (I_0/I) \qquad (2\text{-}20)$$

where

I_0 = initial transmittance of light through clean spot

I = transmittance of light through solid spot.

For estimation purposes, 1 COH unit equals approximately 125 $\mu g\ m^{-3}$.

The preceding description is general and applies to all makes of tape samplers. Deluxe models are available which have direct readout of percent transmittance or COH's on recorder paper, direct printout on tape, telemetering hardware, or computer interfacing.

The optimal range for optical density measurements is from 0.05 to 0.3. The sampling interval usually is adjusted so that optical density falls in this range.

(3) ***Carbon monoxide.*** The nondispersive infrared (NDIR) method is the reference method for measuring carbon monoxide. A typical analyzer (as shown in Fig. 2-31) consists of a sampling system, two infrared sources, sample and reference gas cells, detector, control unit and amplifier, and recorder. The reference cell contains a noninfrared-absorbing gas while the sample cell is continuously flushed with the sample atmosphere. The detector consists of a gas cell having two compartments (both filled with carbon monoxide under pressure) separated by a diaphragm whose movement changes the electrical capacitance in an external circuit and, ultimately, an amplified electrical signal suitable for input to a servo-type recorder.

During operation the optical chopper intermittently exposes the reference and sample cells to the infrared sources. A constant amount of infrared energy passes through the reference cell to one compartment of the detector cell while a varying amount, inversely proportional to the carbun-monoxide concentration in the sample cell, reaches the other detector cell compartment. The unequal quantities of infrared energy reaching the two compartments of the detector cell cause unequal expansion of the detector gas. This unequal expansion moves the detector cell diaphragm, a movement that alters the electrical capacitance of the detection circuitry.

The measuring range of NDIR carbon monoxide analyzers is normally 0 to 50 or 0 to 100 ppm. Filter cells are used to minimize interferences from carbon monoxide and water vapor.

(4) ***Photochemical oxidants*** (ozone). The reference method for measurement of ozone is the chemiluminescent reaction between ozone and ethylene. This method is discussed in the chapter on ozone (Chap. 12, Part Two).

(5) ***Hydrocarbons (nonmethane),*** The reference method for measuring hydrocarbons corrected for methane is the gas chromatographic-flame ionization detection (GC-FID) method. Fig. 2-32 is a typical flow diagram for a GC-FID hydrocarbon monitor.

Measured volumes of air are delivered semicontinuously (4 to 12 times per hour) to the hydrogen flame ionization detector to measure its total hydrocarbon (THC) content. An aliquot of the same air sample is introduced into the stripper column that removes water, carbon dioxide, and hydrocarbons other than methane. Methane and carbon monoxide are passed quantitatively to the gas chromatographic column where they are separated. The methane is passed unchanged through a catalytic reduction tube into the flame ionization detector. Hydrocarbon concentrations corrected for methane then are determined by subtracting the methane value from the THC value. The method is used for semicontinuous operation with the capability of performing one analysis every 5 min.

Instruments such as the Beckman 6800 (see Table 2-18) using the GC-FID method measure carbon monoxide and methane as well as total hydrocarbons.

(6) ***Nitrogen dioxide.*** The 24-hr sampling method, often referred to as the Jacobs-Hochheiser method, was published by EPA as the reference method for the measurement of nitrogen dioxide in ambient air. This method is applicable to collection of 24-hr integrated samples in the field with subsequent analysis in the laboratory.

Nitrogen dioxide is collected by bubbling air through a sodium hydroxide solution to form a stable solution of sodium nitrite. The nitrite ion produced during Sampling is determined colorimetrically by reacting the exposed absorbing reagent with phosphoric acid, sulfanilamide, and N-l-naphthylethylenediamine dihydrochloride. This method is capable of measuring nitrogen dioxide concentrations ranging from 0.01 to 0.4 ppm.

Much criticism has been directed at the extremely low collection efficiency and the inability to automate the system. The chemiluminescent reaction between nitric

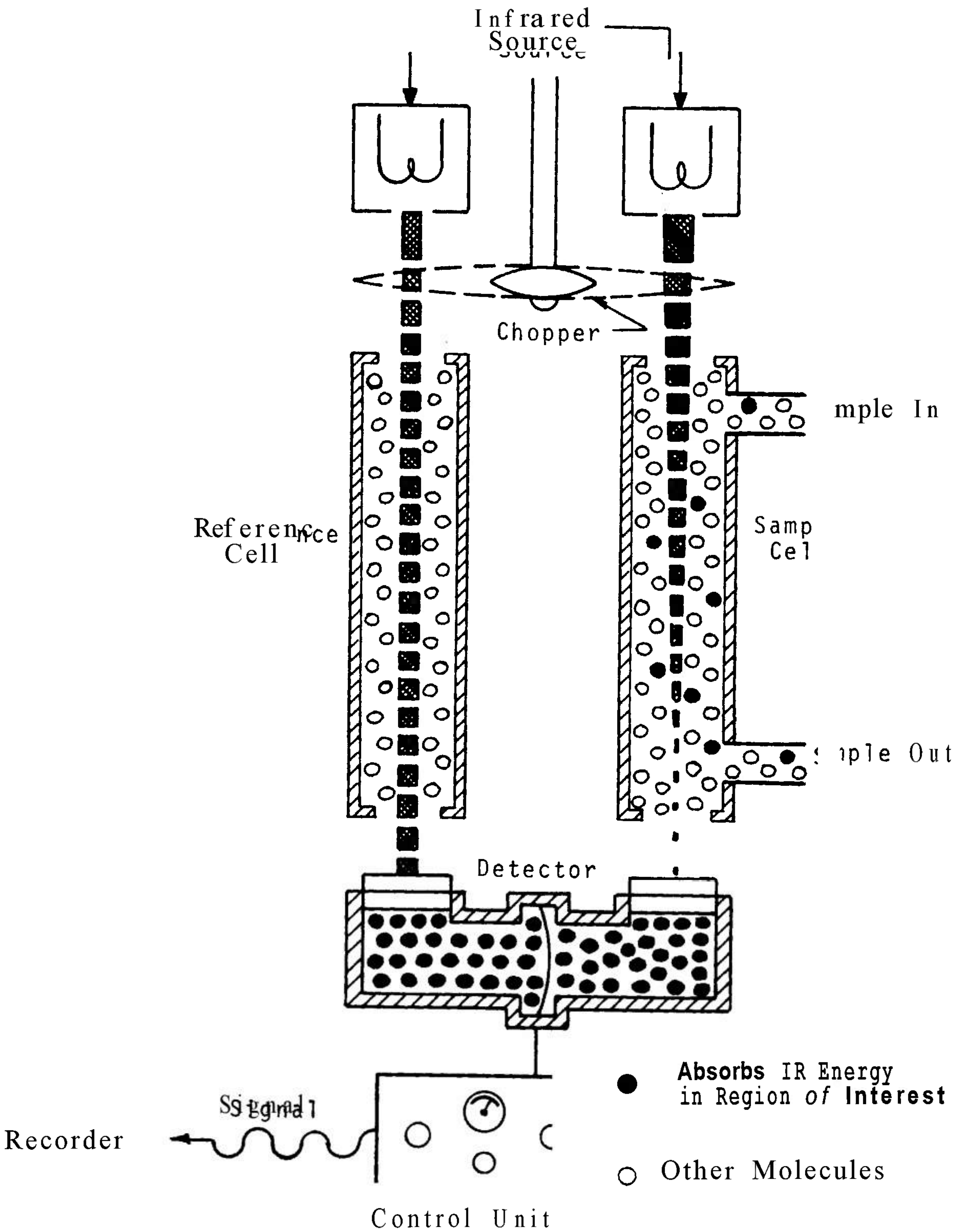


FIGURE 2-31. Schematic Diagram of a Typical Nondispersive Infrared Carbon Monoxide Monitor

TABLE 2-18. PERFORMANCE EVALUATION OF CONTINUOUS MONITORS

Manufacturer	Model	Pollutant measured	Measurement principle	Range, ppm	Minimum detectable concentration	Response Time, min	Flow rate, liters/min	Correlation coefficient of calibration data	Approx. Cost, $*	Remarks
Beckman Instrument Co. 2500 Harbor Blvd. Fullerton, Calif. 92634	910	NO_2	coulometric.	0-1.0	.030	5.8	0.15	0.843	3,200	interference from NO
Thermo Electron Corp. 85 First Avenue Waltham. Mass. 02154	10	NO NO_x	chemiluminescent	0-1.0	0.007	0.42	0.4	0.990	7,250	
Aerochem Research Laboratories, Inc. Princeton, N.J.		NO	chemiluminescent	0-0.5	0.011	0.25	0.01	0.996	8,000 (estimated for production model)	
Beckman Instrument Co.	909	NO	coulometric	0-1.0	0.03	13.20	0.15	0.824	3,200	
Technician Controls, Inc. Tarrytown, N.Y. 10502	Air monitor IV	O_x	colorimetric	0-0.5	0.012	5.9	0.51	0.947	5,240	
Mast Development Co		O_x	coulometric	0-0.5	0.005	3.7	0.14	0.993	950	negative interferences from reducing agents such as SO_2
Beckman Instrument, Co.	908	O_x	coulometric	0-0.5	0.012	5.8	0.15	0.963	2.995	
Power Designs Pacific	1562	THC	Flame ionization detector (FID)	0-20	0.13	0.8	0.03	0.999	4,000	minimal interferences
Beckman Instrumentation	6800	THC CO CH_4	GC-FID	0-10 0-20 0-5		2.5	0.01	0.967 -0.117 -0.993	8,000	
Mine Safety Appliances Co. 201 N. Braddock Ave. Pittsburgh, Pa.	200LIRA	CO	NDIR	0-100		1.0	1.50	0.852	4,000	
Pollution Monitors, Inc. 722 West Fullerton Ave. Chicago, Ill. 60614		SO_2	colorimetric	0-0.5	0.02	8.40	1.00	0.070	1,980	
Phillips, Inc. Eindhoven, Netherlands (U.S. Representative)			coulometric	0-0.2	0.004	3.1	0.15	0.994	5,250	minimal interferences
Beckman Instrument Co.	906A		coulometric	0-0.5	0.011	4.40	0.15	0.990	2,750	
Leeds & Northrup Sumneytown Pike North Wales, Pa. 19454	7860	SO_2	conductimetric	0-0.5	0.012	4.00	2.36	0.957	2,670	
Melpar An American-Standard Company 7700 Arlington Blvd. Falls Church, Va. 22046	LL-1100-1B	SO_2	FPD	0-1.0	0.005	1.1	0.20	0.413	3,750	Responds to all volatile sulfur compounds. SO_2 usually accounts for over 90% of gaseous sulfur in air.
Tracor, Inc. 6500 Tracor Lane Austin, Texas 78721	250H	SO_2 H_2S	GC-FPD	0-1.0	0.006 0.006	3.0	0.01	0.805 0.540	4,000	

*In late 1972

oxide and ozone as described in par. 2-6.1(6) (see Fig. 2-25) is capable of measuring nitric oxide and total nitrogen oxides (i.e., nitrogen dioxide reduced catalytically to nitric oxide and total nitrogen oxide, and measured with nitric oxide to give total nitrogen oxides). Nitrogen dioxide is then determined by taking the difference between the two values. This chemiluminescent method will probably replace the Jacobs-Hochheiser method as the reference method for monitoring nitrogen dioxide.

2-6.4 INSTRUMENTATION

With the great number of monitoring instruments commercially available, the selection of a particular instrument for specific applications can be difficult. In order to select the most appropriate analyzer, the user must know the operational characteristics for each instrument. Suggested performance specifications for automatic monitors for sulfur dioxide, carbon monoxide, photochemical oxidants, nitrogen dioxide, and nonmethane hydrocarbons are given in Table 2-19 (Ref. 33). Since all of the specifications may not be required in all monitoring situations, the user must select the ones important to his application. The specifications shown are realistic and can be met by instruments that are currently available.

(1) *Pollutant monitors—gases.* A great number of companies manufacture air pollution measuring instruments. For example, in preparation for an evaluation study of sulfur dioxide instruments, a survey in April of 1967 showed that 16 monitors were commercially available (Ref. 37). Undoubtedly, many more are now on the market. Many of these instruments have not been collaboratively tested and, even if test data were available, modifications and new techniques being introduced continually make it imperative that the very latest performance data be evaluated before purchasing an instrument.

Operational data on many of the sulfur dioxide instruments can be gained from a laboratory and field evaluation conducted by Rhodes, et al. (Refs. 37,38). Twelve sulfur dioxide instruments using coulometry, conductivity, and colorimetry detection methods were evaluated from September 1967 through February 1968. A comparison of the different instruments showed that correlation coefficients ranged from a maximum of 0.96 to a minimum of 0.40. Downtime varied from 0.0 to 30.3 percent of total operating time; total estimated monthly cost of reagents, electrical power, and chart paper ranged from $6.00 to $21.00; and unattended operation performance varied from 1 to 8 days. Also, operational data such as calibration drift, sensitivity, interferences, and operating range vary between instruments as well as between detection principles. With these differences in instrument performance, the importance of studying the results of evaluation tests, when they exist, before selecting an instrument is readily seen.

A more recent field evaluation of ambient air monitoring instruments involved instruments for measuring sulfur dioxide, ozone, oxidants, nitric oxide, nitrogen dioxide, hydrogen sulfide, methane, carbon monoxide, total hydrocarbon, ethylene, and acetylene (Ref. 39). These instruments are identified by manufacturer and detection principle in Table 2-18. For this evaluation program the instruments were placed in a mobile laboratory and operated for a 3-mo period in Los Angeles, followed by a 6-mo period in St. Louis. Approximately 30 instruments were included in the evaluation. Operational type data on some of the instruments tested are given in the table. These data should be representative of what can be achieved by field monitoring instruments insofar as sensitivity, range, and calibration drift are concerned. An indication of the price range for each instrument is included. Calibration data for the test period were used to determine a single linear regression estimate of the calibration curve for each instrument. The correlation coefficient as listed in column 9 of Table 2-18 can be used as an indication of the long-term stability of that instrument. The higher the value, the greater the stability. Instruments having correlation coefficients greater than about 0.990 show very little drift between calibrations while values below about 0.95 show considerable drift.

(2) *Pollutant monitors—particulates.* Commercial equipment for measuring suspended particulate matter is given in Table 2-20. Evaluation data were not available on any of these instruments. The list is not all inclusive and the omission of any manufacturer of this type equipment is not intentional.

2-7 EFFECTS OF ATMOSPHERIC POLLUTANTS ON MATERIALS

A majority of the data on the effects of air pollutants on materials has been derived from outside exposure studies. For example, most data on metals show the rate of corrosion associated with the general types of atmospheres such as marine, rural, and industrial. In most cases time-varying mixtures of several pollutants were present, making it difficult to ascertain the effects

TABLE 2-19. SUGGESTED PERFORMANCE SPECIFICATIONS FOR AUTOMATIC MONITORS

Specification	Pollutants				
	Sulfur dioxide	Carbon monoxide	Photochemical oxidant*	Nitrogen dioxide	Hydrocarbons (CH_4)
Range	0-2620 μg/m^3 (0-1 ppm)	0-58 mg/m^3 (0-50 ppm)	0-880 μg/m^3 (0-0.5 ppm)	0-1880 μg/m^3 (0-1 ppm)	0-16 mg/m^3 (0-25 ppm)
Minimum detectable sensitivity	26 μg/m^3 (0.01 ppm)	0.6 mg/m^3 (0.5 ppm)	18 μg/m^3 (0.01 ppm)	188 μg/m^3 (0.1 ppm)	0.16 mg/m3 (0.25 ppm)
Rise time, 90%	5 min	5 min	5 min	5 min	5 min
Fall time, 90%	5 min	5 min	5 min	5 min	5 min
Zero drift	± 1%per day and ± 2%per 3 days	± 1%per day and ± 2%per 3 days	± 1%per day and ± 2%per 3 days	± 1%per day and ± 2%per 3 days	± 1%per day and ± 2%per 3 days
Span drift	± 1%per day and ± 2%per 3 days	± 1%per day and ± 2%per 3 days	± 1%per day and ± 2%per 3 days	± 1%per day and ± 2%per 3 days	± 1%per day and ± 2%per 3 days
Precision	± 2%	± 4%	± 4%	± 4%	± 4%
Operation period	3 days	3 days	3 days	3 days	3 days
Noise	± 0.5% (full scale)	± 0.5% (full scale)	± 0.5% (full scale)	± 0.5% (full scale)	± 0.5% (full scale)
Interference equivalent	26 μg/m^3 (0.01 ppm)	1.1 mg/m^3 (1 ppm)	20 μg/m^3 (0.01 ppm)	19 μg/m^3 (0.01 ppm)	0.32 mg/m^3 (0.5 ppm)
Operating temperature fluctuation	± 5 deg C	± 5 deg C	± 5 deg C	± 5 deg C	± 5 deg C
Linearity	2% (full scale)	2% (full scale)	2% (full scale)	2% (full scale)	2% (full scale)

*Corrected for NO_2 & SO_2

TABLE 2-19 (Continued). SUGGESTED PERFORMANCE SPECIFICATIONS FOR AUTOMATIC MONITORS

<u>Specification definitions</u>

Range: The minimum and maximum measurement limits.

Miminum detectable sensitivity: The smallest amount of input concentration which can be detected as concentration approaches zero.

Rise time 90 percent: The interval between initial response time and time to 90 percent response after a step increase in inlet concentration.

Fall time 90 percent: The interval between initial response time and time to 90 percent response after a step decrease in inlet concentration.

Zero drift: The change in instrument output over a stated period of unadjusted continuous operation, when the input concentration is zero.

Span drift: The change in instrument output over a stated period of unadjusted continuous operation, when the input concentration is a stated upscale value.

Precision: The degree of agreement between repeated measurements of the same concentration (which shall be the midpoint of the stated range) expressed as the average deviation of the single results from the mean.

Operation period: The period of time over which the instrument can be expected to be operated unattended within specifications.

Noise: Spontaneous deviation from a mean output not caused by input concentration changes.

Interference equivalent: The portion of indicated concentration due to the total of the interferences commonly found in ambient air.

Operating temperature fluctuations: The temperature range over which stated specifications will be met.

Linearity: The maximum deviation between an actual instrument reading and the reading predicted by a straight line drawn between upper and lower calibration points.

TABLE 2-20. COMMERCIAL EQUIPMENT FOR MEASURING SUSPENDED PARTICULATES

Manufacturer and address	Pollutant measured	Measurement principle	Approx. Cost $*	Remarks
Gelman Instrument Co. P.O. Box 1448 Ann Arbor, Mich. 48106	Soiling	Tape sampler	1,000	With reader & recorder
Instrument Development Co. 1916 Newton Square So. Reston, Va 22070	"	Tape sampler	400 -	Without reader & recorder
Research Appliance Co. Route 8 & Craighead Road Allison Park, Pa. 15101	"	Tape sampler	750	With reader & recorder
Gelman Instrument Co. P.O. Box 1448 Ann Arbor, Mich. 48106	Suspended particulates	Filtration	500	With flow recorder
General Metal Works Air Samplinq Equipment Cleves, Ohio 45002	"	"	350	
Research Appliance Co. Route 8 & Craishead Road Allison Park, Pa. 15101	"	"	398	With flow recorder
The Staplex Co. 774 5th Ave. Brooklyn, N.Y. 11232	"	"	150	Without flow recorder

*In late 1972

due to one individual pollutant. Some materials are attacked by more than one pollutant; several pollutants exhibit synergistic effects on materials. For these reasons, effects on materials by atmospheric pollutants will be discussed for a material or class of materials rather than for the individual or class of pollutants. Further information on effects is found in Chaps. 11 and 12 of Part Two of this handbook series which deal with salt and ozone, respectively.

Table 2-21 (Ref. 28) summarizes the chemical resistance of materials to air pollutants. Some of the tabulated information is substantiated in the literature and will be discussed later; however, some of the information is only expert opinion. The resistance of the material to a given pollutant is rated as excellent (E), good (G), fair (F), or poor (P). These pollutants are organics, nitrogen oxides, sulfur oxides, particulates, and a separate group consisting of carbon oxides, ammonia, hydrogen chloride, and hydrogen sulfide.

As seen from the table, more materials have poorer resistance to sulfur oxides and particulate pollutants than to all other pollutants combined. Nearly all of the materials have good or excellent chemical resistance to nitrogen oxides. Several materials show poor or fair chemical resistance to organic pollutants. Only five materials show poor chemical resistance to the combined group of carbon oxides, ammonia, hydrogen chloride, and hydrogen sulfide; however, 12 are rated as fair.

2-7.1 MECHANISMS OF DETERIORATION

Yocom and McCaldin proposed the following five mechanisms by which air pollutants damage materials (Ref. 7).

TABLE 2-21. CHEMICAL RESISTANCE OF MATERIALS TO POLLUTANTS*

Material	Pollutant**				
	O	N	S	C	P
Ferrous					
Gray iron	F	E	P	F	P
Malleable iron	G	E	F	F	F
Alloy steel	G	E	P	P	P
Carbon steel	G	E	P	P	F
Stainless steel	E	E	E	F	F
Nonferrous					
Aluminum	G	E	F	G	G
Brass, bronze	E	E	F	P	P
Chromium	E	E	G	G	G
Copper	G	E	P	P	P
Gold	E	E	E	G	G
Magnesium	G	E	F	G	G
Molybdenum	E	E	G	G	G
Lead	G	E	E	G	F
Nickel	E	E	F	F	E
Tin	E	E	P	F	F
Silver	E	E	P	F	F
Zinc	F	E	P	F	P
Stone, clay, glass					
Building stone	G	E	P	G	F
Building brick	G	E	G	G	F
Cement, concrete	G	E	P	G	G
Glass	E	E	E	G	E
Carbon, graphite	E	E	E	E	E
Other materials					
Wood	G	G	F	F	F
Paper	G	E	P	G	F
Leather	G	G	P	G	F
Bituminous materials	G	G	E	G	G
Finishes, coatings					
Paint	G	G	F	P	P
Plastic, rubber					
Synthetic rubber	P	G	G	E	P
Natural rubber	P	G	F	E	P
Polyethylene	G	G	G	E	G
Polystyrene	P	E	E	E	P
Polyvinylchloride	P	G	E	E	P
Phenolics	F	G	E	E	P
Polypropylene	G	G	E	E	F
Urea and melamine	E	G	G	E	P
Polyesters	F	G	G	E	P
Acrylics	P	G	G	E	P
ABS	F	G	P	E	P
Cellulosics	F	G	G	G	P
Epoxies	E	G	E	E	P
Acetate	G	G	F	F	P
Nylons	G	G	P	F	G
Fibers					
Cotton	G	G	P	F	P
Wool	E	G	F	E	F
Rayon	F	G	P	F	P
Acetate	P	G	P	G	P
Acrylics	P	G	E	E	P
Nylons	G	F	P	G	P
Polyester	P	G	G	G	P
Polyolefins	P	F	E	G	P

* E = excellent, G = good, F = fair, P = poor

(1) *Abrasion.* Solid particles of sufficient size that are moving at high velocities can cause destructive abrasion when striking an object. Abrasive damage is also caused by particles lodged between moving surfaces as in a bearing assembly.

(2) *Deposition and removal.* Solid and liquid particles settling on material have a soiling effect and, although there may be no chemical interaction with the material, deterioration results from increased frequency of cleaning.

(3) *Direct chemical attack* Some air pollutants are chemically active and react directly and irreversibly with materials. The tarnishing of silver by hydrogen sulfide and the etching of metals by acid mists are examples.

(4) *Indirect chemical attack* Certain materials absorb pollutants and are damaged when the pollutants undergo chemical changes. For example, sulfur dioxide when absorbed by leather is converted to sulfuric acid that deteriorates the leather.

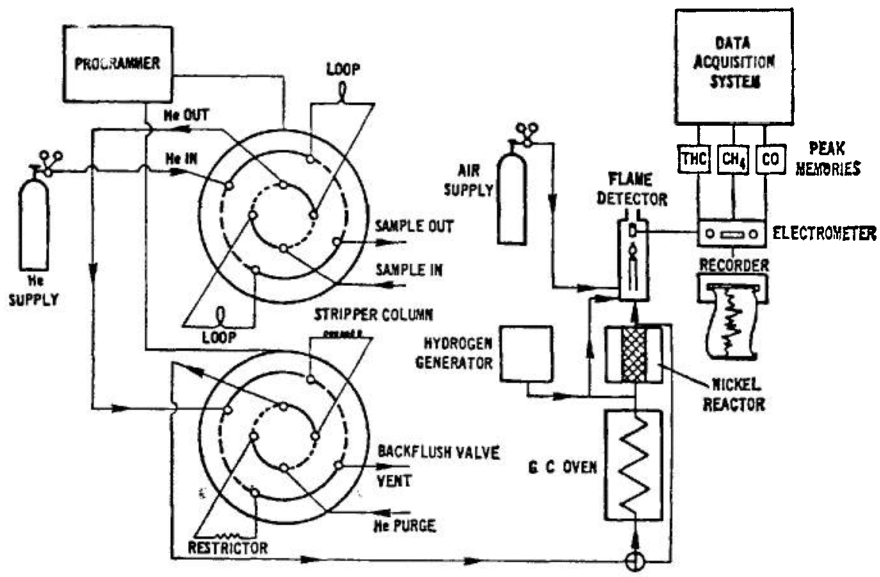


FIGURE 2-32. Typical Flow Diagram of a GC–FID Hydrocarbon Monitor

*(5) **Electrochemical corrosion.*** An electrochemical process is believed responsible for the initial rusting of steel in the atmosphere. The settling of particulate matter on a steel or any ferrous metal surface can create small electrochemical cells. The electrolyte may form from water and natural or pollutant ions scavenged from the atmosphere. An electric current results, i.e., metal goes into solution at the anode and hydrogen is deposited at the cathode, when a difference in potential exists between any two surfaces contacting the electrolyte. Surface potential differences between two metals or two areas of a metal surface can provide the driving potential for the corrosive action.

2-7.2 FACTORS THAT INFLUENCE ATMOSPHERIC DETERIORATION

The severity with which atmospheric pollutants attack materials will in general vary with the locale and the season. The rate of attack is influenced by the relative humidity, the extent of industrial pollution, the quantity and frequency of rainfall, air movement characteristics, the frequency of occurrence and duration of fog, the proximity to the sea, the amount of solar radiation, and temperature ranges.

(1) ***Moisture.*** There would be very little, if any, atmospheric corrosion even in the most severely polluted environments without moisture (Ref. 7). Most metals have a critical relative humidity threshold below which the rate of corrosion is very slow but when exceeded produces a rapid rise in the rate of corrosion. Rain can increase the corrosion rate of some metals while it decreases that of others. By washing the surface of a specimen, rain can remove corrosive pollutants that have collected on the surface, thus reducing the corrosion rate. In other cases it can remove soluble corrosion products that had been protecting the metal against further corrosion. Fogs and dews are, in general, damaging because they have no washing effect on the surface but rather form surface films of moisture which absorb pollutants from the atmosphere.

(2) ***Temperature.*** Temperature influences the rate of those chemical reactions that cause material deterioration. The temperature also determines the rate of drying or the length of time that a surface remains wet. During an atmospheric temperature inversion, exposed objects, especially metals, lose heat rapidly and cool to temperatures below that of the ambient air. **If** their surface temperature falls below the dewpoint, the surface becomes moist and, in the presence of corrosive pollutants whose concentrations are increasing due to the temperature inversion, creates a situation conducive to material damage (Ref. *5).*

*(3) **Solar radiation.*** Sunlight energy is an important element in the nitrogen dioxide photolytic cycle in which damaging agents such as ozone and hydrocarbon free radicals are formed in a series of complex photochemical reactions in the atmosphere (Ref. 11).

(4) ***Air movement.*** Air movement serves to disperse pollutants throughout the atmosphere. Airspeed and atmospheric turbulence determine the residence time of airborne particulate matter, the deposition site, i.e., whether it impacts on vertical surfaces or settles as dustfall on horizontal surfaces, and, for solid particles, the extent of abrasion (Ref. 7). Periods of low wind-speeds are often associated with temperature inversions. In areas such as Los Angeles, high concentrations of atmospheric pollutants build up because of the lack of mixing or turbulent air currents in the inversion layer. Wind direction can be the most important variable, especially if the emissions are from one major source.

2-7.3 METHODS OF MEASURING MATERIAL DETERIORATION

In order to provide quantitative measures of material deterioration resulting from air pollutants, methods have been developed for different classes of materials. These methods, described in the following subparagraphs, are sometimes employed as an approximate measure of the integrated pollutant concentration during the period of exposure.

(1) Metals. Many methods have been used to evaluate the results of corrosion tests. They include appearance ratings, weight losses, weight gains, pit depths, and losses in strength (Ref. 40). Most corrosion data are presented as weight gain or loss. In tests of short duration, a metal sample will gain weight due to the formation of corrosion products. However, weight gains are not completely satisfactory for quantitative purposes because some of the corrosion products may be separated from the specimen. In any case weight gains should be supplemented with an analysis of the corrosion products.

Weight-loss measurements are usually preferred fur test periods of long duration. For this measurement a clean, weighed sample is exposed for a period of time, then cleaned and reweighed. The loss in weight represents the corrosion that has occurred. The usual units are milligrams of weight loss per square decimeter of surface per day or for the period of the test ($mg/dm^2/day$). Some data obtained as weight loss are converted to and reported as loss of metal thickness in mils per year. Bending, tension, fatigue, impact, and electrical resistance measurements are also used in special purpose tests. For example, the electrical resistance across a set of points is used as a measure of the damage caused by air pollutants to electrical contact materials (Ref. 41).

(2) ***Fabrics.*** The primary means of sample evaluation for textiles is to measure the loss in tensile strength. This may be reported as percent breaking strength retained (Ref. 42). Also, for undyed samples the degree of soiling can be determined by reflectance measurements. For materials such as knits, a test of tensile strength of a sample does not subject fibers to straight-line tension; therefore, damage is usually measured visually. In a study conducted to determine the damage to nylon hose by sulfur dioxide and sulfur trioxide, the exposed stockings were stretched over inverted jars and microscopically examined for fiber breaks (Ref. 7).

(3) Dyes. Some dyed fabrics display a pronounced color change when exposed to polluted environments containing above-average concentrations of ozone, nitrogen oxides, or both. The color change is evaluated by means of specially designed colorimeters that detect small changes of color within narrow ranges of the visible spectrum.

(4) ***Building materials.*** It is generally agreed that sulfur dioxide does attack building stone but no carefully planned exposure tests comparable to those for metals have been conducted (Ref. 28). The usual method of evaluating damage to stone and mortar by atmospheric pollutants is to visually note the discoloration and loss of material due to leaching over a period of years. Also, the settling of particulate matter such as soot on the walls of buildings can be evaluated visually by comparing photographs of a building before and after cleaning.

(5) Other *materials.* The measurement of damage to lead-based paint from hydrogen sulfide is usually accomplished by observing the color change or darkening of the paint. Quantitative data are usually derived from exposure chamber tests using simulated polluted atmospheres because hydrogen sulfide tends to produce a mottled effect in actual outdoor exposures making it difficult to evaluate the color change of the paint (Ref. 7). The weakening of leather and embrittlement of paper caused by sulfur dioxide have been observed but have not been quantitatively measured.

2-7.4 MATERIALS DAMAGE

2-7.4.1 Ferrous Metals

The electrochemical theory of corrosion is used to explain the initiation of atmospheric corrosion on ferrous surfaces (Ref. 43). However, once the first rust has formed, the mechanisms and rates of further corrosion become very complex. For example, when iron remains dry for an appreciable time, a protective oxide film is formed which greatly reduces the rate of corrosion. Controlled laboratory tests have shown that the air-developed film protects iron from corrosion in clean air at relative humidities as high as 99 percent. If, however, the film is exposed to 0.01 percent or more of sulfur dioxide at this high relative humidity, corrosion occurs. Also, once the oxide film has been exposed to sulfur dioxide, it no longer protects the surface against corrosion in clean air at relative humidities of 80 percent and above.

A few seconds exposure to air is all that is needed for a 'stainless' chromium steel to develop an invisible oxide film on its surface which renders it inert to most atmospheric pollutants. Parts made of stainless steel located on the Empire State Building have been exposed for 30 yr with no loss of utility or beauty due to corrosion (Ref. 28).

Low carbon (0.019 percent) low copper (0.028 percent) mild steel, because of its sensitivity to atmospheric corrosion, has been used in atmospheric corrosion studies (Ref. **44**). Results from the tests show good correlation between corrosion losses and sulfur dioxide concentrations, and little if any correlation between corrosion losses and dustfall or suspended particulate matter. Fig. 2-33 shows corrosion loss as a function of sulfur dioxide concentrations. A regression analysis of these data yields the relationship:

$$Y = 54.1\ S + 9.5 \qquad (2\text{-}21)$$

where

Y = corrosion weight loss, grams per hundred grams of panel (4 X 6 X 0.035 in.)

S = mean sulfur dioxide concentration, ppm

The regression coefficient was statistically significant at the 1-percent level. Suspended particulate matter measurements were made and analyzed for their contribution to the corrosion loss. Statistical analyses showed that the influence of sulfur dioxide was significant whereas that of suspended particulate matter was not. Dustfall measurements did not show a statistically significant correlation with corrosion rates.

Results from other laboratory and field studies indicate that particulate matter can be an important factor in the corrosion of metals, especially in the presence of sulfur dioxide.

The critical relative humidity for corrosion of ferrous metals is between 70 and 80 percent. The corrosion rate

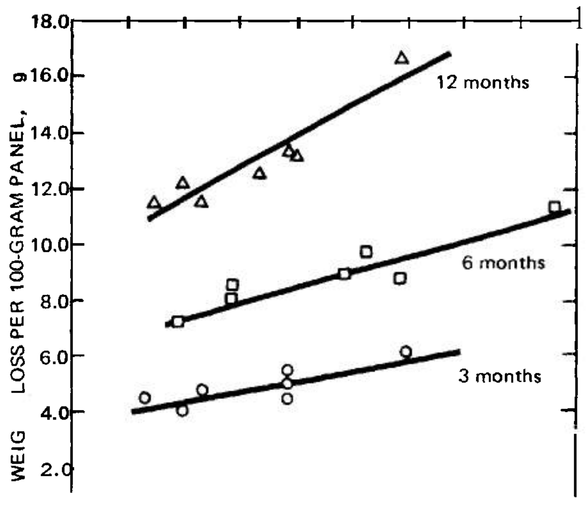


FIGURE 2-33. Relationship Between Corrosion of Mild Steel and Corresponding Mean Sulfur Dioxide Concentration for Varying Length Exposure Periods

is relatively slow for humidities lower than 70 percent but accelerates markedly for values above approximately 80 percent. Laboratory studies using bare and varnished steel panels that were treated with a combination of various powdered oxides, salts, and dusts and then exposed to atmospheres of pure clean air and air containing sulfur dioxide (very low concentration but not specified) at various humidities produced the following results (Ref. 13):

(1) Filiform corrosion, characterized by a filamental configuration, the primary phase in electrolytic corrosion, was noted in all cases.

(2) For relative humidities less than about 70 percent, corrosion rates are low but increase at higher humidities.

(3) The addition of traces of sulfur dioxide to the test atmospheres greatly increased the rate of corrosion in all instances.

(4) In most cases corrosion increased with an increase in relative humidity even in clean air.

Analysis of exposure data for carbon steel shows that increasing the level of oxidants actually retards the rate of corrosion (Ref. **45**). Fig. 2-34 shows the relationship between corrosion rate, sulfur dioxide concentration, and oxidant concentration. The ability of oxidants to decrease the corrosion rate can be caused (1) by inhibiting the mechanism or (2) by improving the protective-

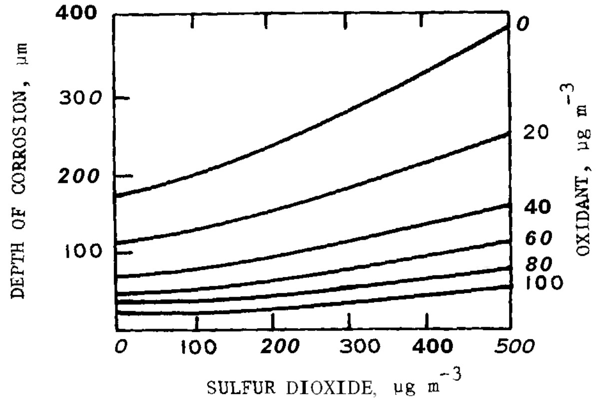


FIGURE 2-34. Effects of Sulfur Dioxide and Oxidant Concentrations of Depth of Corrosion of Carbon Steel Exposed for 10 yr

ness of the rust film. The corrosion rate is proportional to the sulfate accumulation in the oxide film. Such accumulation occurs when the iron oxides react with sulfur dioxide to form sulfates. If oxidants remove the sulfur dioxide from the reaction by oxidizing it to sulfur trioxide, then the rate of corrosion should decrease, thus explaining the data. Also, the protectiveness of the oxide film is increased by oxidizing ferrous oxide and magnetite to the more protective ferric oxide.

2-7.4.2 Nonferrous Metals

The nonferrous metals, as with the ferrous metals, are affected primarily by the presence of sulfur dioxide. The reactions involved in the effects are dependent on the specific metals as is the degree of damage. The more common of these metals are discussed in the following subparagraphs:

(1) *Zinc.* Zinc is used in galvanizing to protect ferrous metals from atmospheric corrosion but is itself subject to corrosion under certain conditions. The two variables most important in determining the amount of corrosion are relative humidity and atmospheric sulfur dioxide concentration.

Special high-grade commercial zinc (99.9 percent pure) panels were exposed at eight rural and eight urban sites for periods of 4, 8, 16, 32, and 64 mo (Ref. 46). Weight-loss data, measured as grams per panel, were converted to corrosion rates in micrometers per year. Sulfur dioxide concentrations and relative humidity were monitored for the duration of the test. The relationship among rate of corrosion, relative humidity, and sulfur dioxide concentration as determined from the study is given by

$$y = 0.001028(RH - 48.8)SO_2, \quad \mu m\ yr^{-1} \tag{2-22}$$

where

y = zinc corrosion rate, $\mu m\ yr^{-1}$
RH = average relative humidity, %
SO_2 = average SO_2 concentration, $\mu g\ m^{-3}$

These results are graphically presented in Fig. 2-35. **Eq.** 2-22 accounts for 92 percent of the variability in the average zinc corrosion rates. The critical relative humidity for zinc in sulfur dioxide free air is approximately **70** percent; however, as **Eq.** 2-22 indicates, in the presence of sulfur dioxide, the surface will be wet and corrosion will occur at relative humidities down to approximately 49 percent. The results of the study were used to predict the useful life of galvanized products in different types of environments (see Table 2-22).

Nickel-brass wire springs used in telephone relays have been damaged by high nitrate concentrations in airborne dust (Ref. 8). Nickel-brass wires, under moderate stress and with a positive electrical potential, suffer a form of stress-corrosion cracking when surface nitrate concentrations are above 2.4 $\mu g\ cm^{-2}$ and when the relative humidity is above 50 percent. The relative humidity is an important controlling factor. When zinc is left out of the nickel-brass alloy, stress corrosion no longer occurs.

(2) ***Copper and silver.*** Copper and copper alloys—in the absence of hydrogen sulfide and sulfur dioxide--

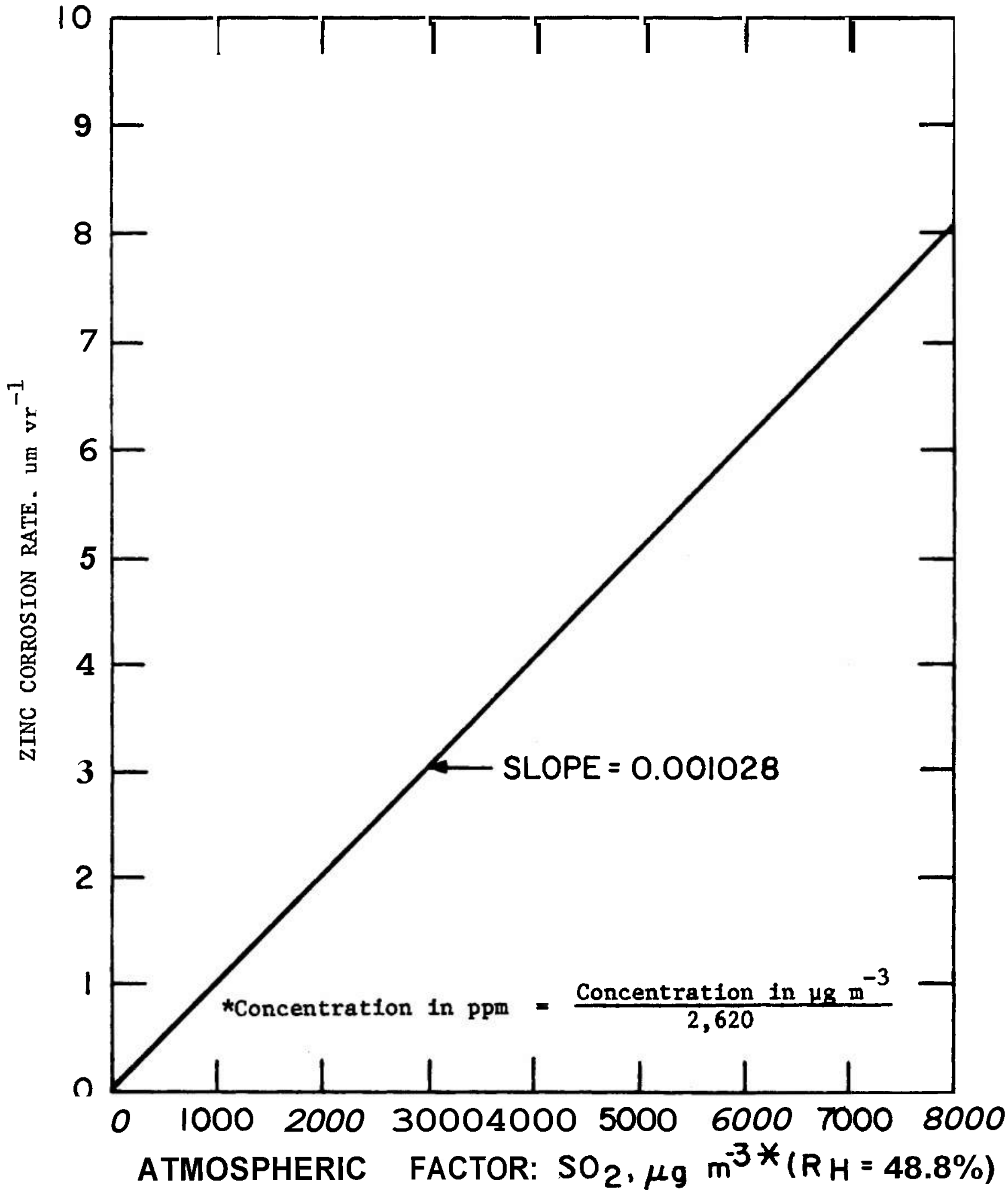


FIGURE 235. Effect of Sulfur Dioxide and Relative Humidity on Corrosion Rate of Zinc

TABLE 2-22. PREDICTED USEFUL LIFE OF GALVANIZED SHEET STEEL WITH 53-μm COATING AT AVERAGE RELATIVE HUMIDITY OF 65 PERCENT

SO_2 concentration, μg/m^3	Type of environment	Useful life, years		
		Predicted best estimate*	Predicted range*	Observed range**
13	Rural	244	41-	30-35
130	Urban	24	16-49	-
260	Semiindustrial	12	10-16	15-20
520	Industrial	6	5.5-7	-
1,040	Heavy industrial	3	2.9-3.3	3-5

*From Eq. 2-22.
**SO_2 concentrations and relative humidity were not observed.

develop a thin, stable surface film that inhibits further corrosion. The critical relative humidity in the presence of sulfur dioxide is about 63 percent. At low relative humidities sulfur dioxide has very little if any influence on the oxidation of copper; however, at high humidities (above *63* percent) the corrosion rate increases rapidly. Fig. 2-36 (Ref. **47**) shows the effects of humidity and sulfur dioxide concentration on the corrosion of copper. The minimum, occurring at a 1-percent concentration of sulfur dioxide, is a result of the change in composition of the corrosion product film as the sulfur dioxide concentration varies about this value. Below 1 percent, the film is the basic sulfate; at 1 percent, it is normal copper sulfate; and above 1 percent, it is the acid salt. The atmospheric concentration of sulfur dioxide is much less than 1 percent.

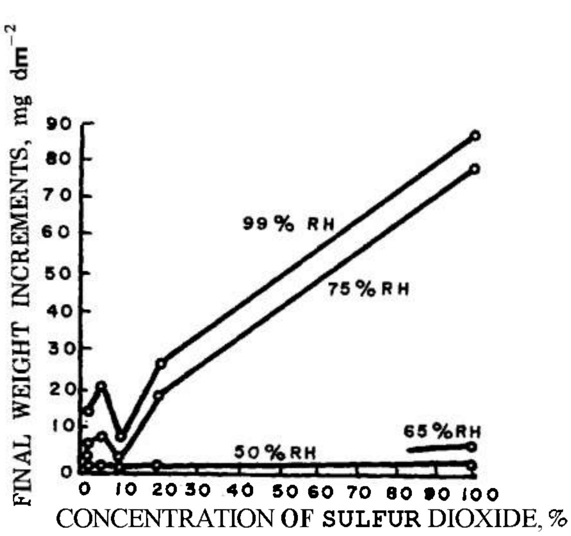


FIGURE 2-36. Relation Between Corrosion Rate of Copper and Concentration of Sulfur Dioxide in Atmospheres of High Relative Humidity

Both copper and silver tarnish rapidly in the presence of hydrogen sulfide. Copper that has developed a surface film in clean air shows a high resistance to hydrogen sulfide. Both moisture and oxygen must be present for hydrogen sulfide to tarnish silver. The formation of a sulfide coating on copper and silver electrical contacts greatly increases their contact resistance and reduces the useful lifetime of the contacts (Ref. 41).

(3) ***Aluminum.*** Aluminum is resistant to concentrations of sulfur oxides normally found in polluted atmospheres. An oxide film normally present on the surface provides excellent protection against atmospheric attack. When in contact with normal humid atmospheres, the film slowly thickens providing even more protection. However, sulfur dioxide or sulfur trioxide gases can break down the film and attack the metal. Figs. **2-37** and **2-38** (Ref. **47**) show the weight gain of two samples of aluminum for 52, **72,** and **85** percent relative humidities and a sulfur dioxide concentration of **280** ppm. One sample was super purity (SP) aluminum, the other was **alloy 3003** aluminum. Although the concentration of sulfur dioxide is much higher than that found in the most polluted environments, the results still

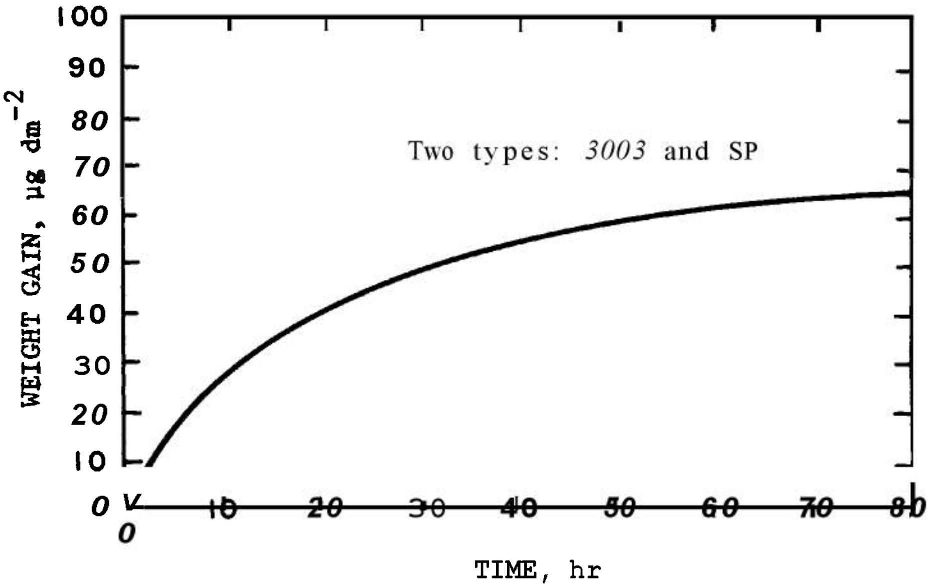


FIGURE 2-37. Atmospheric Corrosion of Aluminum at a Relative Humidity of 52 Percent and Sulfur Dioxide Concentration of 280 ppm

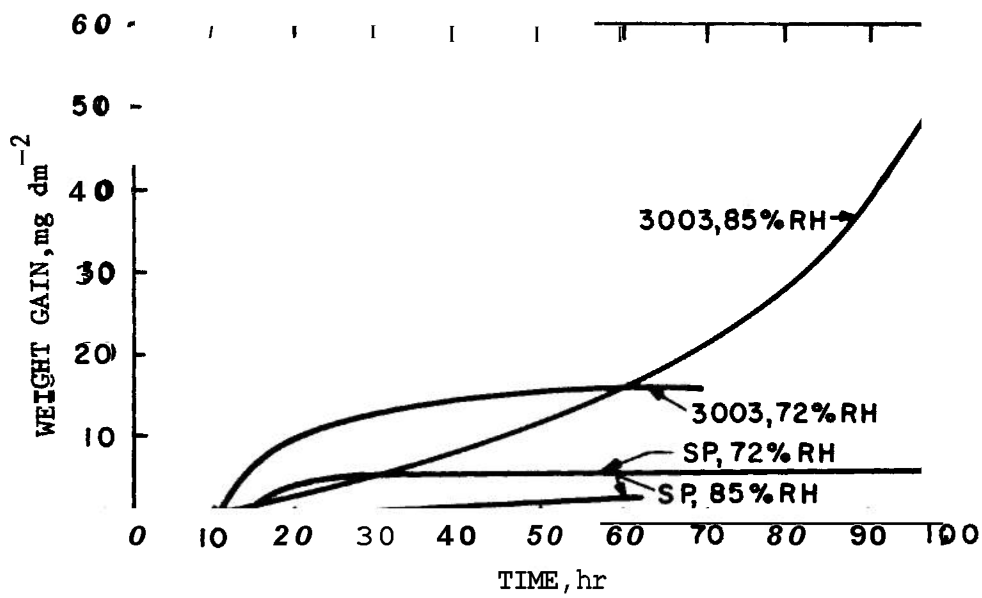


FIGURE 2-38. Atmospheric Corrosion of Super Purity and 3003 Aluminum at Relative Humidities of 72 and 85 Percent and Sulfur Dioxide Concentration of 280 ppm

help explain the mechanism of atmospheric corrosion of aluminum by sulfur dioxide. In Fig. 2-37 both types of aluminum show the same rate of corrosion at 52 percent relative humidity. This curve is very nearly the same as that for the oxidation of aluminum without sulfur dioxide, indicating that even high concentrations of sulfur dioxide do not appreciably attack aluminum at low relative humidities. Fig. 2-38 shows that at the higher relative humidities at which these data were obtained, the rate of corrosion is greater initially but approaches zero after about 60 hr except for 3003 alloy at 85 percent (note the change from μm to mg on the ordinate scales when comparing Fig. 2-38 to Fig. 2-37). At 85 percent relative humidity the rate of corrosion for the 3003 alloy continues to increase even after 100 hr. At the higher humidities (72 and 85 percent), analysis of the white powdery deposit formed on the surface showed it to be $Al_2(SO_4)_3 \cdot 18\ H_2O$, which indicates that sulfur dioxide plays an essential role in the corrosion of aluminum at high humidities.

(4) Nickel. The characteristic fogging of a nickel surface produced by exposure to polluted atmospheres is due to the simultaneous presence of sulfur dioxide and water vapor (Ref. 47). The critical relative humidity is about 70 percent below which the nickel surface will remain bright indefinitely. At humidities greater than 70 percent, the catalytic oxidation of atmospheric sulfur dioxide to sulfur trioxide by the nickel surface forms a dilute solution of sulfuric acid on the surface. In the beginning stages of attack, the surface film can be removed by wiping. As corrosion progresses, the basic sulfate is precipitated and the film becomes adherent giving the surface an etched appearance. After exposing a specimen to an industrial atmosphere for 88 days, the surface film was shown to have the formula $NiSO_4 \cdot 0.33\ Ni(OH)_2$ upon analysis.

Nickel panels exposed to rain do not corrode as rapidly as those that are sheltered. This is attributed to the fact that rain washes the acidic solutions from the surface, keeping it comparatively uncontaminated and free from attack. It has also been shown that preexposure of the sample to an atmosphere containing hydrogen sulfide will suppress corrosion. This effect is believed to be due to a poisoning of the catalytic activity of the surface and not to the formation of a protective surface oxide film as has been the case for other metals such as copper.

Nickel parts of telephone crossbar switches corrode and form a bright-greenish corrosion product. This migrates to the region of the switch contacts causing open circuits. The corrosion is promoted by the presence of anions, principally nitrates, in accumulated dust.

(5) Magnesium. The critical relative humidity for magnesium is about 90 percent. For relative humidities above this value, magnesium hydroxide, believed to be the primary corrosion product, is formed. The magnesium hydroxide absorbs carbon dioxide from the atmosphere to form magnesium carbonate ($MgCO_3$) and this in turn reacts slowly with sulfur dioxide to form magnesium sulfate ($MgSO_4$) (Ref. 47).

2-7.4.3 Building Materials

Building materials are affected by atmospheric pollutants in a variety of ways. Perhaps the most familiar effect is the soiling of buildings by particulate matter. Tarry or carbonaceous materials resulting from inefficient combustion of soot-producing fuel are likely to be acidic as well as sticky. If these are not removed by rain or special washings, they adhere to surfaces and can result in a physical-chemical degradation of the material in addition to their soiling effects.

Limestone ($CaCO_3$) in the presence of moisture reacts with sulfur dioxide and sulfur trioxide to form calcium sulfate ($CaSO_4$) and gypsum ($CaSO_4 \cdot 2H_2O$), both of which are partially soluble in water. Also, carbon dioxide in the presence of moisture produces carbonic acid that then converts limestone into a water-soluble bicarbonate that is then leached away.

2-7.4.4 Textiles

A variety of natural and synthetic textile fibers are susceptible to damage by sulfur dioxide. Particulate matter acts as a soiling agent with deterioration occurring mainly due to increased frequency of cleaning.

Outside exposure studies of cotton fabrics have shown a direct correlation between air pollution and the accelerated degradation of the fabric (Ref. 42). The primary means of sample evaluation used in these studies was to measure the breaking strength retention. Also, the degree of soiling on undyed samples was determined by reflectance measurements. Results of the study showed a strong relationship between retained breaking strength and mean sulfation rate as shown in Fig. 2-39. A similar relationship was observed between retained breaking strength and mean sulfur dioxide concentration as shown in Fig. 2-40. Dustfall and suspended particulate measurements also correlated with fabric degradation and soiling but not as well as sulfation rate and sulfur dioxide concentration. In heavily contaminated sites, the degradation rate was four to five times that of the least polluted sites as shown by Figs. 2-39 and 2-40.

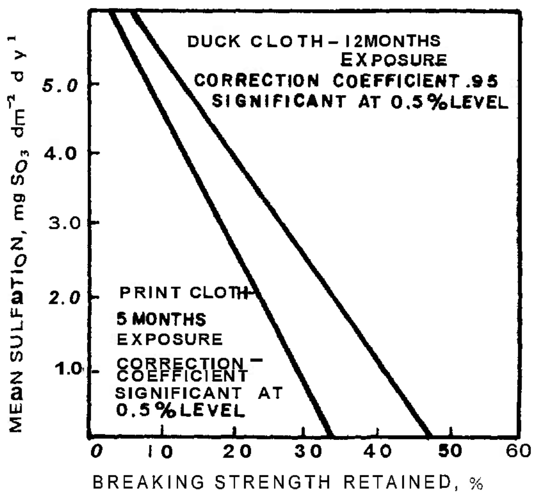


FIGURE 2-39. ***Effect of Sulfation on Breaking Strength of Cotton Fabrics***

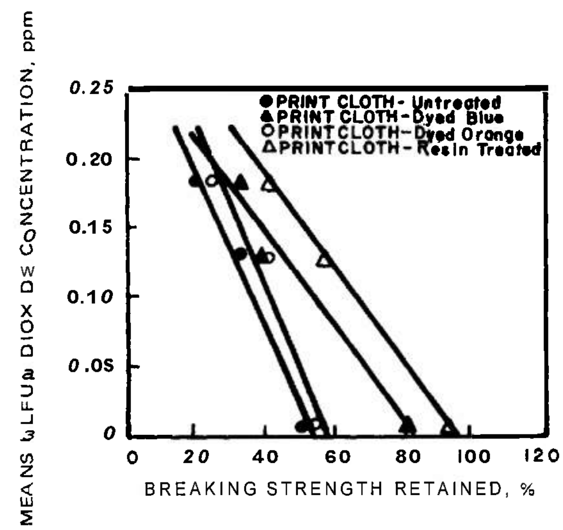


FIGURE 2-40. ***Effect of Atmospheric Sulfur Dioxide Concentration on Breaking Strength of Cotton Cloth (5-mo exposure)***

2-7.4.5 Paints

Painted surfaces are affected by such atmospheric pollutants as sulfur dioxide, hydrogen sulfide, and particulate matter.

Newly applied paints exposed to sulfur dioxide concentrations of 1 to 2 ppm experience drying times from 50 to 100 percent longer than normal. The results are either a softer or a more brittle finish than that achieved in the absence of sulfur dioxide. Sulfur dioxide, in the presence of moisture and ammonia, can form small crystals of ammonium sulfate on paint and varnish surfaces. The crystals become noticeable on the surface as a spreading blemish or bloom. Sulfur oxides have little effect on dry, hard paint films.

Paints containing lead compounds are rapidly darkened when exposed to even low concentrations (as little as 0.05 ppm) of hydrogen sulfide by the formation of black lead sulfide. The degree of discoloration is a function of the amount of lead in the paint, concentration of hydrogen sulfide in the air, duration of exposure, and moisture available at time of exposure. It has been observed, however, that the black lead sulfide is oxidized to lead sulfate turning the paint film white again in the absence of hydrogen sulfide (Ref. 7).

Settled dust particles can seriously impair the anticorrosive properties of freshly applied varnish and paint films. The particles can act as wicks providing a means for corrosive pollutants to reach the underlying metal surfaces.

2-7.4.6 Leather

Leather has a strong affinity for sulfur dioxide, which causes it to lose much of its strength and ultimately to disintegrate (Ref. 13). Leather originally free of sulfuric acid was found to accumulate as much as 7 percent acid by weight when exposed to a sulfur dioxide polluted atmosphere (Ref. 7). One reaction that has been suggested is that minute quantities 'of iron in the leather serve as catalysts to oxidize sulfur dioxide to its acid form.

2-7.4.7 Paper

Paper absorbs sulfur dioxide that is oxidized to sulfuric acid with the small amounts of metallic impurities serving to accelerate the conversion. Exposures to sulfur dioxide (2 to 9 ppm) for 10 days resulted in embrittlement and a decrease in the folding resistance of both book and writing paper. The sulfuric acid content of some papers has been observed to be as high as 1 percent, making the paper extremely brittle (Ref. 7).

In general, cellulosic vegetable fibers—such as linen, hemp, cotton, rayon, jute, and synthetic nylons—are particularly sensitive to attack by sulfur oxides. Sulfuric acid reacts with cellulose fibers producing a water-soluble product with a greatly reduced tensile strength (Ref. 13).

Field studies have shown that absorbed nitrogen oxides reduce the breaking-strength of combed cotton yarn samples. Samples were exposed to filtered air while others were exposed to unfiltered air for a period of 56 days; those exposed to unfiltered air suffered a 10 percent greater loss in breaking strength than the unexposed.

2-7.4.8 Dyes

An exposure study involving 69 dye-fabric combinations indicated a high susceptibility of nearly one-fourth of the combinations to fading when exposed to urban environments (Ref. 48). Fading is much greater at urban sites than at corresponding rural control sites for these dye-fabric combinations showing a high degree of fading. Controlled exposures to irradiated or nonirradiated automobile exhaust show that photochemically produced components of the atmosphere cause the fading. Also, the study revealed synergistic effects of pollutants in combination. The addition of sulfur dioxide to the irradiated automobile exhaust emissions produced more than an additive effect on the fabrics, when compared to the effects of sulfur dioxide in clean air or in irradiated auto exhaust without added sulfur dioxide.

Certain dyed cellulosic fabrics show fading when exposed to nitrogen oxides at relative humidities greater than about 50 percent. Fading occurs in certain blue and green shades, representing dyes from four major classes—direct, sulfur, vat, and reactives dyes—when exposed to different field environments in the absence of light (Ref. 8).

2-7.4.9 Glass and Ceramics

Glass and ceramics show very good resistance to atmospheric pollutants. One major item of interest, however, is the effect of atmospheric pollutants on electrical insulators. Although air pollutants do not in themselves damage the insulator, particulate matter deposited on the surface of insulators used on high-voltage power lines will, in the presence of moisture,, form conducting paths resulting in leakage currents, flashover, or puncture of the insulator. For a more detailed discussion of these effects see Chap. 3, par. 3-5.4, "Electrical Contacts and Connectors", and especially Fig. 3-23 that compares 60-Hz flashover voltages for clean and dry, clean and wet, and dirty and wet insulators.

It is well known that hydrogen fluoride (HF) will etch glass. The concentrations required to produce visible damage to glass and other materials are believed to be far in excess of those required to kill many types of vegetation. Therefore, the probability of military equipment being exposed to high levels of hydrogen fluoride is very low.

2-7.5 ELECTRONIC SYSTEMS AND COMPONENT DAMAGE

A survey of manufacturers of electronic components indicated that airborne particulates are considered responsible for most of the damage to components rather than sulfur dioxide as had been previously indicated (Ref. 49). Particulates cause damage to electronic components in five different ways, i.e.,

(1) Interference with the important photoengraving techniques used in fabrication of many components

(2) Spot formation on the screens of TV and cathode ray tubes

(3) Contamination of vacuums by releasing absorbed gases

(4) Creation of microscopic surface leakage paths in semiconductors and integrated circuits

(5) Creation of gross current leakage paths in all electronic equipment.

The effects of air pollutants on computers are summarized as follows: "silver contacts in relays build up a high resistance surface, copper wiring connectors become unreliable, gasket seals deteriorate, protective finishes become tacky or erode away, bearing life is shortened, reaction products plug small orifices and interfere with precision adjustments, and in general adversely affect the operating life of a computer" (Ref. 50).

2-7.6 CASE HISTORIES[9]

Very few case histories of air pollutant damage have been assembled because of the difficulty in confirming damage caused by air pollutants. For example, how much paint degradation can be attributed to pollutants as compared to the natural environmental factors? What causes an electrical switch to fail? Among the damage incidents that have been traced to air pollutants as the prime causative factor are the following:

(1) *Navigation aids facility—FAA.* A very high frequency omnidirectional ranging (VOR) station operated by the Federal Aviation Administration (FAA) near Charleston, W. Va., started experiencing problems about one year after the equipment was installed. The major problem was sulfiding of silver-plated contacts resulting in arcing and pitting to the extent that replacements were required.

9. A general reference for this paragraph is Ref. 49.

The two main sources of pollutants in the area were chemical plants emitting a variety of substances, including gaseous sulfur compounds, and a nearby municipal burning dump producing all the pollutants associated with combustion.

The solution arrived at by the FAA was to install an air-conditioning system with activated-charcoal filters.

(2) *Telephone switching equipment—N.Y. Bell Telephone Company.* A New York Bell Telephone Company's switching center, containing complex computer-controlled electronic switching networks and located close to a power generating station, experienced erratic computer behavior. Evaluation of the situation by IBM engineers showed that outside particulate contamination was the cause.

The installation of a high-efficiency air filter eliminated the computer malfunctions and decreased maintenance for other switching equipment.

(3) *Others.* Many case histories of electronic components and systems that are affected by air pollutants have been tabulated. They include examples of photochemical oxidants reacting to form an insoluble scum or film on silicon wafers during processing, inoperative electronic equipment such as FM tuners that only needed cleaning to restore normal operation, and increased rejection rates experienced by a manufacturer of sensitive components when a freeway ramp was constructed approximately 400 ft from the manufacturing building.

2-8 PROTECTION AGAINST ATMOSPHERIC POLLUTANTS

Specific design steps for protection against the effects of pollutants are not common since protection is normally obtained by methods employed for protection against other environmental factors. A preferred method, which is receiving much attention, is to avoid such effects by reducing pollution levels or by avoiding regions with high pollution levels. On a local level, electronic facilities can be isolated from areas in which large amounts of engine exhausts or combustion products are produced. In specific instances, the information in the following subparagraphs may be useful:

(1) *Metal components and structures.* Metals exhibit varying degrees of susceptibility to atmospheric pollutants. Therefore, the proper choice of metal or alloy is important for equipment components that will be exposed to polluted atmospheres.

Aluminum and stainless steels develop thin continuous oxide films that provide protection to the underlying metal in all but the most severely polluted areas. Copper develops a corrosion product film that retards further attack. However, ordinary carbon steels require some form of protection when exposed to atmospheric conditions. Protective methods available include coating with a highly resistant metal such as zinc or aluminum, an epoxy or vinyl paint coating, and electroplating with a chrome-nickel-copper combination. The most common methods of protection for exposed structures are galvanizing and painting or a combination of both (Ref. 51).

Since most of these preventive measures apply to systems that are likely to be exposed to marine and high humidity environments as well as polluted environments, it seems reasonable to assume that any equipment designed to operate outdoors (e.g., vehicles, weapon systems, etc.) will be operated in at least one of these highly corrosive environments during its life cycle.

(2) *Electronic systems.* Complex precision electronic systems, such as computers and switching networks, have been affected by high concentrations of particulate matter and sulfur dioxide. The solution to date has been to install air filtering and conditioning systems in the building in which the equipment is located. This does not mean that the equipment itself could not have been designed or redesigned to preclude the effects of air pollutants. For example, the equipment could be housed in an airtight container with a built-in cooling system if necessary. Such an approach may be necessary for electronic systems operating under conditions that make it unfeasible to install air conditioning in a building. This could include equipment operating in combat areas or any mobile or semimobile electronic equipment. Design changes of this type also improve the equipment ability to operate in sand and dust, marine, and high humidity environments.

(3) *Electronic devices.* Semiconductor devices, integrated circuits, relays, switches, etc. have proved to be susceptible to air pollutants, starting with the fabrication stage and extending throughout their useful life. In some highly industrialized areas with high concentrations of air pollutants, it has been necessary to fabricate semiconductor devices and integrated circuits in "clean rooms". Once fabricated they are encapsulated (her-

metically sealed) either in a metal can or some type of ceramic compound that precludes any future damage from air pollutants.

Electrical contacts, such as those on relays and switches, are susceptible to particulate matter, hydrogen sulfide, and sulfur dioxide. These components should be hermetically sealed when possible to prevent damage from air pollutants. Damage to electrical contacts during the fabrication stage does not appear to be a serious problem. In applications in which hermetic sealing is not practical, the contact points are plated with a noble metal, such as gold, that has a high resistance to damage from air contaminants.

2-9 TEST FACILITY REQUIREMENTS

Most material testing has been in the form of outside exposure tests to determine the effects of a particular type of environment on a specific piece of material. The minimum exposure time required in order to acquire valid quantitative data can range from months to years except in special cases where a susceptible material is being tested in a highly polluted atmosphere. Accelerated tests have been studied but none are considered adequate for predicting long-term effects due to a particular environment (Ref. 40).

For meaningful quantitative testing of military equipment, a test chamber in which different environmental conditions can be simulated is required. One such chamber used by IBM to test the effects of air pollution on computers is described by Steading (Ref. 50). In this case one chamber measuring 8 by 8 by 8 ft is used for exposing the test item to various concentrations and mixtures of particulate matter and another chamber is used for dynamic single gaseous testing. Although it would be expensive and possibly difficult to achieve, a test chamber is desired in which an item could be exposed simultaneously to a variety of pollutants, both particulate and gaseous, because pollutants act synergistically in their effect on materials. An example is the combined effect of particulate matter and sulfur dioxide on the corrosion of steel.

Due to the high cost and technical problems involved in building and maintaining a multipollutant test chamber large enough to accommodate large pieces of equipment such as gun systems or vehicles and, since the probability that this type of equipment would be used in highly polluted areas for long periods of time is small, it appears that some form of component testing is the most practical approach. For example, samples of the metals, metal alloys, paints, metal-paint combinations, and relatively small subsystems of different systems can be tested in small environmental chambers from which an estimate of the system overall resistance to air pollutants can be made.

Pollutants that should be included in a test program are (1) different compositions of particulate matter, and (2) sulfur dioxide, nitrogen dioxide, and ozone. The test system must be so designed that pollutant combinations and concentrations, relative humidity, and temperature are controllable and variable over ranges sufficient to allow simulation of environmental conditions likely to be encountered by military equipment.

There are, at present, no standard tests or requirements relating to atmospheric pollutant effects on materiel. Susceptibility to many of the pollutant effects is adequately indicated by the salt spray testing as described in Chap. 11 of Part Two, ***Natural Environmental Factors.***

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CHAPTER 3

SAND AND DUST[1]

3-1 INTRODUCTION

Airbome sand and dust may be the single most damaging environmental factor for military equipment (Ref. 1). A dust-laden atmosphere can present serious problems to the operation and maintenance of mechanical and electrical equipment, can initiate and/or accelerate the deterioration of many materials, and in some instances can be detrimental to the health and well-being of people (Ref. 2).

Desert areas are especially susceptible to low-level sandstorms that damage glass and painted surfaces on vehicles, equipment, and structures (Ref. 3). However, the sand and dust problem is not confined to desert areas. Dry periods of sufficient duration occur in all regions such that vehicular activity can produce heavy dust (Ref. 4). In fact, with the increased use of more and faster vehicles and the increased reliance on helicopters, these localized machine-generated duststorms have become more detrimental to overall military operations than the less frequent naturally occurring duststorms in desert areas.

The purpose of this chapter is to establish qualitatively and, if possible, quantitatively (1) the physical characteristics (e.g., concentration and size distribution) of the sand and dust in the environment to which Army equipment will be exposed, (2) the duration, location, and frequency of these exposures, (3) the degradation potential of sand and dust, (4) methods for protecting against the deleterious effects of sand and dust, and (5) procedures for testing to determine the capability of the equipment to function in a sand and dust environment.

The reporting of experimental data on sand and dust environments seldom if ever distinguishes between the two. In most cases, either of the terms "particles" or "dust" is used to describe all the particulate matter present; however, for test purposes and for other special purposes, more limiting definitions of sand and dust have been used. For example, the standard test dust, "140 mesh silica flour", contains particles up to 150 μm in diameter. Also, an international committee—the goal of which is to establish internationally accepted test procedures for sand and dust testing—has defined sand and dust as hard particles with dust ranging in diameter up to 150 μm and sand ranging from 150 μm to 800 μm (Ref. 5).

Since discussion of sand and dust does not distinguish between the two categories of airborne particulate matter, the context of the terms used in this chapter is that used in the data source. It is assumed that, if one category of particulate matter is used, the data apply equally to both unless a specific distinction is made.

3-2 PROPERTIES OF SAND AND DUST ENVIRONMENTS

A sand and dust environment is usually described by giving values for parameters such as concentration, particle size distribution, shape, composition, and hardness. However, it should be understood that quantitative values of the parameters alone are insufficient to allow one to make an overall evaluation of the environment nor will it necessarily allow him to make valid comparisons between environments. Because of the sensitivity of the data to the various measuring techniques and to the different conditions under which measurements are made, it is necessary to describe test conditions and techniques as well as the parameter values in order to accurately describe a dust environment.

Engelhardt and Knebel (Ref. 4) listed the major variables for which data are required in quantitative descriptions of sand and dust environments as:

(1) Dust producer
- (a) Type
- (b) Size
- (c) Traction media
- (d) Speed

(2) Terrain
- (a) Particle size
- (b) Surface compaction
- (c) Mineralogy

(3) Climatology
- (a) Windspeed
- (b) Wind direction
- (c) Humidity
- (d) Air density

1. This chapter was written by F. Smith of the Research Triangle Institute, Research Triangle Park, N.C.

(4) Sampling Technique
   (a) Location of sampler
      1 Distance from dust source
      2 Height above terrain
      3 Location with respect to wind direction
   (b) Sampling time
   (c) Sampler characteristics.

3-2.1 CONCENTRATION

3-2.1.1 Method of Expression

Concentration is one of the most important parameters used in describing a sand and dust environment. Quantitative expressions of concentration are useless, however, unless the conditions under which the measurements were made are described adequately and the range of particle sizes is specified. Concentration values for a given test are highly sensitive to such variables as the dust producer, climatology, the terrain, and the sampling technique.

Concentration can be expressed as number of particles per unit volume of air or as the weight of particles per unit volume. Both expressions are used in the literature. However, weight per unit volume is the most common term in test specifications. Optical measuring instruments are used occasionally and give concentration in particles per unit volume. Weight-per-unit-volume data are usually given in grams per cubic meter in countries using the cgs system and in grams per cubic foot in the United States and Great Britain ($g\ ft^{-3} \times 35.3 = g\ m^{-3}$).

To convert particles per unit volume to weight per unit volume, or vice versa, one has to know something about the particle size distribution, particle shape, and average density of the sample. The information can be gained from (1) a size analysis, (2) visual or microscopic inspection, and (3) chemical and mineralogical analysis. One such conversion for air-floated dirt in Arizona was reported by Engelhardt and Knebel (Ref. 4):

$$C_w = 3.894 \times 10^{-5}\, C_n,\ g\ ft^{-3} \qquad (3\text{-}1)$$

where

C_w = concentration, $g\ ft^{-3}$
C_n = concentration, million particles ft^{-3}

In deriving the equation, it was assumed that the particle distribution followed certain conditions and that particles were similar in size to those found in previous measurements of air-floated dirt in Arizona. These assumptions allowed the following constraints to be used in the derivation:

(1) Fifty percent of the number of particles are equal to or less than 0.75 μm in diameter.

(2) Ninety percent of the number of particles are equal to or less than 2.5 μm in diameter.

(3) Ninety percent of the weight of the sample is composed of particles greater than 3 μm in diameter. This equation may only be valid for a sample meeting the three constraints; the accuracy of the conversion decreases as the sample deviates from those values (Ref. 4). In general, the assumptions are not fulfilled and this conversion is difficult to make.

3-2.1.2 Typical Atmospheric Concentrations

The concentration of sand and dust in the atmosphere varies widely with geographic location, climatic conditions, and the degree of activity. In metropolitan and industrial areas, industrial activity may be the major source of atmospheric dust. Pauly (Ref. 6) reported concentration ranges, as given in Table 3-1, of atmospheric dust measured at various points within regions having a temperate climate. Although these data may not be quantitative, they show that atmospheric dust is always present in varying amounts throughout the country. In general, this variation is more related to air pollution than to natural sand and dust.

3-2.1.3 Concentration vs Altitude in Duststorms

Typical concentration values are presented in Table 3-2 from measurements made at various altitudes by

TABLE 3-1. DUST CONCENTRATIONS IN VARIOUS REGIONS

Region	Average dust concentration, $\mu g\ ft^{-3}$
Rural and suburban	1.3 to 3.2
Metropolitan	3.2 to 13.0
Industrial	13.0 to 48.5

TABLE 3-2. VARIATION OF DUST CONCENTRATION WITH ALTITUDE

Weather condition	Height, ft	Air temperature, °C	Mean concentration, g $ft^{-3} \times 10^{-6}$
Clear to slight haze; visibility about 80 mi	500 1000 2000 4000 6000	33.0 30.5 30.0 29.0 19.0	6.0 6.3 4.9 3.9 1.5
Slight haze; visibility about 20 mi	500 1000 2000 4000 6000	34.0 33.0 32.0 27.0 21.5	6.7 7.4 5.7 3.9 5.4
Moderately dense duststorm; visibility about 1,000 ft; wind 20 to 25 kt	500 1000 2000 3000 4000	27.0 25.0 24.0 23.0 22.0	57.0 493.0 197.0 51.0 18.0

flying an aircraft over an Australian desert (Ref. 6). The methods used in collecting these data were not discussed. The occurrence of the maximum concentration values at 1,000 ft was thought to be due to the rolling nature of the duststorm and to the thermal upcurrents.

3-2.1.4 Concentrations Associated With Vehicular Activity

Engelhardt and Knebel made several measurements in an effort to determine the effects of vehicle speed and distance on concentration (Ref. 4). The duration of the dust cloud generated by the vehicles varied from 4 to 34 s. The sample collected for the duration of the cloud gave an average value of the concentration. The data exhibit a wide variance, and no conclusions about the relationships of speed and distance to concentration were drawn. However, specific examples are given as indications of the range of concentrations that can be expected under similar conditions.

Dust produced by two convoys of mixed vehicles moving at 15 mph and ranging in size from 1/4-ton to heavy tractor-trailer units was sampled. One convoy consisted of 27 vehicles and the other 26. Concentrations were 0.09 and 0.11 mg ft^{-3} (assumed to be averages from the onset of the first dust cloud to the passing of the last), windspeed was 1,200 ft min^{-1}, the terrain was slightly dusty, and the sampler distance from the roadway was 27 ft (Ref. 4).

Typical average ambient dust concentrations surrounding the U S Army Overland Train Mark II while in desert operation (Yuma Proving Ground, Yuma, Ariz.) were 4.0 and 5.4 mg ft^{-3} at heights of 10 and 8 ft, respectively. These were averages of eight test runs. The range was from 2.6 to 5.2 mg ft^{-3} at the 10-ft height and 2.8 to 7.1 mg ft^{-3} for the lower position (Ref. 7).

Concentrations as great as 100 mg ft^{-3} measured about 6 ft above ground occurred adjacent to tanks moving across deserts. Table 3-3 shows average concentrations for an M48 Tank operating over desert terrain (Ref. 6).

TABLE 3-3. AVERAGE DUST CONCENTRATIONS—M48 TANK OPERATING OVER DESERT TERRAIN

Position	Dust concentration, mg ft^{-3}	
	Single	Convoy
Crew compartment (hatches open)	6	8
Crew compartment (hatches closed)	18	-
Engine compartment	170	
4 ft above carburetor	4	13
8 ft above carburetor	1.2	4

TABLE 34. AVERAGE DUST CONCENTRATIONS—H-21 HELICOPTER

Hover height, ft	Dust concentration, mg ft^{-3}		
	Phillips Drop Zone, Yuma, Ariz.	Vehicle Dust Course, Yuma, Ariz.	Lee Drop Zone, Ft. Benning, Ga.
1	12.4	15.5	18.4
10	18.5	18.1	17.6
75	5.3	13.6	3

3-2.1.5 Concentrations Associated With Aircraft

The dust cloud generated by a tandem-rotor **H-21** helicopter was studied as a function of soil type, hover height, and disk loading at three heights at each of three test sites. The highest concentrations were measured directly below the rotor blade overlap and the lowest were beneath the rotor hubs. The average dust concentrations at the point of highest density (i.e., rotor blade overlap) are given in Table **3-4** (Ref. 8).

Dust concentrations of 40 mg ft^{-3} were measured during takeoff and approach maneuvers. With another helicopter hovering in the immediate area, concentrations were **64** mg ft^{-3}.

Maximum and minimum concentrations near the rotor plane of various aircraft are given in Table 3-5 (Ref. 9). The maximum, *85* mg ft^{-3}, measured at the engine intakes of the **KAC** Mockup of an **X-22** is less than the 170 mg ft^{-3} measured in the engine compartment of the M48 Tank (see Table **3-3**).

3-2.2 PARTICLE SIZE

In general, particle size refers to the mean diameter of the particle in a dust sample. However, because the shapes of sand and dust particles range from almost perfect spheres to irregularly shaped objects with protrusions, jagged edges, and cracks, methods for analyzing particle size must be specified (see par. 3-3, **MEASUREMENTS**). For this discussion, "size" ordinarily refers to particle diameter or Stokes' diameter.[2] Settling velocities in still air for various Stokes' diameters are shown in Fig. 3-1 (Ref. 10); these velocities are used to divide the range of sizes of natural sand and dust into the following three categories:

(1) ***Instantaneously airborne dust.*** Particle sizes of 150 μm and larger have falling velocities in still air greater than 90 cm s^{-1}. These settling velocities are greater than the air motions usually encountered; therefore, to become airborne, these larger particles must be thrown by some artificial means such as vehicles, helicopters, or missiles. Their residence time in the air is normally short. Particles in this size range remain close to the surface and usually account for less than 50 percent by weight of the dust in suspension (Ref. 4).

(2) ***Temporarily airborne dust.*** Dust particles less than about 150 μm in diameter may be raised either by artificial means or by natural winds of relatively high speeds. Particles between 2 and 150 μm have settling velocities between approximately **2** and 90 cm s^{-1}. Although particles in this size range are to a large extent removed from the atmosphere by gravity, their settling velocities are sufficiently low to allow them to remain airborne for a considerable time, particularly if the airflow is turbulent (Ref. 11). Particles in this category typically comprise between 50 and **100** percent by weight of the dust in suspension.

(3) ***Permanently airborne dust.*** For particles less than **2** μm, settling velocities in still air, though finite, are small compared with air motions. Atmospheric residence times of 9 to 90 yr have been estimated for particles of 1 μm diameter (Ref. 11). Dust particles of this size range are permanently airborne in the sense that gravitational fallout is not significant. Their proportion **by** weight of the total dust in suspension is typically less than **3** percent.

2. See par. 3-3.2.1—the Stokes' diameter, applied to an irregularly shaped particle, is the diameter of a spherical particle with the same density and settling velocity.

TABLE 3-5. DUST CONCENTRATIONS—VARIOUS AIRCRAFT

Source of test data	Maximum, mg ft^{-3}	Minimum, mg ft^{-3}
Full-scale dual tandem test rig, two Lycoming T-53 engines	31	-
KAC mockup of X-22 at engine intakes	85	-
Kaman HTK helicopter	8	2.7
Kaman HTK helicopter hovering near an HOK helicopter	24.5	5.4
Vertol Model 107 helicopter	7.5	1.0

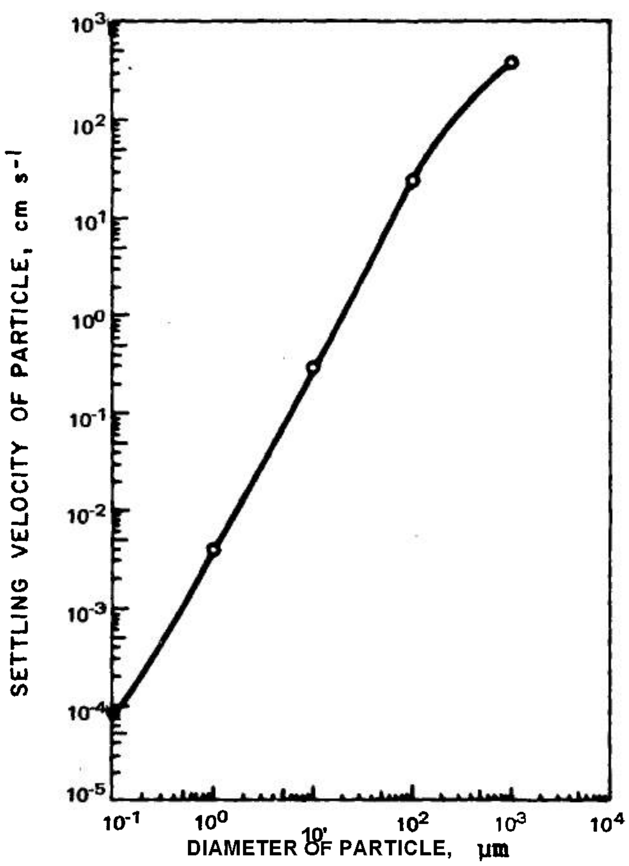


FIGURE 3-1. Settling Velocities for Particles in Still Air (at 0°C and 760 torr for particles having a density of 1 g $^{-3}$).

3-2.3 SIZE DISTRIBUTION

3-2.3.1 Methods for Displaying Particle Size

Atmospheric dust (previously classified as permanently airborne) constitutes a continuous spectrum of sizes with a definite largest value and a smallest value. Experimentation has shown that Gaussian or normal distributions of particle sizes rarely, if ever, occur. Particle sizes usually approximate closely a lognormal distribution (Ref. 12). Fig. **3-2** (Ref. 10) and Fig. **3-3** (Ref. **13**) show the linear and logarithmic frequency distribution curves for the lognormal distribution. In each figure, the area under the curve has a numerical value of one and the ordinate is the probability of the particle having a diameter within 1 μm of the abscissa value.

When plotted using log-probability scales, a cumulative lognormal distribution is a straight line. Such a plot is shown in Fig. 3-4 (Ref. **13**). In actual practice, the straight line is fitted to the data points visually or mathematically, as required by the spread of the data.

A lognormal distribution curve can be specified in terms of (1) the most probable size, which in this distribution is identical with the geometric mean M_g, or (2) the geometric standard deviation σ_g. It can be shown that the 50-percent point of the cumulative graph (Fig. **3-4**) corresponds to M_g, while the ratio of the 84.1-percent point to the 50-percent point is σ_g.

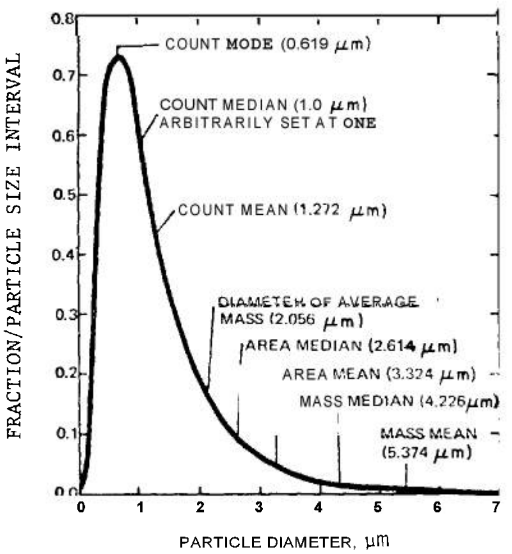


FIGURE 3-2. Lognormal Distribution of Particles (Various average diameters are shown. The graph is drawn from probability theory, assuming a count. median diameter of 1 μm and shows the numerical values relative to that diameter of several other weighted-average diameters discussed in the text.)

The lognormal distribution has the same σ_g for moments about the count, area, and weight mean geometric diameters. Thus, for the area distribution, after M_g and σ_g for the count distribution are known,

$$\ln M_a = \ln M_g + 2\sigma_g^2 \quad (3\text{-}2)$$

and for the weight distribution

$$\ln M_w = \ln M_g + 3\sigma_g^2 \quad (3\text{-}3)$$

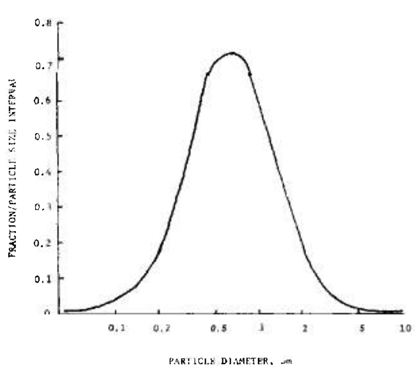


FIGURE 3-3. Logarithmic Plot of Particle Size Distribution (If the particle size distribution is lognormal, the graph is symmetrical when plotted logarithmically; contrast the figure with Fig. 3-2).

where M_a and M_w are the geometric means of the area and weight distributions, respectively.

Averages of particle size may be based on averages of numbers, areas, masses, etc. Several of the most important averages are indicated in Fig. **3-2;** the numerical values calculated for the distribution are given relative to a count (number) median diameter of 1pm. More extensive mathematical treatments of particle statistics are given by Orr and Dalla Valle (Ref. 12) and by Herdan (Ref. 14).

Two convenient and often used means of displaying particle size distribution data are tables and the percentage smaller diagram. These methods are applicable to any data whether lognormal or not. For example, if sifting data are presented on a percentage smaller diagram (Fig. 3-5), the percentage weight of all particles that passed through a specific sieve is plotted against the size of the sieve aperture (particle diameter), read off the abscissa. Starting with the largest sieve mesh, a series of points is obtained, until the weight of particles passing through the finest sieve is small or zero. The ordinate gives the percentage of all the sand and dust having a particle diameter that is smaller than that of the corresponding abscissa. The percentage of particles with sizes between d_1 and d_2 is given by the difference $P_1 - P_2$ between the corresponding ordinates. The predominant diameter for the sample is at the point of greatest slope of the curve.

3-2.3.2 Vehicle Air Inlet Size Distributions

The particle size distributions of airborne dust samples collected from the interior and usually in front of tanks driven in the dust cloud of a preceding tank are given by Fig. 3-5 (Ref. **2).** Data were taken from two tank ranges, both in the Fort Knox, Ky., area. The distributions from both ranges are almost identical. The data show that the dust contains approximately 22 percent by weight of particles below an equivalent diameter of 3 μm, and **33** percent by weight of particles less than 10 μm. The predominant diameter is estimated to be approximately 17 μm. Particles larger than about 70 μm were rare.

Table 3-6 (Ref. **4)** contains data on the size distributions collected at the air inlets for engine air for two types of tanks and the crew air for one of the tanks. The distribution of coarse test dust was included in the table for comparison, since it is supposed to be representative of airborne dust. In all but one particle size class, the coarse test dust specification fell within the range of the measured data; for the greater than 40-μm size, the coarse test dust specification of 39 percent was larger than any of the three measured values.

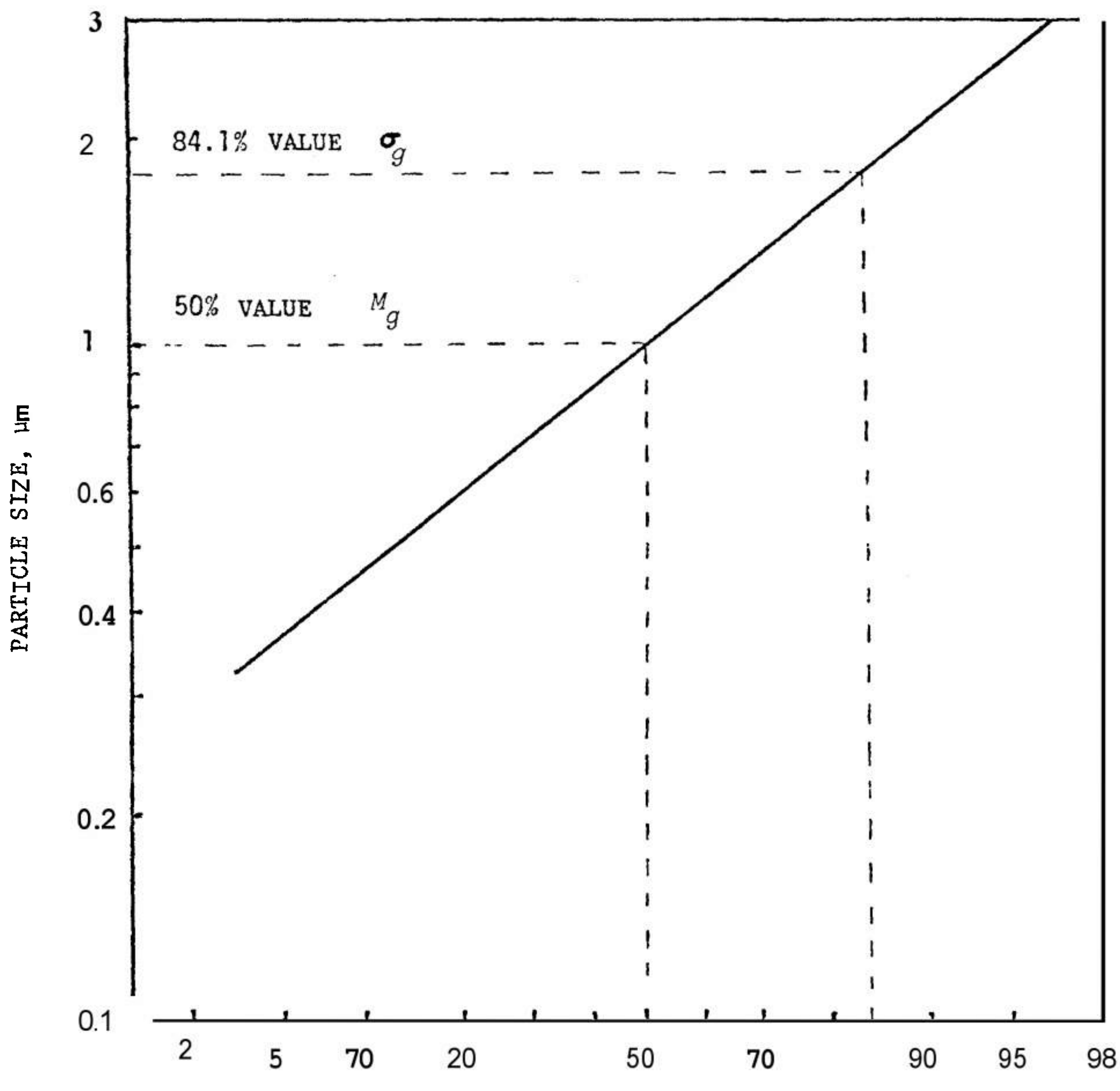


FIGURE 34. Cumulative Log-probability Curve (This is for the distribution of Fig. 3-2. [In a cumulative plot, the experimental points fall on a straight line when the size distribution in lognormal. The 50-percent point corresponds to the geometric mean, M_g (1.0 μm in this case), and the ratio of the 84.1-percent point to this (about 1.8/1.0 or 1.8, in this case) is the geometric standard deviation, σ_g. In practice, the experimental points usually lie near a straight line.])

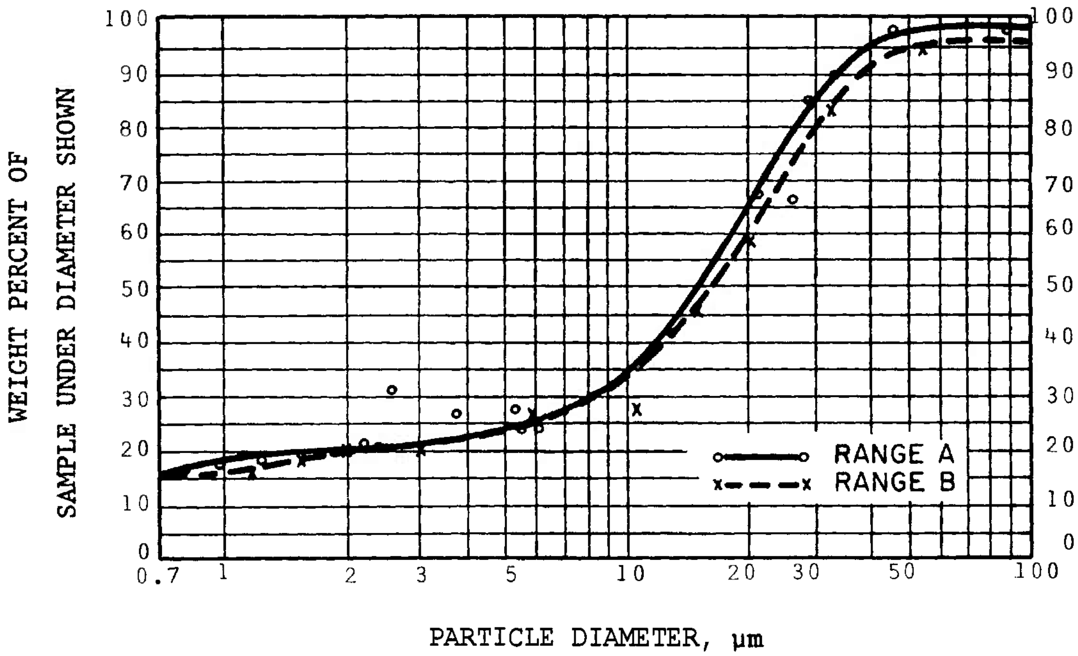


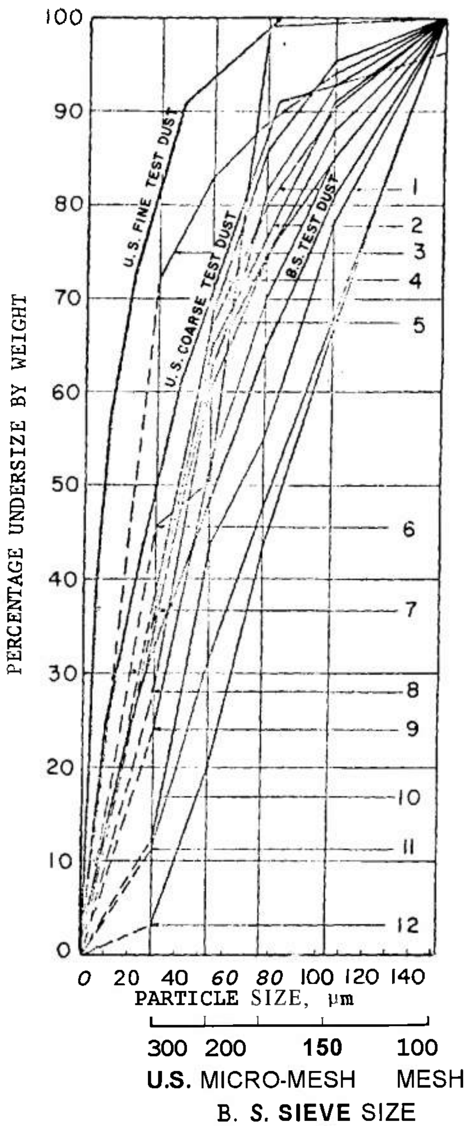
FIGURE 3-5. Particle Size Distribution of Dust Clouds Generated by Tanks

TABLE 3-6. PARTICLE SIZE DISTRIBUTIONS OF DUST COLLECTED AT AIR INLETS OF ARMY TANKS (percent within range)

Size range, μm	M4A1 Tank, engine air, % **	M48 Tank, engine air, %	M48 Tank, crew air, % **	Coarse test dust*, %
0-10	12.5	42.4	60.2	24
10-20	28.0	13.7	15.7	14
20-40	43.0	16.8	12.2	23
> 40	11.5	27.1	10.9	39

*Coarse dust for testing air cleaners per Society of Automotive Engineers "Air Cleaner Test Code," also known as AC Coarse dust.

**No explanation was given in the reference for data in these columns not adding up to 100%.



Dust no.	Area
1	New South Wales, Australia
2	Nairobi, Kenya
3	Rangoon, Burma
4	Jos, Maidurguri, Northern Nigeria
5	Mexicali, Mexico
6	Lagos, Nigeria
7	Gippoland, S.E. Victoria, Australia
8	Maidurguri, Northern Nigeria
9	Tijuana, Mexico
10	Safat, Kuwait
11	Cunnamulla, S.W. Queensland, Australia
12	Canada

FIGURE 3-6. Particle Size Distribution of Standard Dusts and Dusts Removed From Used Paper Elements Received From Abroad.

Fig. 3-6 shows the particle size distribution of Samples obtained from the analysis of air filters of vehicles operating in various geographical localities. These data show particle sizes up to 150 μm, with the percentage by weight for particles larger than 74 μm ranging from a high of about 55 percent to a low of 10 percent.

Tests were conducted to determine the particle size distribution of the dust passing through the air cleaners and entering a gas turbine engine powering the U S Army Overland Train Mark II at the Yuma Proving Ground, Yuma, Ariz. Model air cleaners were used to duplicate the performance of the main engine air cleaners (Ref. 7). Particle size distributions of the dust entering and passing the filters are given in Figs. 3-7 and 3-8, respectively. These figures show that the dust encountered by the Overland Train is finer than standard AC fine test dust. Approximately 50 percent by weight of the particles was larger than 3.0 μm.

3-2.3.3 Size Distribution Associated With Aircraft

Dust clouds generated by a tandem-rotor H-21 helicopter were studied as a function of soil type, hover heights, and disk loading (Ref. 8) at three sites (Phillips Drop Zone and Vehicle Dust Course, both in Yuma, Ariz., and Lee Drop Zone at Ft. Benning, Ga.). Figs. 3-9, 3-10, and 3-11 compare the particle size distributions at three hover heights (1, 10, and 75 ft; measured from ground to wheel; the sampler was at least 6 ft higher) with the size distributions for the three sites. The sample station was located on the starboard side in the zone of blade overlap. This was the point of highest dust concentrations. All distributions were normalized to a maximum particle size of 500 μm because no particles greater than 500 μm were found in any of the samples; however, even with the helicopter at 75 ft, there was a significant percentage of 100 μm and larger particles.

Similar tests conducted on V/STOL aircraft (Ref. 9) operating in ground proximity show that the particle size distribution of the airborne sample collected at the rotor plane more nearly approaches that of the particle size and distribution of the terrain sample than did the helicopter samples.

3-2.3.4 Size Distribution vs Altitude

Table 3-7 (Ref. 6) gives the particle size distributions expected in duststorms at varying heights. These data

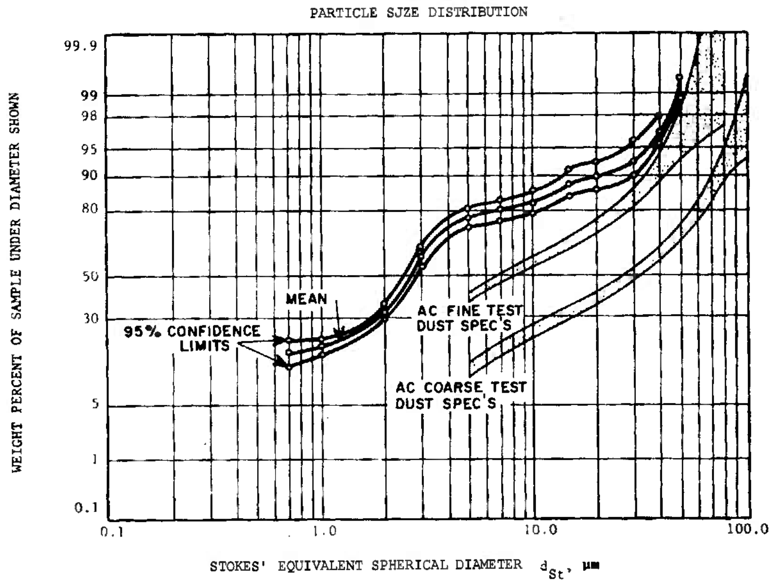


FIGURE 3-7. Size Distribution of Dust Entering the Model Air Cleaners (in the tests on the Overland Train Mk. II)

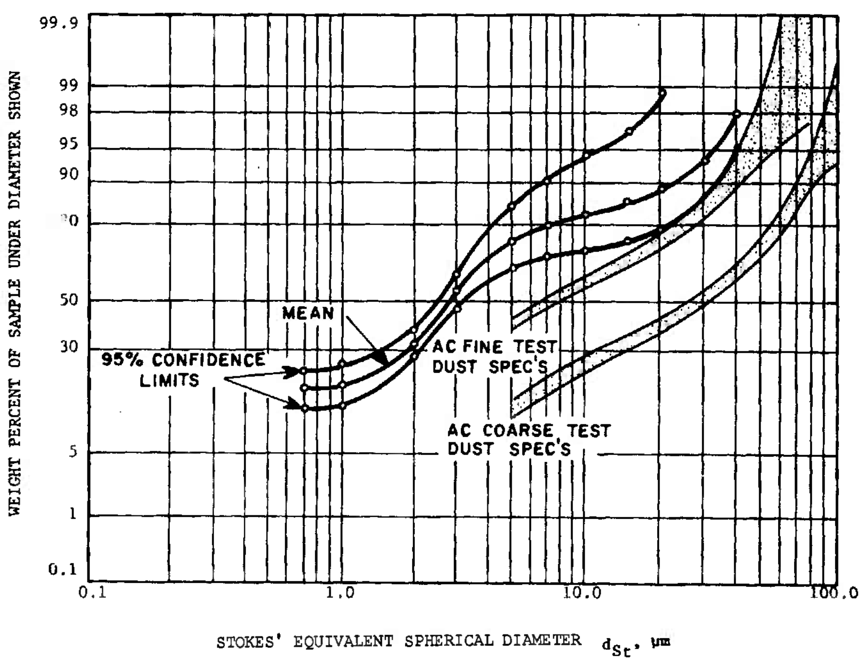


FIGURE 3%. Size Distribution for Dust Passing the Model Air Cleaners (In the tests on the Overland Train, this dust is representative of the dust reaching the gas turbines.)

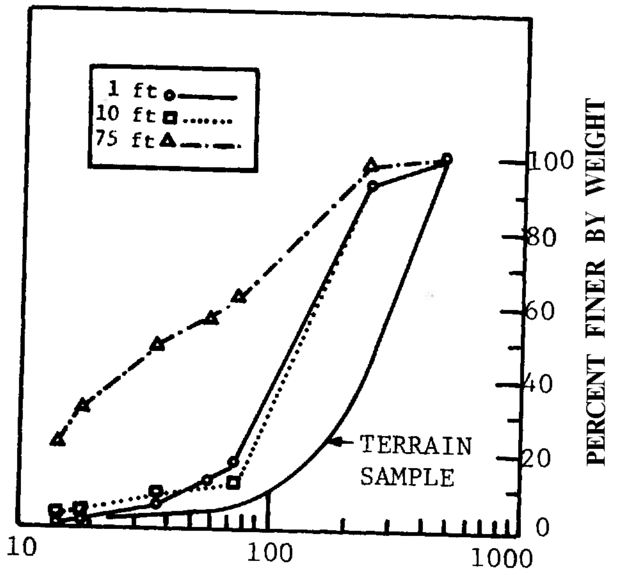


FIGURE 3-9. Typical Particle Size Distribution, Lee Drop Zone, Ft. Benning, Ga.

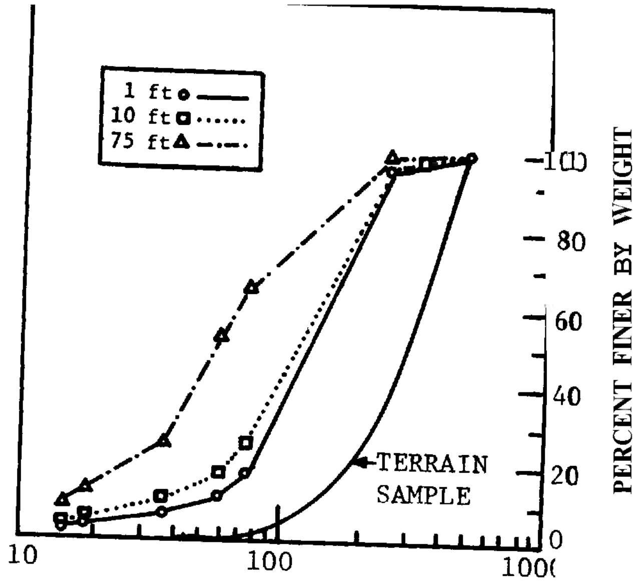


FIGURE 3-10. Typical Particle Size Distribution, Phillips Drop Zone, Yuma, Ariz.

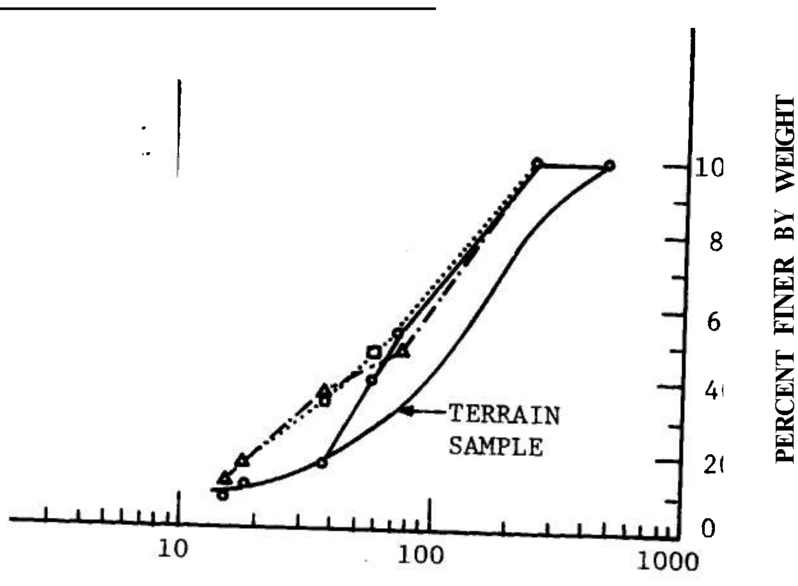


FIGURE 3-11. Typical Particle Size Distributic Vehicle Dust Course, Yuma, Ariz.

TABLE 3-7. VARIATION OF PARTICLE SIZE DISTRIBUTION WITH HEIGHT IN DUSTSTORM

Height, ft	Particle size distribution, μm percent b4				
	0-5	5-10	10-20	20-40	over 40
500	25.0	35.0	30.0	8.0	2.0
1000	43.0	31.0	19.5	5.6	0.9
2000	50.0	28.0	15.5	4.5	2.0
3000	66.5	22.0	9.0	2.1	. 0.4
4000	64.0	21.0	11.5	2.8	0.7

were collected by flying an aircraft through duststorms. The data, given as percentages by count, cannot be directly compared with size data given by weight. However, the use of **Eq. 3-3** would allow construction of the weight distribution.

3-2.4 PARTICLE SHAPE

3-2.4.1 General

Shape influences the abrasiveness and penetrativeness of individual particles. For example, the more angular, the greater the ability to abrade (Ref. 6). To some extent the shape is determined by the material from which the dust originated and in part by the relative humidity of the air. Long exposure to wind and water erosion tends to smooth sharp edges (Ref. 15).

The perfect, nonambiguous shape would be a sphere; however, sand particles vary in shape from almost perfect spheres, for grains that have been exposed to wind and water abrasion for long periods of time, to sharply angled particles, for freshly ground or broken powders or sand. **As** a result of this nonsphericity, the comparison of particle size determinations by different methods requires the use of factors of proportionality called shape factors.

3-2.4.2 Particle Shape Factors[3]

Shape factors have three functions: (1) they determine proportionality between particle sizes measured by different methods; (2) they are the conversion factors for expressing size measurements in terms of an equivalent sphere; and (3) they transform the second and third power of the variable, particle diameter, to the particle surface and volume, respectively.

With respect to point (1), investigations of the shape factor, which corrects the difference between particle sizes measured by sedimentation and by sieving (i.e., Stokes' diameter divided by the sieve opening), have resulted in values ranging from 1.2 to 0.9. The ratio of the projected diameter, obtained by microscopic analysis, to the sieve aperture, through which the particle will just pass, is constant at approximately **1.4** for a great range of material.

To transform or compare particle size expressed as a linear measure such as the mean projected diameter d_p to the mean surface diameter (Stokes' diameter) d_{St} as determined by sedimentation or elutriation, the following relationship is used:

$$d_{St} = d_p\sqrt{\alpha_s/\pi} \tag{3-4}$$

where α_s is the surface shape factor for that sample and is defined in this instance as:

$$\text{average surface area of particle} = \alpha_s d_p^2 \tag{3-5}$$

Likewise, to compare d_p to the mean equivalent diameter d_e, the diameter of a sphere having the same density and volume as the particle, the following expression is used:

$$d_e = d_p\sqrt[3]{6\alpha_v/\pi} \tag{3-6}$$

where α_v is the volume shape factor for the sample defined as

$$\text{average volume of particle} = \alpha_v d_p^3 \tag{3-7}$$

Several experimentally determined values are crushed quartz, α_v = 0.27 to 0.28 and α_s = 2.0 to 2.5; white sand, α_s = 2.1 to 2.7.

3-2.5 COMPOSITION AND HARDNESS

The mineralogical composition of airborne dust varies with time and location (Ref. 11); however, the most common highly abrasive component is silica (SiO_2). Silica when dry has a value of 7 on the Mohs' scale of hardness, and this value decreases only to between 6.5

3. A general reference for this paragraph is Ref. 14.

to 5.5 when the silica becomes hydrated (Ref. **3**). Therefore, both states would be erosive to a variety of materials. Most test dusts contain a high percentage of silica in an effort to represent the worst-case conditions. Evidence indicates, however, that other components may be significant in evaluating the erosive and corrosive properties of a particular dust.

Soil samples from the southeast Asian area had china clay ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$) as the principal constituent (Ref. **3**). China clay breaks down exothermally at approximately 2000°F to alumina (Al_2O_3) having a hardness value of about 9. The heat evolved from this reaction is similar in amount to that of the thermite reaction, which has been used for welding. Therefore, in addition to releasing enough energy to possibly cause high temperature corrosion, the reaction forms particles of alumina, which are even harder than silica particles (Ref. **3**).

In particular localities, materials other than silica may be important constituents of sand. These include the white gypsum sands (hardness **2**), of Southwestern United States, the black seashore sands containing magnetite (hardness **6**) found in various parts of the world, some stream sands containing corundum (hardness **9**), and sands made of calcite (hardness **3**) in marine or former marine locations (Ref. 16).

The principal constitutents of naturally occurring sand and dust and the relative hardness values of the particles are listed in Table **3-8**.

Kuletz and Schafer carried out an extensive study to determine quantitatively the constituents of sand and soil samples collected from widely scattered locations around the world (Ref. **3**). Analytical data on **43** of the **264** samples are in Table **3-9**. These data show that the three principal constituents are silica, alumina, and iron oxide and that the percentage of each of the three major constituents varies widely from sample to Sample. Of special interest is the variation in silica from a low of 0.13 to a high of 95 percent. Although a chemical analysis does not reveal the actual composition of the particles (Ref. 6), it does in this case clearly show that silica or quartz is not always the major constituent.

Several surface soil samples taken from two tank ranges in the Ft. Knox, Ky., area were analyzed for silica content (Ref. 2). The percentage composition varied from a low of **68** percent to a high of **78** percent indicating that a fairly large variation is possible in samples taken from within the same general area.

3-3 MEASUREMENTS

The information required to accurately describe a sand or dust environment includes (1) concentration (count or weight), (2) particle size distribution, **(3)** particle shape, **(4)** chemical composition, and in some cases, (5) surface area or volume. In a limited number of cases, the information may be obtained directly from the suspended particles, but, in the majority of cases, it is necessary to collect a sample before making an analysis.

Concentration and particle size distribution are the two most frequently measured parameters. In both instances, using techniques that will insure the collection of a valid sample is as important as the accuracy of the analysis.

TABLE 3-8. CONSTITUENTS OF NATURAL DUSTS

Constituent	Composition	Hardness Mohs scale
Quartz	SiO_2	7
Feldspar	$KAlSi_3O_8$ $NaAlSi_3O_8$ $CaAl_2Si_2O_8$ $CaAl_2Si_2O_8$	6
Limestone Limestone	$CaCO_3$ $CaCO_3$ $MgCO_3$ $MgCO_3$	3
Pure clay, kaolin, china clay	$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	2

3-3.1 SAMPLING METHODS

Sample collection from a laminar flow of dust particles generally requires isokinetic sampling (i.e., air velocity inside the sample probe is equal to the air velocity outside the probe). For particles larger than about **5** μm, the inertial effect can cause selective or erroneous samples if the sampling velocity is not the same as the flowstream velocity at the sampling point. The error, which is a function of particle size, increases as the particle size increases. Table 3-10 (Ref. 17) gives some ranges of the effects due to nonisokinetic Sampling that adequately covers most dust size distributions encountered. For airborne particles having no appreciable inertia and small terminal velocity, a valid sample may be collected regardless of sampling rate. Separation of dust from air (i.e., sampling method) may be accomplished in several ways, but only those methods suitable for field use and applicable to a wide range of particle sizes are discussed here, namely:

TABLE 3-9. CHARACTERIZATION OF SOIL SAMPLES

Location	Composition (percent by weight)[a]									Ignition[b] loss, %	Density, g/cm³	Average particle size, μ
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	CaO	MgO	K_2O	Na_2O			
Da Nang, Vietnam	80.21	7.81	8.69	0.68			0.08			3.35	2.735	20
Korat, Thailand	77.37	8.90	3.97	0.67			0.29			6.93	2.654	28
Subic Bay, Phillipine Islands	39.07	29.22	15.34	1.70			0.20			13.27	2.851	14
Hong Kong	74.75	11.94	2.59	0.40	0.06	0.84	0.13	3.30	0.88	5.00	2.70	9
Naha, Okinawa	67.59	12.15	4.59	c		5.37	1.46			6.41	2.731	21
Iwokene, Japan	67.94	16.17	4.85	c		2.92	0.89			2.14	2.626	32
Atsugi, Japan	32.54	26.45	15.40	c		1.02	1.96			13.97	5.128	d
Sasebo, Japan	69.83	12.46	5.72	c		0.31	0.63			6.93	2.700	22
Agana, Guam	14.09	26.75	15.37	c		12.28	0.40			27.31	3.239	17
Fiji Island	43.99	23.01	12.23	0.93	0.14	3.76	2.98	0.27	2.33	7.63	3.03	4
Moorea, Tahiti	15.69	2.15	1.93	0.33	0.03	35.58	2.22	0.33	0.77	39.69	2.93	8
Pago Pago, Amer. Samoa	13.25	6.08	8.29	0.93	0.10	39.23	3.65	0.29	0.65	28.63	3.20	7
Wake Island	0.13	Nil	0.99	--		51.12	1.23			44.54	2.780	36
Midway Island	29.99	22.14	21.37	c		2.88	0.91			16.57	3.391	15
Oahu, Hawaii	31.71	21.73	26.32	c		0.60	0.94			14.62	4.546	13
Innisfail, Queensland, Aust.	32.81	28.32	22.69	2.85	0.13	0.75	0.55	0.05	0.15	12.06	3.08	5
Adak #1, Alaska	54.27	25.49	1.80	c		11.45	4.37			0.40	2.899	188
Adak #2, Alaska	31.09	13.79	2.30	c		2.86	0.49			44.78	2.072	22
Anchorage, Alaska	64.94	15.84	5.69	0.90		0.70	1.84			4.19	2.728	35
Kodiak, Alaska	57.06	18.39	6.66	c		1.98	1.54			11.34	2.387	10
Tanana Valley, Alaska	81.43	7.15	3.37	0.63		1.80	1.44			1.52	2.690	45
Alcan Highway (Dawson Creek-Delta Junction)	56.70	14.51	8.48	0.85		7.75	3.65			7.91	2.744	8
Yhite Horse, Yukon	68.14	13.22	3.13	0.60		5.66	1.88			3.96	2.476	20
Sea-Tac, Wash.	66.60	14.12	3.70	0.73		0.58	3.17			8.30	2.543	34
China Lake, Calif.	69.50	13.22	3.97	c		5.47	1.15			2.58	2.685	61
Sierra Nevada (Fish Creek), Calif.	54.57	18.85	10.37	c		6.71	3.20			3.00	2.796	36
Yuma, Arizona	82.07	5.80	1.30	0.28		4.84	1.55			2.75	2.646	47
Flagstaff, Arizona	54.28	18.31	10.57	c		4.33	2.44			5.38	3.274	--
Four-State Corners, U.S.	83.01	6.22	1.37	c		2.00	0.65			2.87	2.777	>25
Providence, R. I.	76.83	11.41	2.23	c		1.64	0.43			4.75	2.718	20
Harrisburg, Pa.	68.41	13.22	5.35	1.10		1.10	1.63			7.46	2.711	10
Fairfax, Va.	65.18	14.18	7.28	1.37		2.28	1.35			6.39	2.735	19
Eqlin AF8, Fla.	95.18	1.94	0.31	c		0.49	0.52			1.10	2.644	>52
Guatemala City, Guatemala	42.74	20.07	7.41	c		5.45	1.15			17.99	2.796	19
Ft. Clayton, Panama	36.73	25.88	16.71	c		0.37	0.44			12.23	4,239	11
Coco Solo, Panama	44.50	24.55	10.08	c		0.21	0.99			12.38	4.500	11
Bermuda	2.11	1.75	0.79	c		50.05	0.95			42.46	2.699	26
Ramey AFB, Puerto Rico	36.53	7.10	3.33	0.28	0.08	25.43	0.75	0.57	0.67	24.20	2.93	7
Argentia, Newfoundland	15.73	9.79	3.49	0.48	0.06	1.39	1.19	1.10	1.81	63.88	1.34	19
Keflavik, Iceland	31.34	23.88	15.25	c		3.89	1.27			15.99	3.368	6
Heyford, England	69.77	7.40	4.99	0.47	0.14	4.42	0.48	1.41	0.42	8.34	2.97	8
Ross Island, Antarctica	44.17	14.36	13.89	3.55	0.22	9.27	8.61	1.83	2.88	0.79	3.09	12
Taylor Valley, Antarctica	60.77	12.96	7.08	1.08	0.12	5.61	4.74	2.25	2.95	2.11	2.98	10

NOTE: Absence of data in composition section does not mean oxides were not present; depends on testing technique.

[a] All metals reported as oxides.

[b] Ignition loss: 1 hr at 1292°F

[c] Any minor amount of TiO_2 would be included in the Al_2O_3 value.

[d] Porosity too high, out of range. Particles are large fused agglomerates which crush to micron size particles.

TABLE 3-10. EFFECT ON DEPARTURE FROM ISOKINETIC CONDITIONS ON SAMPLE CONCENTRATIONS

U_0/U[a]	C/C_0[b]	
	Range	Typical Value
0.6	0.75-0.90	0.85
0.8	0.85-0.95	0.90
1.2	1.05-1.20	1.10
1.4	1.10-1.40	1.20
1.6	1.15-1.60	1.30
1.8	1.20-1.80	1.40

a $U_0/U = \dfrac{\text{stream velocity}}{\text{sampling velocity}}$

b $C/C_0 = \dfrac{\text{concentration measured}}{\text{true concentration}}$

(1) ***Filtration.*** Filters are among the most commonly used sample collection devices. Samples collected on filters are suitable for determining (a) concentration by weight, (b) size distribution, and (c) chemical composition. The choice of filter media is governed by the types of tests to be undertaken and the information that is sought. For example, in the determination of weight concentration per unit volume of air, the primary objective is to collect a weighable quantity of dust within a reasonable sampling period by using a filter that has comparatively low resistance to high flow rates. For determination of the size distribution and the shape of particles, a membrane filter must retain particles on its surface and prevent them from penetrating into the interior of the filter bed; filters are available for sampling particles down into the submicrometer region. For chemical or spectrographic analysis of the particles, the filter must be free from organic or inorganic impurities that might cause interference.

(2) ***Impingement.*** Wet or dry impingers are available for the collection of particles. Wet impingers collect particles on a surface submerged in a liquid. Dry impingers (impactors) collect particles by impaction on a dry surface. In both types of apparatus, collection occurs as a result of inertial forces, as the particles tend to resist a change in direction when the airstream is deflected by a surface or other obstacle.

After collection in a wet impinger, analysis may be performed of weight, particle size, or chemical composition. Samples collected on impactors also lend themselves to direct examination under the microscope.

In general, high collection efficiencies are obtained by impingement for particle sizes down to about 2 μm or when operated at sonic velocities, for particles as small as 0.1 μm with wet impingers (Ref. 18).

The greatest disadvantage of using impactors for sample collection is that the high airflow velocities can cause agglomerated particles to separate and thus yield an erroneously high number of fine particles in the sample.

(3) ***Sedimentation.*** The effectiveness of this technique depends on natural sedimentation of particles from the airstream. In still air, particles larger than about 5 μm settle out and are collected as dustfall. In actual practice with even small turbulences to keep the smaller particles airborne, the smallest particles settling out are about 10 μm in diameter. Dustfall values are given as weight per unit area.

This technique is used to give comparative measures of the amount of dustfall in a particular area over a period of time. The sample can be further analyzed for particle size, shape, and composition. The concentration (number) of airborne dust particles C may be approximated by

$$C = J/V, \text{ cm}^{-3} \tag{3-8}$$

where

J = dustfall, $cm^{-2}\ s^{-1}$

V = settling velocity, cm s^{-1}

The settling velocity is determined by the area mean size (Stokes' diameter) of the dust particles (Ref. 19). The collected sample distribution favors the larger particles with large fallout velocities and is truncated on the lower end where settling velocities are less than the turbulent forces keeping the particles airborne.

(4) Centrifugal A much used method of separating dust particles from the airstream is to accelerate the airstream into a spiraling motion. The spiral becomes smaller as the air progresses through the collector and the centrifugal forces impel the particles outward to the side of the collector. This method is most efficient for

sampling high concentrations of large particles (Ref. 20), and it is particularly well suited for high flow rates; e.g., a reasonably sized sample must be collected in a short period of time when sampling vehicle-generated dust clouds.

3-3.2 PARTICLE SIZE ANALYSIS[4]

3-3.2.1 Means of Separation

Particle size is basically determined by (1) sieving, (2) microscopy, (3) sedimentation or elutriation, and (4) impaction. No one method is applicable for the overall size range of sand and dust. The first three methods are suited best to analysis on a discrete sampling basis in an offstream environment. They cannot be applied to airstream, real-time monitoring. In the fourth method, cascade impactors automatically separate the sample into particle size ranges; however, the deposited material has to be removed for weighing and for any further analyses. Impactors can be used onstream but not for real-time monitoring. A fifth method, radiation scattering, is available for particle size analysis under laboratory or controlled conditions, but because it is not presently adaptable to field test conditions, it is not included in the following discussion.

(1) *Sieving.* Dry sieving is usually the first step in size analysis of particles greater than 74 μm in diameter. Particle size is taken as the diameter of a sphere that will just pass through the aperture of the smallest sieve. Sieving may be carried out with one sieve at a time or with a series of sieves, each having progressively smaller openings. The particles retained by each screen are weighed to give the particle size distribution by weight of the sample.

The American Society for Testing and Materials Standard **STP 4.47,** ***Manual on Test Sieving Methods,*** sets forth the proper methods for conducting sieve operations.

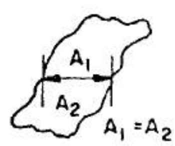
Sieving is one of the oldest, most direct, and simplest means for determining the size and size distribution of sand and dust particles. Dry sieving is used universally in size differentiation of particles larger than 74 μm in diameter (Ref. 4).

The arithmetic mean diameter of a sieve sample is the sum of the weight fractions retained on each sieve, multiplied by the corresponding diameter (taken as the size of the openings of the last sieve the sample passed through) and then divided by the total weight of the sample.

Particles that pass through a 74-μm sieve are generally referred to as subsieve particles, even though wet sieving can be used to extend the lower limit to 37 μm. Particle diameter has been defined in a number of ways for the subsieve-sized particles, and some of these definitions extend into the sieve-sized range as well.

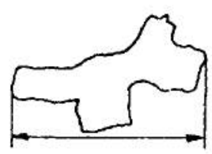
(2) *Microscopy.*[4] Of the many different methods available for analyzing particle size, microscopy is the only direct method. Microscopic measurements and counts are extremely tedious and time consuming but reliable and reproducible if performed by experienced technicians.

The sizes of irregularly shaped particles, when determined by microscopic measurement, are stated as projected diameters or statistical diameters. The projected diameter is the diameter of a circle equal in area to the profile of the particle viewed normal to the position of greatest stability. The two most commonly used statistical diameters are Feret's and Martin's diameters, as shown in Fig. 3-12. Feret's diameter is the mean of the distances between two tangents on opposite sides of each particle image in the sample, the tangents being drawn perpendicular to the direction of traverse. Martin's diameter is the mean of the lengths of a line that intercepts each particle image in the sample and divides it into equal areas (A_1 and A_2); the bisecting line is always parallel to the direction of traverse. Martin's



MARTIN'S

(A) Martin's diameter measuring mean length of line dividing particle into equal areas



FERET'S

(B) Feret's diameter measuring mean distance between tangents on opposite sides of particle image

FIGURE 3-12. Particle Sizing Models (Each particle shown is representative of all particles in the sample which are measured and averaged.)

4. A general reference for this paragraph is Ref. 21

diameter is slightly smaller than the mean projected diameter, and Feret's is greater. The projected diameter more nearly corresponds to the Stokes' diameter derived from sedimentation and elutriation measurements.

(3) Sedimentation.[5] The sedimentation method of particle size analysis is based on the terminal settling velocity at which particles fall under gravity through the sedimentation medium. The particle diameter determined by this method is termed the Stokes' or sedimentation diameter, and may be defined for irregular particles as the diameter of a sphere having the same settling velocity under gravity and the same density as the particle being observed. In some cases, a term called the reduced sedimentation or equivalent diameter is used for a sphere of unit density having the same settling velocity as the particle.

Stokes' diameter is calculated from the following relationship:

$$d = \{18\eta U_t/[(P_p - P_s)g]\}^{1/2}, \text{ cm} \tag{3-9}$$

where

η = absolute viscosity of sedimentation medium, poises
U_t = terminal settling velocity of the particle in the sedimentation medium, cm s^{-1}
P_p = density of particle, g cm^{-3}
P_s = density of sedimentation medium, g cm^{-3}
g = acceleration due to gravity, 980 cm s^{-2}

The sedimentation medium can be either a gas or a liquid.

(4) ***Elutriation***.[5] In both the sedimentation and the elutriation methods, the size of the particle is calculated from its rate of fall by the use of Stokes' law. In elutriation, the dust sample is introduced into an upward moving stream of liquid or gas of known and adjustable velocity, so that different particle fractions are lifted or elutriated and the sizes are calculated from the known velocity of the medium. This technique requires a minimum quantity of several grams of sample to perform particle size classification.

(5) Impaction. Impactors (described in par. 3-3.1) can be used for both concentration and particle size analyses. By connecting several stages in series so that each stage collects all particles above a certain cutoff diameter, the sample is separated into size groups. Seven stages have been successfully used for particle size analysis (Ref. 21). Each successive stage has a smaller cutoff diameter than the previous one, and the particles collected on each stage have diameters between two fixed values. The smallest particle size collected on the last stage of a typical commercial cascade impactor is well into the submicron range.

3-3.2.2 Correlation of Data From Different Methods

Definitions found in the literature are presented in Table 3-11 (Ref. **4**). In previous studies, particle size in the subsieve range has been measured in a variety of ways. This variation makes data comparisons between data sources difficult and in many cases invalid unless the specific measuring techniques are defined and the particle shape factor for that sample is known. For example, particles classified according to their geometrical similarity (as in sieving and microscopy) and according to similarity in hydrodynamic or aerodynamic behavior (as in sedimentation or elutriation) will in most cases show great variations in equivalent diameters. Factors of proportionality between particle sizes determined by different methods are defined as shape factors (discussed in par. 3-2.4.2).

3-3.2.3 Instrumentation

Table 3-12 summarizes the instruments available for sample collection. This table excludes those limited to laboratory applications and includes the types most frequently used in sand and dust field studies.

3-4 FACTORS INFLUENCING THE SAND AND DUST ENVIRONMENT

The sand and dust environment is influenced or controlled by such factors as terrain, wind, temperature, humidity, and precipitation. None of these factors alone will dictate whether an area has a dust problem or not; rather a critical combination of two or more is usually required. In the most severe naturally occurring situations, such as in desert areas, all factors generally have values in the range that is highly conducive to heavy dust concentrations.

5. A general reference for this paragraph is Ref. 21.

TABLE 3-11. DEFINITIONS OF PARTICLE DIAMETER

Parameter	Description
Diameter	Measured diameter of a sphere or particle in one direction
Area-diameter (projected)	Diameter of a circle having the same area as the projected area of the particle
Area-length diameter	Diameter obtained by dividing projected area by measured diameter
Volume-surface diameter	Diameter obtained by dividing the volume of a particle by the surface area
Area-diameter	Diameter of a sphere having the same cross-sectional area as the particle
Volume (mass) diameter	Diameter of a sphere having the same density and volume or mass as the particle
Stokes' diameter	Diameter of a sphere having the same density and free falling velocity as the particle in air

3-4.1 TERRAIN

Particle size, surface compaction, and mineralogical composition are the prime characteristics of a soil that establish the potential dustiness of a particular area. The general guidelines developed by Engelhardt (Ref. 4) point out that a soil with about 9 percent by weight of particles less than 74 μm can experience moderate dust conditions and a soil with about 14 percent or higher by weight of particles less than 74 μm can result in heavy dust conditions; this indicates that many localities outside of the desert areas might experience moderate to heavy dust conditions. Even tropical areas such as Vietnam have sufficiently dry periods for the soil, under heavy traffic conditions, to produce a dusty environment (Ref. 3). Also, physical features of the terrain that encourage strong winds and/or dry soil' conditions increase its potential as a dust producer. A topographic feature such as a mountain notch increases windspeed materially as air is forced through the constriction. Another condition that produces local winds of sufficient speed to cause duststorms is associated with many of the basins of interior drainage. A basin with a playa, salt flat, or lava flow in the lowermost portion experiences a marked diurnal wind cycle (Ref. 22); i.e., during the day the air over the flat basin surface is heated and forced upward over the center of the basin, and at night the action reverses. These two features, although very important to the military when operating in these areas, account for only a small percentage of the total dust producers of the earth.

In general, the physical geography of the surface of the earth determines those areas where high concentrations of airborne sand and dust may be encountered. The major deserts of the earth listed in Table 3-13 are the primary sources of naturally occurring windblown sand and dust (Ref. 6). The major deserts constitute about one-fifth of the total land area of the earth.

3-4.2 WIND

Wind affects the environment by carrying sand and dust into suspension. The ability of wind to initiate and sustain sand and dust movement depends on the particle size and degree of coherence of the surface over which the wind is moving. Wind erodes the surface and translocates the particles. Its effectiveness depends, among other things, upon the speed, direction, angle of attack, and gustiness (Ref. 11).

TABLE 3-12. INSTRUMENTS FOR SAMPLE COLLECTION

Sampling method	Instruments	Possible analyses	Particle size range, μm	Required skill for analysis	Required operator skill	Remarks
Sedimentation	Dust jars, screens, glass plates, boxes	Count, weight, chemical	> 1	Considerable	Considerable	Gives weight per unit area, simple equipment, useful for size analysis.
Impingement	Cascade impactors	Count, weight, chemical	0.1–100	Considerable	Some	Fractioning aerosols. Not suitable for high concentrations or large samples. Good for short sampling periods where small sample is adequate.
	Greenburg-Smith impinger	Count, chemical	1-> 500	Considerable	Some	Collects sample in liquid. Good for sampling non-agglomerated hard particles and low volume sampling.
Centrifugal	Cyclones	Weight, count, chemical, sizing	> 1	Considerable	Some	Inexpensive, rugged and simple, good for field use as high volume samplers in high concentrations of large particles.
Filters	Fiber filters	Weight, chemical	> 0.5	Considerable	Some	Low resistance to air flow, some are difficult to stabilize for weighing.
	Granular filters	Count, chemical, weight	> 1	Some	Some	Some are made of soluble materials, e.g., sugar or salicylic acid, for easy separation from collected sample.
	Controlled pore filters	Particle sizing, count, weight, chemical	> 0.1	Some	Some	Collects sample on the surface, can be made transparent with mineral oil for counting or sizing by microscope. May be dissolved or ashed to recover sample.

TABLE 3-13. MAJOR DESERTS OF THE WORLD

Name	Location	Estimated area, 10^6 mi^2
Sahara	North Africa	3.0
Australian	Australia	1.3
Arabian	Arabian Peninsula	1.0
Turkestan	Southwest Russia	0.75
North American	United States and Mexico	0.5
Pataqonian	Prgentina	0.26
Thar	India and Pakistan	0.23
Kalahari	South Africa	0.22
Takla Makan	China	0.20
Iranian	Iran	0.15
Atacama-Peruvian	Chile and Peru	0.14

3-4.2.1 Pickup Speed

One of the most important factors involved in sand movement is the shear stress produced at the sand surface by the wind. When the shear speed exceeds a critical or threshold value, the sand particles start to move. Fig. 3-13 shows the variation of the threshold speed with grain size (Refs. 15,22,23). The fluid threshold is defined as the windspeed at which sand movement is initiated by wind pressure alone. The impact threshold is the windspeed required (1) to bounce rolling grains into the air, and (2) as they descend downwind, to knock other grains into the air by impact, the impinging grains generally rebound into the air. The ordinate of the graph in Fig. 3-13 is not a measurement of windspeed; it is a measure of wind gradient whose threshold value varies directly with the square root of grain diameter. Higher wind gradients are required to transport grains of larger sizes. This graph, a summary of research performed principally in a laboratory above smooth surfaces with incoherent sand, shows that the wind gradient necessary to set particles in motion is a minimum for particles approximately 100 μm in diameter and that it increases as the particle size either increases or decreases (Ref. 15).

The relationship between windspeed and shear speed or wind gradient is a linear function for a particular surface. Windspeeds of 763, 914, and 1190 cm s^{-1} measured 1 ft above the sandbed resulted in shear speeds of 39, 47.6, and 70 cm s^{-1} respectively, when calculated from Zingg's formula (Ref. 23). There are, however, so many variables involved that in general the pickup speed of wind is not unique for a given particle size. Therefore, a graph of windspeed vs particle size similar to the plot of wind gradient vs particle size (Fig. 3-13) would have little value or application for field conditions. Nevertheless, the relationship has been investigated in the laboratory and in the field, and some useful generalizations about speed ranges can be made. These generalizations are cited by Clements (Ref. 22): (1) winds of 50 mph or more are required to set in motion particles as large as 2,000 pm; (2) particles between 1,000 and 2,000 μm will be transported, under ideal conditions, by winds of 35 to 45 mph; (3) winds between 11 and 30 mph transport particles from 80 to 1,000 pm; and (4) as the particle diameter decreases below about 80 pm, the pickup speed required increases, and particles of 2 μm or less are not moved by winds up to 50 mph.

3-4.2.2 Typical Windspeeds

Windspeeds as high as 103 mph have been recorded for duststorms in the Sudan (Ref. 24) and 85 mph in the United States (Ref. 22). However, measurements made in the desert areas in Southwestern United States over the past several years indicate that: (l) winds over 50 mph are extremely rare and probably occur only as gusts, (2) only about 1 percent of the time does the windspeed exceed 30 mph, and (3) only about 20 percent of the time does it exceed 15 mph (Ref. 22).

3-4.2.3 Vertical Distribution

Studies of the vertical distribution of windblown sand and dust indicate that approximately 95 percent, by weight, of the total is carried within 10 in. of the ground and that at least 50 percent remained below the 2-in. level (Ref. 22). Particle size decreases rapidly with altitude, as shown by Table 3-7; these data show that at 3,000 and 4,000 ft there are few particles 40 μm and

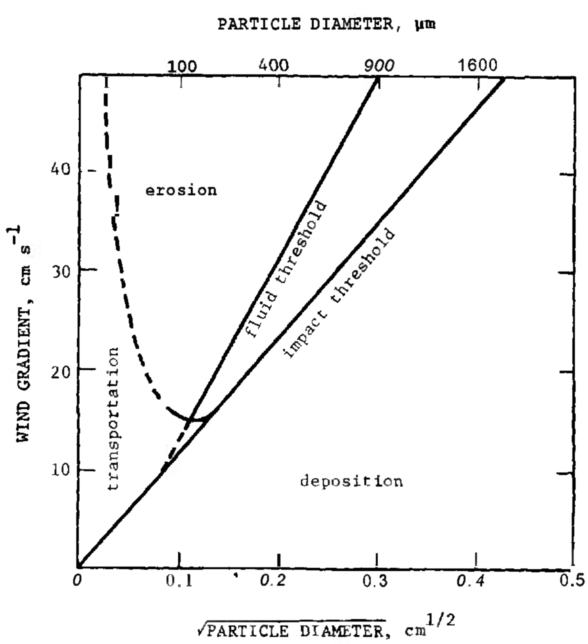


FIGURE 3-13. Sand Particle Dynamics

larger. In West Africa, aircraft crews have reported dust layers at altitudes in excess of 12,000 ft (Ref. 25), and analysis showed the particles to be mostly in the 0.1 and 0.5 μm range. Although no particle size data were given, aircraft crews reported dust clouds up to 17,000 ft over England (Ref. 26); this dust is believed to have originated in the southern Sahara 3 or 4 days previously.

See Chap. 10, "Wind", in Part Two of this handbook series, for land areas that experience continuous or seasonal high winds.

3-4.3 HUMIDITY AND PRECIPITATION

Experiments in the laboratory have demonstrated that moisture increases the threshold shear speed necessary to initiate sand movement. For a given windspeed, the number of particles becoming airborne would decrease with an increase in moisture content. For a particular size sand, under laboratory conditions, a change in the relative humidity of the ambient air from 40 to 100 percent changed the threshold shear speed from 35 cm s^{-1} to approximately 42 cm s^{-1}. Also, a change in water content of the sand, as experienced when precipitation occurs, from approximately 0.1 to 1 percent changed the threshold shear speed from 35 to 54 cm s^{-1}. This latter change in shear speed corresponded roughly to a change in windspeed from 29 to over 40 ft s^{-1} (Ref. 23).

The preceding data indicate a decrease in the number of particles becoming airborne, and thus a reduction in concentration, as the moisture in the atmosphere or in the soil increases. However, measurements of dust concentrations in London indicate that, for relative humidity fluctuations, between 30 and 60 percent of the concentration level is unaffected, but a rapid increase in concentration occurs when the relative humidity rises to a range between 50 and 100 percent (Ref. 6). It has been estimated that deserts and other areas that have a minimum of precipitation cover approximately 40 percent of the land area of the earth and that another 40 percent is seasonally dry, which means potentially severe dust conditions for part of the year. To locate areas having little rainfall and low relative humidity, see Chap. 4, "Humidity", and Chap. 7, "Rain", in Part Two of this handbook series.

3-4.4 TEMPERATURE

High air temperatures combined with low relative humidities aid in drying out the soil, thereby reducing the cohesion of the surface particles and increasing the probability of dust movement. Large temperature gradients may produce convection currents capable of carrying dust particles to high altitudes (Refs. 22,27). For world areas where high temperatures are normally encountered see Chap. 3, "Temperature", in Part Two of this handbook series.

3-5 EFFECTS OF SAND AND DUST

Sand and dust, consisting of finely divided solid particles in various sizes having various degrees of hardness and chemical reactivity, may act as agents of deterioration either chemically, physically, or both. It depends on the particular circumstances and the nature of the material they contact.

Physically, sand and dust carried in forceful winds may abrade moving parts of machinery or stationary surfaces. Sharp-edged particles penetrate cracks, crevices, bearings, seals, and electrical connections causing a variety of damage to equipment.

Chemically, various mineralogical components of sand and dust can have a deteriorating effect on materials because in the presence of moisture they can cause an acid or alkaline reaction. For example, hydrated aluminum silicates found in many clays give alkaline reactions, while other hydrated salts give acid reactions (Ref. 28).

Practically all military materiel is subject to varying degrees of damage from sand and dust under certain environmental conditions. The types of damage are generally (1) abrasion, (2) clogging and blocking, and (3) corrosion (Ref. 16).

3-5.1 EROSIVE EFFECTS

3-5.1.1 Erosion

Sand and dust, blown by winds of high velocity, can erode stationary surfaces, and particles made instantaneously airborne by moving vehicles (especially helicopters and V/STOL aircraft) can cause similar damage. Erosion can promote or accelerate the corrosion of metallic surfaces by removing or disturbing protective coatings. The cutting effect of windblown sand and dust is very noticeable on wooden objects (telephone or telegraph poles) in desert areas. Glass components such as car windshields can become pitted and frosted during sandstorms (Ref. 22).

Wind-driven sand and dust can roughen the surfaces of insulants and insulators, thus impairing their surface electrical properties. The surface conductivity of phenolics with roughened surfaces has been measured as 10 times greater than identical materials with smooth surfaces, at a relative humidity of ***50*** percent.

Bitter (Refs. 29,30) derived an expression describing the wear or erosion of materials as a function of particle velocity, angle of impact, and material properties based on the postulation that two separate mechanisms are involved in the removal of material by the impact of a particle.

First, the impacting particles with speed high enough to cause plastic deformation of the surface will, after a sufficient time, work-harden the surface to such an extent that brittle fracture will occur. This mechanism, called deformation erosion loss W_D, is a function of the component of particle velocity perpendicular to the specimen surface.

The second mechanism of erosion is due to the cutting action of the particle. The cutting erosion loss W_C is a function of the component of particle velocity parallel to the specimen surface.

Both types of wear occur simultaneously and total erosion loss W_t equals the sum of the two types of loss. Figs. 3-14 and 3-15, respectively, show total wear curves of a soft, ductile material and a hard, brittle one under the same conditions. For soft materials and relatively small impact angles, the erosion is due primarily to cutting; as the material becomes harder and the impact angle approaches 90 deg, deformation becomes the main cause.

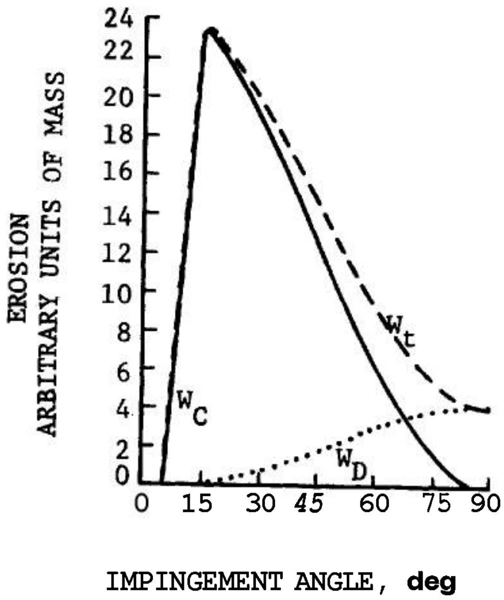


FIGURE 3-14. Erosion of a Soft, Ductile Material.

Bitter's analysis included the effects of several parameters, some of which are very difficult to measure. Wood (Ref. 31), in making certain simplifying assumptions, derived the following expression for total wear W_t composed of measurable quantities:

$$W_t = \quad W_D \quad + \quad W_C$$

$$W_t = \left[\frac{(1/2)M(V\sin\alpha)^2}{\epsilon}\right]\frac{\gamma}{g} + \left[\frac{(1/2)M(V\cos\alpha)^2}{\rho}\right]\frac{\gamma}{g},\ \text{g} \tag{3-10}$$

where

W_D = deformation erosion loss, g
W_C = cutting erosion loss, g
M = mass of dust impacted on specimen, g
V = particle velocity, cm s^{-1}
α = angle of impact, deg
γ = density of specimen material, g cm^{-3}
g = acceleration due to gravity, 980 cm s^{-2}
ϵ = deformation energy value (energy required to remove a unit volume of material from the specimen surface by deformation erosion with units of (g-cm) cm^{-3} in cgs units)
ρ = cutting energy value (same units as ϵ)

In Figs. 3-16 through 3-21, the results of a set of experiments designed and conducted by Wood to evaluate the degree of erosion caused by airborne dust under various conditions are compared with the computed values using Wood's equation (Ref. 31). Fig. 3-16 gives the particle size distributions of the different test dusts (quartz, commonly referred to as silica flour). Figs. 3-17 through 3-19 show erosion loss as a function of particle size and impact angle, particle speed, and specimen temperature, respectively. Eq. 3-10 does not account for any effects due to concentration; however, Fig. 3-20 shows a slight increase in erosion loss as the concentration decreases over the range tested.

The relationships of ρ and ϵ to particle size for a given set of conditions are presented in Fig. 3-21. The generally good correlation between the experimental results and theory supports the postulated dual mechanism of erosion and indicates that erosion loss of various metals may be adequately described by Eq. 3-10

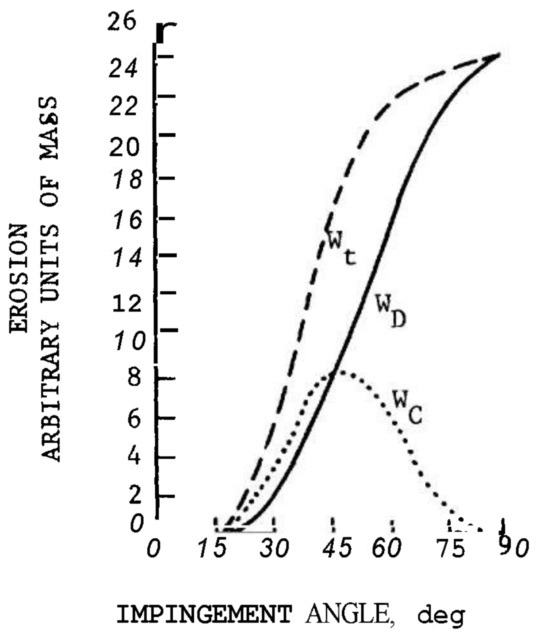


FIGURE 3-15. Erosion of a Hard, Brittle Material.

with an additional factor or term to account for effects of concentration.

Examples of erosion by sand and dust are numerous. Gas turbine engines powering the Overland Train Mark II (Ref. 7) and operating 200 hr without air filters, in dust concentrations estimated to range from approximately 4.7 down to 0.73 mg ft^{-3}, required major overhauls because of excessive erosion in the compressor section caused by ingested dirt. After installing an air filter that was attested 86 percent efficient in removing dust from the airstream, the turbines operated for an additional 468 hr with no damage to either the turbine or the compressor.

Helicopter rotor blades have been severely eroded after a few minutes of operation in dusty areas. An H-21 helicopter had three layers of wood on the leading blade edge worn away after only 20 min of hovering in dust (Ref. 8). Metal blades were then installed and the leading edges were covered with a 1/8-in. polyurethane film, which provided excellent protection; however, the unprotected tip caps were completely eroded through after less than 2 hr of hovering over a dusty surface.

A 45-hp gas turbine engine with an 1800-cfm airflow was tested in an atmosphere containing quartz dust with a maximum particle diameter of 74 μm and a controlled concentration of 6 mg ft^{-3}. After 15 hr of operation at rated power, the engine was effectively destroyed—the turbine scroll, nozzle vanes, and compressor and turbine blades were severely eroded (Ref. 31).

Windblown low-level sandstorms have been known to seriously damage painted surfaces and glass on stationary vehicles, equipment, and structures within a few hours (Ref. 32).

3-5.1.2 Abrasive Wear of Mechanisms

Abrasive wear may be defined as the scrubbing or cutting action of extraneous material introduced between two rubbing or sliding surfaces. Mechanisms that require air for operation (e.g., the internal combustion engine) are particularly susceptible to abrasive wear through the ingestion of airborne sand and dust. The wear can be reduced by air filtering (Ref. 7).

A series of wear tests was conducted on an aircraft engine to determine the most damaging dust sizes (Ref. 28). Various quantities, concentrations, and sizes of synthetic dusts were injected into the engine under controlled conditions. The results showed that generally the amount of wear was proportional to the weight of the ingested dust and that the amount of wear produced by a specific weight decreased as the dust concentration increased. (The latter result agrees with the erosion data in Fig. 3-20.) Also, wear increased as the mean particle size decreased from 125 μm down to about 15 μm, where the wear curves peaked and started to decrease as particle size became smaller; the erosive effects of 100 μm particles were only approximately one-half those caused by 15 μm dust.

The braking systems of vehicles are particularly susceptible to the abrasion by sand and dust. Particles penetrating the brake drum area greatly increase the rate of wear of the brake drum surfaces. In both engines and braking systems, sufficiently high temperatures are experienced to cause china clay to break down exothermally (as discussed in par. 3-2.6), releasing energy to further increase the ambient temperature, and forming the highly abrasive compound alumina. The high percentage of china clay in the dirt samples from Southeast Asia and the high failure rate of engines and braking systems of vehicles operating in that area support the possibility of this occurring.

3-5.2 CORROSIVE EFFECTS

Airborne sand and dust may produce objectional effects merely by settling on surfaces. Particulate matter in conjunction with other environmental factors

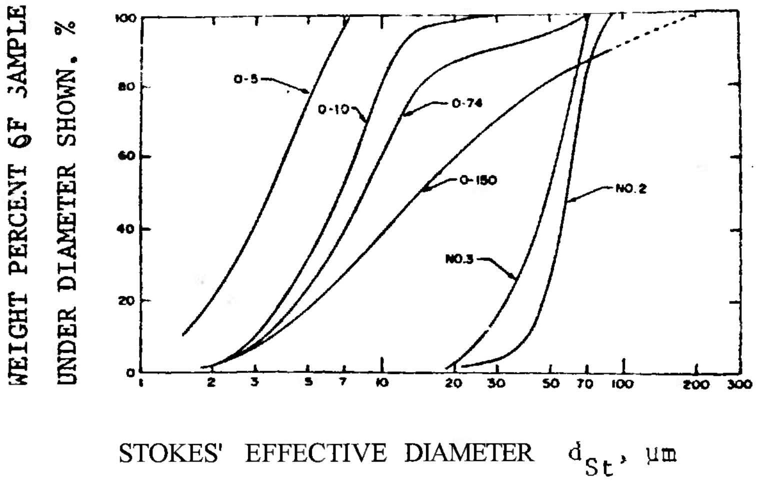


FIGURE 3-16. Test Dust Particle Size Distribution.

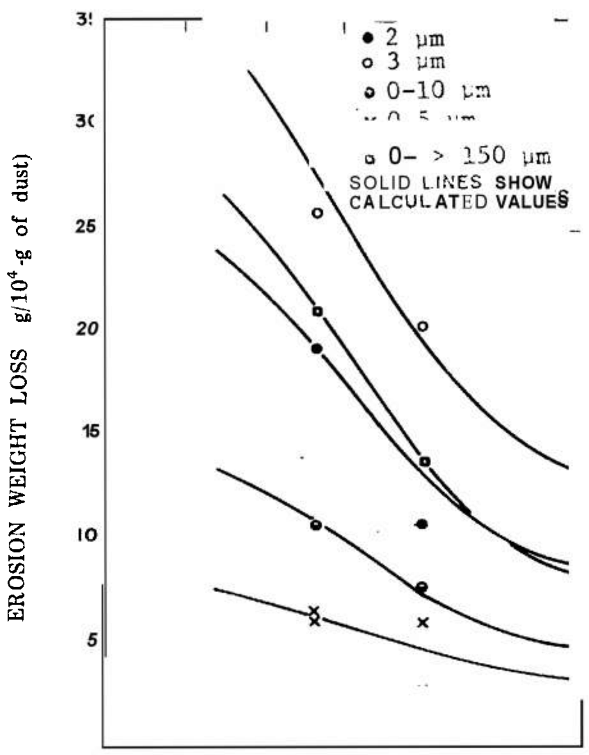


*FIGURE 3-17. Erosion Loss as a Function of Particle Size (Material type: **4140** steel; dust velocity: **800** fps; material temperature: ambient; dust size: see code above.)*

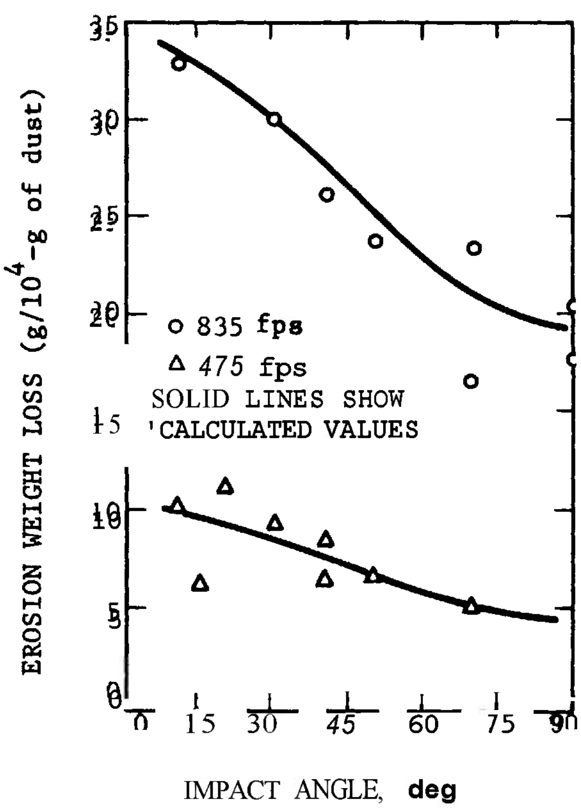


*FIGURE 3-18. Erosion Loss as a Function of Particle Velocity (Material Type: **C-1050** steel; material temperature: ambient; dust velocity: see code above; dust size: **0–74** μm.)*

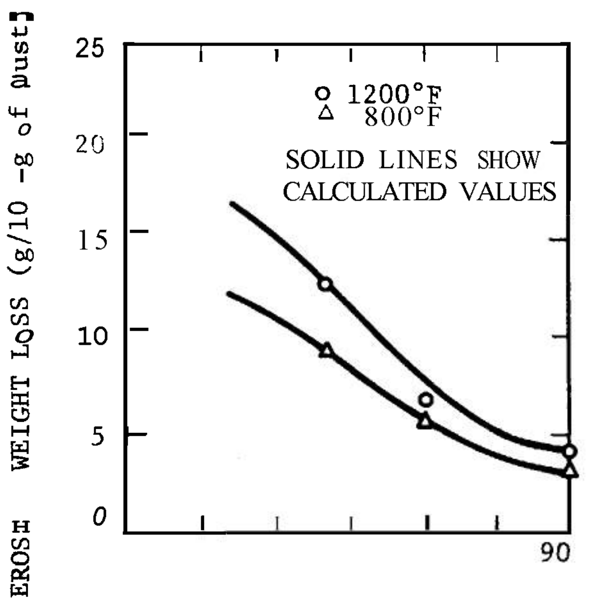


FIGURE 3-19. Erosion Loss as a Function of Temperature (Material type: Multimet; material temp.: see code above; dust velocity: 600 fps; dust size: 0–74 µm.) (Multimet is the tradename for an alloy with the composition 21% Cr, 20% Ni, 20% Co, 3% Mo, 2.5% W, and the balance Fe.)

such as moisture and sulfur dioxide (SO_2) plays an important role in the corrosion of metals (Ref. 33). Particles may contribute to accelerated corrosion in two ways. First, they may be capable of absorbing active gases (such as SO_2) from the atmosphere. The nature and extent of the deterioration depend on the chemical activity of the particles in their environment, and on the relative susceptibility of the receiving metal.

Secondly, inert hygroscopic particles can act as corrosion nuclei or as catalysts for other corrosion reactions on metal (Ref. 10).

3-5.2.1 Chemically Inert Particles

A film of hygroscopic particles on a surface tends to maintain higher levels of moisture and of any corrosive gases present in the atmosphere on the surface than would otherwise exist at equilibrium with the ambient air. Thus, the particles become agents of deterioration indirectly by facilitating the actions of other atmospheric constituents. For example, charcoal (carbonaceous) particles are not only condensation nuclei but absorbed gases to the corresponding oxidized acids. Carbonaceous dust increases the rate of corrosion in the presence of sulfur dioxide traces, presumably through the absorption of sulfur dioxide, which is transformed to highly reactive sulfuric acid, under the catalytic action of traces of metals, especially iron (Refs. 10,13,19). Monel 400 (30 percent copper and 70 percent nickel) has superior corrosion resistance, but it becomes pitted when soot particles accumulate; it has been hypothesized that the unburned carbon in the soot leads to the formation of local galvanic cells, resulting in premature perforation and accelerated attack of the metal sheet (Ref. 19).

Inert nonabsorbent particles have little effect on the corrosive process except by helping to retain the moisture and by screening the metal at the point of contact, corrosion even in the presence of sulfur dioxide (Ref. 19); however, removal of the deposited particles usually results in erosion of the protective surface (oxides or paint) and leaves the surface exposed to other more corrosive atmospheric compounds.

3-5.2.2 Chemically Active Particles

Particles originating from natural or industrial sources may be chemically active and may provide corrosive electrolytes when dissolved. Many clays, which are principal sources of natural dusts, are hydrated silicates of aluminum and give alkaline reactions, while some soils contain several of the soluble sulfate salts that give acid reactions (Ref. 28).

Active hygroscopic particles, such as sulfate and chloride salts and sulfuric acid aerosols, act as corrosive nuclei. On a metal surface, they can initiate corrosion, even at low relative humidities (Ref. 19). Field experiments show that the rate of corrosion for various metals is accelerated in urban and industrial areas because of the greater atmospheric concentrations of both particulate matter and sulfur compounds. Fig. 3-22 (Ref. 10) shows the relationship between rate of rusting for steel specimens and the dustfall levels in four diverse areas, ranging from a heavily industrialized area to a rural area. Table 3-14 (Ref. 10) ranks types of atmospheres by their corrosive effects on steel specimens.

Corrosion rates are usually low when the relative

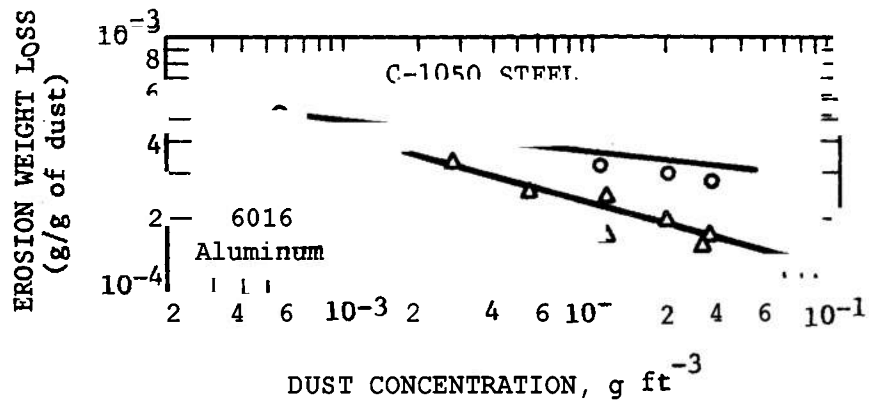


FIGURE 3-20. Erosion Loss vs Dust Concentration (Material type: noted; material temperature: ambient; dust velocity: 475 fps; dust size: 0–74 μm.)

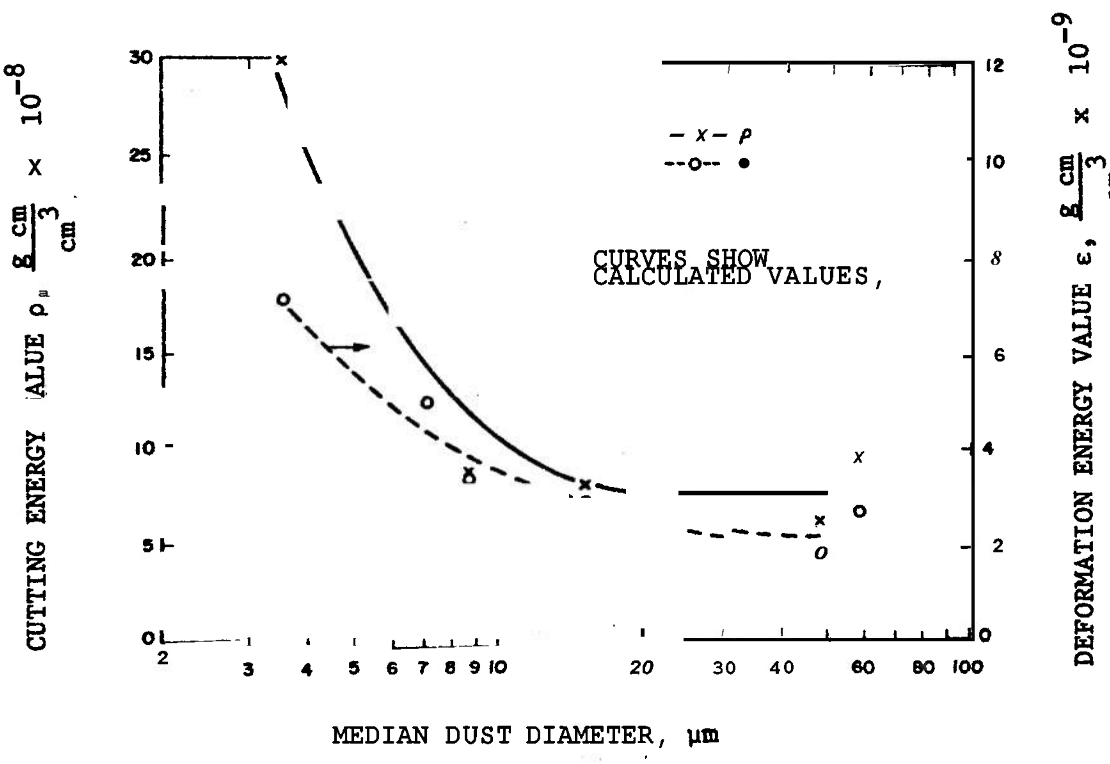


FIGURE 3-27. Effect of Dust Size on Energy (Data obtained with type 4140 steel at ambient temperature and a dust velocity of 800 ft s^{-1}).

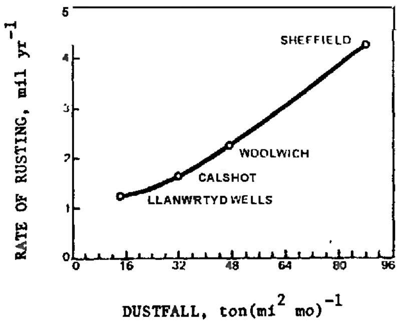


FIGURE 3-22. Rate of Rusting vs Dustfall (At four locations, the figure plots the rate of rustling of mild steel versus dustfall, and shows that corrosion is four times as rapid in an industrial area (Sheffield) as it is in the rural area (Llanwrtyd Wells).)

humidity is below a critical level, which for many metals is about 70 percent (Ref. 34); but they increase with increased humidity even in clean air, and they increase greatly with traces of sulfur dioxide in the air. In some cases where suspended particulate levels correlated well with weight loss due to corrosion, further analysis indicated that sulfur dioxide concentrations had the dominant influence on corrosion (Ref. 35).

3-5.3 ELECTRICAL INSULATORS

Silica sand and the majority of dusts (natural and industrial) usually deposited on insulator surfaces are poor conductors when dry. However, when wetted by high humidity, fog, or rain, the soluble compounds go into solution forming a conducting electrolyte. The insoluble particles remaining on the surface tend to retain the electrolyte on the surface and to increase the effective thickness of the moisture film. This can be a very serious problem in areas such as California where the summers are rainless and dust can collect over a 3- to 4-mo period forming a thick layer of electrolyte when wetted by the first autumn rain (Ref. 36).

As a result of the conductivity of such surface films, the leakage currents flowing over contaminated powerline insulators can be on the order of one million times those that flow through clean, dry insulators. Fig. 3-23 (Ref. 36) compares the arcing distances for 60-Hz voltages on clean and dry, clean and wet, and dirty and wet insulators. In recent years, increased power requirements have caused power companies to gradually increase transmission line voltages from about 250 kV to as high as 750 kV. This has increased the rate of insulator breakdown, resulting in flashover problems as well as the less dramatic power losses due to leakage currents.

TABLE 3-14. CORROSION OF OPEN-HEARTH STEEL SPECIMENS

Location	Type of atmosphere	Annual weight loss, g	Relative corrosivity
Khartoum, Sudan	Dry inland	0.16	1
Abisko, North Sweden	Unpolluted	0.46	3
Aro, Nigeria	Tropical inland	1.19	8
Singapore, Malaya	Tropical marine	1.36	9
Basrah, Iran	Dry inland	1.39	9
Apapa, Nigeria	Tropical marine	2.29	15
State College, Pa., USA	Rural	3.75	25
Berlin, Germany	Semi-industrial	4.71	32
Llanwrtyd Wells, British Isles	Semimarine	5.23	35
Calshot, British Isles	Marine	6.10	41
Sandy Hook, N.J., USA	Marine-semi-industrial	7.34	50
Congella, South Africa	Marine	7.34	50
Motherwell, British Isles	Industrial	8.17	55
Woolwich, British Isles	Industrial	8.91	60
Pittsburgh, Pa., USA	Industrial	9.65	65
Sheffield Univ., British Isles	Industrial	11.53	78
Derby South End, British Isles	Industrial	12.05	81
Derby North End, British Isles	Industrial	12.52	84
Frodingham, British Isles	Industrial	14.81	100

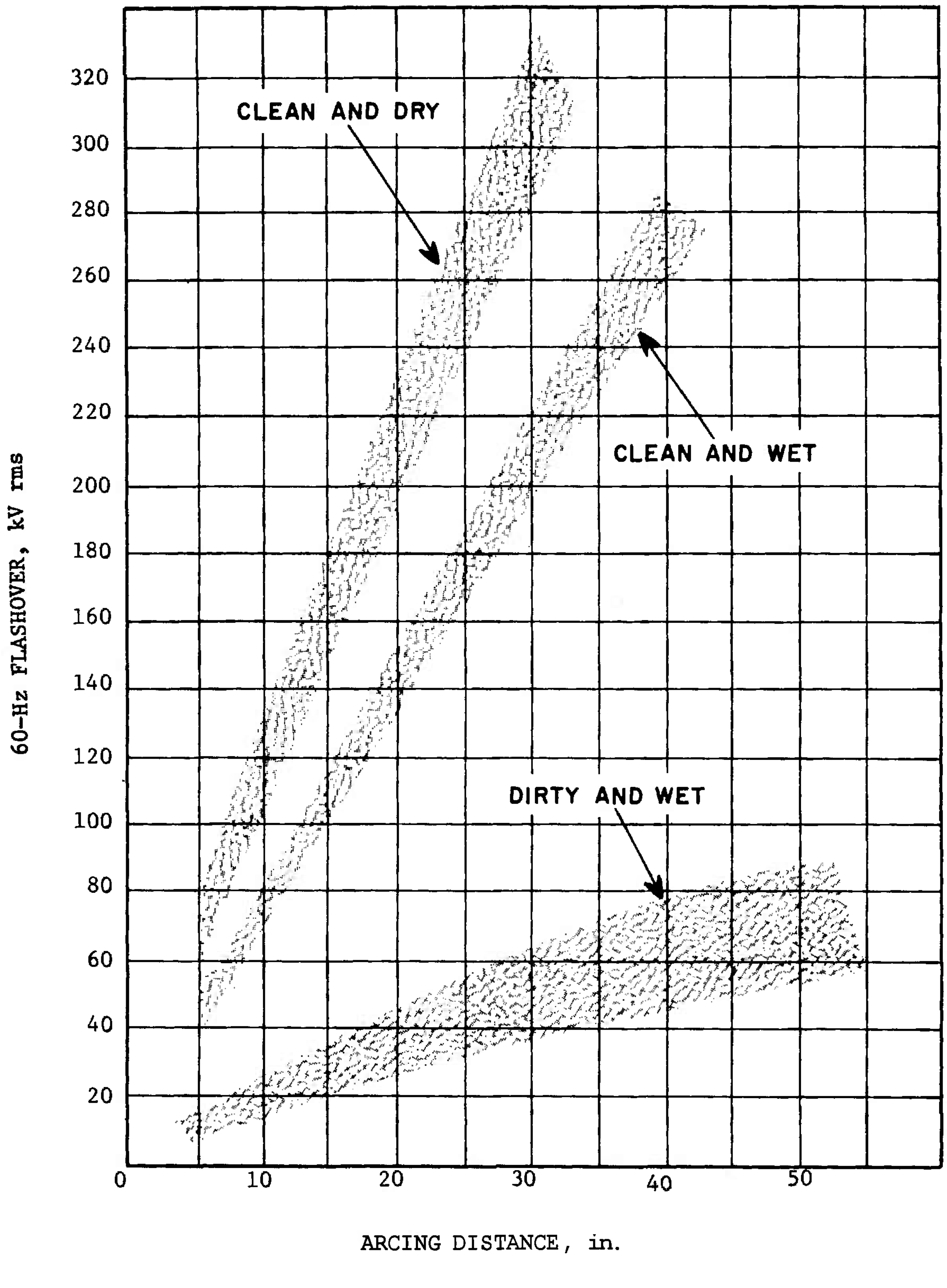


FIGURE 3-23. 60-Hz Flashover Voltage of Dirty Insulators (various types and sizes, plotted as a function of the arcing distance).

For insulators in a strong electric field such as on high voltage powerlines, the buildup of the film is aided by the attraction of airborne particles to the areas having large voltage gradients. Silica and silicate dust are not as critical in this phenomenon as salts or certain deliquescent atmospheric pollutants. See Chap. 2, "Atmospheric Pollutants", for a more detailed discussion on this subject.

3-5.4 ELECTRICAL CONTACTS AND CONNECTORS

As previously stated, industrial particulate matter can, under certain conditions, accelerate the corrosion rate of metals. Robbins (Ref. 37) states that the effects of particulate material from industrial sources on electrical contacts are almost entirely chemical rather than physical or mechanical. These effects are discussed in Chap. 2 of Part Two of this handbook series.

Naturally occurring sand and dust particles are generally poor conductors, especially when dry. Therefore, on switches, relays, or any electrical contacts, they degrade the component operating characteristics by increasing the contact resistance (Ref. 34). For low voltages, a sand particle between the contacts can cause system malfunction; for high voltages, the increased contact resistance can cause arcing and rapid deterioration of the contact surfaces.

The accumulation of sand and dust in electrical connectors can (1) make connections and disconnections difficult, (2) erode the contact surface area through abrasive action when connections and disconnections are made, and (3) increase the contact resistance.

3-5.5 ELECTROSTATIC EFFECTS

Electrons are easily attached to grains of sand- or dust-containing compounds, such as silicon dioxide, because of the high electron affinity of the oxygen. Different theoretical calculations of the maximum number of electrons that can be attached to a grain of dust 10 μm in diameter and with a density of 2.3 g cm^{-3} have been made. The results vary from values less than 2,800 e to 7,600 e, where e is the electronic charge (Ref. 38).

The mechanism of dust electrification has been studied in laboratory experiments and, although the problem is still not fully understood, some essential conclusions about silica dust are summarized as follows (Ref. 27): (1) electrification of dust particles occurs at the instant of dispersal into a cloud; (2) the larger, heavier particles acquire positive charges, and the finer, lighter ones, negative charges (the larger ones settle out leaving a negative potential gradient); (3) small concentrations of dust in the air are enough to give a measurable potential, the magnitude of which increases with the dust concentration; and (4) humidity has no significant effect on electrification unless it is so high that the particles stick and cannot be dispersed.

Measurements of the vertical electric field at ground level and 1 m above ground level were made by Bicknell and reported by Stow (Ref. 39). For a moderate storm, the potential at 1 m was 5 kV m^{-1} and at ground level was 50 kV m^{-1}. For a more severe storm, readings greater than 20 kV m^{-1} were observed at 1 m, and greater than 200 kV m^{-1} at ground level. Bicknell suggests that the field was due mainly to positively charged sand particles blowing along the ground rather than dispersed clouds of negatively charged particles at altitudes greater than one meter.

Fig. 3-24 (Ref. 40) is a record of the electric field as a function of time' associated with a large dust devil in the Sahara Desert. The dust devil was estimated to be between 100 and 200 m high and about 8 m in diameter, and its distance of closest approach to the measuring instrument was about 30 m. Fig. 3-25 (Ref. 27) is a 24-hr record of the potential gradient and the air-to-earth current flow during the dry windy season (Harmattan season) around the Sahara Desert. This is a typical diurnal reversal for this season of 4,500 V m^{-1}. The positive potentials, usually less than 100 V m^{-1}, occur at night and are referred to as normal fair-weather values. The reversals in potential are common around noon as a result of sand particles being kept aloft by convection currents.

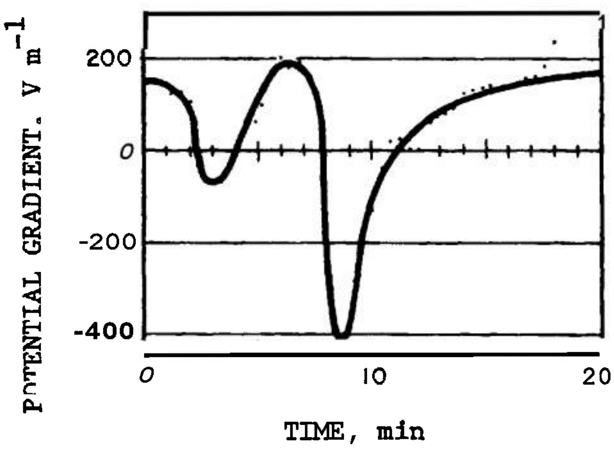


FIGURE 3-24. Potential Gradient Record for Sahara Dust Devil (29 SEP 59, with closest approach of 30 m).

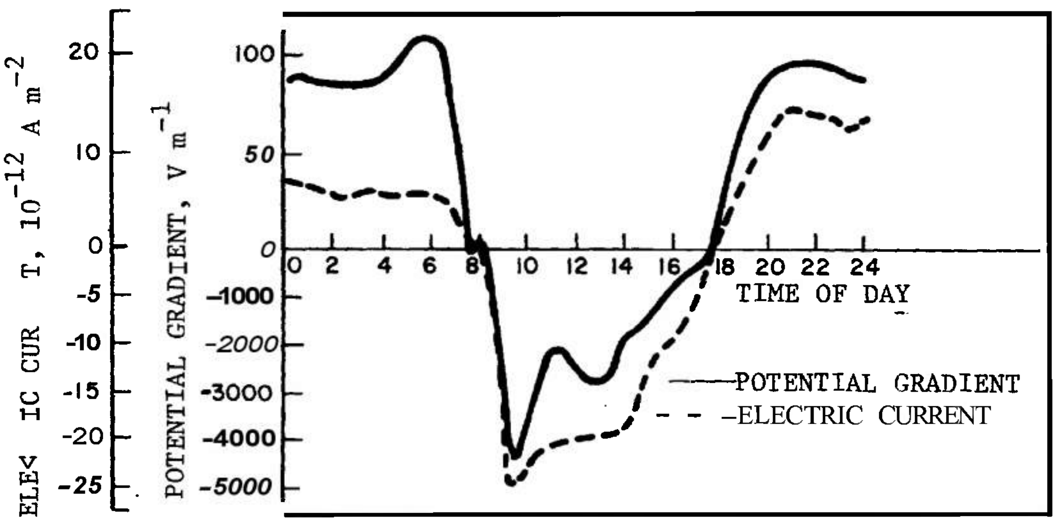


FIGURE 3-25. Air-to-earth Current and Potential Gradient of a Dust Cloud Over West Africa (note scale for negative values.)

3-5.6 GUIDED MISSILE OPERATION

The subsystems of a guided missile system and its support equipment are subject to the same deleterious effects of sand and dust previously described in this chapter. The following specific effects have been reported (Ref. 16):

(1) The control of the guided missile system can be endangered by the additional friction produced in the hinge bearings of control surfaces or jet vanes.

(2) The sensitivity of the guidance system can be reduced by abrasion of the radome and/or tracking window, or by interference with the propagation of electromagnetic radiation.

(3) Explosions or motor burnout can occur because of hot spots produced in cooling passages of regeneratively cooled liquid rockets.

(4) Sand and dust in propellants or propellant systems can clog up fuel-metering passages and thus cause erratic operation or even explosions; particulate impurities contacting heavily concentrated hydrogen peroxide have also caused explosions.

3-5.7 EFFECTS ON VISIBILITY

Particle size and shape as well as concentration of the dust affect visibility in a dust environment. Thus, consistent correlation between visibility and concentration is difficult to achieve since most visibility measurements were merely observations of people caught in the storm.

A series of tests measuring the concentration of dust clouds created by moving vehicles also included visibility, evaluations by an observer standing by the sampling instrument (Ref. 4). Tests where the particle size distribution was 28 percent by weight less than 74 μm-diameter gave the results shown in Table 3-15.

Clements (Ref. 22) states that in desert sandstorms where most particles are within 2 or 3 ft of the surface, the visibility of a person standing is usually on the order of hundreds of feet.

3-5.8 OTHER EFFECTS

(1) *Cooling systems.* A dust layer on wet or oily surfaces of cooling systems, particularly heat exchangers and condensers, reduces the rate of heat transfer from the surface and thereby lowers the cooling efficiency of the system (Ref. 6).

(2) *Lubricated surfaces.* Sand and dust on lubricated surfaces such as on bearings, control cables, and hydraulic struts mix with the lubricant, forming a highly abrasive compound that increases the rate of wear of the components (Ref. 28).

(3) *Paint films.* Dust particles on wet varnish and paint films produce visible imperfections and reduce the electrical resistance and anticorrosive properties of the film. Laboratory tests have shown that dust settling on freshly painted metal panels during the drying

TABLE 3-15. VISIBILITY IN DUST (Ref. 4)

Dust concentration, mg ft^{-3}	Visibility, ft
0.1	No effect
0.2	No effect
0.231	50
0.235	50
0.87	10
2.41	10
2.5	0

3-6 SAND AND DUST PROTECTION

The deleterious effects of sand and dust can be reduced or eliminated by one or more of the following procedures:

(1) Choose abrasive-resistant materials for exposed surfaces; for example, cover metal helicopter blades with a 1/8-in. polyurethane film (Ref. 8), and keep the radius of curvature of bends in air ducts large and use a hard substance.

(2) Provide filters in the air intake systems of air-breathing engines and crew or instrument compartments requiring outside air for proper operation.

(3) Provide dust shields for exposed surfaces susceptible to abrasion, such as bearings.

(4) Recommend frequent greasing and cleaning of equipment.

(5) Place delicate instruments and equipment in protected positions.

(6) Ground and/or shield properly all electronic equipment installed in localities having a high sandstorm risk in order to avoid build-up of electrostatic charge.

(7) Use hermetic sealing where possible, especially for electronic equipment such as relays and switches.

(8) Provide a conditioned environment, such as those designed for telephone relay stations, to protect against the stress corrosion cracking of wire spring relays due to high concentrations of nitrate dust (Ref. 37); this involves installation of filter, dehumidifier, and air conditioner.

(9) Adopt designs that minimize formation of sand and dust films on surfaces.

3-7 DESIGN AND TEST

An infinite number of combinations are possible for types of military equipment and for the sand and dust environments that the equipment is likely to be exposed to during its life. However, three broad levels of dust exposure appear to cover nearly all military materiel:

(1) The first and least severe level pertains to equip-

this environment includes all stationary and auxiliary equipment exposed to the dust clouds generated by: other equipment and all ground vehicles used in normal military operations.

(3) The third and most severe level would include all aircraft and all items used in association with helicopters and other light aircraft that take off and land on unpaved surfaces.

The first two levels are somewhat normal conditions for military equipment, whereas the third is classified as severe.

With minor changes, the test dust specified by MIL-STD-810, *Environmental Test Methods,* would be adequate for levels one and two (Ref. 41). One possible change would be to specify quantities of other minerals in the test dust. Other minerals might include corundum, which is more abrasive than quartz; jeweler's rouge (Fe_2O_3), which has a polishing effect on metal surfaces; and china clay, because of its possible breakdown at high temperatures, with the release of large quantities of energy and the resultant formation of highly abrasive particles.

For testing against the severe dust condition, as experienced by vehicles operating on dry dusty terrain, the most representative, and perhaps the most economical method would be to test under actual environmental conditions. For example, the dust-sampling exercises carried out with tanks, the Overland Train

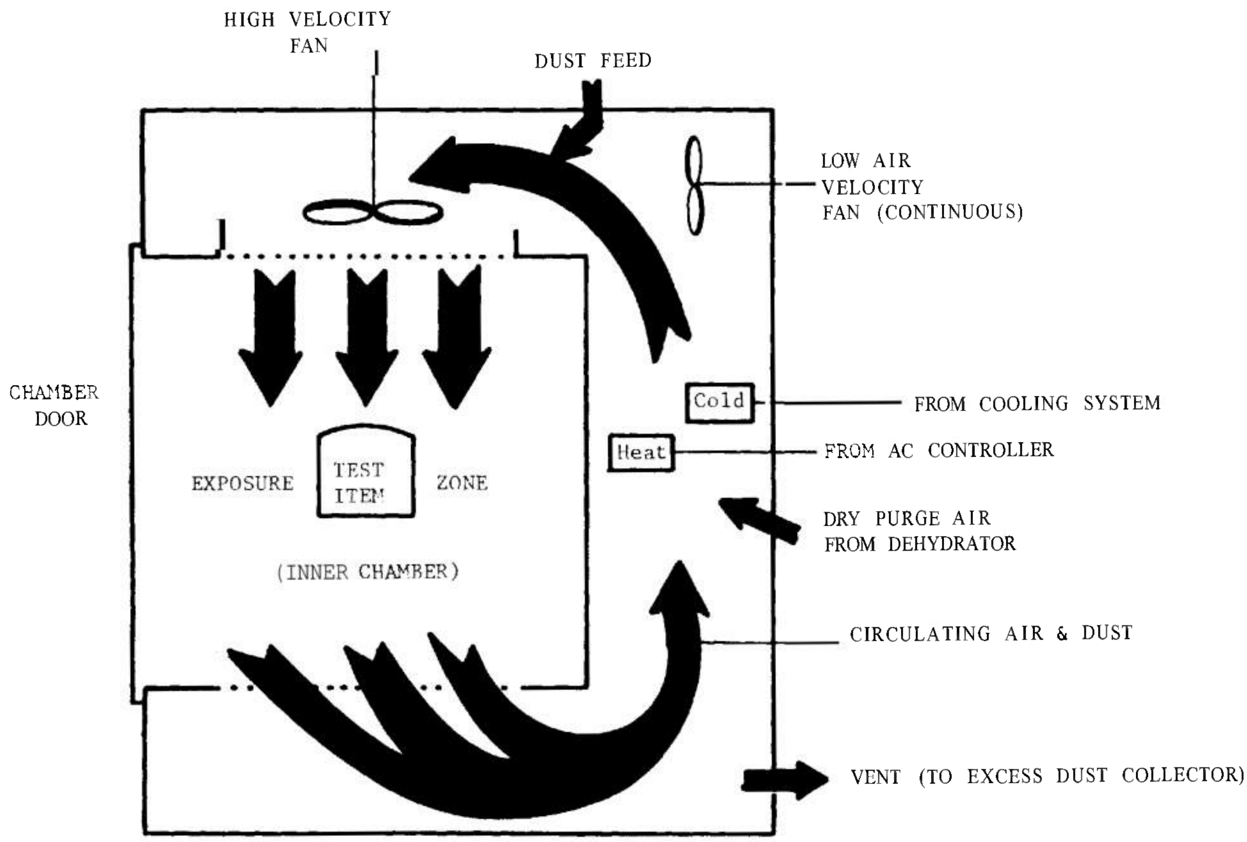


FIGURE 3-26. Functional Diagram of Dust Test Chamber.

Mark II, helicopters, and VTOL aircraft (reported in this chapter) on concentration and particle size distributions demonstrated very convincingly the severity of the dust environment generated by these vehicles. The Vehicle Dust Course at Yuma Proving Ground was disked prior to the testings. This serves to keep the surface conditions as standard as possible from test to test which is desirable even if it does result in a condition more severe than will normally be encountered by the vehicle. Support equipment could also be tested by subjecting it to the rotor downwash of a helicopter hovering over such a prepared dry surface.

3-8 TEST FACILITIES

3-8.1 SIMULATION CHAMBER

The dust test facility of the U S Army Electronic Proving Ground at Yuma, Ariz., fulfills the requirements of MIL-STD-8 10, when operated in accordance with MTP 6-2-537. The facility is used to determine the adverse effects of simulated dry-dust (fine sand) laden atmosphere on the performance and physical characteristics of communication, surveillance, and avionic electronic equipment relative to requirements expressed in applicable documents on Required Operational Capability (ROC). Data describing the test chamber follow:

(1) ***Chamber configuration.*** The inner exposure chamber measures 4 by 4 by 4 ft. It has a dusttight door with an observation window that forms the front wall and substantial gratings that form the essentially open ceiling and floor. The door contains a window for observation of test conditions. Within the inner chamber, racks support test items of various configurations in the exposure zone without affecting the dust flow. Fig. 3-26 shows a functional schematic diagram of the inner and outer test chambers.

(2) ***Air circulation system.*** The low velocity fan circulates the dust-laden air through the chamber at velocities between 100 and 500 fpm, and the high velocity fan increases the airflow up to about 2,000 fpm.

(3) ***Relative humidity control.*** Low relative humidity levels are maintained by introduction of about 4 ft^3

min^{-1} of compressed air that has been dried to a relative humidity of less than 5 percent by a desiccant-type dehydrator unit.

(4) ***Dust density control system.*** Dust (silica flour 140-mesh) is dispensed from a hopper to the chamber through a valve regulated by a dust density control unit, which maintains a chamber dust concentration of 0.3 ± 0.02 g ft^{-3}. This unit is a smoke meter which senses the density of dust in a light beam falling on a photoelectric cell and gives a continuous real-time readout of density in g ft^{-3}.

(5) ***Temperature control system.*** The circulating air is maintained at a selected temperature by the combined action of cooling, heating, and control systems. The regulating span is approximately 1 deg F. The settings normally used are 73° and 145°F.

3-8.2 DESERT TESTING FACILITIES

The Yuma Proving Ground, Yuma, Ariz., consists of some 375 mi^2 of American desert set aside for testing military equipment such as trucks, tanks, and helicopters to determine their capability to function in a desert environment. Since it is a natural desert, the combination of high temperature, low humidity, and full solar radiation is realizable a high percentage of the time. Also, an abundance of sand and dust sized particles can be assured by plowing and disking the test surface before and, if necessary, during the test.

The severity of the dust environment attainable by this method is established by the results of the tests on the U.S. Army Overland Train Mark II (Ref. 7) and the H-21 helicopter test (Ref. 8). Both tests were conducted at the Yuma Proving Ground.

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CHAPTER 4

VIBRATION

4-1 INTRODUCTION

Military materiel is exposed to vibration in both logistical and operational phases of its life cycle. Vibration constitutes an important environmental factor that often degrades performance of materiel and otherwise affects military operations. It is important to note that much materiel, because of its innate nature or because its ultimate operational use has required vibration-resistant design, can survive any common vibratory stress. A second large category of materiel is readily susceptible to vibration damage. This includes most electronic equipment, precision instruments, and many complex assemblies.

The most severe vibration encountered by most materiel is that found in transportation systems. The transport vehicle as well as the handling and service systems is often characterized by severe vibratory stresses. Thus, data on vibrations encountered in transportation systems as well as techniques for packaging or cushioning to shield materiel from vibrations are important to the consideration of this environmental factor.

This chapter provides a general framework of information on vibration for the design engineer who requires such knowledge in his activities; it is not directed to the specialist. Sufficient source information is provided to direct the handbook user to more comprehensive data sources when these are required. Subjects included in this chapter are the background basic engineering knowledge (included in this introduction), a description of vibration sources, measurements, compilations on vibration effects, vibration control methods, simulation, testing, and specifications.

Vibration combines with other environmental factors to produce additive or synergistic effects on materiel. The relationships of vibration to acoustics, shock, and acceleration are particularly strong. In addition, natural environmental factors such as temperature, wind, and humidity affect both vibration and the effects of vibration on materiel. Information relevant to these combined effects is found in this chapter as well as in other chapters of this handbook and in other parts of the Environmental Series of Engineering Design Handbooks.

The remainder of this introduction is directed toward introducing the subject of vibration. This is accomplished by describing the semantics and mathematical tools employed in the field. Vibration is a large and complex field of science and engineering to which a large number of texts are devoted and in which current research justifies several specialized journals.

Vibration is an oscillating motion of a mechanical system about an equilibrium condition. The nature of the vibration as a function of time determines whether it is classified as a periodic or random vibration. A periodic vibration repeats itself exactly, after a period of time called the period, as expressed by the equation

$$y(t) = y(t + T) \tag{4-1}$$

where

$y(t)$ = any quantity associated with the vibration, such as displacement, acceleration, or stress

t = time

T = period of the vibration

The frequency of the vibration f is given by

$$f = 1/T \tag{4-2}$$

Periodic phenomena—also called steady-state vibrations—can be separated into harmonic and complex types. A simple harmonic vibration can be described by a sine or cosine function. Such a function is shown in Fig. 4-1(A) as is a more complex periodic function for comparison, Fig. 4-1(B).

Complex periodic phenomena can be represented in a series of harmonic functions using a Fourier series expansion. The components of such a series are at frequencies that are multiples of a fundamental frequency as expressed mathematically by

$$y(t) = C_0 + C_1 \cos(2\pi f_1 t + \phi_1) + C_2 \cos(4\pi f_1 t + \phi_2) + C_3 \cos(6\pi f_1 t + \phi_3) + \cdots = C_0 + \sum_{n=1}^{\infty} C_n \cos(2\pi n f_1 t + \phi_n) \quad (4\text{-}3)$$

where

f_1 = fundamental frequency of the periodic function
$y(t)$ = any property of the vibration, e.g., displacement
$C_0 \ldots C_n$ = constants describing the amplitude of the Fourier components
ϕ = phase angle of Fourier components

This expansion states that a periodic function consists of a DC component C_0 and an infinite number of sinusoidal components having amplitudes C_n and phases ϕ_n. The frequencies of the sinusoidal components are all multiples of f_1, the fundamental frequency. Many periodic functions consist of only a few components. A simple sine wave harmonic motion has a Fourier series in which all values of C_n are zero except that $n = 1$. For aperiodic or random vibration, the amplitude-time history never repeats itself exactly. In essence, any given sample record presents a unique set of data and is a sample of a large set of possible records that might have occurred. The collection of all possible records that might have occurred is called an ensemble, which describes the random process (Ref. 2). Because a random process is not an explicit function of time but is probabilistic in nature, a prediction of exact amplitudes at some future time is not possible. Consequently, a random process is described in terms of statistical averages rather than exact analytic functions. The techniques for analyzing and interpreting random vibration data are different, therefore, from those employed with periodic vibration data. Fig. 4-2 is representative of a random disturbance. Statistically, the probability of finding the instantaneous magnitude of the vibration within a certain range can be predicted.

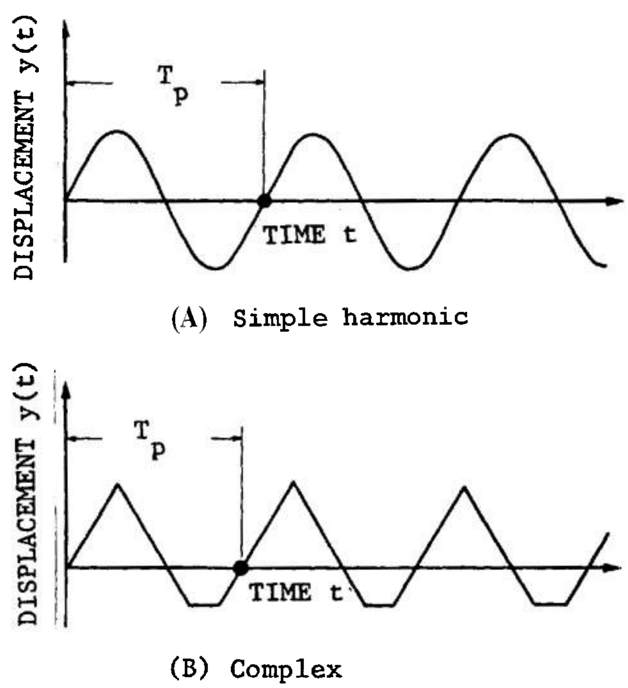


FIGURE 4-1. Periodic Waveforms (Ref. 1).

With the specification of the vibration input to a system, it is possible to perform a mathematical analysis and obtain the system response. One of the simplest models of a vibration system is a single-degree-of-freedom system consisting of a mass on a spring with a damper or damping factor (see Fig. 4-3). If the system behaves linearly, then the equation of motion for no external force applied is

$$m(d^2y/dt^2) + C(dy/dt) + ky = 0 \quad (4\text{-}4)$$

where

m' = mass of the isolated system, g
k = spring or isolator stiffness, g s^{-2}
C = damping, g s^{-1}
y = displacement, m

When a force $f(t)$ is applied to the system, the equation of motion becomes

$$m(d^2y/dt^2) + C(dy/dt) + ky = f(t) \quad (4\text{-}5)$$

Solution of the equation gives the displacement $y(t)$ of the mass m produced by the excitation $f(t)$. The analysis of various types of systems and their response to various types of vibration inputs are discussed in detail in the literature (Refs. 3-10).

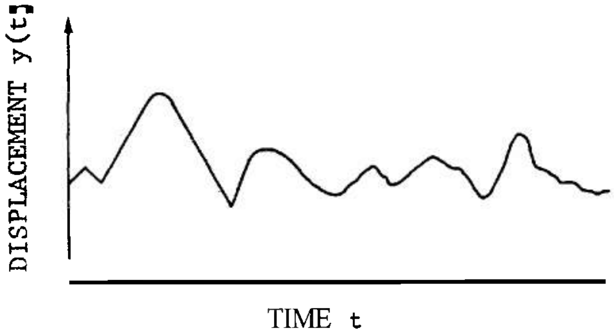


FIGURE 4-2. Random Disturbance (Ref. 1).

Two parameters, amplitude and frequency, are required to describe simple harmonic motion. In actual tests, the amplitude can be that of the linear or angular displacements, velocity, or acceleration measured with respect to arbitrarily chosen rectilinear axes (Ref. 11). Each of these parameters of motion is a function of time. If the vibratory motion is complex periodic motion, then the amplitude and frequency of each sinusoidal component must be described. Random vibration can be described in the same manner. However, since random vibration actually has an infinite number of sinusoidal components, special methods must be used in analyzing the data. A term often used in vibration testing is the root mean square of the amplitude (rms). The rms value is the square root of the average of the squared amplitudes. For sinusoids it is 0.707 of the peak amplitude. For complex periodic motion, the rms value is the square root of the sum of the squares of the rms values of the component sinusoids. The power associated with the vibration is directly proportional to the square of the rms values of the acceleration. A proportionality factor (a function of the mass and natural frequency of the system) is usually ignored so that the square of the rms values is usually—although incorrectly-called power.

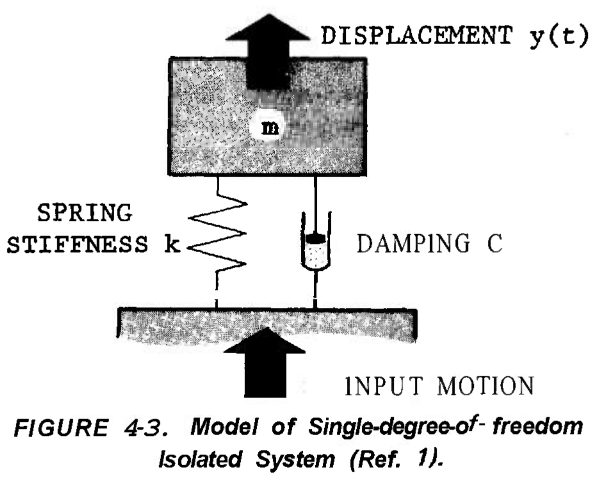


FIGURE 4-3. Model of Single-degree-of- freedom Isolated System (Ref. 1).

Thus, a variety of vibration parameters can be measured. In one study (Ref. 12) the vibration parameters and units of measurements in Table 4-1 were suggested as being useful in the measurement and analysis of data. In actual practice, acceleration is the parameter most often employed because its measurement is easier than either displacement or velocity.

4-2 SOURCES OF VIBRATION

Since the predominant source of vibration in the environment is transportation systems, most of the available data derive from this source. The data include on-road and off-road vehicular transportation, air transport, rail transport, water transport, and the important transportation system interfaces characterized as handling. A second important source of vibration is that related to weapons, both the firing of guns or launching of rockets and the explosion of the ammunition upon delivery. A third important source of vibration is that related to machinery, primarily rotating machinery, the most common type. The propulsion machinery in the transportation system is a primary contributor to vibration but, in addition, generators, electric motors, and other types of machinery generate vibrations to which all materiel is exposed. In some industrial environments—such as printing plants, machine shops, and textile mills—vibrations are extremely intense. Other vibration sources are important at times, e.g., seismic vibrations associated with earthquakes.

It is important to note that the source of vibrations need not be in direct contact with a structure or with materiel in order to affect it. Par. 4-2.1.3.1 discusses the coupling of vibrations between aircraft structures by acoustical transmission. A number of other examples follow, wherein acoustically coupled vibrations are important. The muzzle blasts of major caliber guns produce acoustic pressure levels that can provide sufficient loading on nearby structures to induce structural vibration. Explosions both underground and aboveground also induce structural vibrations. One of the most common relatively high-level acoustic disturbances encountered in everyday life is the sonic boom caused by the passage of an aircraft whose speed exceeds that of the speed of sound. Hubbard surveys the aerospace vehicle noise-induced vibration problem (Ref. 13). In this discussion an example is included that deals with the effect of sonic boom on house wall vibrations. The sonic boom as measured had an approximate duration of 0.5 to 1.0 s. The house wall response to the sonic boom contains large amplitude, low frequency vibrations that

TABLE 4-1. VIBRATION PARAMETERS (Ref. 12)

Vibration parameter	Common units of measurement
Displacement	Meters (inches) peak-to-peak (or double amplitude)
Velocity	Meters (inches) per second, peak, or average
Acceleration	Gravitational units g, peak, average, or root-mean-square
Jerk	g per second, peak
Force	Newtons, pounds, or tons

were identified with resonances of the vertical wall studs of the house. Higher-frequency responses were superimposed on the low frequency ones and were caused by resonances of the panels between the vertical wall studs of the house. Because the sonic boom tends to load the entire wall surface of the building in phase, the studs are very efficiently excited. Extensive discussions of vibration induced by acoustic waves are available in the literature (e.g., Chap. 48 of Ref. 10).

In addition to acoustic waves inducing vibration in structures, vibration in equipment and structures can also induce acoustic waves in the air. A wide variety of commercial and industrial machines, as a result of their operation in some vibratory mode, produce acoustical noise levels that are undesirable. These equipments include printing presses, air-handling systems, book-trimming machines, nailmaking machines, air-conditioning systems, gearing systems, and textile machinery.

Traffic movement is another source of vibration in man-made structures such as bridges, buildings, and other portable or movable equipment. In certain applications that require significantly vibration-free environments, the effects of local traffic are important.

In the subparagraphs that follow, descriptive data on the vehicular components of the transportation system, on machinery, and on seismic vibrations are presented.

4-2.1 VEHICULAR VIBRATIONS

Transportation systems expose nearly all types of materials to vibration. Although large classes of materiel are unaffected by this exposure, the detrimental effects of vibration are sufficient to cause modification or alternate selection of materiel types. Packaging of materiel to survive the many environmental factors characterizing the transportation system—of which vibration is one of the more important—has become an important factor, as described in AMCP **706-121,** ***Packaging and Pack Engineering*** (Ref. 14). Some modes of transport are sufficiently stressful to warrant separate consideration as given in AMCP **706-130,** ***Design for Air Transport and Airdrop of Materiel*** (**Ref.** 15). The reduction of vibration is an important design engineering task, as described in, for example, AMCP **706-356,** ***Automotive Suspensions*** (Ref. **16).**

Although the stress of the transportation system on materiel is one receiving much attention, materiel is still damaged in transit. The purpose of this paragraph is to describe vibration associated with vehicles, primarily as concerned with transport, but, because of the close association, is broadened to include operational vehicles. More data and information are available than could be included here and can be obtained from the references cited.

4-2.1.1 Road Vehicles

The vibration environment experienced in road transport interacts with both personnel and materiel to produce a number of undesired effects. Personnel are subject to an upper vibration limit to which they may be subjected without degrading their ability to perform useful functions. Similarly, there is a limit to the type or intensity of vibration to which materiel can be exposed without damage. Finally, the vehicles are subjected to vibrations originating at the road-vehicle interface plus those vibrations contributed by the engine or other internal operating machinery. An important factor in vehicle vibration is the acoustic noise level that results. Some transport vehicles have inherent noise levels that may cause hearing loss to the occupants (see Chap. 7 of this handbook). In addition, noise associated with the vibration environment is an annoyance and a distraction.

In a study of road vehicle noise, Priede has found that vibration in a road vehicle results from three different sources: (1) the engine, transmission system, and accessories; (2) road excitation; and (3) air buffeting (Ref. 17). Air buffeting is negligible except at very high speeds; since even then it is not usually the predominant vibration source, it generally can be ignored. Most vehicular vibration is caused by engine and road-excited vibratory sources. These are coupled directly or acoustically to the vehicle surfaces, causing them to vibrate. These emit noise, which adds to the direct noise from sources such as the exhaust, air inlet, grilles, engine, transmission, cooling fan, and tires. The noise level is a good qualitative measure of vehicular vibrations. Vibrations can be reduced by vehicle modifications. Fig. **4-4** indicates the noise generated by a 10-ton diesel truck and the effect of certain modifications on that noise, The origins of vehicular noise are listed in Table **4-2.**

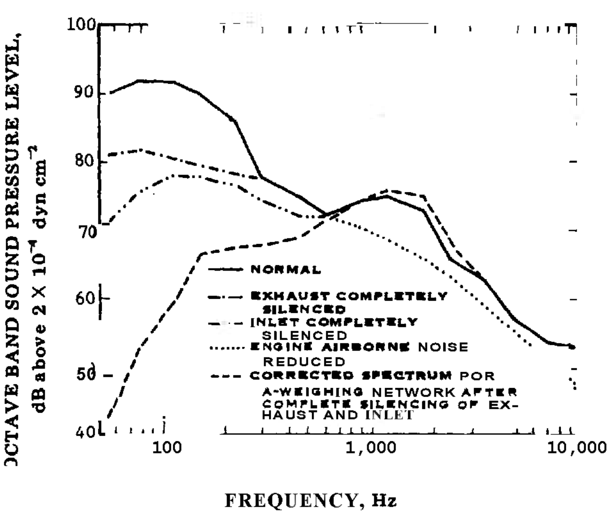


FIGURE 4-4. Noise Generated by a 10-ton Truck, Normal and With Modifications (Ret 17).

The vibration environment of cargo is defined as the motion of the surface or structure supporting the cargo or its container. Vibration frequencies in trucks, for example, depend on the natural frequency of the unsprung mass on the tires, the natural frequency of the suspension system, natural frequencies of the body structure, and the various internal vibration sources. Vibration amplitudes depend on road conditions and speed of travel. Road shocks can result in extreme body displacements and can cause unlashed cargo to bounce on the floor of the carrier. The vibrations due to sources other than the road inputs and occasional wind gusts are normally of low amplitude, provided that the vehicle has received proper maintenance. Poorly maintained vehicles can exhibit large vibration amplitudes that originate within the vehicle.

Extensive measurements of the vibration environment on a flatbed tractor-trailer have been reported by Foley (Ref. 18). Measurements were made at various locations on the cargo floor of a tractor-trailer combination both unloaded and with a cargo of radioactive material casks weighing 15 tons. Sixteen different road conditions were encountered, and representative data are presented for each and for the various speed and roadtype combinations likely to be encountered in a crosscountry trip. Fig. 4-5 presents the data for the loaded trailer. A series of filters, as described in Table **4-3,** were employed in the data acquisition system.

In Fig. **4-5** the data are plotted for the center frequencies of the filters and give the probabilities that the peak acceleration will be less than a given value for that frequency band. Measurements made at various locations on the cargo floor in the vertical direction only are summarized in the figure. The environment over most roads consists of low-level, complex vibrations upon which are superimposed a great number of repetitive shock pulses.

A similar study was performed on a modified tractor-trailer combination (Ref. 19). In these tests the effects of rebuilding and reinforcing the trailer were determined. Rg. **4-6** presents the data measured in the vertical direction for the various locations on the cargo floor for all road types and vehicle speeds. Weighting factors were employed to account for the probability of occurrence of the various road speeds and road-type combinations. Measurements for the lateral vibration direction and for the longitudinal direction were of lower amplitude. Rebuilding and reinforcing the trailer produced a significant reduction in the vibration levels at the high frequencies. Fig. **4-7** shows data at 10, 40, and **60** mph (i.e., the speed effect). Fig. **4-8** gives data for loaded and unloaded trucks, and Fig. **4-9** gives the effect

TABLE 4-2. ORIGINS OF VEHICLE NOISE (Ref. 17)

Origin of noise	Noise inside the vehicle	Noise outside the vehicle
Engine vibration	Major source of low frequency noise	Not important
Engine airborne noise	Major source of high frequency noise	Major source of high frequency noise
Engine exhaust	Not important	Major source of low frequency noise
Engine inlet	Not important	Major source of low frequency noise following exhaust
Fan noise	May be noticeable	Can be significant in low and middle frequency ranges
Road-excited vibration	Major source of low frequency noise	Not important
Road-excited tire noise	Not important	Important

of location on the truck bed on the vibration environment. The effect of direction of measurement is shown in Fig. 4-10 by plotting the 90-percent probability curves. From these data, the following conclusions are drawn:

(1) Higher speeds result in higher levels of acceleration

(2) An unloaded vehicle experiences higher levels of acceleration than a loaded one

(3) The aft location is less severe than the forward location in the vicinity of the fifth wheel.

An additional item of significance is that the peak amplitude levels are approximately 10 times larger than the rms values.

In another study Foley investigated the vibration environment on a 2-1/2-ton flatbed truck (Ref. 20). Not only were the normal operating conditions of the vehicle investigated but also certain abnormal conditions were in'cluded. The abnormal conditions were

(1) Driving with two wheels on the shoulder of the road

(2) Driving completely on the shoulder

(3) Driving off the road in desert brush

(4) Driving on the median of a four-lane highway

(5) Driving on a dirt road.

Fig. 4-11 presents the data for normal on-road conditions. Comparisons of the normal with abnormal conditions indicated little difference between the two. In the figure, weighting factors were applied to account for the frequency of occurrence of the various conditions investigated. Fig. 4-12 presents the data for the 2-1/2-ton flatbed truck under abnormal conditions. The curves represent the vertical direction composite. In this study, Foley concluded that the severest vibrations occur in the vertical direction and result from potholes and bumps. The location of the cargo on the truck bed had an effect on the severity of the vertical inputs. The cargo located over the rear wheels received the roughest ride.

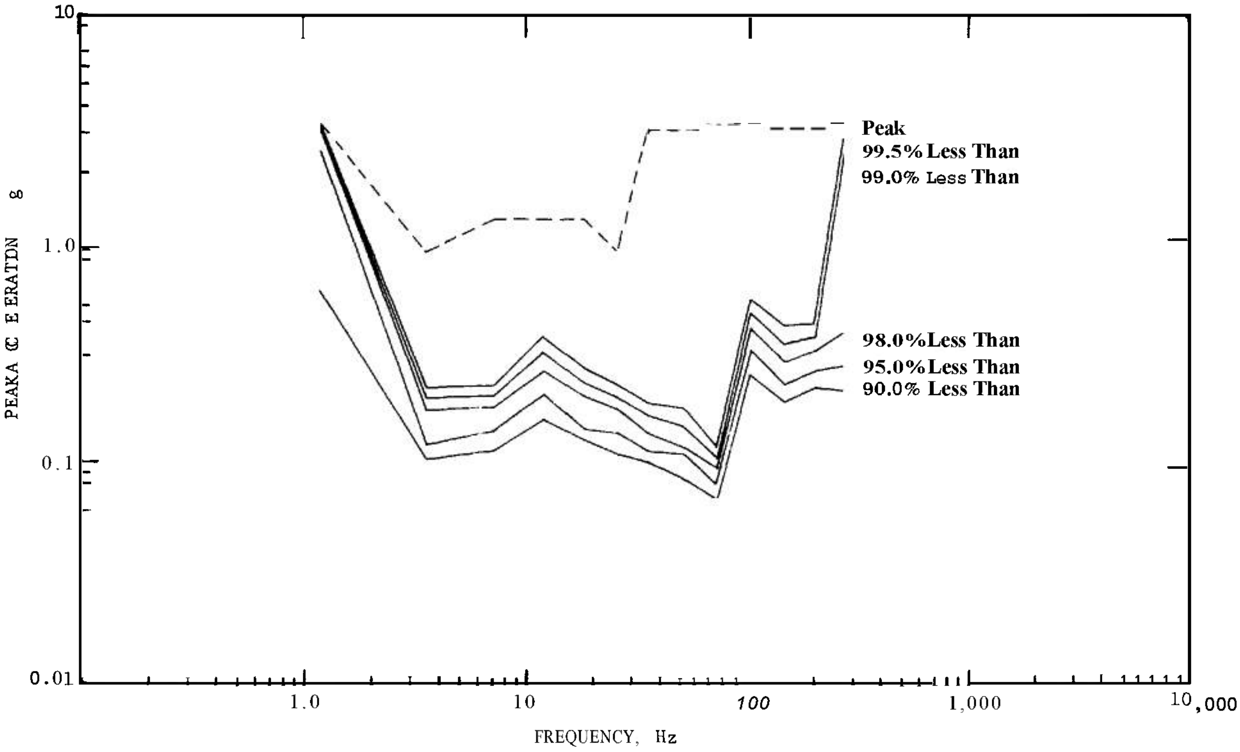


FIGURE 4-5. Vertical Vibration Spectra of Tractor-trailer (Ref. 18).

TABLE 4-3. FILTER FOR CHARACTERIZATION OF VIBRATIONS ON TRUCKS (Ref. 18)

Bandwidth, Hz	Center frequency, Hz
0 to 2.5	1.25
2.5 to 5	3.75
5 to 10	7.5
10 to 15	12.5
15 to 23	19
23 to 30	26.5
30 to 44	37
44 to 63	53.5
63 to 88	75.5
88 to 125	106.5
125 to 175	150
175 to 283	206.5
283 to 313	275.5

Schock and Paulson have examined the effect of road conditions on the vibration environment (Ref. 21). Fig. 4-13 presents some of these data. The upper curve includes peak values representing the environment experience in traversing rough roads, ditches, potholes, railroad crossings, and bridges. The lower curve was obtained using paved road data. These two curves show the differences in vibration levels between vibrations that occur while traversing various types of rough roads and a maximum vibration environment occurring during operation on paved roads.

Fig. 4-14 shows the effects of cargo load. Tests were conducted with three standard commercial tractor-trailer combinations. Tests were run at two load conditions, empty and full over a first-class asphalt road. Vertical accelerations were monitored at three locations on the cargo floor—over the fifth wheel, the center of the van floor, and over the rear axle. It can be seen from these curves that the vibration levels are little affected by load in the lower frequency ranges. In the higher frequency ranges, however, the vibration levels are reduced for loaded trucks.

The vibration environment on the cargo floor of an air-ride trailer van has been determined (Ref. 22). Air-ride vans employ air bags instead of springs for the suspension system. Fig. 4-15 summarizes the vertical

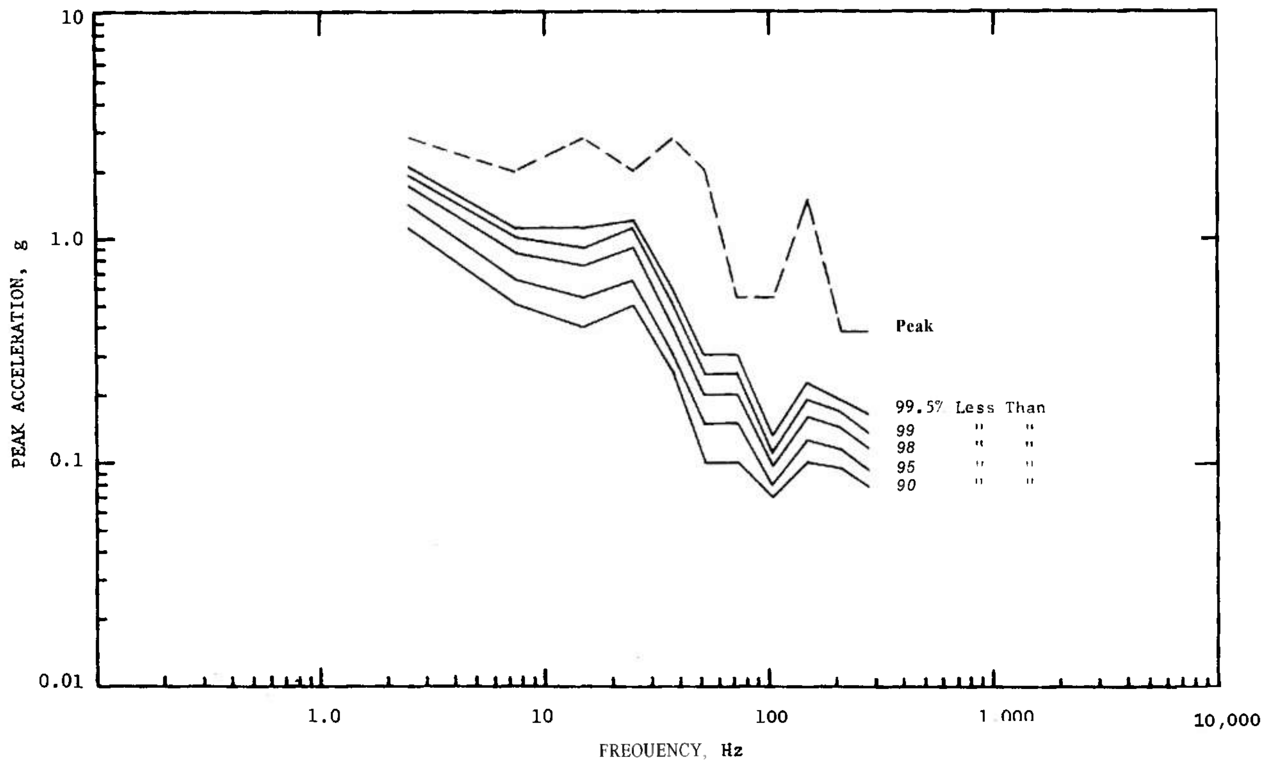


FIGURE 4-6. Vertical Vibration Spectra of Rebuilt Tractor-trailer (Ref. 19).

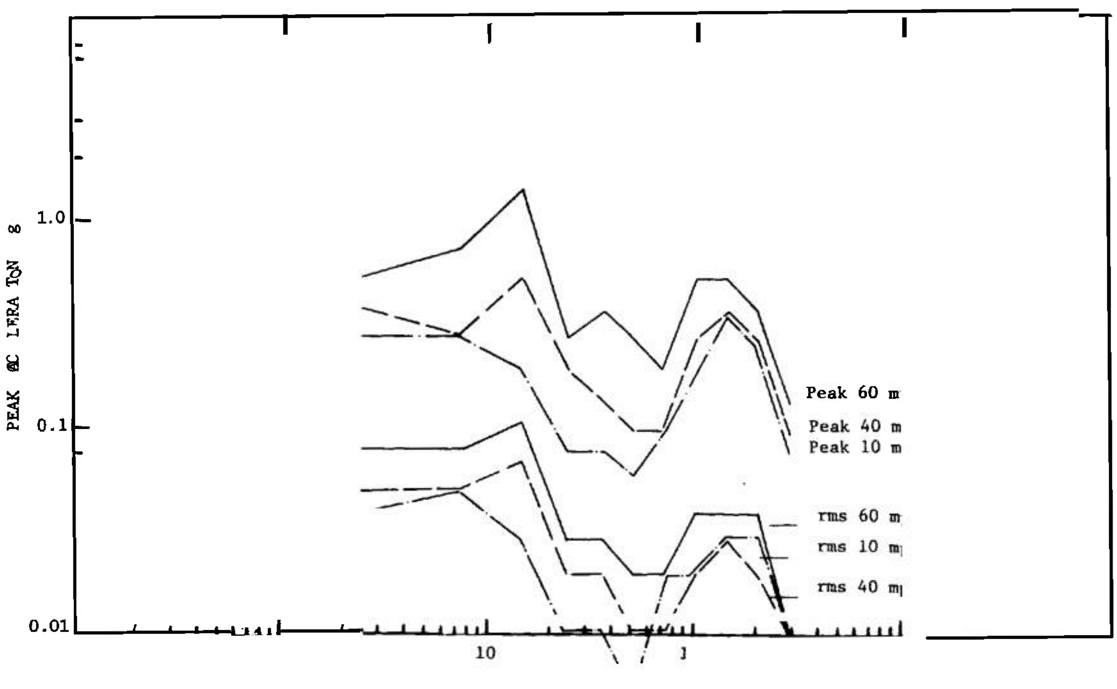


FIGURE 4-7. Vibration Spectra of Rebuilt Tractor-trailer at Various Speeds (Ref: 19).

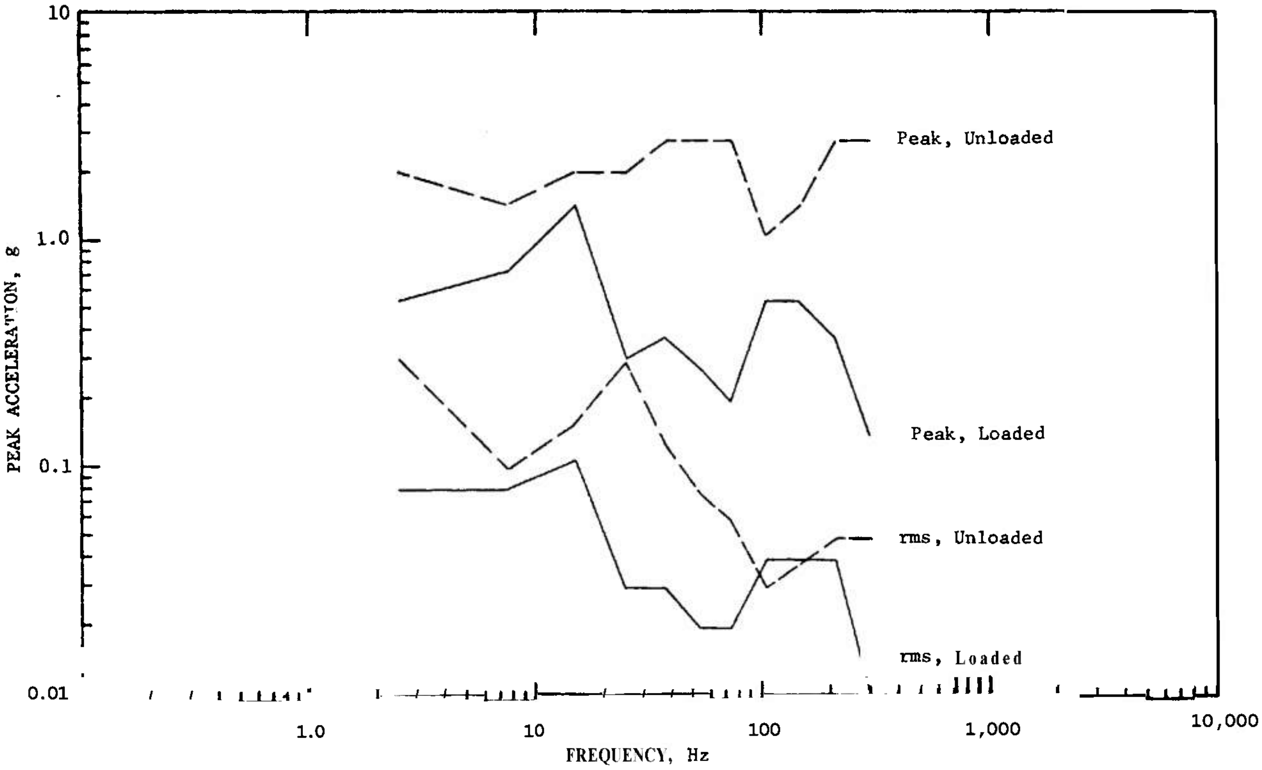


FIGURE 4-8. Vertical Vibration Spectra for Loaded and Empty Tractor-trailers (Ref. 79).

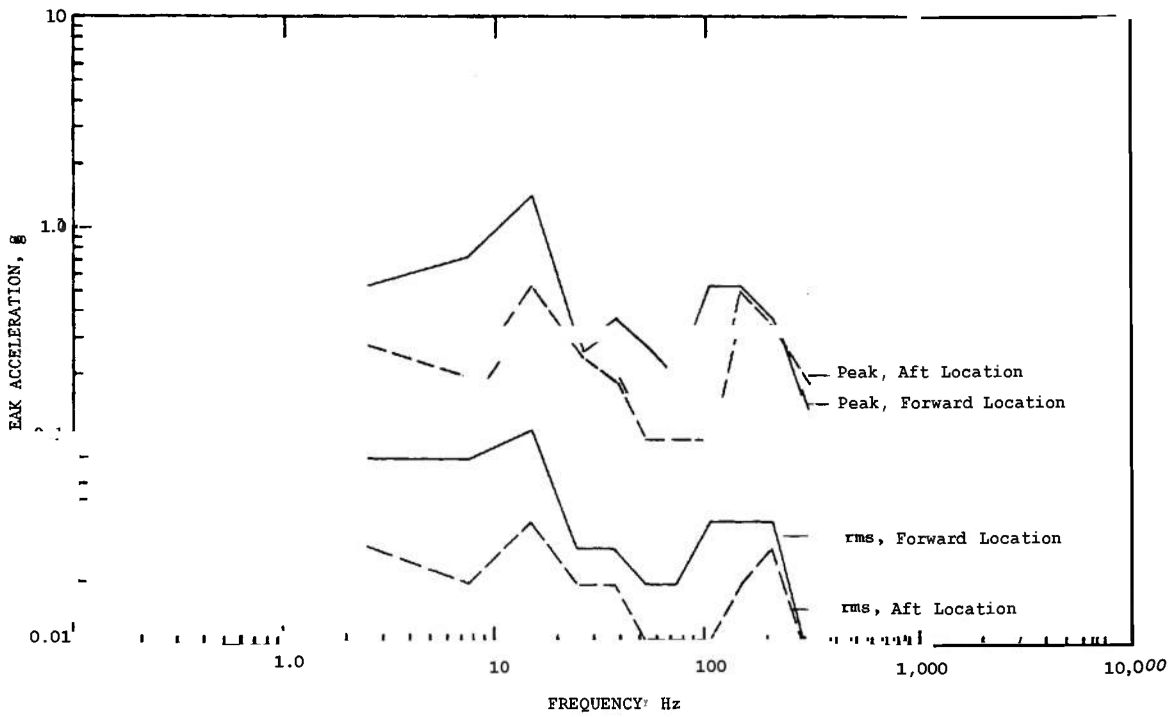


FIGURE 4-9. Vertical Vibration Spectra at Different Points on Trailer (Ref. 19).

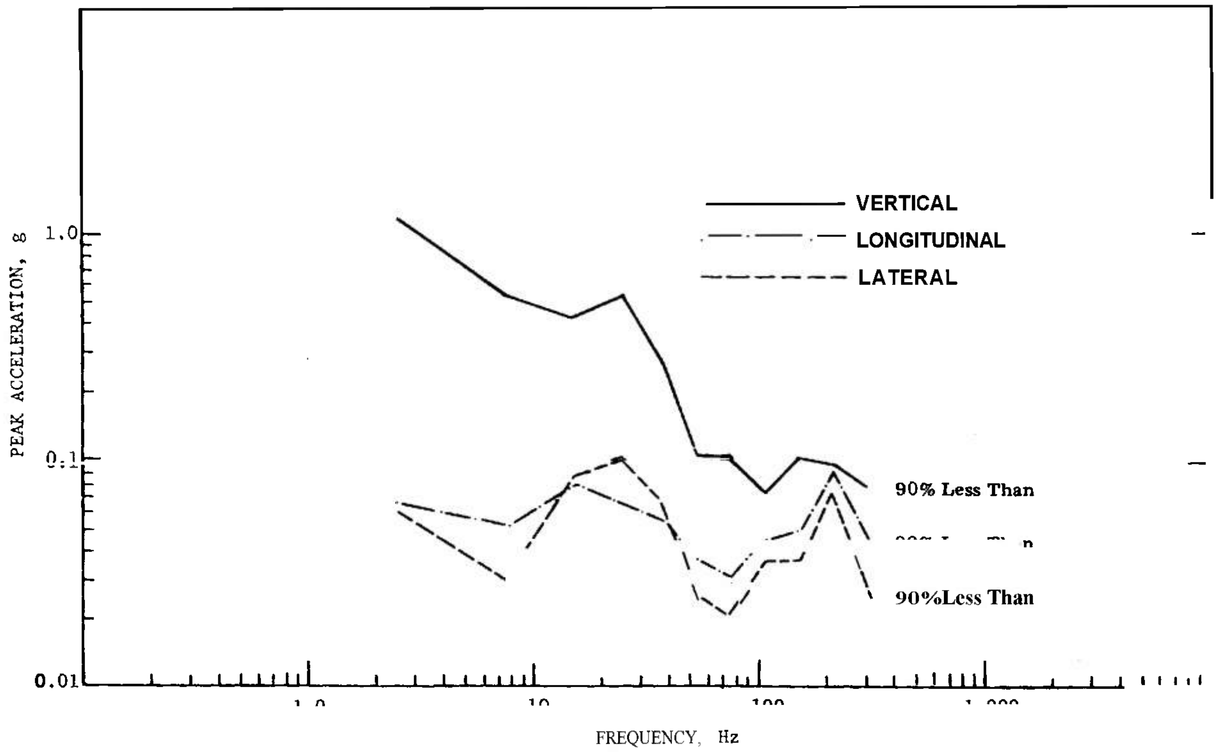


FIGURE 4-10. Vibration Spectra of Rebuilt Tractor-trailer in Three Dimensions (Ref. 19).

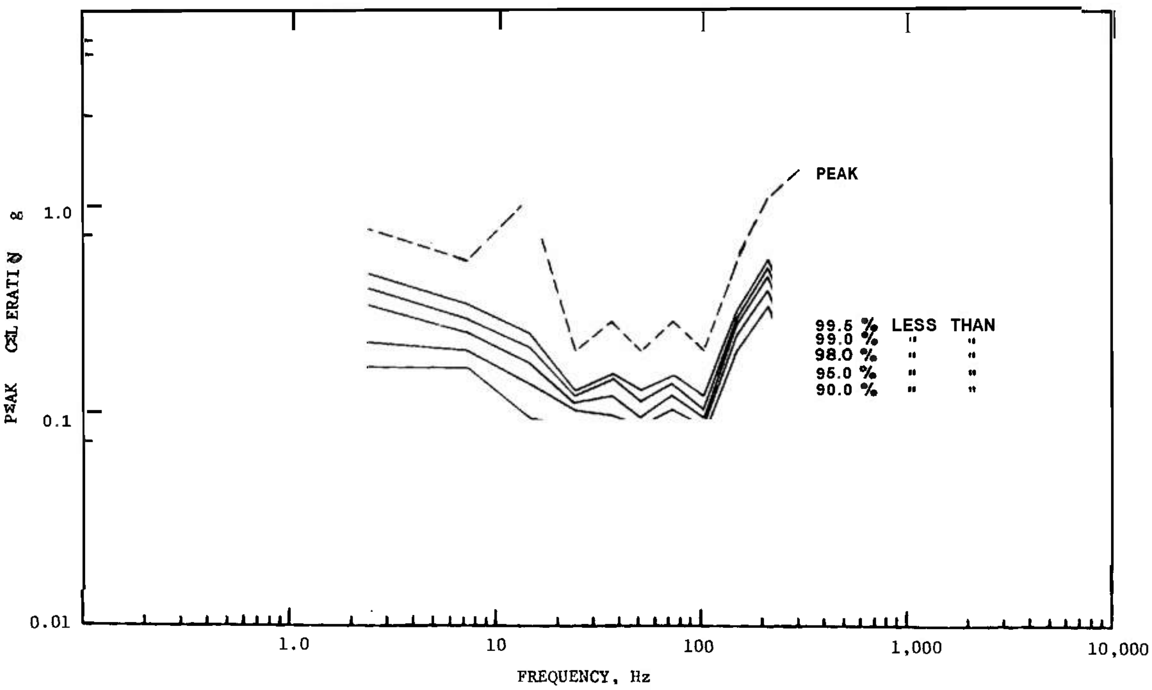
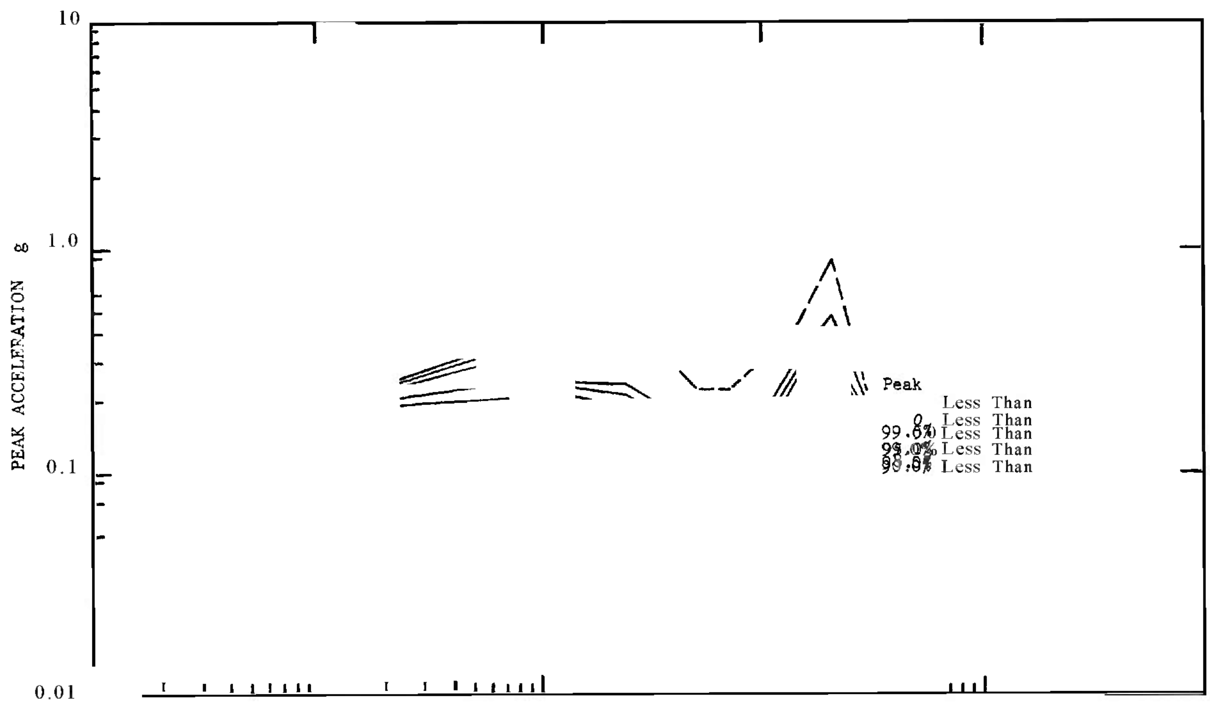


FIGURE 4-11. Vertical Vibration Spectra of Flatbed Truck With Normal Road Conditions (Ref. 20).



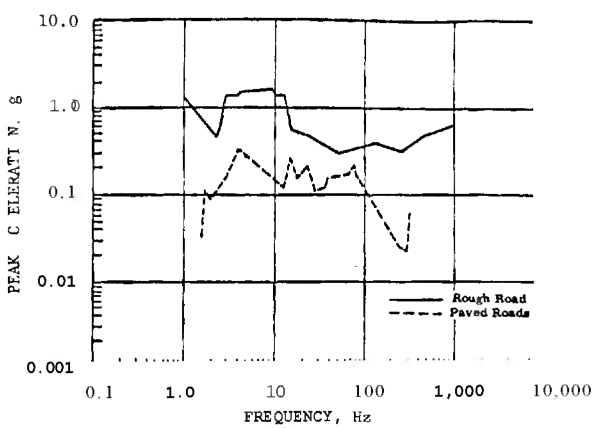


FIGURE 4-13. Comparison of Truck Vibration Spectra on Paved and Rough Roads (Ref. 21).

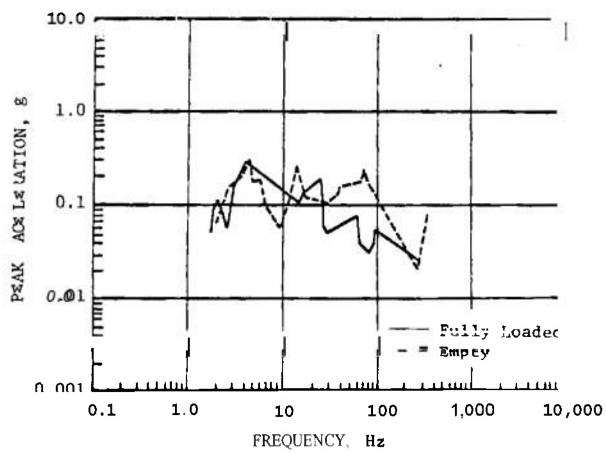


FIGURE 4-14. Comparison of Vibration Spectra for Empty and Loaded Trucks (Ref. 21).

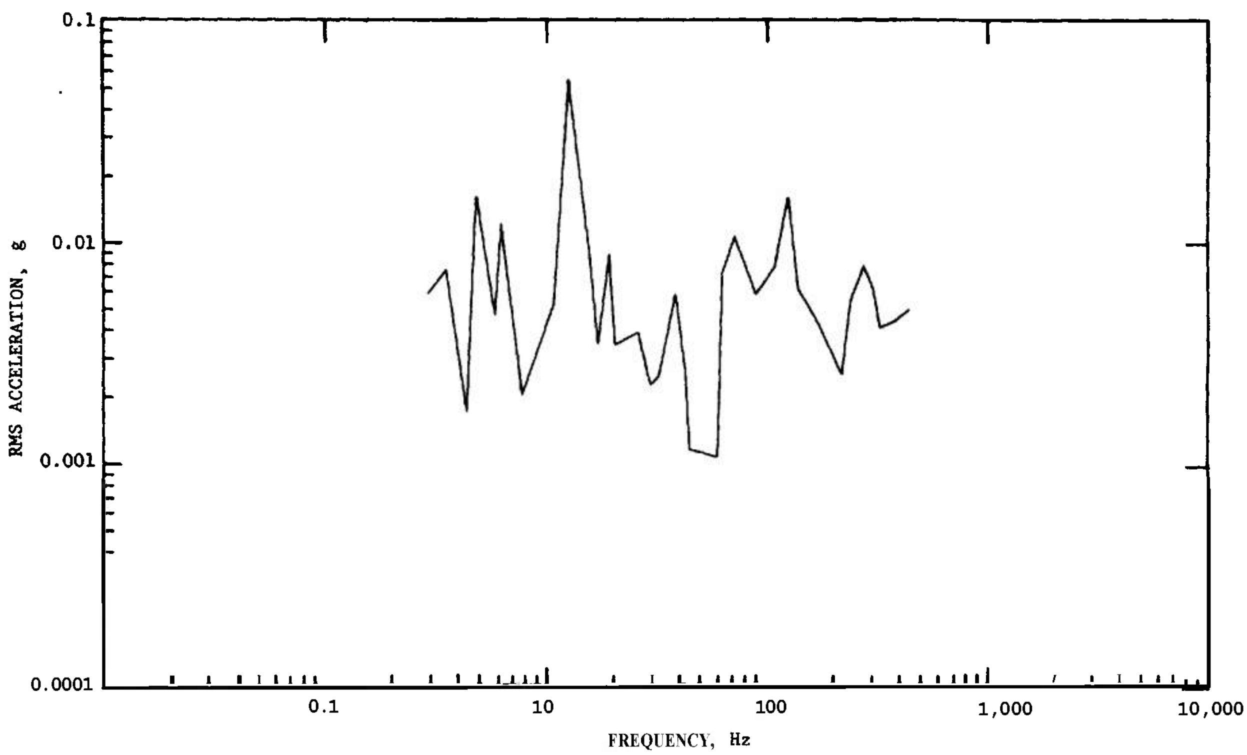


FIGURE 4-15. Vertical Vibration Spectra of a Tractor-trailer With Air-ride Suspension (Ref. 22).

component of the vibration environment recorded during cross-country shipment of fragile components.

The vibration on a single rear axle panel truck with leaf spring suspension is shown in Fig. 4-16 (Ref. 23). Only the vertical vibrations are shown because the longitudinal and lateral vibrations were relatively minor. The most severe vibrations occurred at the rear center. The lowest levels of vibration were recorded at two positions, a position far forward and in the center of the truck.

To illustrate the vibration environment on a tracked vehicle, the dynamic environment of an M113 Armored Personnel Carrier has been measured (Ref. 24). Data were obtained over a range of vehicle speeds and road conditions, and measurements were made at a number of points on the vehicle itself. Basically, vibration data were accumulated for vehicle speeds between 5 and 35 mph on both dirt and asphalt roads. Fig. 4-17 shows the accelerometer locations used in the test. Measurements were made on both hard (concrete) and dirt tracks at speeds of 5, 10, 15, 20, 25, 27, 30, and 34 mph. Broadband acceleration levels for all of the measurement locations A through E are presented in the graphs of Fig. 4-18. As would be expected, the vibration levels increased with vehicle speed. Some exceptions occurred in the measurements made on the vehicle deck and the floor (positions B and C). These locations exhibited the highest vibration levels at 29 mph. In most cases, the longitudinal vibration was lowest. Another significant feature is that a strong spectral peak was observed at the tread engagement frequency. This frequency is equal to the velocity divided by the tread length. This spectral peak appeared in all the data in varying magnitudes, usually being higher in value at the higher speeds.

4-2.1.2 Rail Transport

Vibrations in railroad cars result from a variety of sources. Vertical vibrations are caused by unevenness or roughness of the rail, discontinuities at the rail joints, flat spots on the wheel, and wheel unbalance. Lateral vibrations are caused by the tapered wheel treads and the wheel flanges as well as by the tracks. Longitudinal vibrations are caused by starts, stops, and slack run-outs and run-ins. Slack run-outs and run-ins are caused by the slack in each coupler, which can build up to large values on long trains. Data from a number of sources have been compiled to describe the vibration environment in rail cars (Ref. 21).

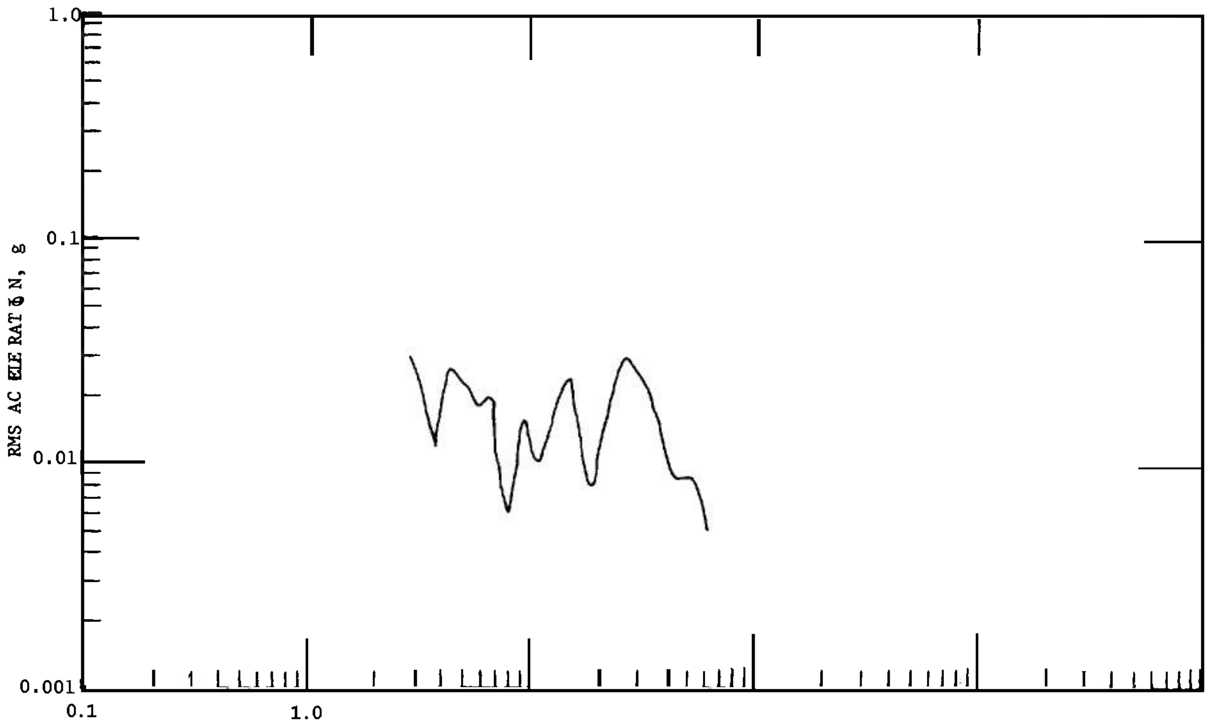


FIGURE 4-16. Vertical Vibration Spectra of Panel Truck (Ret 23).

Fig. 4-19 shows the transient and continuous vibration environments for standard draft gear. These data represent the highest vibration levels that would be encountered during over-the-road operations. In the lower half of Fig. 4-19, the effect that soft-ride equipment has on the over-the-road vibration environment is indicated. These data were obtained from the maximum acceleration recorded on the floor of a MINUTEMAN transporter railroad car during cross-country operation. The truck-suspension system for this missile car consisted of a combination air and coil spring system in the vertical direction and a pendulum system with snubbers in the lateral direction. Damping is provided in both directions of motion. In the longitudinal direction, isolation is provided by a sliding center seal and a hydraulic cushioning device.

Fig. **4-20** shows the effect of train speed on vibration levels for speeds of 20, 40, 73, and 80 mph. The data at 20 mph cannot be correlated with the other speed data because in this case frequencies greater than 25 Hz were not measured, whereas, at the other speeds, the frequency ranges of interest were 20 to 10,000 Hz. Fig. 4-21 shows the effect of orientation or direction of measurement on the vibration environment. In these data, the effect of transient vibration has been omitted. These data indicate that the vertical vibration environment is the most severe, particularly in the lower frequency ranges.

In a survey of environmental conditions involved in the transportation of materials, Ostrem and Libovicz (Ref. **25**) presented data on the railroad environment compiled by Gens (Ref. **26**). Their frequency spectral data for flatcars are in Figs. **4-22, 4-23,** and **4-24.** Fig. **4-22** presents the data for the vertical direction, Fig. **4-23** for the transverse direction, and Fig. **4-24** for the longitudinal direction. Events included in these data are train leaving switching yards, stopping, crossing intersecting track, climbing a hill, going downhill with braking, on level runs at **40** mph, crossing switches, crossing bridges, on rough track, on curves, and in tunnels. Rating factors were used to account for the probability of occurrence of these events when developing the data presented in the figures. In Fig. **4-25,** data are presented to compare the 90-percent probability curves for the longitudinal, vertical, and transverse reactions. **As** can be seen from the figure, the vertical vibration environment is consistently higher than the other two directions. In this study it was concluded that the rail environment consists of low-level random vibratidn with a number of repetitive transients superimposed on the low frequency ranges.

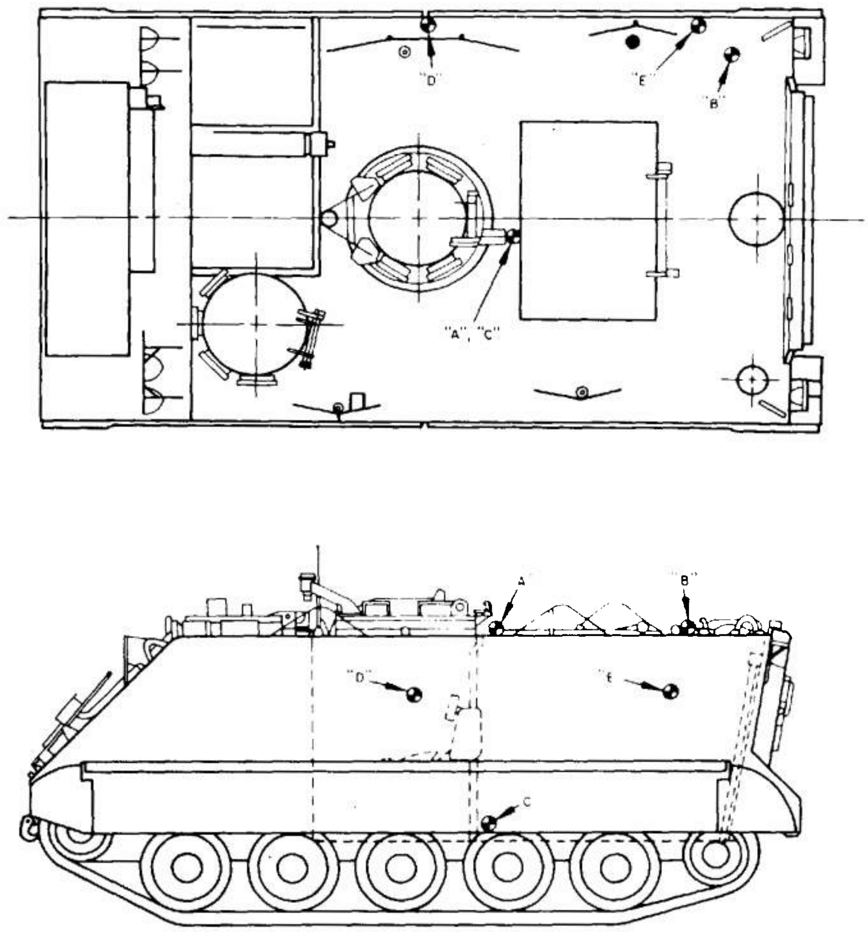


FIGURE 4-17. Accelerometer Locations on M1 13 Tracked Personnel Carrier (Ref. 24).

4-2.1.3 Air Transport

While air transport, including missiles and rockets, is of increasing importance, it actually transports a low percentage of the required materiel to an area of operations. However, the materiel conveyed by air is often the more critical and more complex items that are sensitive to vibration, all of which must be capable of air transport. Of equal importance, fixed-wing aircraft, helicopters, and other aircraft serve as operational platforms for a variety of materiel that is exposed to the environmental factors associated with such vehicles.

4-2.1.3.1 Fixed-wing Aircraft

Composite aircraft vibration envelopes for propeller-driven aircraft, jet aircraft, and helicopters have been prepared (Ref. 21). These data are presented in Fig. 4-26. These data were obtained by using the maximum vibration levels for the respective classifications. Data for the C-123, C-130, and C-133 aircraft were used in developing the curve for propeller-driven aircraft. The curve for the jet aircraft was developed using data from the KC-135 aircraft. The curve for the helicopter employed data on the H-37 helicopter. It can be seen from the figure that the vibration levels are highest for the helicopter and lowest for the jet.

The vibrations encountered in aircraft result from runway roughness, propulsion or power plant dynamics, unbalance in propellers or rotors, aerodynamic forces, and acoustical pressure fluctuations. For the propeller-driven aircraft, characteristic frequencies are associated with the blade passage frequencies. Further, the surrounding air can also induce vibrations due to its turbulent nature. A survey of pre-1969 vibration measurements on various aircraft operating under a variety of conditions is available (Ref. 27). These data

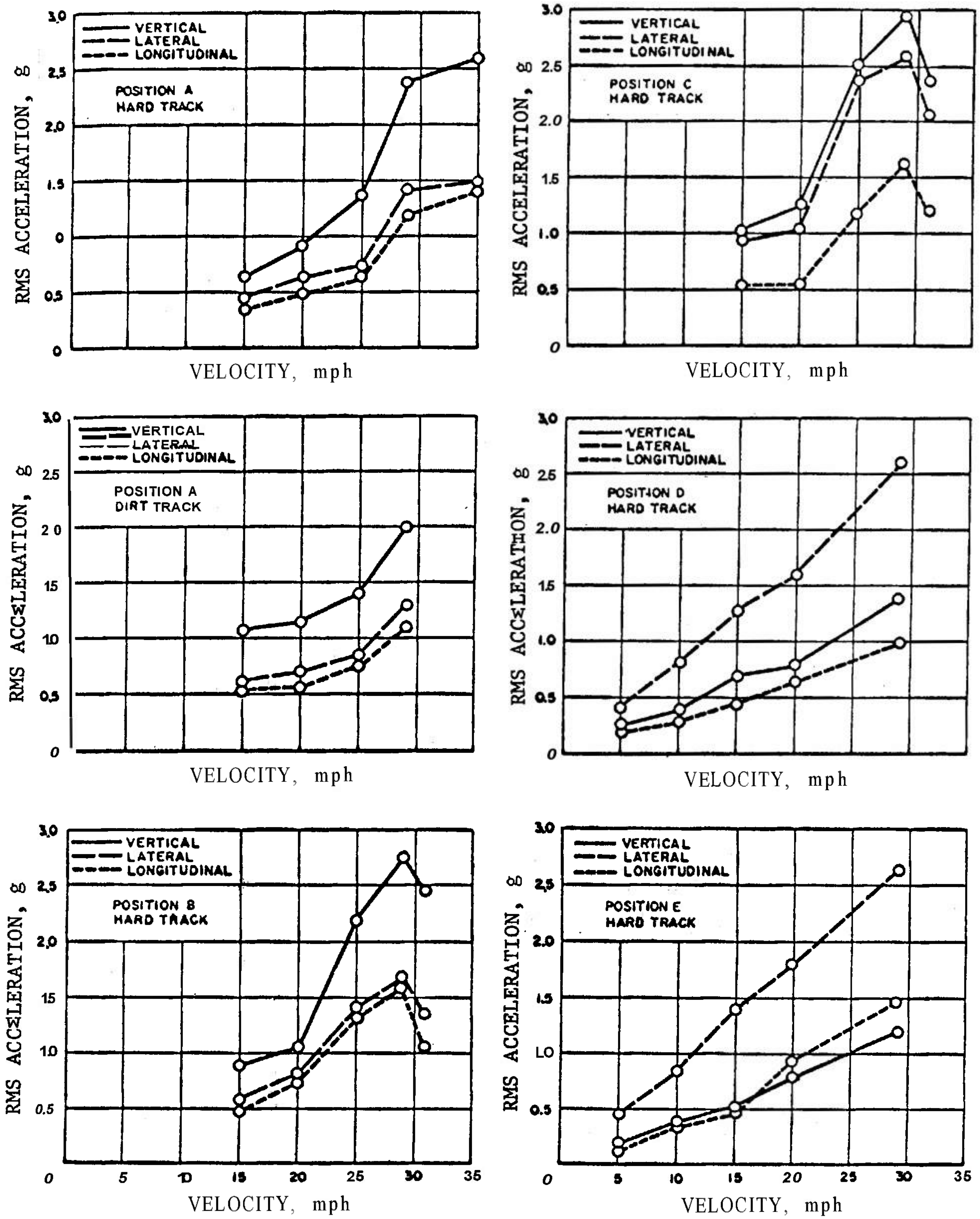


FIGURE 4-18. Velocity Dependence of Vibration Amplitude (Acceleration) for M1 13 Personnel Carrier (Ref. 24).

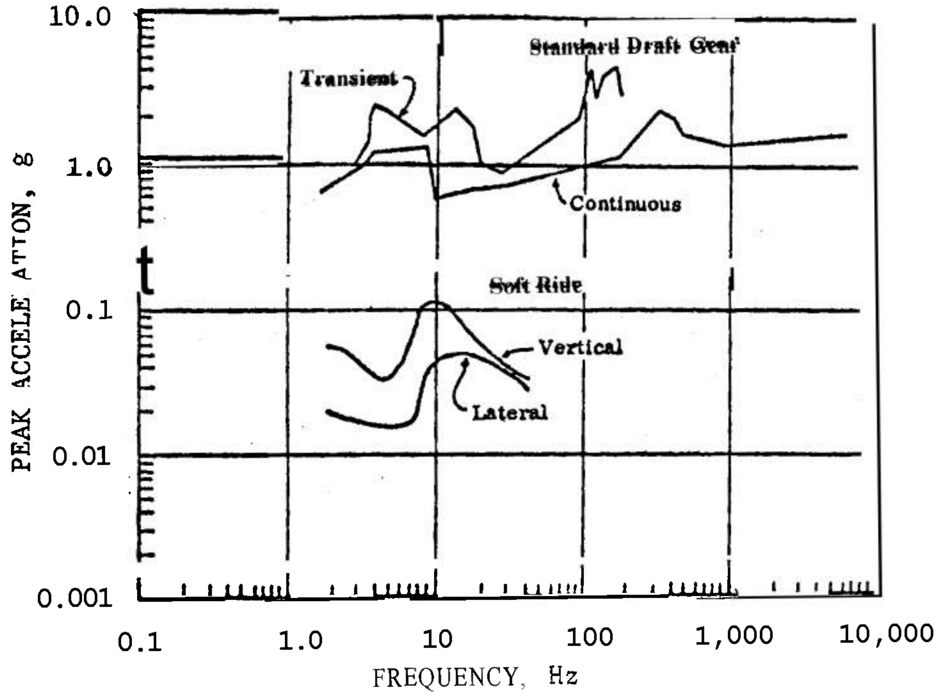


FIGURE 4-19. Vibration Frequency Spectra for Railroads--Various Conditions (Ref. 21).

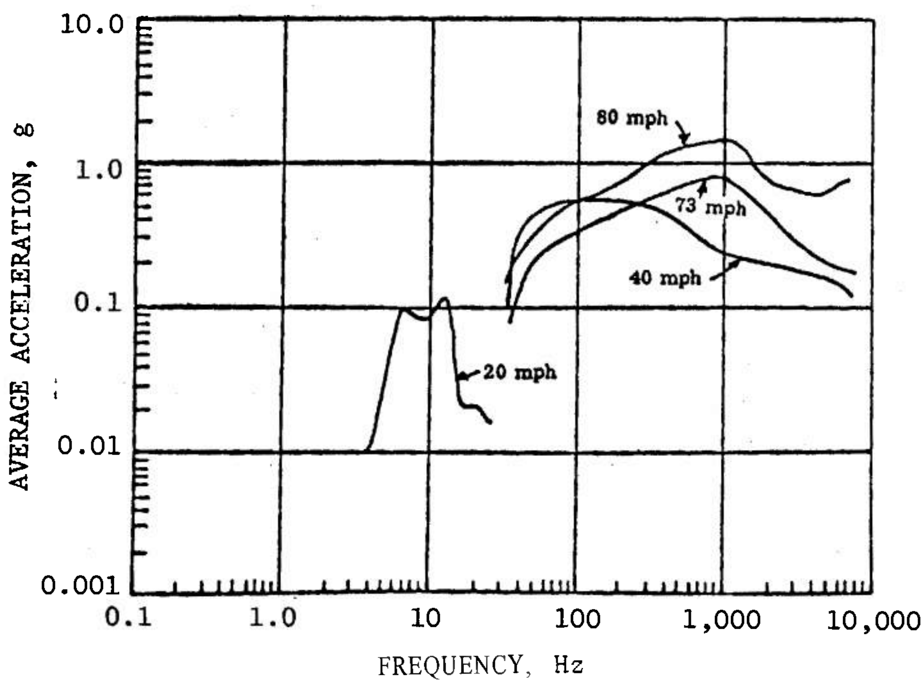


FIGURE 4-20. Vibration Frequency Spectra for Railroads-Various Speeds (Ref. 21).

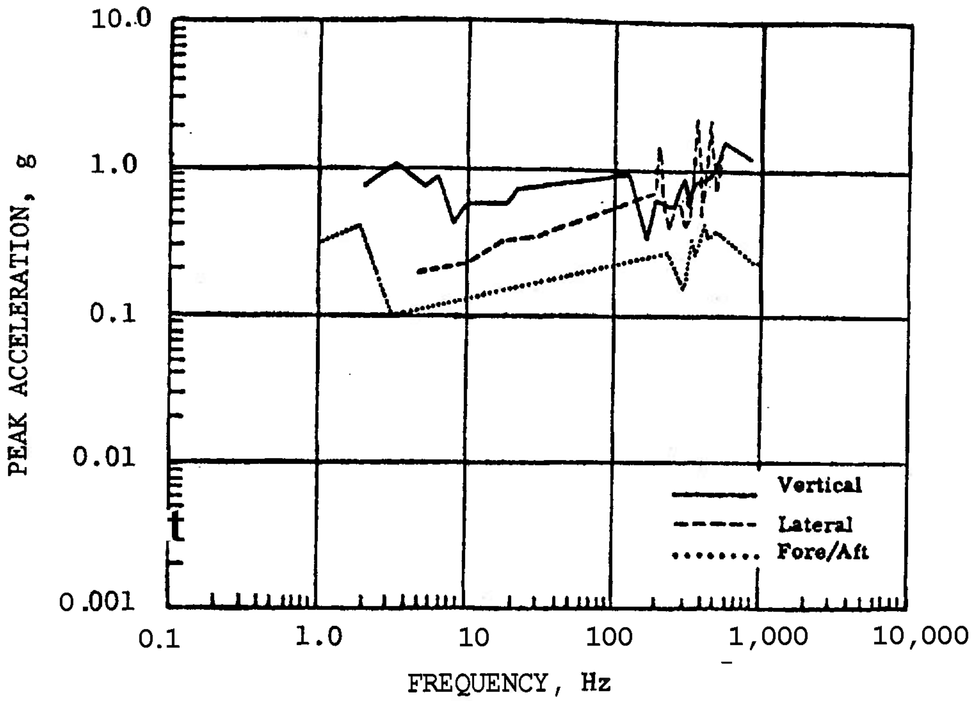


FIGURE 4-21. Directional Composite of Railroad Vibration Spectra (Ref. 21).

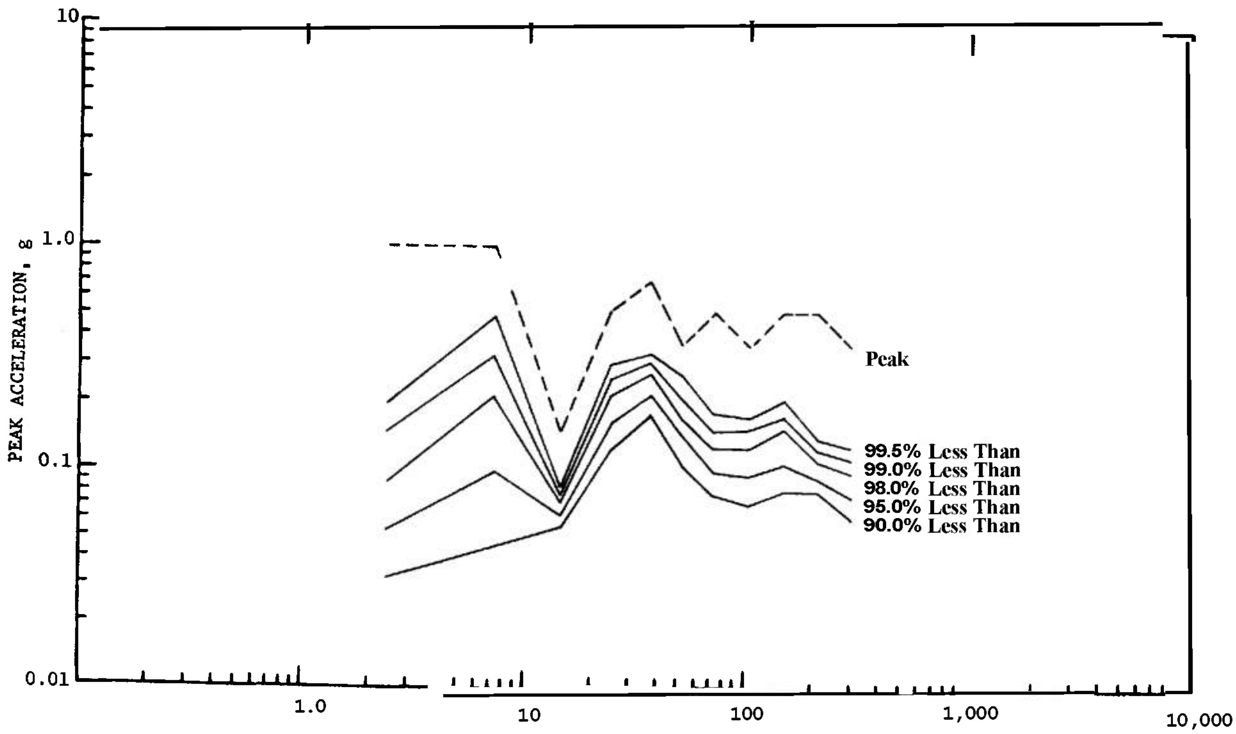


FIGURE 4-22. Composite Vertical Vibration Spectra of Railroad Flatcar (Ref. 25).

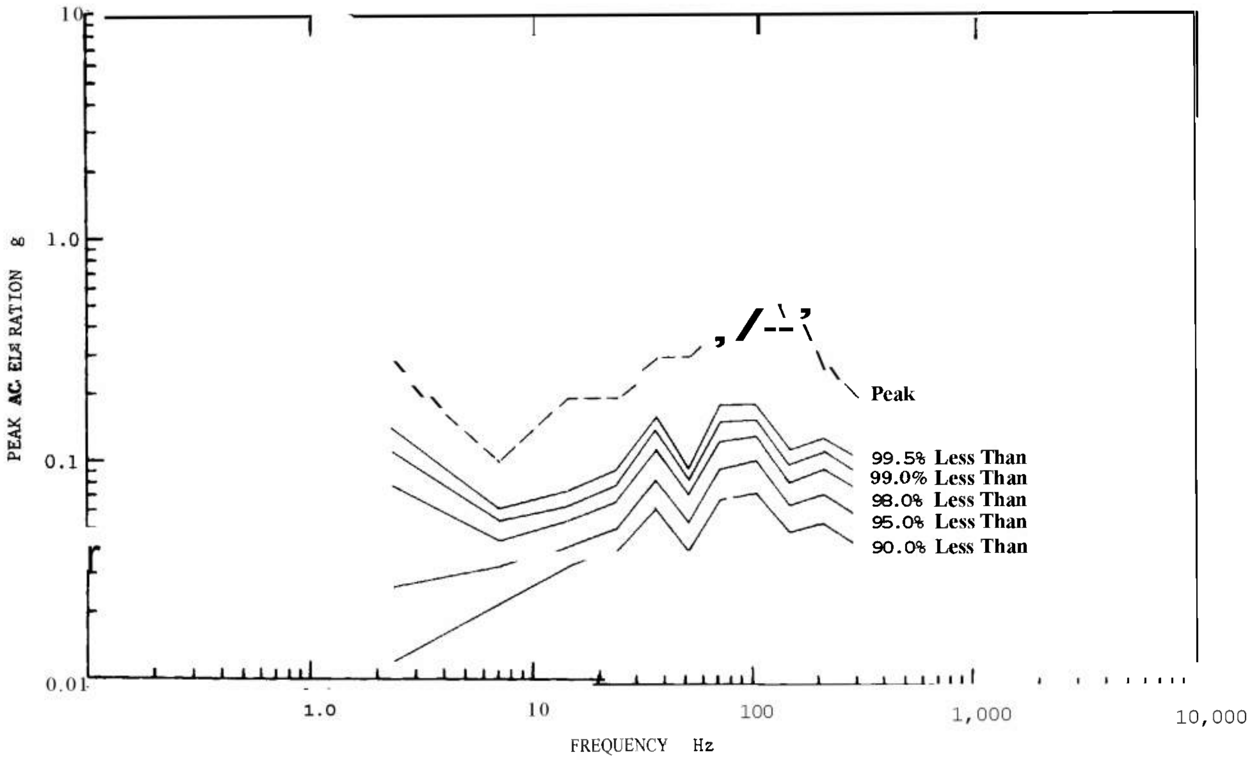


FIGURE 4-23. Composite Transverse Vibration Spectra of Railroad Flatcar (Ref. 25).

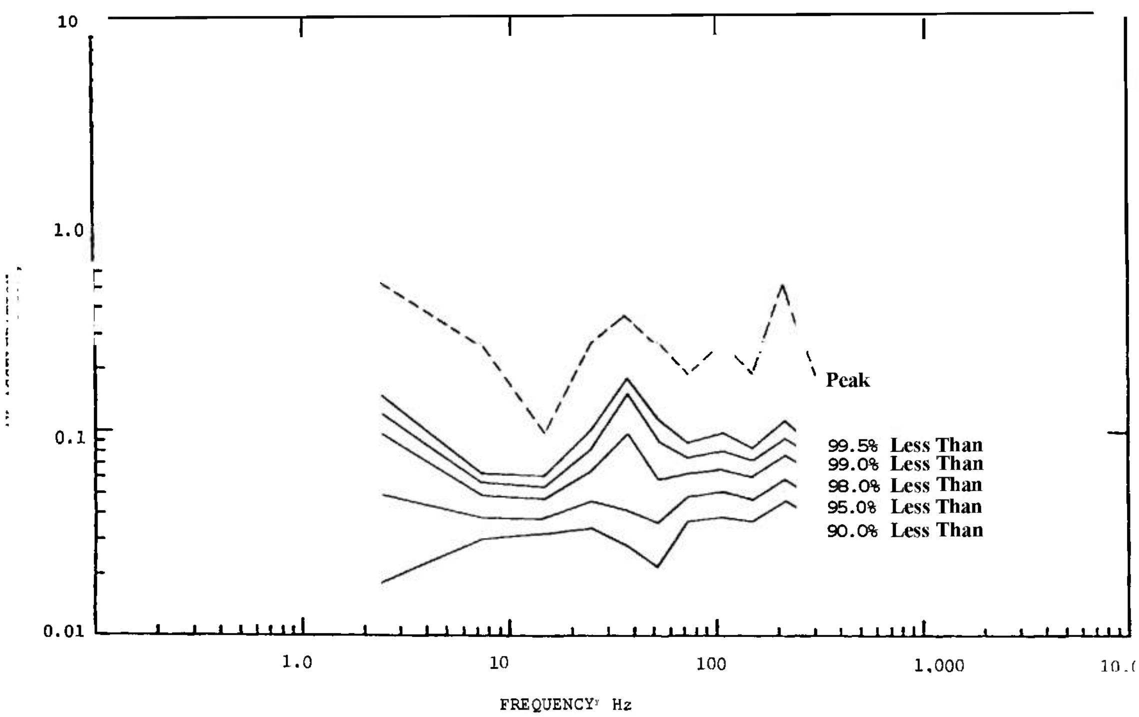


FIGURE 4-24. Composite Longitudinal Vibration Spectra of Railroad Flatcar (Ref. 25).

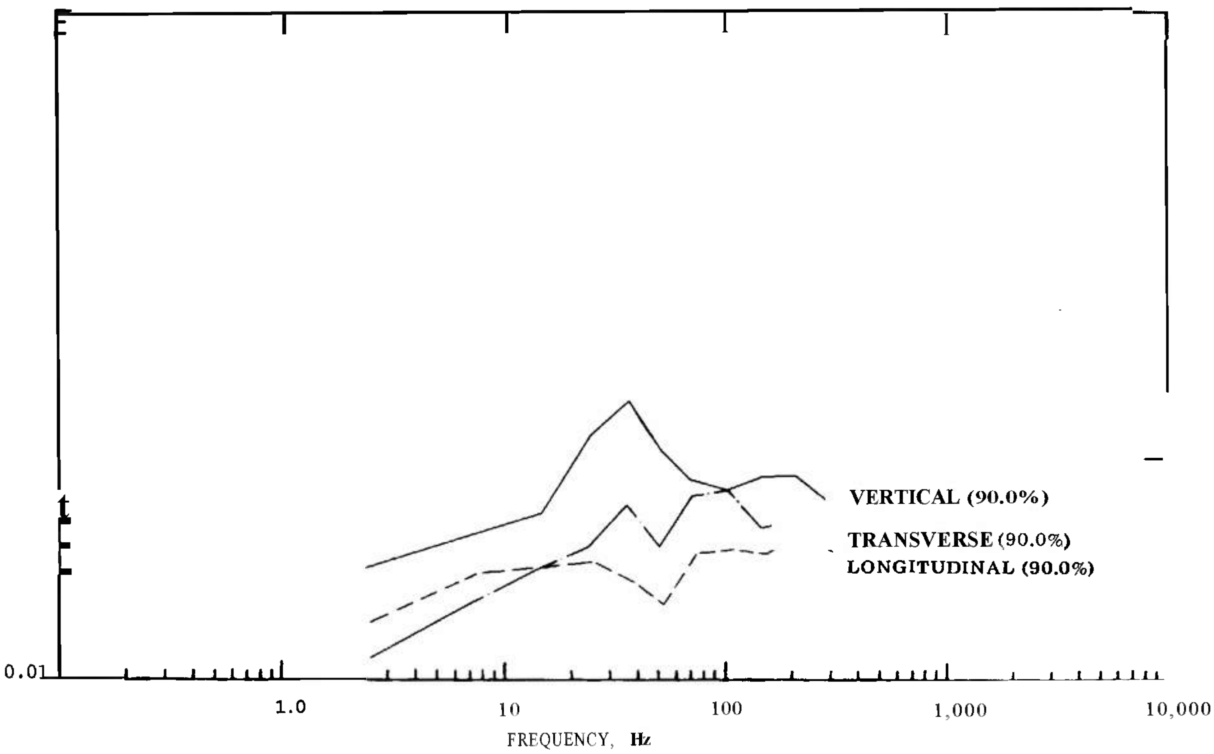


FIGURE 4-25. Comparison of Directional Frequency Spectra of Railroad Flatcar (Ref. 25).

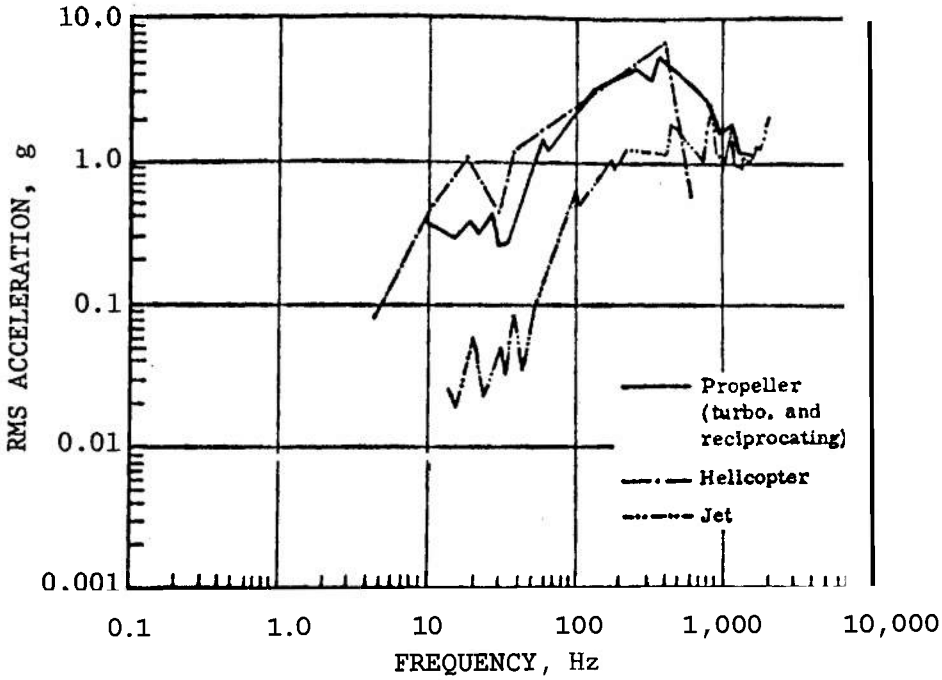


FIGURE 4-26. Aircraft Acceleration Spectra (Overall Composites) (Ref. 21).

are summarized in Fig. **4-27** (Ref. **25).** Comparison with Fig. **4-26** reveals that, although minor differences do exist in the data from these two surveys, the overall levels and general shapes of the curves are very similar. More recent data on the vibration environment of a KC-135 transport—a version of the commercial Boeing 707 jet—are available (Ref. **28).** The severest environment was measured in the vertical direction and occurred during takeoff. Fig. **4-28** presents the frequency spectral data in the vertical direction for this **turbojet** aircraft and the peak values of the vibration environment encountered are given. More recent measurements of the vibration environment on the cargo floor of C-130 and C-133 turboprop aircraft are available (Ref. **22).** In the C-130 aircraft it was found that the maximum vibration environment was obtained during takeoff. The predominant frequency or the frequency of highest acceleration occurred at **68 Hz,** which corresponds to the propeller blade passage frequency. For the C-133 turboprop aircraft, the takeoff condition also represents the most severe vibration environment, and there is a corresponding peak in the vibration spectrum at the propeller blade passage frequency, which in this case is **48 Hz.**

Catherines has investigated the vibration environment of a STOL aircraft (Ref. 29). Measurements were made during evaluation of the operating characteristics of a STOL aircraft in the New York area. The aircraft is a four-engine turboprop, deflected-slipstream aircraft capable of takeoffs and landings over 50-ft obstacles within a distance of approximately 1,000 ft. Fig. 4-29(A) is a histogram of the maximum accelerations measured during three phases of the flight: takeoff, cruise, and landing. Both lateral and vertical accelerations were measured. The data were compiled by averaging the maximum accelerations that occurred during six takeoff and landing exercises. For comparison purposes in Fig. 4-29(B), similar acceleration measurements were made during a single flight between New York and Newport News, Va., on a Boeing 727. It can be seen that the magnitude of the vibratory responses are essentially the same during takeoff and landing maneuvers for the STOL aircraft and for the 727 aircraft. During cruise conditions, however, the acceleration levels of the STOL aircraft are significantly larger than those measured on the 727.

Fig. 4-30 shows typical power spectral density plots measured in the vertical direction on the STOL and the

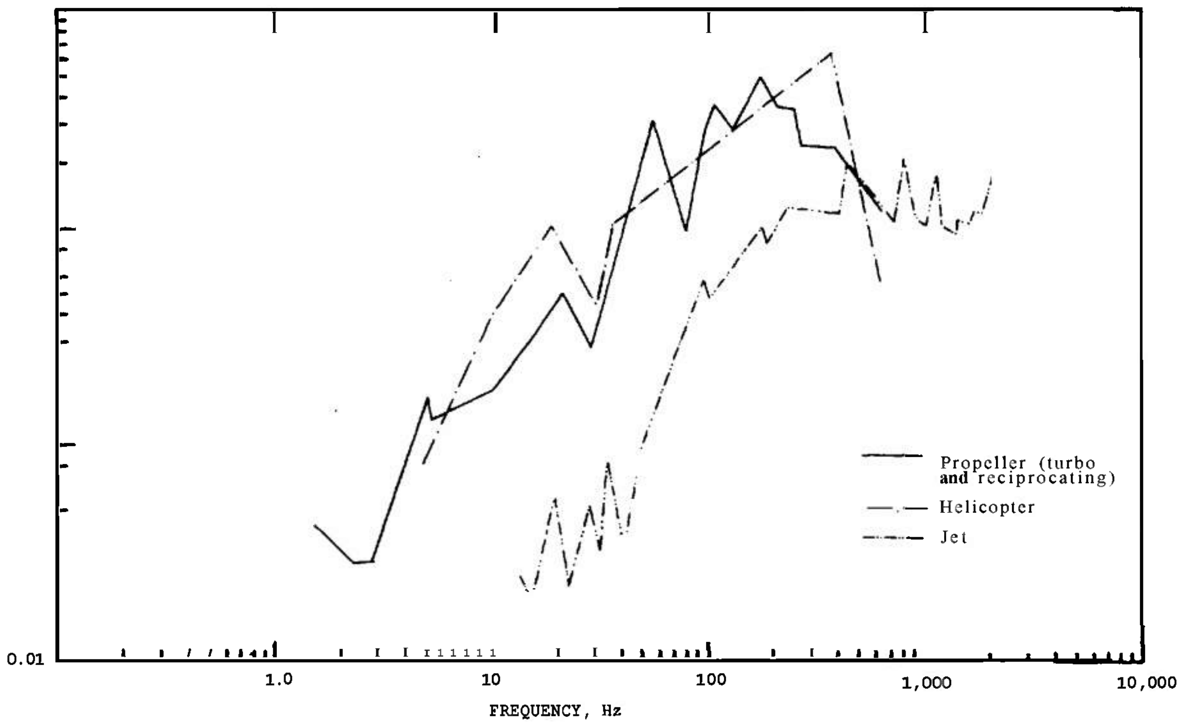


FIGURE 4-27. Composite Vibration Spectra for Different Types of Aircraft (Ref. 25).

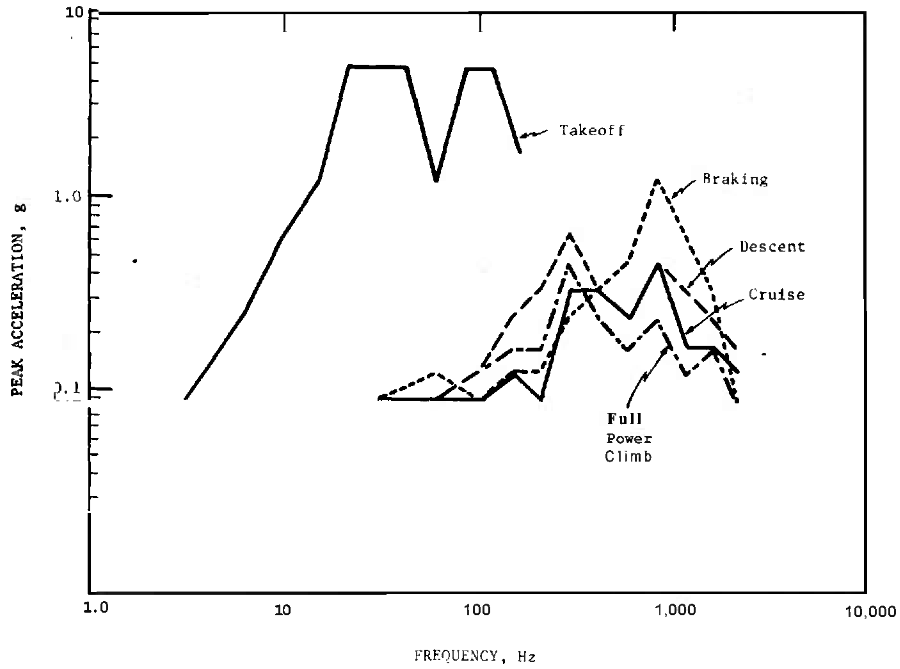


FIGURE 4-28. Vertical Vibration Spectra of Turbojet Aircraft for Various Flight Phases (Ref. 25).

727 aircraft during cruise conditions. Power spectral density is the limiting mean-square value (e.g., of acceleration, velocity, displacement, stress, or other random variable) per unit bandwidth; i.e., the limit of the mean-square value in a given rectangular bandwidth divided by the bandwidth, as the bandwidth approaches zero. The data were obtained over 12-min periods of level flight for each aircraft. The major response of the STOL aircraft occurs at a frequency of about 0.10 Hz and is characterized by slow boatlike motions. For the 727 aircraft, the response does not peak out above a frequency of 0.05 Hz, indicating a quasi-steady-state motion.

In the aircraft data presented to this point, the measurements have been made within the passenger or cargo areas of the aircraft; i.e., they have been made inside the aircraft. From a transport standpoint, however, a significant number of aircraft stores are carried externally on aircraft during captive flight. These stores include armament, photographic equipment, fuel, and a wide variety of other materiel. A detailed study of the sources of and responses to the vibration environment of externally carried aircraft stores has been made (Ref. 30). Significant vibration occurs throughout the flight including taxi, takeoff, flight to the mission, maneuvers during mission accomplishment, return to the base, and landing. Since the character of the environment varies appreciably throughout the flight, it is necessary to specify the more severe maxima that occur across the frequency spectrum and the time duration of these maxima during each mission.

During takeoff and landing, the two important sources of vibration are engine noise and runway roughness. Table 4-4 shows a comparison of the internal acoustic and vibration environments measured in the vicinity of the external microphones mounted on the surface of the aircraft. These data indicate that the internal vibration environment is produced primarily by the jet engine noise impingement. During takeoff roll, some of the highest vibration levels measured below 100 Hz are recorded. The dominant vibrational levels are associated with the fuselage and wing/pylon natural frequencies. These vibrations, which are introduced into the vehicle through the landing gear, vary randomly in amplitude. In general, the amplitudes increase with increasing aircraft forward speed. Fig. 4-31 presents typical vibration spectra measured on a munition dispenser on a jet airplane and on a single store on a propeller airplane during takeoff roll. Although the weight of the two stores is approximately the same, the

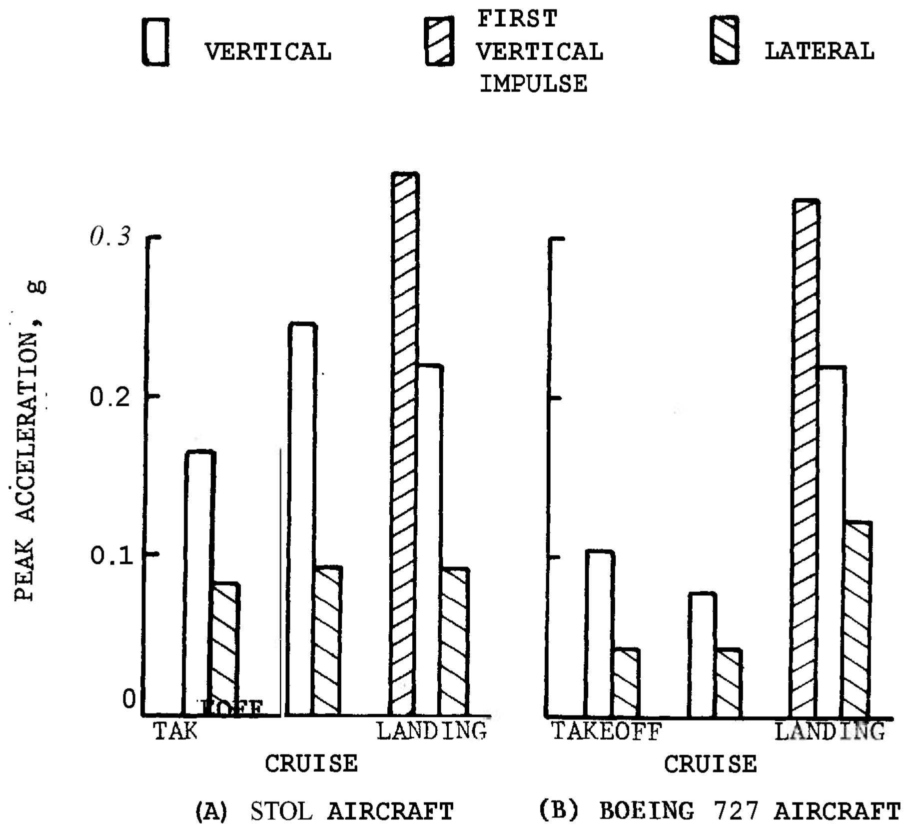


FIGURE 4-29. Maximum Accelerations Measured During Three Phases of Flight (Ref. 29).

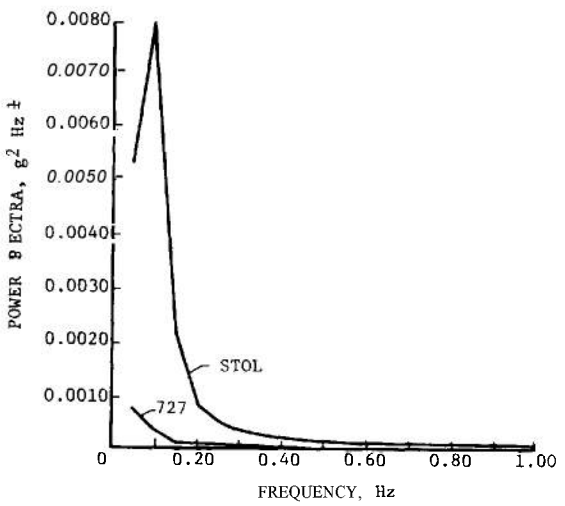


FIGURE 430. Sample Power Spectral Densities for STOL and Boeing 727 Aircraft During Cruise; Vertical Direction (Ref. 29).

six stores on the propeller-driven vehicle are carried on single pylons, three to a wing.

In general, the vibration levels are consistent, except near 100 Hz, which is associated with propeller blade passage frequency. Further analysis of the data has shown the environment to be broadband random (approaching Gaussian distribution) in character except for sinusoidal traces at some propeller blade passage and engine harmonics.

Fig. 4-32 shows continuous recordings of overall vibration and acoustic environments measured on a munition dispenser during flight on a jet aircraft. The overall levels shown were measured continuously as the aircraft slowly increased its speed at altitudes of 3,000, 15,000, and 30,000 ft, respectively. The data are from flush-mounted external microphones and from internal microphones and accelerometers located in the front ends of the forward store on a multiple ejection rack (MER) carrying four stores located under the fuselage and on the inboard shoulder stores of a triple ejection rack (TER) attached to the inboard wing pylon as

TABLE 44. COMPARISON OF OVERALL ACOUSTIC AND VIBRATION ENVIRONMENT WITHIN A MUNITION DISPENSER TO THE ACOUSTIC ENVIRONMENT MEASURED AT THE ADJACENT DISPENSER SURFACE (Ref. 30)

Location	External microphone, dB	Internal microphone, dB	Equipment rms vibration, g	Bulkhead rms vibration, g
Aft fuselage	145	136	0.6	9.0
Aft wing	138	128	0.4	4.5
Fwd wing	136	127	0.4	3.5
Fwd fuselage	138	126	0.3	3.3

shown in the figure. Levels increase uniformly with aircraft velocity and decrease with increasing altitude.

The firing of guns on the aircraft structure generates large vibrations. Fig. 4-33 shows the vibration response to 20-mm gunfire during a flight at 250 kt and at 3,000-ft altitude (Ref. 30). The gunfire-induced vibrations are 10 times higher than those measured just before gunfire. The measured vibration was induced both by gun blast impingement on the nose of the store and from the mechanical motion of the gun that is transmitted through the pylon.

In addition to the vibration environment induced by gunfire on externally mounted stores, gunfire introduces vibration into the structure of the aircraft. The ground and flight vibration environment within the A-7D Corsair II tactical fighter aircraft produced by the rapid fire M61 Gun has been measured (Ref. 31). This six-barreled gun fires 20-mm rounds at selected rates of either 6,000 or 4,000 shots per minute (spm) compared to 960 spm for the older Mk 12 Gun, such as used on the earlier A-7A. Figs. 4-34 and 4-35 present typical gunfire and no gunfire data plots measured 2 and 25 ft from the M61 muzzle. From these data it is concluded that the vibration environment induced by the M61 Gun has the characteristics of those produced by a periodic pulse-type input similar to that of a slower rate Mk 12 Gun. The vibration environment produced by the Mk 12 gunfire is a series of shock pulses spaced 60 ms apart. The amplitude of each shock pulse increases to a maximum, then decays to its initial condition before the next round is fired. This allows the equipment located in the vicinity of the gun to absorb the shock pulse and return to equilibrium before the next shock pulse is initiated. The vibration environment produced by the M61 Gun, however, is a series of shock pulses spaced 10 ms apart. The amplitude of this vibration increases for the first few rounds, then becomes relatively constant throughout the remainder of the steady-state firing because the time between successive rounds is short and the shock pulse from one round does not have time to decay before the next pulse is initiated. Consequently, the vibration problems associated with the M61 Gun are magnified with respect to the lower rate Mk 12 weapon.

In a similar study the statistical characteristics of the structural response were measured on the A-7 airplane while firing the M61 rapid-fire Gun (Ref. 32). Amplitude versus frequency plots from narrowband analysis and amplitude versus occurrence plots are presented, which provide a graphic presentation of the gunfire signal characteristics and the environment induced by operation of the gun on the aircraft structure. Fig. 4-36 is the amplitude versus occurrence plot of the overall flight gunfire signal within 25 in. of the gun muzzle. This plot has a Gaussian shape indicating a random amplitude distribution. Analysis of the signals present in the amplitude spectrum charts indicates that the lower harmonics tend toward a constant amplitude distribution (Ref. 32). From this analysis, it is deduced that the gunfire fundamental and first two or three harmonic frequencies have a constant amplitude distribution while the remaining higher order harmonics have an increasingly random amplitude characteristic. The increase in randomness at the higher harmonics is due in part to the randomly distributed firing rate deviations, which produce a normal fluctuation of 10 percent in the gunfire fundamental

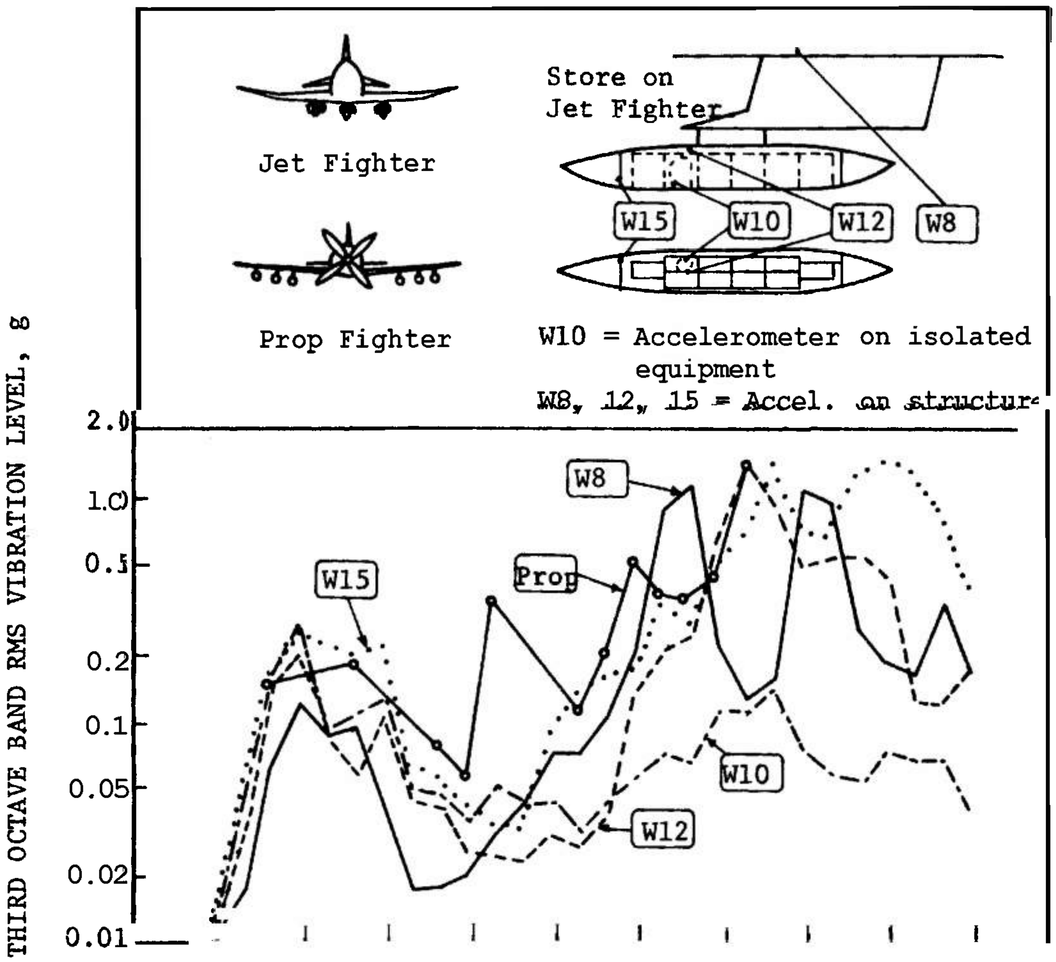


FIGURE 4-31. Typical One-third Octave Band Vibration Spectra Measured During Takeoff Roll From a Munition Dispenser Carried on a Jet Airplane and a Single Store Carried on a Propeller Airplane (Ref. 30).

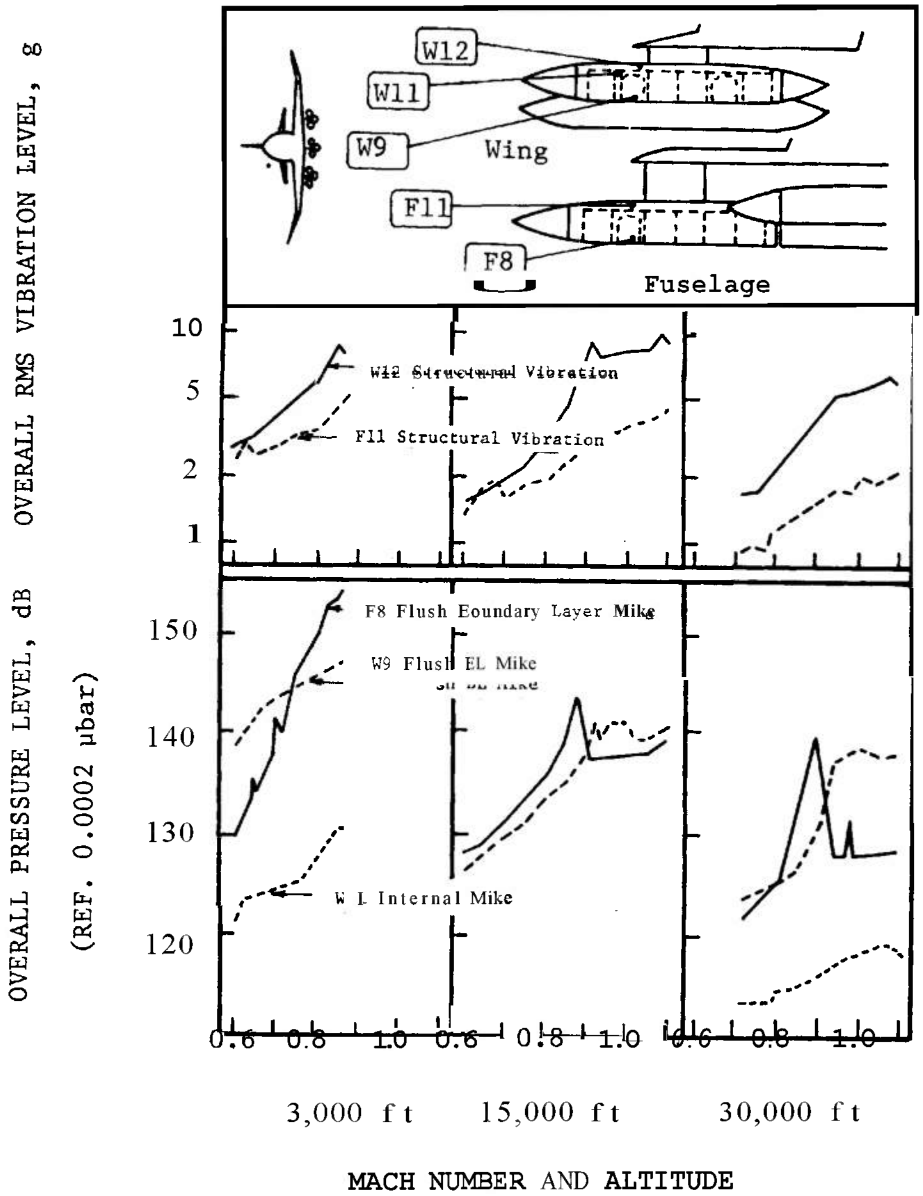


FIGURE 4-32. Typical Variation of Overall Vibration and Acoustical Environment as a Function of Airspeed and Altitude for a Munition Dispenser Carried on a Jet Airplane (Ref. 30).

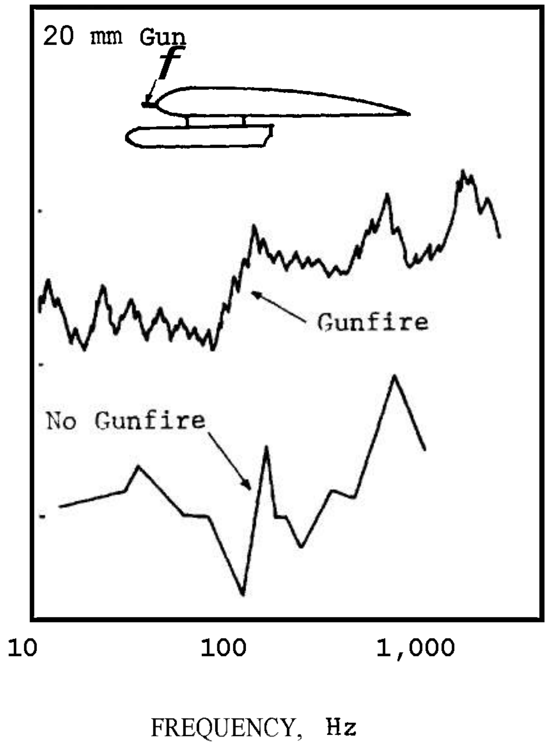


FIGURE 4-33. Example of Gunfire Response Spectra Measured on a Store During Flight (Ref. 30).

and harmonic frequencies. This is reinforced by the tuningdetuning effect of the aircraft structure resulting from the changing flight loads during the time the gunfire maneuver is performed.

It is concluded in this study that the gunfire response may best be described as a series of periodic signals with varying amplitudes occurring at the gunfire rate and its harmonics, superimposed on a broadband random vibration background.

4-2.1.3.2 Helicopters

The vibration characteristics of the HH-43B helicopter have been measured (Ref. 33). This helicopter has a pair of contrarotating rotors with blades **47** ft long and is powered by a turbojet engine. Events studied were motor starts, rotor engagement, takeoff, hover, climb, cruise at 90 kt, straight flight, and descent. A summary of the data is given in Fig. **4-37.** Major conclusions from this study were:

(1) Hovering produces the severest vibration environment, while rotor start and engagement produce the least.

(2) The longitudinal vibration in the helicopter is largest.

(3) Straight or level cruise results in insignificant levels when compared to hover, climb, and high speed events.

Inflight vibration data on a series of helicopters have been obtained for upgrading of environmental design criteria and verification of dynamic prediction techniques (Ref. **34).** Three different helicopters were used in this study. Helicopter A is a single-engine aircraft in the 9,000-lb weight class. The aircraft missions are to transport personnel and equipment, medical evacuation, and ambulance service. When equipped with armament, it may be used to deliver point target and area firepower. Helicopter B is a lightweight, single-engine, four-place helicopter. The missions of this helicopter are observation, target acquisition, reconnaissance, and command control. When equipped with an armament subsystem, it is capable of defense against groundbased fire from automatic weapons and small arms. Helicopter C is an armed tactical vehicle with two seats and weighs approximately 5,000 lb empty with a gross weight of 9,500 lb. The primary mission of helicopter C is fire support.

The vibration amplitudes were measured with a vibration transducer located in the nose and cargo areas of each of the three helicopters. The data represent the maximum levels measured in the three orthogonal directions for all of the flight conditions of the test. Fig. 4-38 is a summary plot showing the maximum double amplitude levels measured for all of the helicopters. Low frequency accelerometers with a response from 0 to 160 Hz were employed to obtain the maximum vibration levels on the cabin floor of each of the three helicopters. Vertical and lateral direction data were obtained. Further details of the data analysis, as well as detailed data presentation are in the reference (Ref. 34).

4-2.1.3.3 Missiles and Rockets

Missiles and rockets have a distinctive environment associated with their operation. Table **4-5** lists the operational phases of a space vehicle mission and possible sources of vibration in each phase (Ref. 35). Of course, in the prelaunch phase, the missile must be tested according to vibration testing specifications and, usually, static firing of the vehicle takes place. Also, the launch vehicle must be transported to a launch site. During the transportation phase, it undergoes the vibration environment associated with the particular mode of transportation. During the initial launch readiness phases of the mission while the launch vehicle is in place on the firing pad, local ground wind can exert forces on the missile and induce vibrations. The vibration environment associated with the actual operation of the space vehicle, however, is considerably more complex.

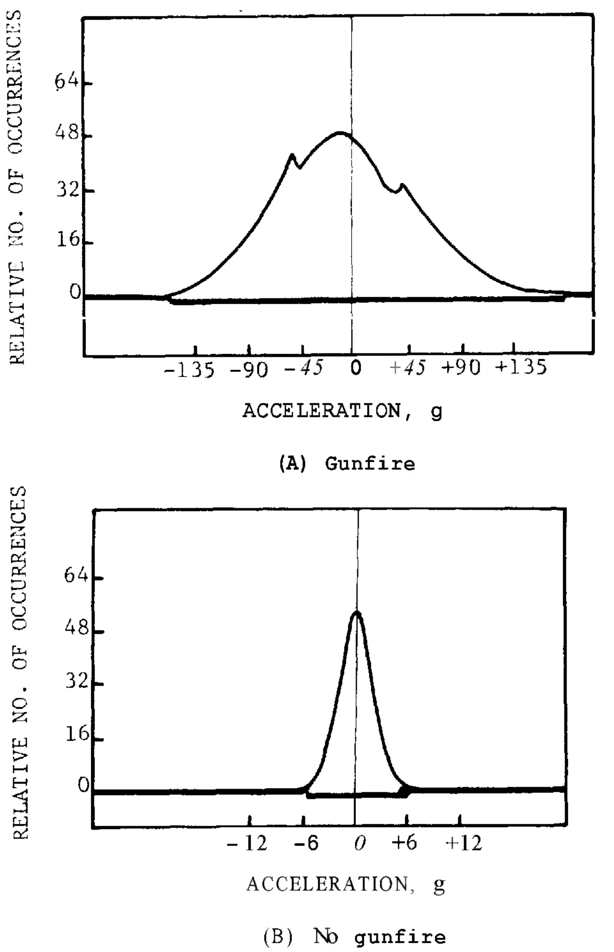


FIGURE 4-34. Vibration Amplitude Data Measured 2 ft From M61 Gun Muzzle (Ref. 31).

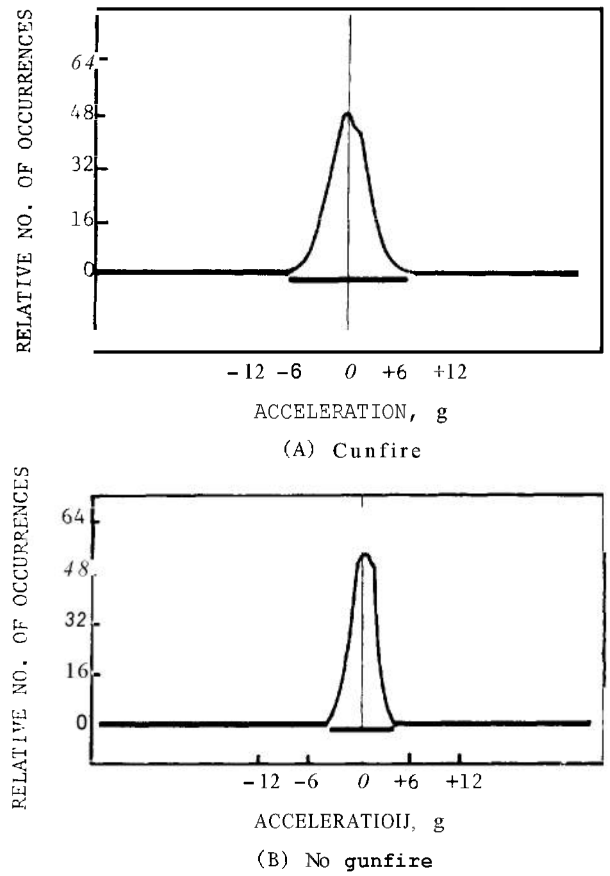


FIGURE 4-35. Vibration Amplitude Data Measured 25 ft From M61 Gun Muzzle (Ref. 3.1).

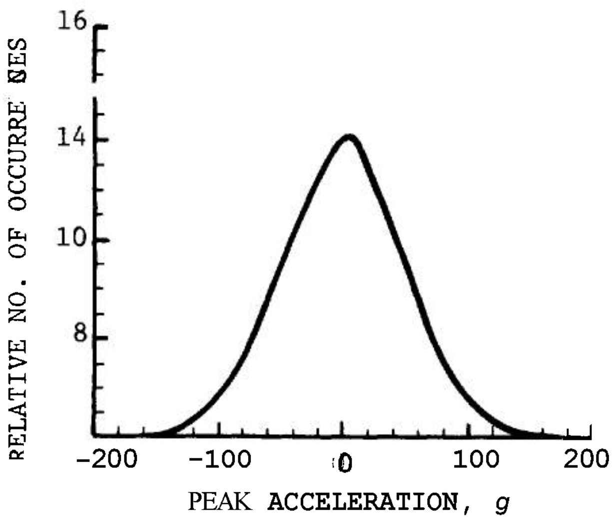


FIGURE 4-36. Amplitude vs Occurrence Plot of Overall Flight Gunfire, Signal Within 25 in. of Gun Muzzle (Ref. 32).

The sinusoidal vibration of solid propellant motors of the POSEIDON missile has been investigated (Ref. 36). During early testing of the developmental motors for the POSEIDON missile, severe vibration environments were observed in the data from both first and second stage motors. An 80-Hz oscillation was measured on the first stage motor which began 8 s after ignition and lasted for about 12 s. Fig. 4-39 shows a frequency versus time plot from a typical motor. An envelope of frequencies measured during all ground test firings of tactical configuration motors is also shown. The frequency profile from motor to motor is nearly identical. The peak-measured amplitudes were ±8 G on the forward dome, ±10 G on the aft dome, and ±22 G on the nozzle, which is connected to the motor by a flexible joint. The largest accelerations occurred in the longitudinal direction.

In a description of the environmental factors involved in missile operation, vibration data on 10 different missiles are presented (Ref. 37). Fig. **4-40** summarizes the vibration characteristics of seven operational

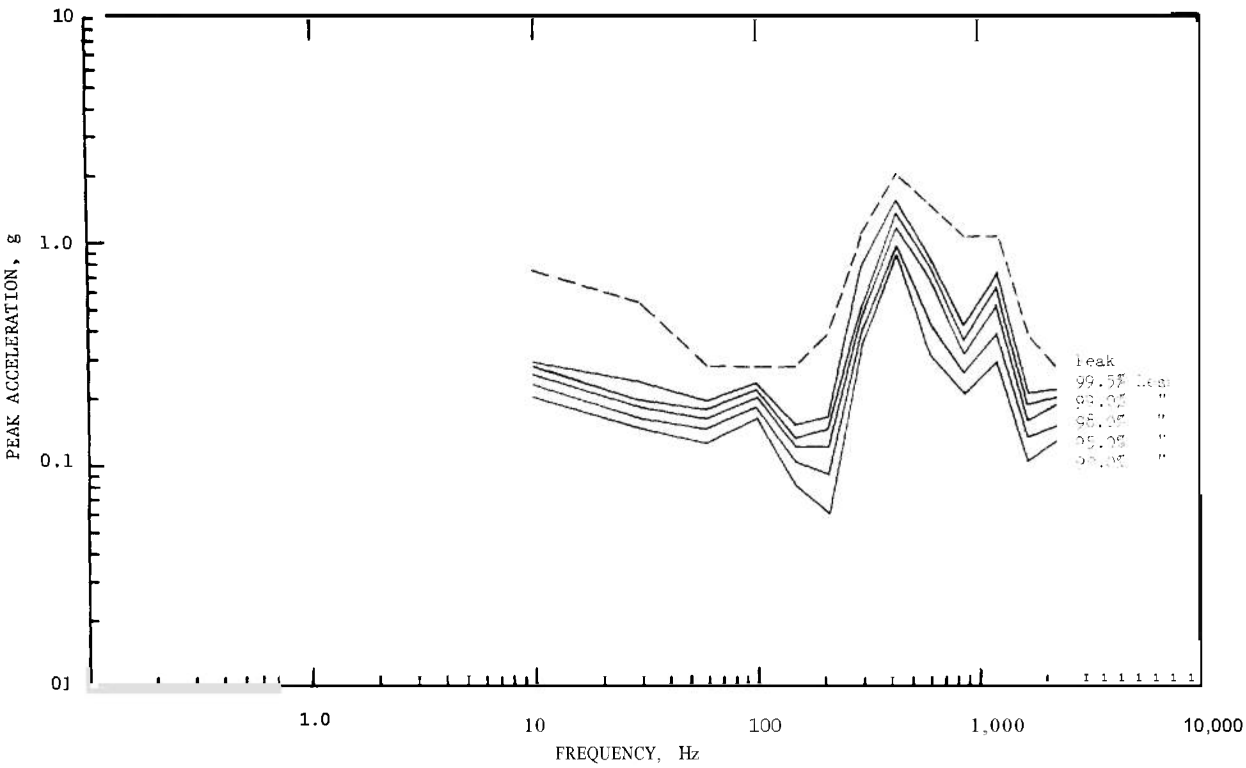


FIGURE 4-37. Composite Vibration Spectra of HH43B Helicopter (Ref. 25).

missiles during the boost phase. Fig. 4-41 summarizes the vibration characteristics of four operational missiles during substained flight after boost.

4-2.1.4 Water Transport

In ships the propellers, the propeller shafting, power plants, auxiliary machinery, and the hydrodynamic forces as the ship passes through the water all contribute to the vibration environment. Phenomena at the ship-water interface include slamming, pounding, and wave-induced motion of the ship. Slamming is the impacting of the ship with the water after the bow has left the water, pounding is the impacting of the waves on the ship when all portions of the bottom are submerged, and wave-induced motion is the motion of the ship in response to the waves. Buchmann describes in detail the vibration sources in ships (Ref. 38). Measurements on 10 ships ranging from 70 to 1,000 ft in length are given. Another summary of vibration data for many sizes and types of ships is available (Ref. 27). A detailed discussion of ship motion due to wave action is given by St. Dennis (Ref. 39).

A characteristic vibration frequency associated with ships is the blade passage frequency, which results from the nonuniform pressure field acting on the hull as each propeller blade passes near the hull.

To obtain the vibration environment on dry-cargo vessels, seven accelerometers were installed at various locations aboard a 550-ft dry-cargo ship operating in regular North Atlantic service (Ref. 40). Data were recorded intermittently over a 15-mo period. Wave-induced acceleration reached a maximum of 0.88 G in the vertical direction at the bow. Slamming produced higher frequency vibrations in excess of 1.5 G. An analysis of the data involved in slam resulted in the conclusion that, operating on the same route over a 7-yr span, the most probable maximum bow acceleration on the vessel would be 2.97 G (peak-to-peak).

A survey of shock and vibration environments in transportation includes data on ship vibrations (Ref. 21). Fig. 4-42 depicts the vibration or acceleration envelopes for ships under normal maneuvers in calm seas, for maximum vibration in rough seas, and slam and emergency maneuvers. Data for these curves were obtained on a 572-ft-long, single-propeller ship.

Figs. 4-43 and 4-44 show the effect of sea state for two different ship lengths; one 820 ft long, and the other 380 ft long. As indicated in the curves, the acceleration levels increase with increasing frequency from 4 to 10 Hz and are relatively constant at high frequencies. The accelerations for the small ship are almost twice as large as those for the larger ship. For both

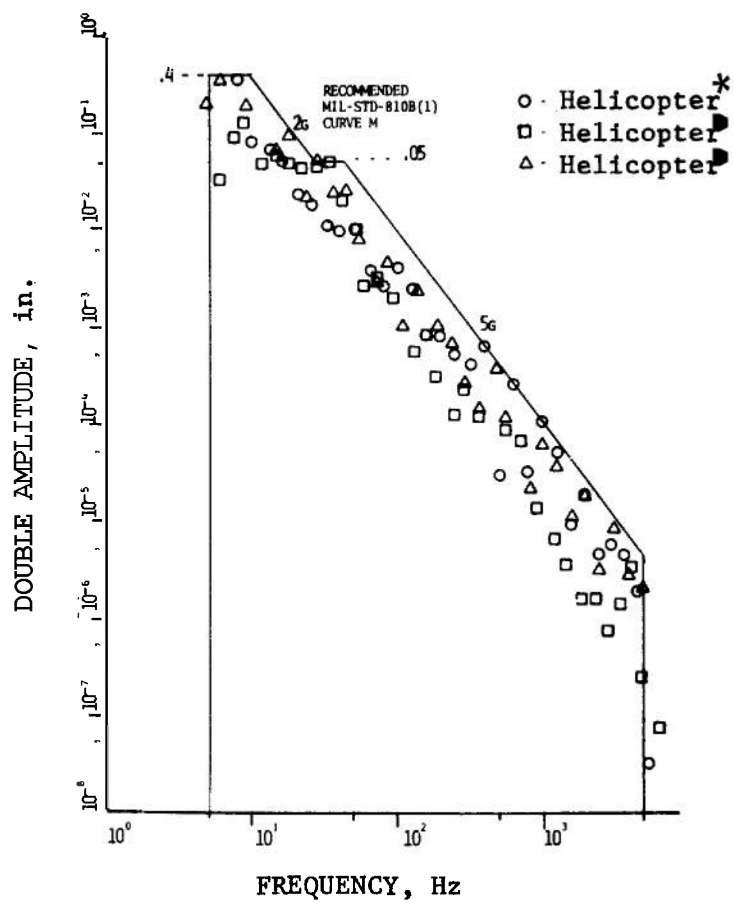


FIGURE 4-38. Helicopter Vibration Envelope (Ref. 34).

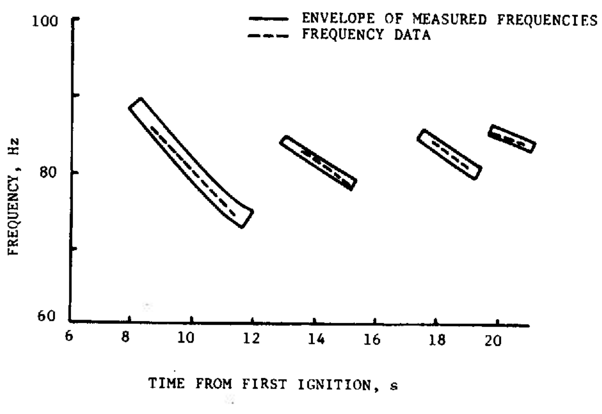


FIGURE 4-39. Vibration Frequencies Measured During a Typical Static Rocket Motor Firing (Ref. 36).

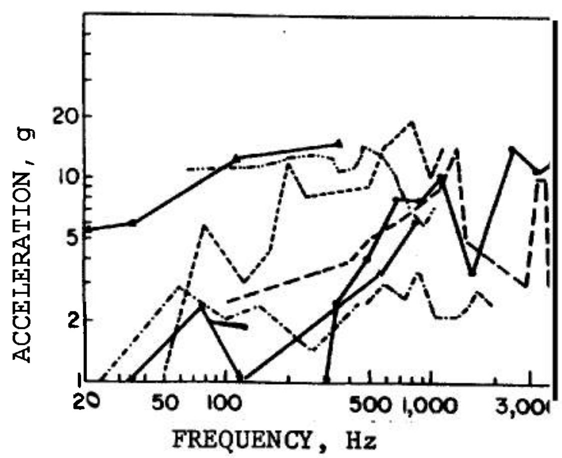


FIGURE 4-40. Vibration Characteristics of Seven Operational Missiles During Boost Phase (Ref. 37).

TABLE 4-5. SOURCES OF VIBRATION IN VARIOUS MISSILE OPERATIONAL PHASES (Ref. 35)

Operation	Phase	Source
Prelaunch	Functional checkout	Vibration testing Static firing
	Transportation: Air	Air turbulence Propeller noise
	Ground	Rough highways
	Water	Rough water
	Launch readiness	Ground wind
Launch	Liftoff	Ignition Engine noise Tiedown release
	Ascent	Engine roughness Aerodynamic noise/buffet Pogo phenomena Control system instability
	Staging	Separation Stage ignition
Space	On station	Control system instability
Atmospheric	Entry	Aerodynamic noise/buffet Aerodynamic stability

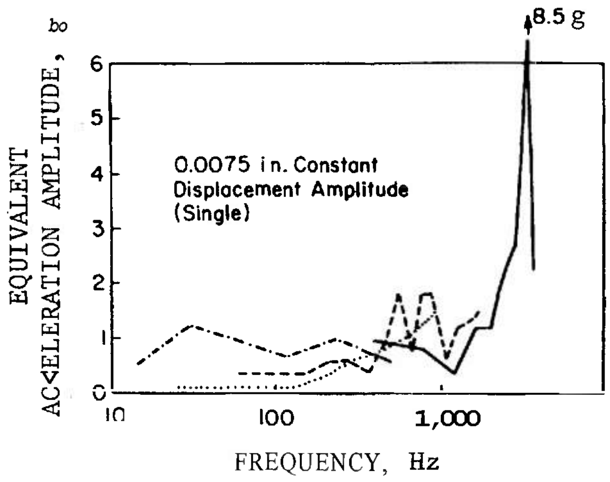


FIGURE 4-41. Vibration Characteristics of Four Operational Missiles During Sustained Flight After Boost (Ref. 37).

ships, the acceleration increases by a factor of two in rough sea. The vibration frequencies above 10 Hz are due to machinery vibrations and thus are less a function of sea state than the lower frequency motions.

A rather recently developed water transport craft is the hovercraft. These air-cushion effect vehicles are being used increasingly in estuaries, rivers, swamp lands, and sea transportation. Lovesey has investigated hovercraft noise and vibration (Ref. 41). These vehicles have been designed to travel at high speed over the short-wavelength, high-amplitude waves that exist in the marine environment. Wavelengths that are shorter than half of the cushion length are, in effect, damped out by the air-cushion suspension system and have little effect on the motion of the hovercraft. Wavelengths equal to or slightly greater than the cushion length produce maximum pitch forces and the hovercraft motion depends upon the cushion stiffness and damping. When wavelengths are many times the cushion length, the craft will tend to follow the water surface and produce high-amplitude, low frequency oscillations. In hovercraft, motion is confined almost exclusively to the vertical axis. Low frequency vibrations in the longitudinal and transverse axes are very small because of the stiffness of the hovercraft structure. In a comparison of a 28-ft launch traveling over smooth sea at 28 kt with a small hovercraft over smooth sea at 45 kt, it was found that accelerations in the vertical direction for the hovercraft were less than one-third as much as those for the launch. At wave frequencies of approximately 1.3 Hz, the acceleration measured on the hovercraft was 0.14 G, while that on the launch was 0.6 G.

4-2.2 STATIONARY AND PORTABLE EQUIPMENT

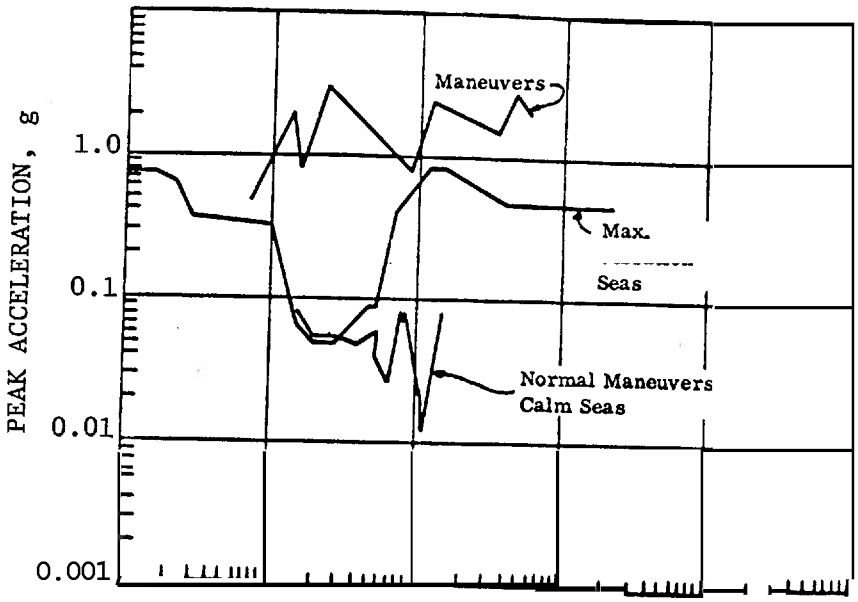
All rotating machinery is subject to vibration as a result of mass unbalance that imposes a once-per-revolution acceleration on the system. The mass unbalance of a system is related to mass distribution in the rotating piece. In reality, because of factors such as material heterogeneity, machining errors, keyways, slots, and windings, complete balance is never achieved. Much time and effort is extended each year on the dynamic balance of rotating machines using both stationary and portable balancing equipment.

Perhaps the most common vibration environment induced by the rotation of unbalanced masses occurs in the automotive industry with the wheels of vehicles. It is necessary to balance vehicle wheels in order to eliminate the vibration associated with the mass unbalance during high-speed operation. Every rotating system must be balanced if vibration is not to become objectionable at high-rotation rates. The rotating systems of internal combustion engines—the crankshafts and the other moving components of the system including pulleys, drive shafts, drums, and other components—on motor vehicles must be balanced. For electrical machinery the rotating members must also be balanced if severe vibration environments are to be avoided. All rotating equipments produce significant vibration environments under certain conditions.

Vibrations are also introduced in cutting operations with machine tools and in high-friction devices (brakes) used to slow rotating equipment. The vibrations induced by cutting operations are not caused by simple unbalance but rather are due to inhomogeneities in the work piece material, disturbances in the work piece or tool drives, interrupted cutting, and the cutting process itself. Chatter is a self-induced vibration that is induced and maintained by forces generated in the cutting or braking process. More information on the vibration of rotating machinery is available (Ref. 10).

4-2.3 NATURAL SOURCES

Although all of the matter comprising our environment is made up of constantly moving particles, relatively few sources of significant vibration occur naturally. Water waves that occur naturally, e.g., wind induced, are discussed in par. 4-2.1.4 and will not be further covered in this paragraph. The remaining two major sources of vibration in the environment are those that can be attributed to earth crustal movement and wind.


PEAK ACCELERATION, g
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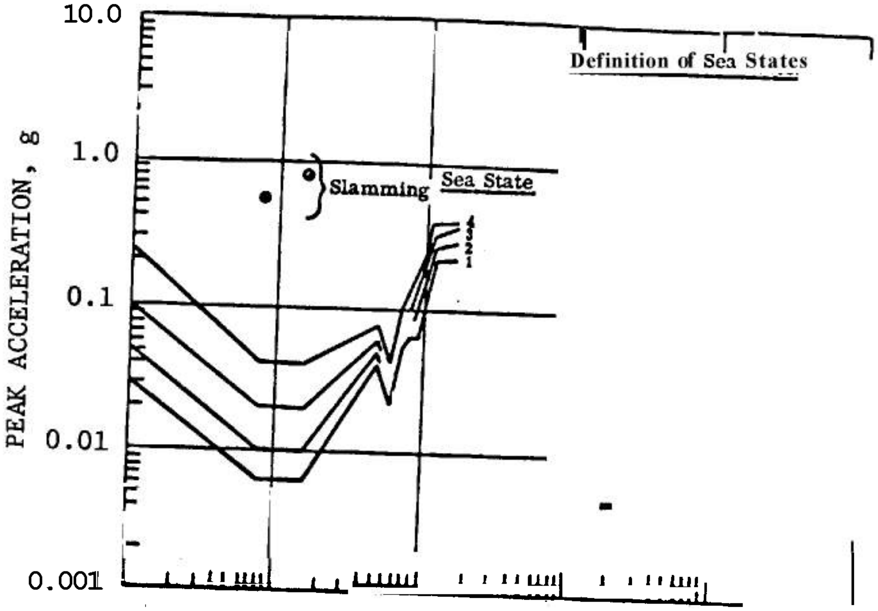
Calm Seas


PEAK ACCELERATION, g
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Definition of Sea States
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Sea State
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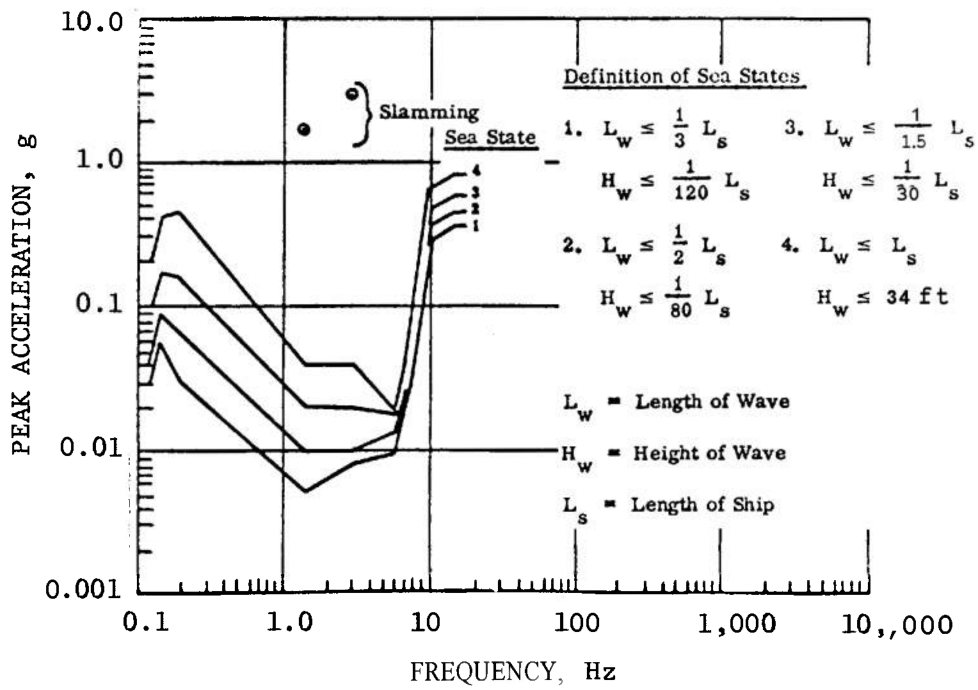


FIGURE 4-44. Effect of Sea State on Vibration of a Ship 380 ft Long (Ref. 21).

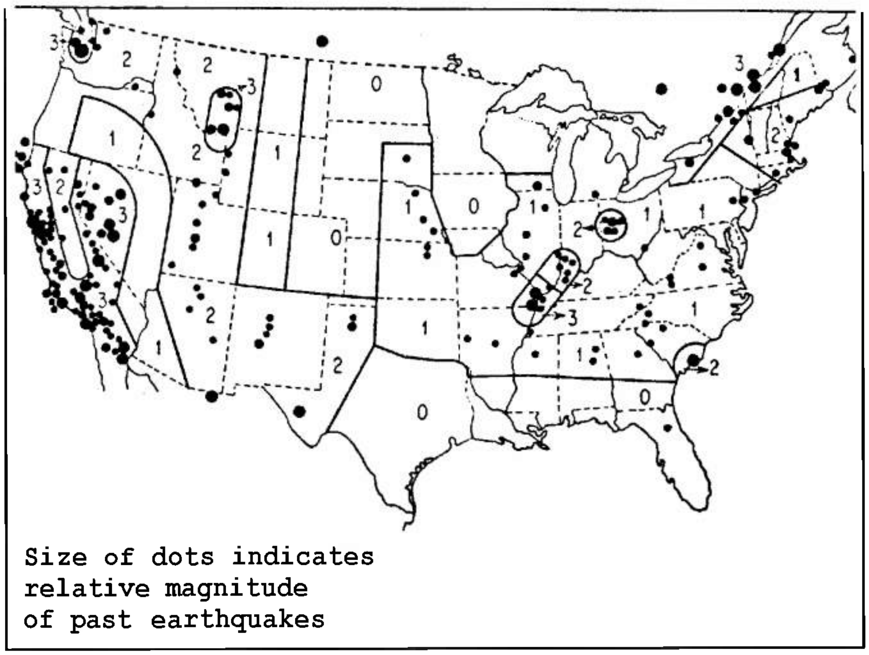


FIGURE 4-45. Seismic Probability Map of the United States (Ref. 42).

Moderate ground winds can produce large periodic oscillatory motion in large tall structures. Smokestacks are particularly vulnerable to this mode of excitation. In addition, long slender elastic space launch vehicles in the prelaunch configuration can be excited into vibration as a result of ground winds in what is known as the Karman vortex phenomenon (Ref. 37). The stresses generated during these vibrations can result in structural failure in the launch vehicle. The conditions required to produce this dangerous effect are not always apparent because a unique combination of booster geometry and ground windage is necessary. Other tall structures, such as some of the skyscrapers in our larger cities, are subject to vibration under the effects of wind. Indeed, it is not uncommon to experience displacements perceptible to the average person while standing on the top of tall buildings.

The most destructive naturally occurring vibrations are those caused by earthquakes. Seismic waves can induce vibrations sufficient to destroy most man-made structures. Basically, an earthquake produces a motion of the ground by the passage of stress waves that originate from the rupture of stressed rock. Earthquakes may occur in all parts of the world; however, certain regions have higher frequencies of occurrence than others. The three major earthquake zones are the Himalayan region of northern India, the Mediterranean-Near East area, and the Circum-Pacific belt (Ref. 10). California, which lies in the Circum-Pacific belt, has experienced a number of severe and destructive earthquakes. The central and eastern parts of the United States have on occasion experienced strong earthquakes but the frequency of occurrence is significantly less than that in California. Fig. 4-45 indicates seismic activity in the United States. The relative magnitudes of past earthquakes are indicated by the size of the dots (Ref. 42). On this figure, the United States is divided into zones that show the probable severity of earthquake damage.

Earthquakes may originate at depths as great as 400 mi beneath the earth surface, but ground motions of significance are always produced by shallow shocks originating less than 50 mi beneath the surface. The immediate cause of a shock is a shear-type failure on a fault plane in the rock of the crust of the earth. When slow shearing deformation of the crust takes place, stresses build up on the fault; when a portion of the fault is overstressed, slipping begins. The sudden release of stress by the slipping of the fault diminishes the strain energy in the rock, thus sending out stress waves. The intensity with which the surface of the ground shakes depends upon the amount of strain energy that is released by the slipping. A detailed discussion of the vibration of structures induced by seismic waves is available (Ref. 10). The base of a structure is moved by the ground both horizontally and vertically during an earthquake. The two perpendicular horizontal components are approximately of equal intensity. The vertical component is usually less intense with a higher frequency spectrum than the horizontal.

At El Centro, Calif., during the earthquake of May 18, 1940, the ground motion lasted for a total of 45 s, but the most severe part of the earthquake occurred during an interval of only 10 to 15 s (Ref. 43). The maximum acceleration of 0.33 G measured at El Centro was the strongest ground motion that has been recorded with the possible exception of very recent earthquakes.

Seismic-induced earth vibrations not only can cause destruction of buildings but, even when intensities are not sufficient to destroy buildings, significant damage can occur as the result of vibration of equipment contained within the structure. For example, relays are particularly susceptible to such vibration. In certain critical applications involving perhaps nuclear power plants and nuclear weapons, measures to safeguard against defects in control systems as a result of seismic-induced vibrations in the structure must be carefully taken into account.

4-3 MEASUREMENTS[1]

To measure the vibration environment either in the laboratory or in the field, an instrumentation system is required.

Basically, measurement is the accumulation of data. To measure the vibration environment, those parameters that vary in the vibration environment must be monitored using sensors or transducers capable of providing an output related to the parameters that are varying. Measurement is not enough, however. The data accumulated by the sensors are usually complex, so that the raw data cannot be used for anything but the most general conclusions. In addition, sensors and transducers are capable of producing these complex data at rates beyond the capacity of the human mind to absorb. For this reason two other steps are required in quantifying the vibration environment of any given item or materiel; data recording and data analysis. All three of these topics will be discussed.

1. General references for this paragraph are Refs. 2-10.

4-3.1 SENSORS

Vibration is measured with reference to a point fixed in space. Two basically different types of instruments are employed: (1) a fixed reference instrument in which one terminal of the instrument is attached to a point whose motion is to be measured, and (2) mass-spring instruments or seismic instruments in which the only terminal is the base of a mass-spring system, which is attached at the point where the vibration is to be measured (Ref 9). The motion of the point is inferred from the motion of the mass relative to the base. In most applications the seismic-type instrument is employed for the measurement of vibration because it is impossible to establish a fixed reference on the vehicles that are to be measured. Basically, three quantities can be measured in vibration studies: (1) displacement, (2) velocity, and (3) acceleration. Of course, these three quantities are interrelated mathematically, velocity being the derivative with respect to time of the displacement and acceleration being the second derivative. As a result, if any one of these quantities is known, simple differentiation or integration permits recovery of the other two. In early studies of vibration, velocity was the parameter most often monitored. Velocity meters, however, tend to be rather large and difficult to use. Consequently, with the advent of sensitive, small acceleration transducers (accelerometers), most vibration studies have employed accelerometers as the measuring transducer. Not only are accelerometers much smaller than velocity transducers, but their useful frequency range is considerably greater.

An important consideration in measuring the vibration environment is that the transducer must generally be attached to the structural member whose vibration response is being measured. If the transducer is large, the measured vibration is that associated with an area rather than a point on the structure. Further, if the transducer mass is large, it can affect the vibration response being measured.

Frequency response is another important property of vibration transducers. Early vibration studies and measurements considered the common upper frequency limit to be approximately 50 Hz. Today, however, many vibration analyses and measurements require frequency responses of 5,000 Hz or above. Two reasons account for this interest in the higher frequency range: (1) fast moving vehicles, especially aircraft and space vehicles, have been developed, and (2) the vibration encountered in these vehicles as well as in a number of ground environments are of a random nature rather than being periodic. Analyses of randomly occurring vibration phenomena require a wider frequency response in the sensor in order to obtain meaningful results.

Most of the sensors used for Army materiel tests have electrical outputs and are called transducers because they transform mechanical motion into an electrical output. Displacement and velocity transducers have a relatively soft suspension while the accelerometer has a stiff suspension. The displacement transducer measures the movement of the case with relation to a soft-sprung internal mass or an external stationary reference. In a displacement meter, the natural frequency of the internal mass is low since it is mounted so that the ratio of the exciting frequency to the natural frequency is high. A differential transformer is often used to measure relative motion. In a differential transformer, the relative motion between the transformer core and the windings generates flux as the core cuts through fields of the primary and secondary winding. The electrical output so produced is proportional to the absolute displacement.

A displacement meter is relatively large and heavy in order to allow sufficient space for the relative movement to take place without interference from the case. This limits the usefulness of these meters since the weight will change the natural frequency of any lightweight equipment on which it is mounted.

One type of displacement meter that uses a fixed reference is a capacitance pickup. To measure displacement, a probe is brought near a vibrating object. The meter measures the change in capacitance, which varies directly with the displacement. The advantage of this type of meter is that it does not touch the specimen and, therefore, does not change the frequency of vibration. One disadvantage is the errors in amplitude measurements that are caused by irregular contour of the specimen.

The velocity pickup is a small, electromagnetic generator that measures the instantaneous velocity of a vibrating object. Either the coil or the magnet of the generator is mounted on a soft suspension and remains stationary with respect to the case throughout the usable frequency range of the meter. The velocity meter requires no external power for operation but is rather large and heavy because of the large relative motion required.

The accelerometer has a high natural frequency since the mass is suspended by means of a stiff spring. The case and the mass have essentially the same motion. By using a sensing unit that has an output proportional to the force, the acceleration of a vibrating object can be accurately determined. Two types of sensing elements are commonly used in accelerometers: wire strain gages and piezoelectric crystals.

Strain gage accelerometers contain resistance-wire strain gages to which a mass is attached. When the accelerometer is subjected to a force, the change in acceleration causes a proportional change in resistance which is detected by a Wheatstone bridge.

Piezoelectric accelerometers are by far the most popular transducer used in vibration and shock testing. Piezoelectric crystals generate an electrical output proportional to the acceleration of the internal mass, and are high frequency response, high impedance devices. The piezoelectric crystal may be mounted so that it is bent or is compressed by the load mass. Piezoelectric materials used in transducers include ammonium dihydrogen phosphate (ADP), quartz, and ceramic materials such as barium titanate.

Still another type of sensor is the optical pickup. This is a noncontact device in which a light beam is deflected or reflected by the vibrating object. Optical vibration measuring instruments are presently in a period of rapid development and offer the possibility of being very useful vibration measuring instruments. One of their primary advantages is that they do not mechanically load the vibrating item and, consequently, do not change its natural frequency, as does any attachment-type transducer. The major disadvantages of optical transducers are their high cost and their reputation for being laboratory instruments rather than field instruments. For convenience, vibration-measuring instruments have been given a variety of names: vibrographs, vibrometers, mechanical recording accelerometers, seismographs, electronic vibration meters and recorders, visual displacement indicators, measuring microscopes, stroboscopes, framing cameras, and mechanical strain recorders. A number of these are described in the *Shock and Vibration Handbook*, as are a number of special purpose vibration transducers and inductive-type pickups (Ref. 9). The *ISA Transducer Compendium* also contains a very complete compilation of various transducer types and an excellent sampling of commercially available vibration transducers (Ref. 44).

A recently developed portable instrument for vibration analysis and transducer calibration employs the laser (Ref. 45). This unit uses an acoustically driven liquid diffraction cell to modulate the frequency of a reference or 'local oscillator' laser beam. A second unmodulated beam is reflected from the vibrating surface. When the two beams are combined on a photodetector, a beat frequency at 25 MHz is produced. Periodic motion of the reflecting surface then modulates sidebands about the 25-MHz beat frequency. The amplitude and frequency of the vibration are determined by demodulation of the phase-modulated 25-MHz signal or by direct measurement using a spectrum analyzer. Measurements of vibration amplitudes from 0.25 in. to less than 0.04 in. and frequencies from 10 Hz to 700 kHz have been made with this instrument. Fig. 4-46 is a schematic diagram of the laser vibration analyzer optical system.

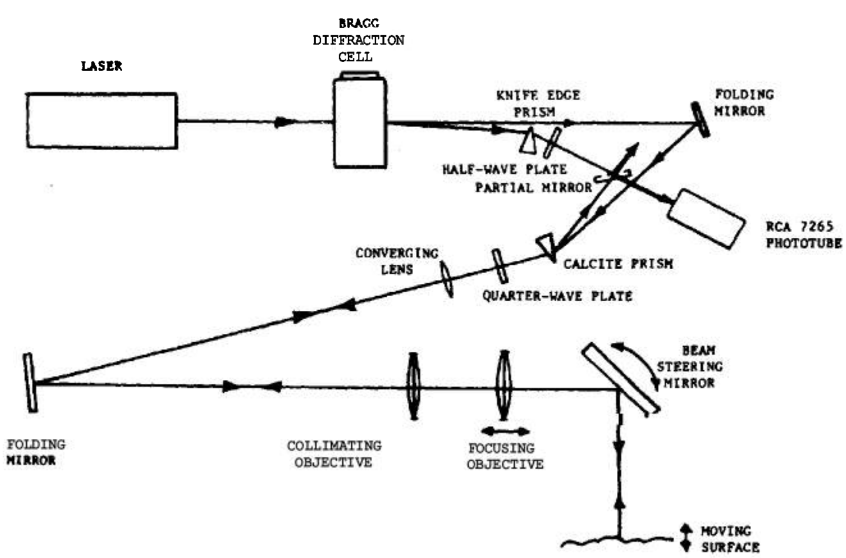


FIGURE 4-46. Laser Vibration Analyzer Optical System (Ref. 45).

4-3.2 DATA RECORDING

Once the vibration information has been obtained by the sensor, it is necessary to record or display the information in order for it to be useful. Many types of instruments are available for recording vibration measurements. The specific instrument chosen depends on the type of environment to be recorded and, on whether a transient indication or a permanent record is desired. One of the most popular output devices is the oscilloscope. An oscilloscope presents the output of a transducer on a cathode-ray tube. An oscilloscope can be used with the appropriate transducer to indicate the level of displacement, velocity, or acceleration. The instantaneous presentation from a nonperiodic transient can be photographed for subsequent study. A storage oscilloscope with a long persistence screen can be used to retain an image for study. Oscillographs differ from oscilloscopes in that they provide a permanent record of the transducer output by writing on a moving strip of paper. An oscillograph will make a reproduction of wave shapes within its frequency range. One type of oscillograph writes mechanically on the paper. Consequently, its frequency response is restricted to about 100 **Hz.** Another type of oscillograph known as a galvanometer type employs the varying voltage from the transducer to move a low inertia mirror. The movement of the mirror deflects a light source and performs a trace on sensitized paper. The result is a quickly developed permanent record of vibration data with a frequency response up to approximately 3,000 **Hz.**

In addition to visual displays, photographic recordings, and paper tape recording, magnetic tape recording is widely used. When extensive analysis of the vibration data is required, magnetic tape recording is indispensable. The frequency response of magnetic tape recording is sufficient to record the output of any vibration transducer.

4-3.3 DATA ANALYSIS[2]

Two types of analysis are employed for vibration data. The first determines the various frequencies present and their amplitudes; the second, the statistics of the data. Data analysis systems can vary from very simple systems in which meters are used to determine only the general level of vibration present to extremely complicated systems capable of a variety of frequency and statistical analyses. An important first step is to determine whether the vibration is random or periodic. The procedures for reducing, analyzing, and interpreting data representing a random vibration are different from those for a periodic vibration. A periodic vibration is completely described by a Fourier series, which gives the amplitude, frequency, and phase of all harmonic components of the vibration. In practice, however, only the amplitudes and frequencies are necessary for engineering applications. For this, a periodic vibration is described by a discrete frequency spectrum. A typical discrete frequency spectrum is illustrated in Fig. 4-47. Each harmonic component appears in the frequency spectrum as a line with zero band width and an instantaneous amplitude y. The peak amplitudes of the components (C_0, C_1, C_2, etc.) are equivalent to the coefficients in the Fourier series for the periodic vibration. The fundamental vibration frequency has an amplitude C_1 at a frequency f_1. The mean square amplitude of the vibration σ_y is equal to the sum of the mean square values of the individual components minus the square of the mean.

$$\bar{y} = C_0$$

$$\overline{y_1^2} = \frac{1}{2} C_1^2$$

$$\overline{y^2} = C_0^2 + \frac{1}{2}\sum_{i=1}^{\infty} C_i^2$$

$$\sigma_y^2 = \overline{y^2} - (\bar{y})^2 = \frac{1}{2}\sum_{i=1}^{\infty} C_i^2$$

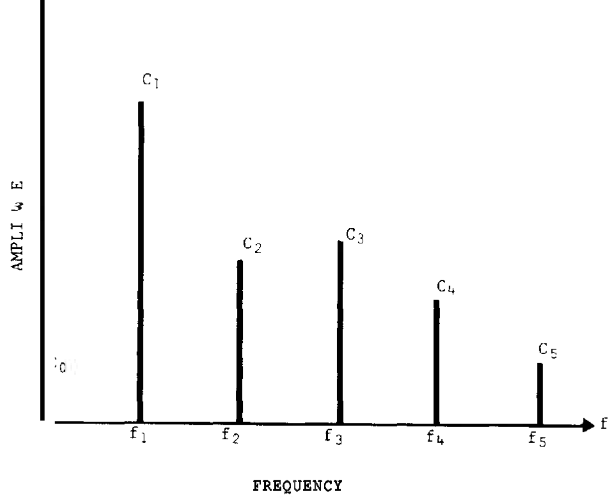


FIGURE 4-47. Typical Discrete Frequency Spectrum (Ref. 2).

2. A general reference for this paragraph is Ref. 2.

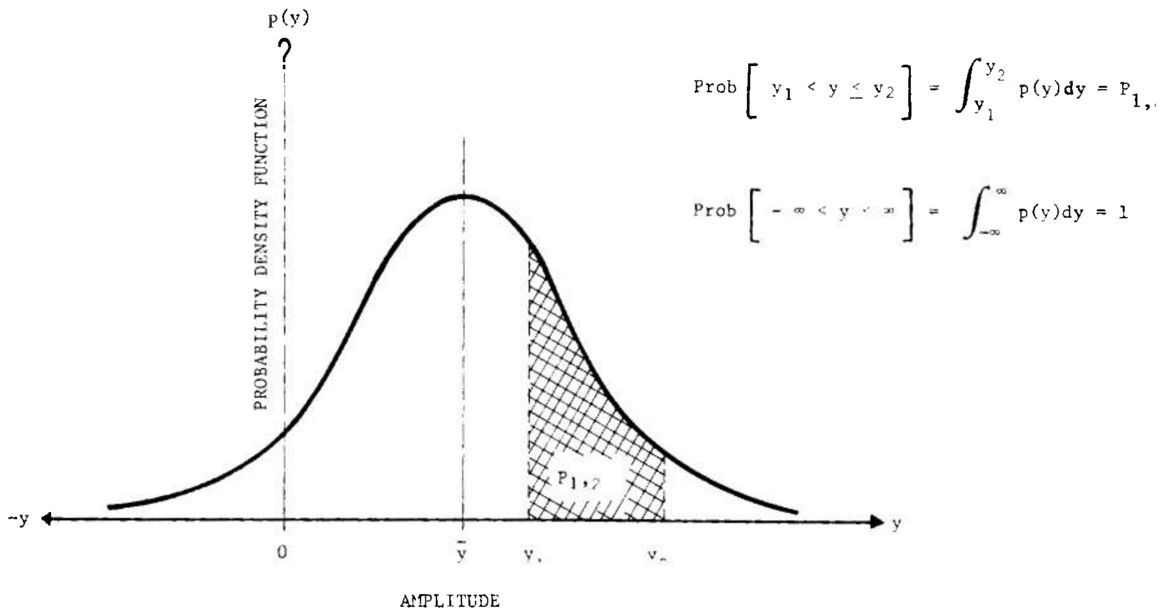


FIGURE 448. Typical Probability Density Plot (Ref. 2).

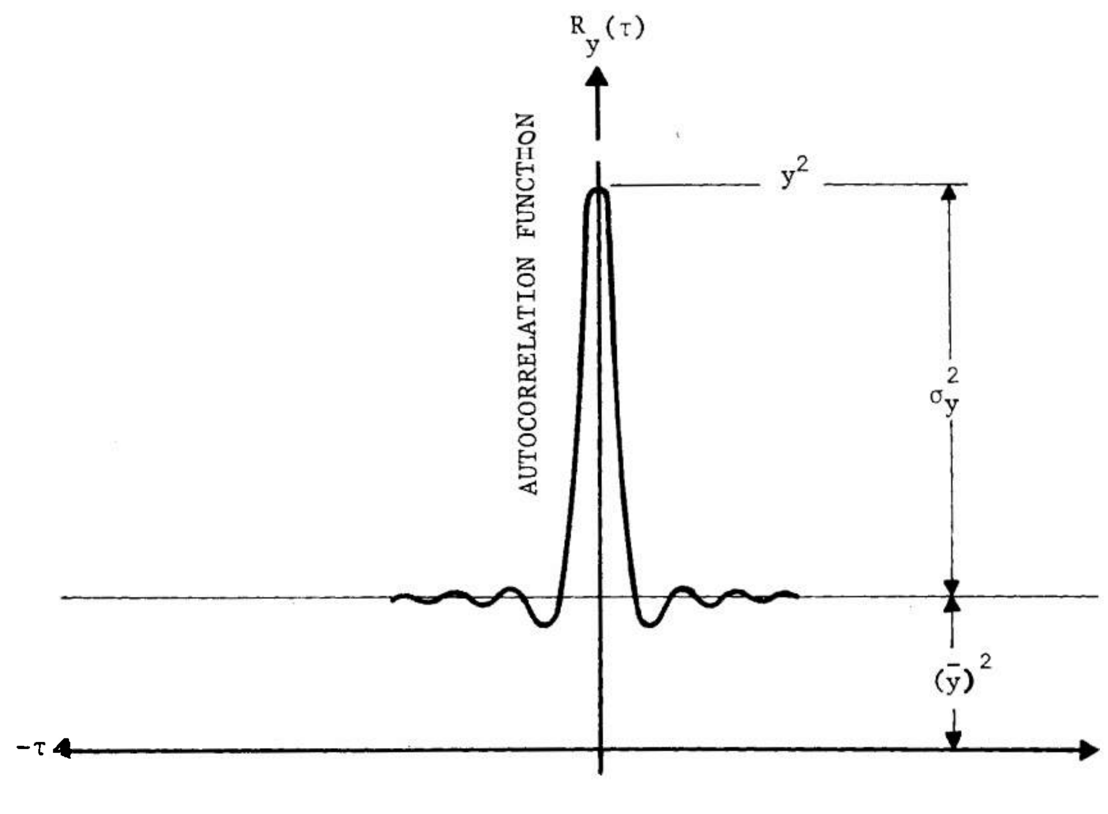


FIGURE 449. Typical Autocorrelation Plot (Ref. 2).

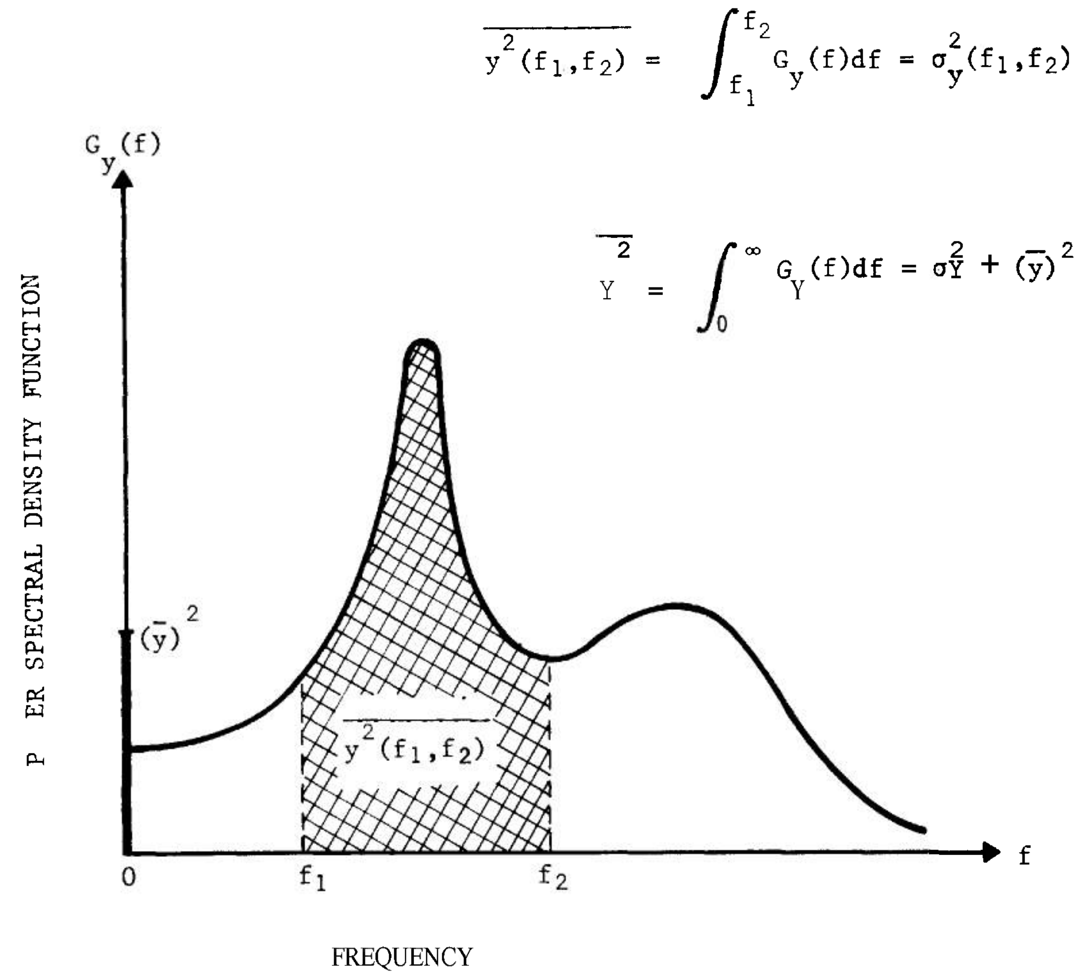


FIGURE 4-50. Typical Power Spectral Density Function (Ref. 2).

For random vibrations, a reasonably detailed description is given by three functions. The first of these is the amplitude probability density function, which is a statistical description of the amplitude characteristics of the vibration. A typical probability density plot is given in Fig. 4-48. The second descriptor is the autocorrelation function, which is a statistical representation of the fine correlation characteristics of the vibration. Fig. 4-49 gives a typical autocorrelation plot. The third description is the power spectral density function, which is a statistical description of the frequency composition of the vibration. Fig. 4-50 gives a typical power spectrum.

If data from two or more vibration measurements are made simultaneously on the same system, further information can be obtained from several joint properties. These properties include the joint amplitude probability density function, the cross correlation function, the cross power spectral density function, and the coherence function. Fig. 4-51 is a typical joint probability density plot. In this the probability density $P(x,y)$ is plotted versus x and y. The volume under the joint probability density plot bounded by the amplitudes x_1, x_2, y_1, and y_2 is equal to the probability that $x(t)$ and $y(t)$ will simultaneously have amplitudes within those ranges at any given time. The total volume under the

$$\text{Prob}\left| x_1 < x \le x_2;\ y_1 < y \le y_2 \right| \quad \int_{y_1}^{y_2} \int_{x_1} p(x,y)\,dx\,dy = P_{1.2}$$

$$\text{Prob}\left[-\infty < x < \infty;\ -\infty < y < \infty \right] = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p(x,y)\,dx\,dy = 1$$

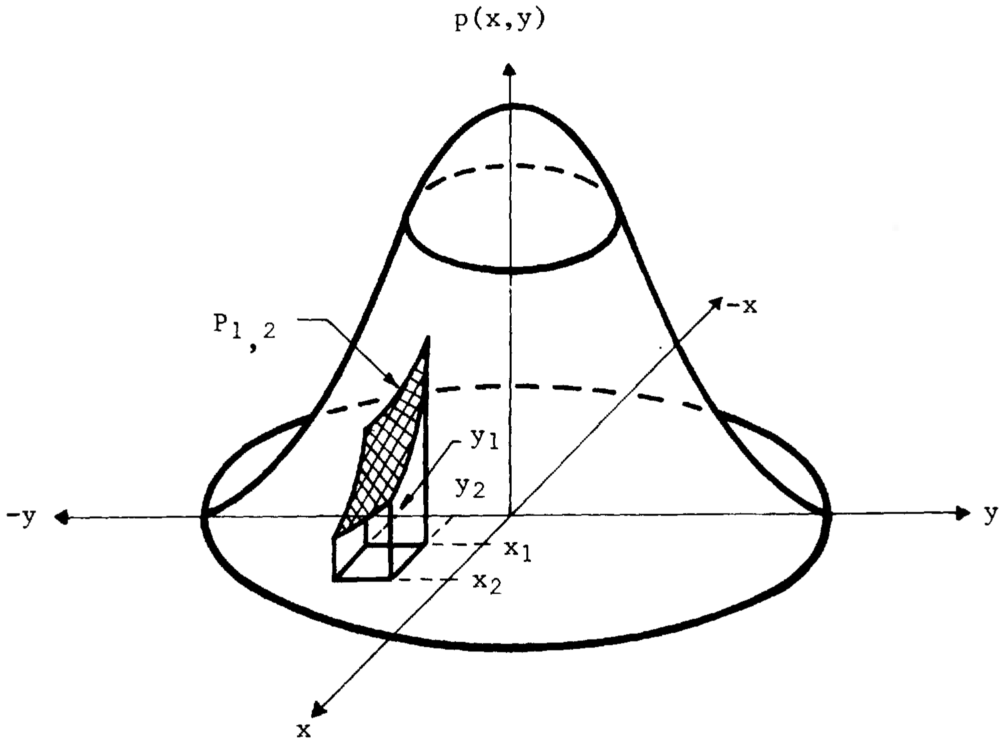


FIGURE 4-51. Typical Joint Probability Density Plot (Ref. 2).

plot is equal to unity since the probability of the two vibration responses simultaneously having any amplitudes must be unity. A typical cross correlation plot is illustrated in Fig. **4-52.** The value of the cross correlation function for two vibration responses indicates the relative dependence of the amplitude of one vibration response at any instance of time on the amplitude of the other vibration response that had occurred τ seconds before. Cross correlation functions are useful tools for localizing vibration sources by determining time delays in structural transmission paths. The cross power spectral density function has applications to the evaluation of structural transfer characteristics; however, because of its mathematical complexity, discussion of this function is not given in this handbook but may be found in Ref. 2.

In general, the cross correlation function is used for investigation of structural transmission paths and time delays while the cross power spectrum is used for evaluating structural transfer characteristics. The coherence function is used as a measure of the linearity of a structure. For example, if two vibration responses in a

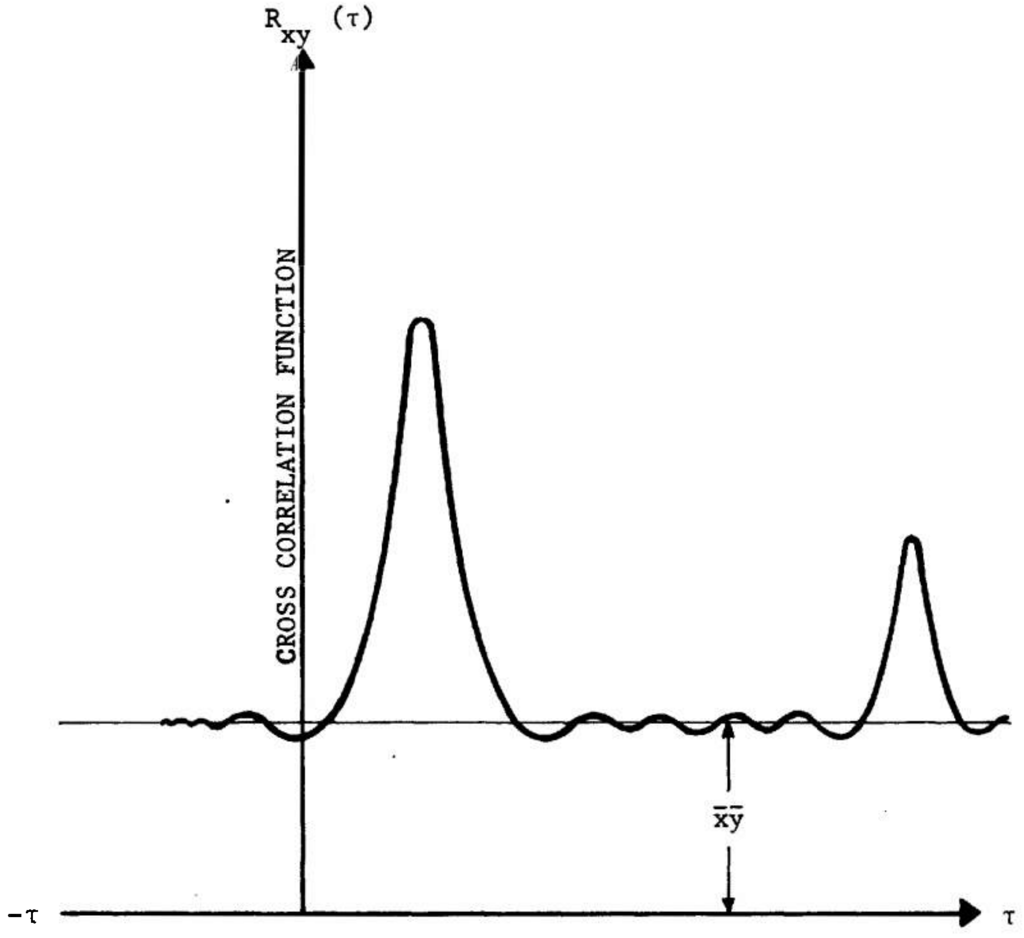


FIGURE 4-52. Typical Cross Correlation Plot (Ref. 2).

structure are completely uncorrelated (uncoherent), then the coherence function will equal zero. If the two vibration responses are correlated in a linear manner, the coherence function equals unity. Nonlinearities will produce a coherence function for the input-output relationships that is less than unity.

When a sample vibration response record in the form of an analog voltage signal is given, a discrete frequency spectrum for the sample data can be obtained using a wave analyzer or spectrum analyzer. Of the two basic types of spectrum analyzer, one employs a collection of contiguous, bandpass filters and the other employs a single, narrow frequency, bandpass filter. In the first type the filters may have either a constant bandwidth or bandwidths that are proportional to their center frequencies. When a periodic signal is applied to the bank of filters, each filter passes those frequencies lying within its pass band and excludes all others. The output amplitudes from the filters are then detected and recorded simultaneously as a function of time. As a result, the spectrum of the applied signal is separated into as many intervals as there are filters in the bank. This multiple-filter-type analyzer is sometimes called a real-time spectrum analyzer because its operation is substantially instantaneous; this is its primary advantage. The primary disadvantage of such a filter is its high cost. If high frequency resolution is to be obtained, large numbers of expensive filters and amplitude detectors must be employed in the analyzer. Fig. 4-53 is a functional block diagram of such a multiple-filter-type spectrum analyzer.

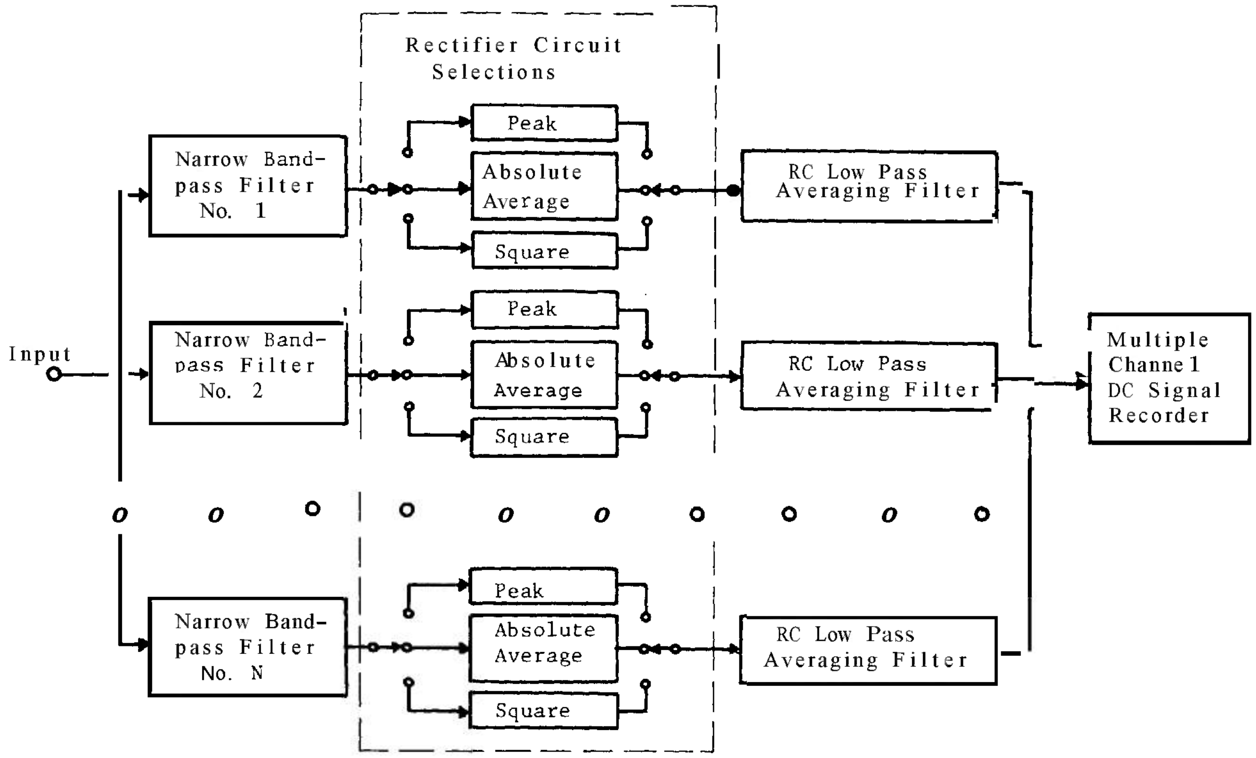


FIGURE 4-53. Functional Block Diagram for Multiple-filter-type Spectrum Analyzer (Ref. 2).

The second type of spectrum analyzer has a single, narrow frequency, bandpass filter. The vibration signal is tuned in frequency by heterodyning it with a tunable oscillator such that the output of the filter is the spectrum for the applied signal. The primary advantage of this type of spectrum analyzer is its very high resolution. Since only a single fixed filter is used, its characteristic is optimized at low cost. The basic disadvantage of the single-filter-type analyzer is that the time required to perform an analysis is relatively long because the entire frequency range of the signal must be scanned with the one narrow bandpass filter. Fig. 4-54 is a functional block diagram of a single-filter-type spectrum analyzer.

Both types of spectrum analyzers have an output amplitude detector circuit that computes one or more of three different amplitude functions: the peak amplitude, the rectified average amplitude, or the mean square amplitude. The relationships among these three signals for a simple harmonic vibration that can be expressed as

$$y(t) = C \sin(2\pi f t) \tag{4-6}$$

are as follows:

Instantaneous amplitude $= C \sin 2\pi ft$
Peak amplitude $= C$
Rectified average amplitude $= 0.636\ C$
Mean square amplitude $= 0.5\ C^2$
Root mean square (rms) amplitude $= 0.707\ C$.

A more detailed discussion of the various data analysis techniques may be found in the Vibration Manual (Ref. 2) and other references (Refs. 1,3,4,5,7,8, and 9).

4-3.4 MODELING

If during the design of an equipment the vibration

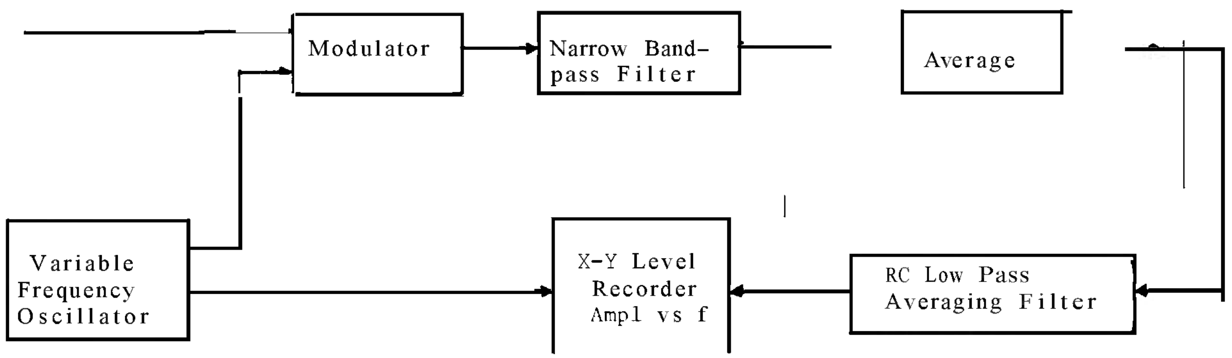


FIGURE 4-54. Functional Block Diagram for Single-filter-type Spectrum Analyzer (Ref. 2).

characteristics have been determined, it may be possible to calculate the response of a system to a given vibration environment by the use of a mathematical model. Usually the fundamental natural frequencies and vibration modes can be easily calculated. The natural frequencies of a linear system depend on the unique. arrangement of the mass and elasticity parameters of the system. The vibration mode is the configuration of the vibration when a system vibrates at its natural frequencies. After the formulation of a mathematical model, several methods of solution are available. Two of the basic methods of solution are the Stodola Method (Ref. 46) and the Holzer Method (Ref. 47). These two basic techniques allow the use of newer mathematical methods and the digital computer to calculate natural frequencies of systems. For example, several computer codes are available for natural frequency calculation in the NASA Computer Software Management and Information Center (COSMIC) at the University of Georgia. For general vibration analysis of large structures, the SAMIS system is a large capacity computer program useful for natural frequency calculations in which the specific problem must be modeled to fit the format of the computer program (Ref. 48). A second large computer program named NASTRAN (NASA *STR*uctural *AN*alysis) is capable of performing static and dynamic analysis of large complicated systems (Ref. 49). Both of these programs can be obtained through NASA's COSMIC Center.

Another technique employed in vibration analysis is to build scale models of the system. Models are particularly valuable for the analysis and design improvement of complicated or irregularly shaped structures or of machinery structures on distributed foundations. A model study gives good understanding of the behavior of the entire structure. A variety of materials are used to construct the models. In some cases, special materials are required for accurate modeling. Plastic, however, has a number of advantages:

(1) Deflections are large and consequently easily measured.

(2) The drive forces required to excite the structure are small.

(3) The model natural frequencies are relatively low so that small models can be used.

(4) Model cost is low.

(5) Structural modifications can be made easily.

(6) High impedance foundations are usually available.

The accuracy of the results obtainable with plastic models depends on:

(1) The incorporation of details in the model

(2) The accuracy of fabrication of the model parts

(3) The care with which the joints are made

(4) The accuracy with which the characteristic properties of the material of which the model is fabricated are known.

Plastic models can be used for four main types of test:

(1) Static deflections and stresses
(2) Natural frequencies
(3) Vibration amplitudes and stresses
(4) Mode shapes (Ref. 50).

In summary, knowledge and insight gained in plastic model studies of a structure permit the designer to optimize the design and achieve minimal operating deflections and stresses for given weight and cost.

4-4 EFFECTS OF VIBRATION

Vibration in the environment can degrade materiel and impair personnel efficiency, thereby creating needs for additional or more suitable materiel to protect against vibration, to better endure vibration, to reduce vibration, or to change the frequency of vibration. All of the effects of vibration are not detrimental; in a vibration-free environment it is sometimes necessary to introduce vibration in order to free an electric meter movement to obtain a correct reading or to obtain a flow of granular material in a desirable mode. In this discussion, only the detrimental effects are considered. These are categorized into direct effects on materiel and personnel.

4-4.1 MATERIEL DEGRADATION

Vibration may affect materiel in many ways. Generally, these may be classified into one or more of the following categories:

(1) Malfunction of sensitive electric, electronic, and mechanical devices

(2) Mechanical and/or structural damage to structures both stationary and mobile

(3) Excessive wear in rotating components

(4) Frothing or sloshing of fluids in containers.

Rather than attempt to detail the effects of vibration on materiel, several examples of the effects on particular structures and components will be given. First, in a general sense, the response of a structure to shock and

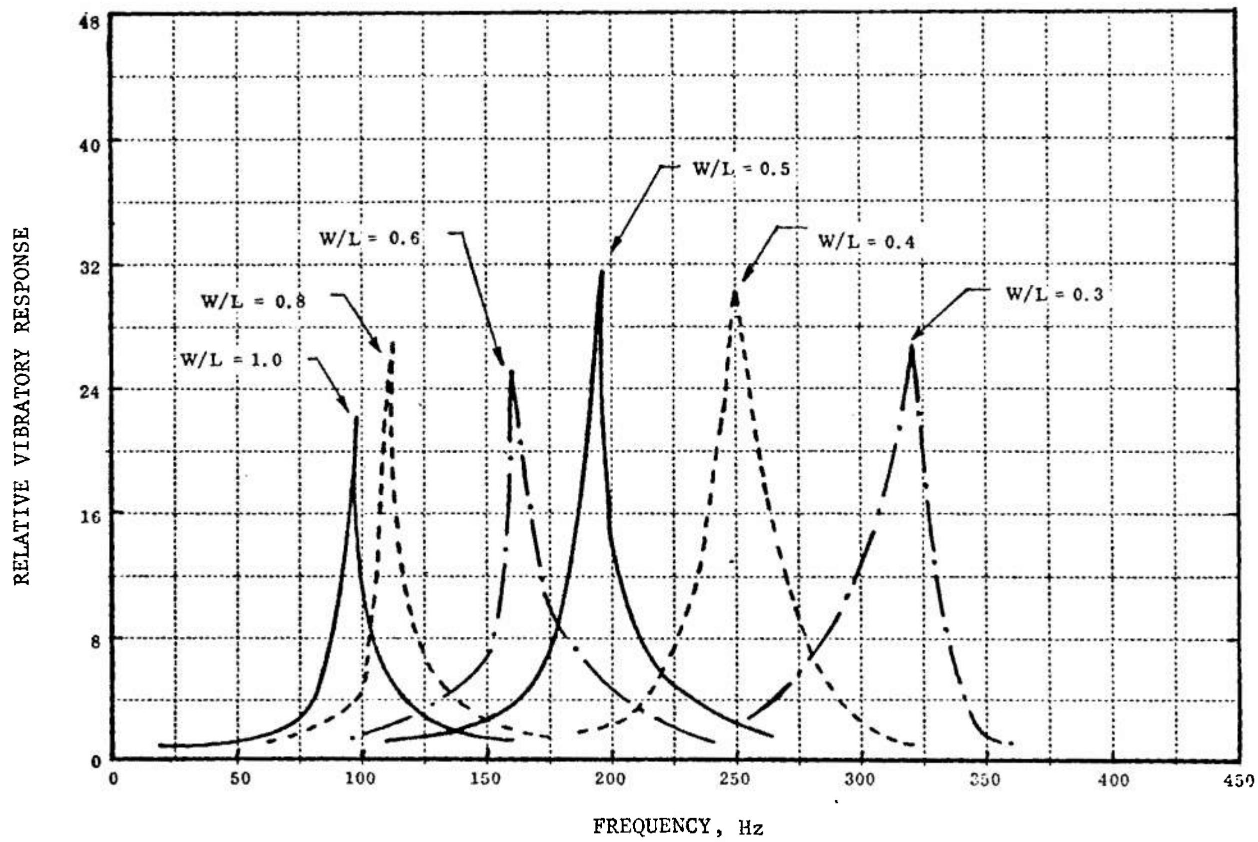


FIGURE 4-55. Effect of Width-to-length (W/L) Ratio on Vibrations of Circuit Boards (Ref. 52).

vibration is dependent not only upon the magnitude of the disturbance, but also upon the dynamic characteristics of the structure itself. A continuous vibration of the same frequency as the natural frequency of a structure, even though the vibration amplitude is small, may damage the structure. A different vibration frequency, even though of much greater amplitude, may produce no effect. It is important to note that vibration can cause the progressive deterioration known as fatigue that leads to failure of material or parts.

Failure can occur either through fatigue, excessive single stress, or excessive deflection. Fatigue failures usually imply a large number of stress cycles; however, when a component is vibrating at hundreds of cycles per second, the total time required for failure may be short. Excessive single stresses may cause brackets or other supporting structures to yield or fracture. Excessive deflection of parts may result in mutual collisions with high impact, causing failure. In the aerospace program, several launch vehicles have experienced 'pogo-type' longitudinal vibration incidents (caused by coupling between propulsion or control systems and longitudinal vibration modes of the mechanical structure), which caused excessive loads and resulted in booster malfunction (Ref. 35). In another case, control system coupling with the launch vehicle structure in the launch mode required engine shutdown to prevent failure from vibration of the structure while the vehicle was supported on the launch stand, thus requiring control system redesign (Ref. 35). Another example occurred with respect to the POSEIDON missile. In this case, the motor vibration environment on the second stage forward dome was very severe (Ref. 36). The firing units attached to the second stage forward dome were unable to survive motor vibration test and a vibration isolator was required to protect these packages.

Another rather severe vibration environment is that of gunfire vibration in aircraft. Tests have demonstrated that equipments most susceptible to gunfire are those located within a 3-ft radius of the gun muzzle and mounted on the structural surface exposed to the gun blast. Prime examples of such equipment are UHF antennas and their accessory hardware. Next in order of failure susceptibility is equipment mounted on drop-down doors and access panels, equipment mounted in cavities adjacent to the aircraft surface, and, finally, equipment located in the interior of the vehicle structure. Typical equipments in these latter categories are auxiliary hydraulic and power units (including mounting bracketry); switches; relays; infrared, photographic, communication, and navigation equipment; and radar systems (Ref. 51).

Vibration can also cause bouncing of motor and generator brushes; sticking of switches and valves; misalignment of optical equipment; and fracturing of propellant, pneumatic, and hydraulic lines.

The effects of vibration on sensitive electrical and electronic equipments and their associated mechanical hardware have been summarized (Ref. 37). Data taken from a series of tests indicated the kinds of damage given in Table 4-6. An example of the vibration effects on electronic components is found in printed circuit boards, which are used for mounting components in a variety of electronic equipments. The boards are subjected to the vibration experienced by the overall package and are normally packaged in rows in a chassis. It is possible for excess vibratory motion to cause impact between boards. In one test of printed circuit boards of varying length-to-width ratios, the vibration response to an acceleration input of 2.8 G with a sweep rate of 0.5 octave min^{-1} was measured (Ref. 52). Resonant frequencies were noted and a slow sweep through the lowest resonant area was conducted to determine the fundamental frequency. Fig. 4-55 demonstrates the effect of the width-to-length ratio on the vibratory response. In these tests the spacing between supports was varied. Fig. 4-56 demonstrates the effect of width-to-length ratio and support on the natural frequency.

High intensity acoustic waves can also cause vibration difficulties with sensitive electronic, mechanical, and hydraulic equipment. Permanent failure of the equipment due to mechanical damage of one or more of the parts can occur, or malfunction can occur only during the portion of time when the equipment is exposed to the intense sound waves. With permanent failures, the susceptible points in the equipment can usually be determined by inspection. However, when malfunctions occur only during exposure to the acoustic environment, location of the failure is much more difficult and simulation may be required in order to observe the malfunctions. Large, poorly supported panels are extremely susceptible to acoustically induced vibration and damage.

Although the vibration environment is within the normal vibration specifications of particular units, under certain circumstances when other environmental factors are near their specified limits, damage can occur. For example, in the transportation environment when materiel is shipped in containers that are sensitive to humidity or moisture, the presence of humidity or moisture can significantly change the ability of the container to withstand vibration in its environment. Temperature at extreme limits can also cause significant

TABLE 4-6. VIBRATION INDUCED DAMAGE TO ELECTRICAL AND ELECTRONIC EQUIPMENT (Ref. 37)

Component category	Damage observations
Cabinet and frame structures	Among some 200 equipment cabinet and frame structures subjected to shock and vibration, damage included 30 permanent defonnations, 17 fractures in areas of stress concentration, two fractures at no apparent stress concentrations, 23 fractures in or near welds, and 26 miscellaneous undefined failures.
Chassis	Nearly 300 chassis subjected to shock and vibration experienced 18 permanent deformations, eight fractures in or near welds, nine fractures at no apparent stress concentrations, 46 fractures at points of stress concentration, and 12 miscellaneous failures.
Cathode-ray tubes	Cathode-ray (CR) tubes are susceptible to vibration damage if they are improperly mounted and supported. CR tubes with screens larger than 5 in. are oarticularly susceptible. Of 31 cathode-ray tubes subjected to shock and vibration, the deflection plates of one tube became deformed, another had a filament failure, five suffered envelope fractures, and one had a glass-socket seal break.
Meters and indicators	Although the moving coil type of meter comprises the majority of units in this category, other indicators such as Bourdon tubes and drive-type synchros were also tested. Of the latter group, most of the failures were either erratic performance or zero shift difficulties. Nearly 200 units were subjected to shock and vibration. Two suffered permanent deformation of the case, one had elements loosened, 12 gave erratic readings, one had the glass face fractured, two developed internal open circuits, two had loose or damaged pivots, three had deformed pointers, and 10 others failed from miscellaneous causes.
Relays	Relays present a particularly difficult problem for dynamic conditions because of the difficulty in balancing all of the mechanical moments. Shock generally causes failure in the form of the armature failing to hold during the shock. A total of 300 relays were subjected to shock and vibration. Armature difficulties accounted for 29 defects, four relays had contacts fuse or burn because of arcing, one had the coil loosened on the pivots, two had the springs disengaged from the armature, and four sustained miscellaneous defects.
Wiring	Wiring failure from shock and vibration is a serious problem. A defect not only results in malfunctioning of the equipment but presents a difficult troubleshooting job in locating the wire break. In a number of equipments subjected to shock and vibration, the failures were as follows: 10 cold solder joints opened, 14 lead-supported components had the leads fail. insufficient clearance caused three cases of arcing, and insufficient slack caused nine lead failures. in addition, three plastic cable clamps fractured, 14 solder joints or connections failed, 16 solid conductor wires broke, and 92 sustained miscellaneous failures.
Transformers	In electronic equipments transformers are probably the heaviest and densest components found on an electronic chassis. Because of the weight and size of transformers, shock and vibration are more likely to produce mechanical rather than electrical failures. While not all mechanical failures immediately prevent the transformer from functioning properly, they eventually result in destruction of the transformer and damage to surrounding components. Of 80 transformers subjected to shock and vibration, 17 had the mounting stubs break at the weld, four had the bottom frame fail, and two suffered brohen internal leads due to motion of the coil in the case.

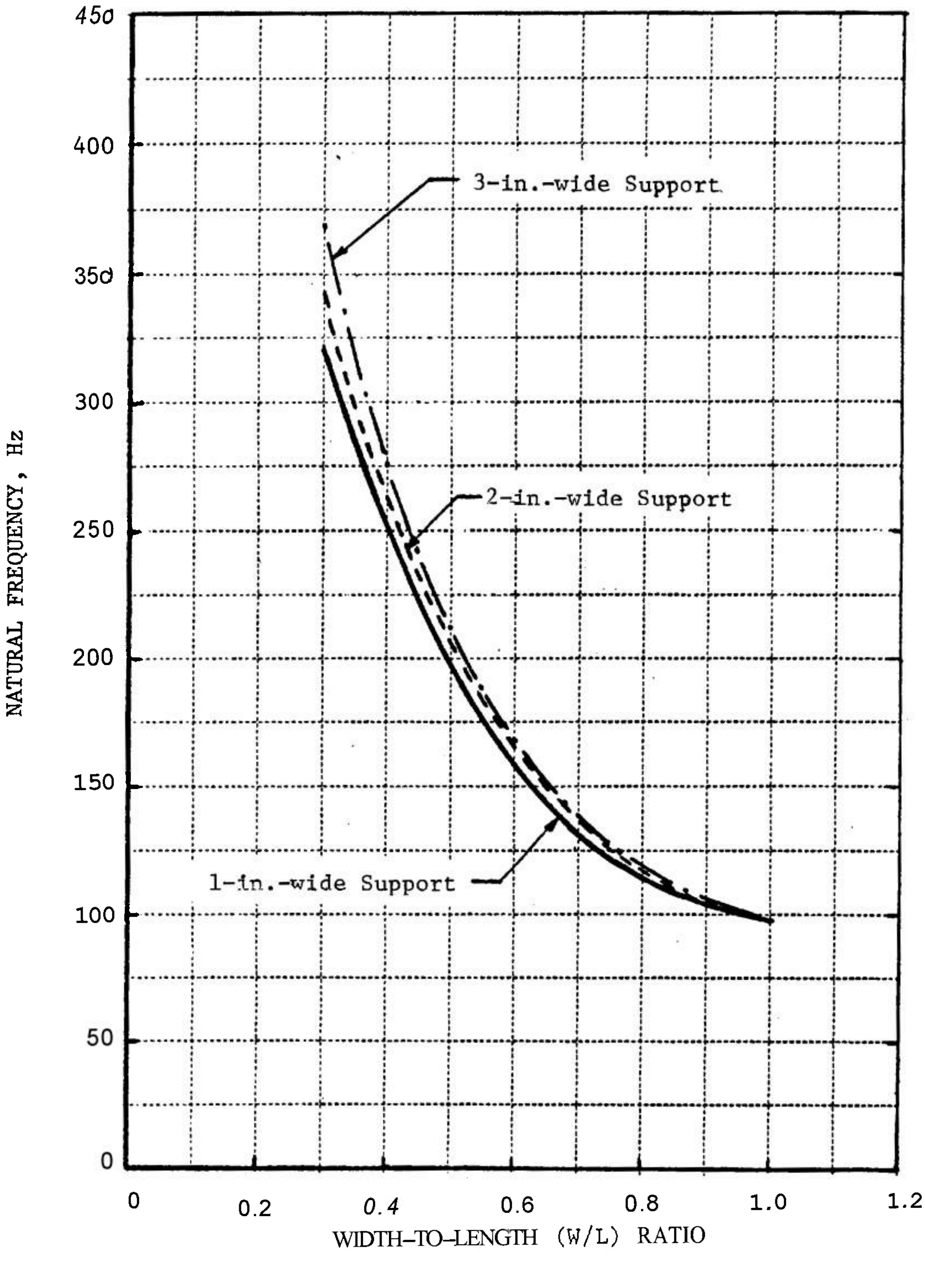


FIGURE 4-56. Natural Frequencies of Printed-circuit Boards (Ref. 52).

difficulties with certain materiel under normal vibration environments or vibration environments within the limits of specifications. Elastomeric materials lose their resiliency as the temperature is lowered. When temperature becomes sufficiently low, the elastomeric materials become brittle and subject to failure by vibration that would ordinarily be within the vibration limits of the elastomeric material. An example is the failure of rubber engine shock mounts on vehicles in the cold climates. Other structural materials, when their temperatures are raised near the deformation point of the material, are significantly more susceptible to failure from vibration.

Under some circumstances, vibration from various sources can contribute additively to the stresses placed on materiel and cause failure. For example, acoustically induced or seismically induced vibration can be superimposed on the normal vibration environment of materiel and contribute, by their joint action, to failure of the materiel. When considering the vibration environment of materiel, the possibility of more than one source contributing to the vibration environment of the materiel should be considered. Further, the effects of other environmental factors on vibration should also be carefully evaluated.

In a publication of the Naval Submarine Base, New London, Conn., the problem of recommended noise and vibration levels for diesel-, electric-, and nuclear-powered submarines is discussed (Ref. 53). In this publication it is pointed out that for more than 10 yr, operating forces and auxiliary machinery repair groups have desired numbers that would classify machinery operational performance qualities relative to probability of failure. In this publication a series of curves known as "Chapman Curves" establish six zones of machinery condition based on the measured vibration levels of the rotating machinery. These zones and their meaning are shown in Fig. 4-57. The ordinates on the graph show peak-to-peak vibration amplitudes in mils and the conversion to displacement decibel levels. The abscissa line indicates the frequency in Hz or revolutions per second. The opinion is voiced in this paper that rotational unbalance in machinery is the most important factor influencing degradation of bearings and that monitoring vibration levels can serve as a tool for preventive maintenance.

4-4.2 PERSONNEL PERFORMANCE DEGRADATION

Vibration is one of the most pervasive environmental factors in human experience. Indeed, even the unborn fetus is subject to vibration as a result of locomotion of the mother and other vibration influences to which the mother is subjected. Vibration is usually considered an externally applied stress (Ref. 54). Yet, this is not always the case since many forms of vibration are self-induced as the result of various forms of human locomotion, such as walking, running, swimming, and jumping. However, most scientific investigations into the vibration environment of man have been primarily concerned with externally applied vibrations. Much of the early work was involved in defining and ascertaining ride comfort conditions in various forms of transport. Certainly, many of the earlier forms of transportation provided a more uncomfortable environment from the standpoint of vibration than the modern automobile, train, or airplane under normal operation. An example is the severe vibration environment on a loaded wagon drawn by a team over the rough and unsurfaced roads of the 19th century.

The human organism in its sensing of vibration classifies vibration in a variety of ways, ranging from pleasant to unpleasant, discomfort, and even injury. The use of vibratory energy for massaging muscles is a widely established custom as is the use of special vibrating machines installed in chairs, beds, or other such devices, which are then applied to the human body (or upon which the human body is positioned) in order to undergo pleasant vibration stimulation.

Considerations of the vibration effects upon the human being are chiefly concerned with their influence upon his physical comfort, health, sensory and mental acuity, and proficiency in performing assigned tasks. Of interest are such periodic mechanical forces that displace or damage body organs, rupture tissue, or produce perceptible feelings of pain, annoyance, or fatigue. In general, these are high amplitude, low frequency vibrations, although vibrations in the audiofrequency range can cause damage to hearing.

The effect of vibrations on the human body depends upon the physical parameters of the impinging energy, its direction of application relative to the axes of the body, and the mechanical impedance and absorption coefficients of body tissue, organs, and the body as a whole. Furthermore, since the applied frequencies will react with the natural frequency of the body and of its parts to produce resonances, the resonant frequencies of the body and its parts assume special importance (Ref. 16).

With the advent of high speed modern transport, vibration as an environmental hazard has taken on new significance. Injury and other physiologic and pathologic effects are becoming important in the study of vibration environment.

The range of human sensitivity to vibration is much

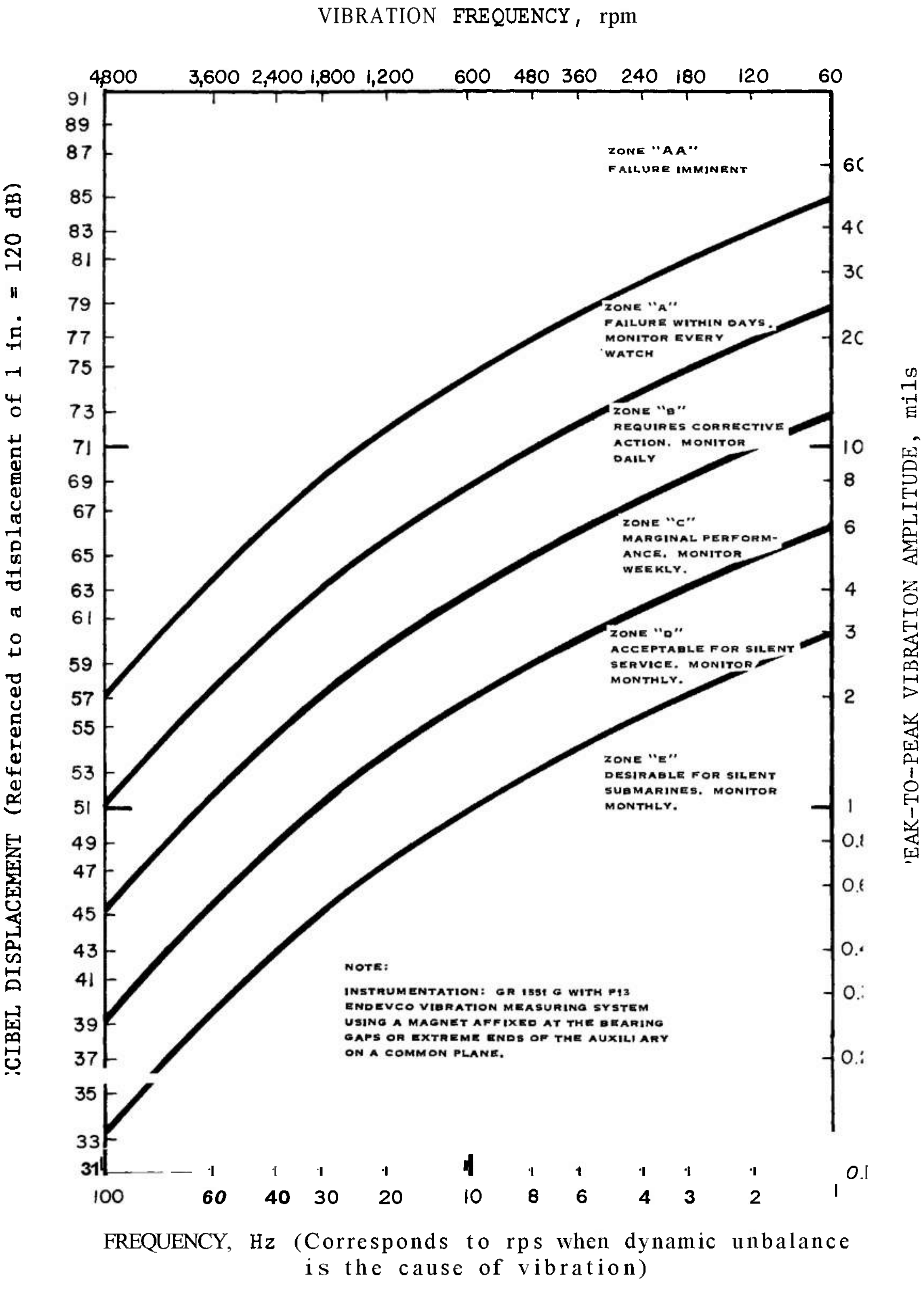


FIGURE 4-57. Practical Guide to Condition of Rotating Machinery–Chapman Curves (Ref. 53).

broader than the range of human hearing, extending from well below 1 Hz up to at least 100 kHz (Ref. 55). Oscillations in the lowest frequencies (0.1 to 3 Hz) are characteristic of large artificial structures, such as tall buildings, large ships, and long suspension bridges, that transmit vibration to man. The range of 3 to 30 Hz principally comprises those vibrati that are encountered in commonplace events invt .. ing vehicles and machinery. Vibrations in many building components, such as walls, floors, and house frames, that are caused by a variety of natural and man-made sources also fall in this range. For frequencies above 30 Hz, human sensitivity to vibration merges with and, generally speaking, becomes subordinate to the response to audible noise. In this higher range, smaller building components, such as panels, wall fittings, windows, and glasses on shelves vibrate when stimulated.

The human being has a variety of sensory mechanisms that respond to vibration. The two means of sensing vibration are indirect sensory mechanisms (which involve seeing and hearing the surrounding environment vibrate) and the organs of direct vibratory sensation. Two basic types of organs of direct sensation permit the sensing of vibration. First, the organs of balance, which connect the inner ear with the brain, act as integrating accelerometers. Their principal function is to detect tilts and turns of the head, induced in the normal range of bodily activity and movement. These organs can produce false information (as can many other human sensors), which can lead to total disorientation. Under proper stimulus they can also produce physiologically disturbing effects, e.g., motion sickness.

In addition to the organs of balance, large numbers of small mechanoreceptors distributed throughout the body sense vibratory forces and displacements. Those found in the muscles, tendons, and joint capsules sense slow changes or sustained mechanical stimuli and provide information about load and position of the limbs and trunk to the brain, which is required for the normal regulation of static and active posture. Receptors in the skin and in connective tissue inside the body form a vibrotactile array that responds most strongly to those vibrations ranging from approximately 30 Hz up into the audiofrequency range. They provide the touch sensation and also detect high frequency, ground structure borne vibration.

The human body itself is an elastic structure subject to resonant vibrations. Different parts of the body are resonant at different frequencies. Table 4-7 lists some of the body resonances that fall within the range of 3 to 40 Hz. Induced motion of an organ or part of the body as a result of resonance may cause physical damage as a result of unnatural displacement of body parts with respect to each other. Even if physical damage is not caused, performance of the human organism can be affected. For example, induced motion of the hand and eye significantly degrades the performance of an individual.

TABLE 4-7. HUMAN BODY RESONANCES (Ref. 56)

Body part	Frequency, Hz
Axial compression of the spine	11-14
Hand	17-25
Eyeball	10-70
Muscles of the face	10-30
Whole body	5

One of the striking facts about the scientific and technical literature concerning the effects of vibratio on human organisms is that the results obtained i different studies vary widely and the conclusions ar different. No doubt a significant portion of this variation results from differences in method plus inadequat measurements or characterization of the vibratory environment. Another factor is that many of the vibratio studies have involved subjective evaluations whose results are expressed in qualitative terms, thus contributing to the difficulty of comparing research results.

In evaluating the effects of helicopter vibration on pilot performance, five indexes of pilot performance—tracking, visual acuity, orientation and vertigo, speech, and reaction time—are considered (Ref. 56). The effects of vibration on these indexes are given in Table 4-8.

Vibration is a fundamental factor in the human environment; therefore, it is important to assess the effect of vibration on man. The International Standards Organization (ISO) has been working on the problem for some time. A study of the effect of sinusoidal vibration on man has been compared with proposed recommendations by the ISO (Ref. 57). In this study, data were obtained on vibration annoyance levels on man in the standing position. The data indicate a minimum sensitivity at 1.7 Hz, with a greater sensitivity at 0.7 Hz,

TABLE 48. EFFECTS OF HELICOPTER VIBRATION ON PILOT PERFORMANCE (Ref. 56)

Performance index	Effect
Tracking ability	Transverse vibration degrades tracking performance more than vertical vibration. Steady-state vibration over comparatively long periods degrades tracking performance. Immediate post-vibration tracking ability has been found to be worse than performance on preliminary tests. Other factors such as stress, motivation, and fatigue are believed to operate but have not yet been reliably measured. On simple motor tasks, those that require the maintenance of intensity, for example, the strength of grip, are not generally affected by vibrations. Precision of muscular coordination on the other hand is degraded.
Visual acuity	Visual acuity is degraded during vertical sinusoidal vibrations at frequencies above 15 Hz, particularly in the bands 25 to 40 Hz and 60 to 90 Hz but degradation of visual acuity at frequencies down to 8 Hz are reported.
Orientation and vertigo	As a result of several studies and interviews with helicopter pilots, it is concluded that vibration can produce difficulties in both vision and balance. Visual problems associated with rotor shadow flicker effects, reflected light from the rotors, and the passage of white clouds are also involved in orientation and vertigo difficulties experienced by helicopter pilots, but the interaction among these visual effects and vibration has not been determined.
Speech	Speech degradation due to vibration is the subject of conflicting reports. However, the majority report some speech degradation, particularly at forcing frequencies between 3 and 15 Hz when acceleration amplitudes exceed 0.5 *g*.
Reaction time	Several studies of reaction time as a function of the vibration environment in helicopters have not yielded any significant correlation between reaction time and the vibration environment.

and maximum sensitivity occurring between 6 and 15 **Hz.** Fig. **4-58** compares the observed annoyance levels for vertical vibration in the standing position with the ISO recommendations. The comparison shows good agreement within the common frequency range of 1 to 20 Hz. Basically, the ISO proposals are designed to cover safe exposure, fatigue-decreased performance **(FDP),** and comfort.

Several studies have been made on the combined effects of vibration and other environmental factors on the tracking performance of human beings. Heat and noise are considered to be normal environmental factors that are likely to occur in the vibration environment. In some studies, no effect has been determined while, in others, additive-type effects appear to be present. One study of the combined effects of vibration and noise emphasized mental performance that is not normally affected by vibration (Ref. 58). By avoiding the direct effects of vibration, those effects that are primarily due to effects on the central nervous system were sought. Results indicate that 110-dB noise combined with 5-Hz vibration at a peak of 0.25 *G* produces a significant reduction in mental performance, while the same level of vibration combined with lower intensities of noise produced no significant effects. No significant effects of noise alone were found in the tests. In another experiment, it was concluded that a 5-Hz vibration decreased mental performance more than either 7 or 11 **Hz** when all three frequencies are presented in conjunction with high intensity noise. This agrees with the general pattern of sensitivity found for subjective judgments and tracking performance. It is concluded that the combined effect of high intensity noise and vibration at 5 Hz produces a greater degradation in performance than either stress alone.

Vibration effects on human beings have been summarized by Hanes (Ref. 59). After an extensive survey of the literature, the following conclusions were drawn:

(1) Sensitivity to vertical (foot-to-head direction) sinusoidal, or approximately sinusoidal, vibration varies with frequency, but the data for various studies show so little agreement that no clearly defined narrow region of maximum sensitivity can be defined.

(2) The first conclusion also applies to sensitivity to horizontal (front-to-back or side-to-side direction) sinusoidal, or approximately sinusoidal, vibration.

(3) Among the various investigations, sensitivity to

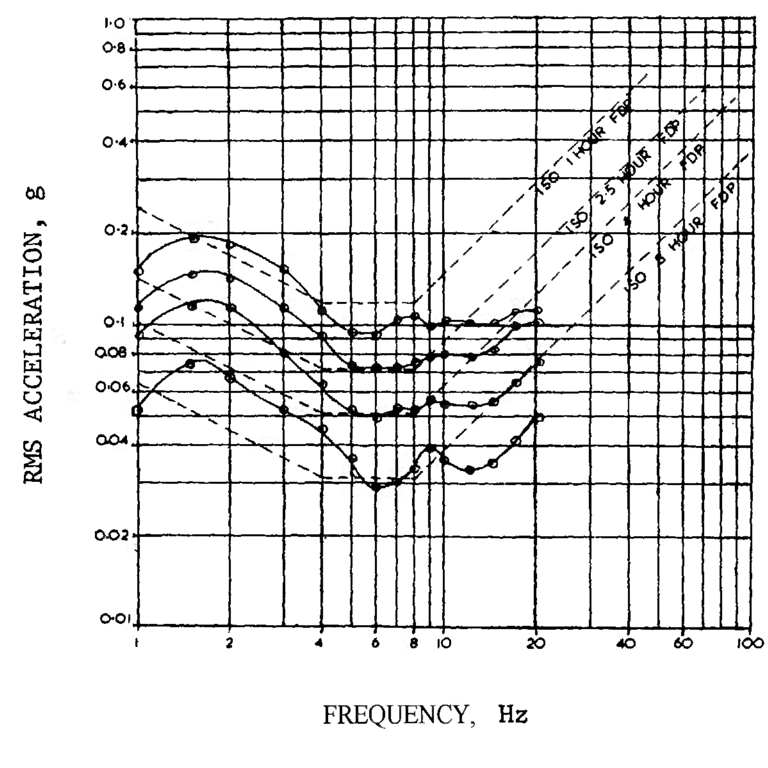


FIGURE 4-58. A Comparison Between the Observed Annoyance Levels and the ISO Proposals (Ref. 57).

vertical vibration has not been shown consistently to be either greater or smaller than sensitivity to horizontal vibration.

(4) Interaction occurs among frequencies and among axes of vibration, but the available data are not sufficient to permit specification of such effects.

(5) Sensitivity to random vibration within narrow frequency bands also appears to vary with the frequency region.

(6) Individual differences and sensitivities are very large and highly sensitive to procedural differences.

(7) Evidence suggests that, for actual vehicles, a single index, such as mean square acceleration for only one axis of motion, might well provide as good a practical measure of vibration sensitivity as is possible.

(8) The available data on human sensitivity to vibration provide no satisfactory basis for choosing any one of the recommended comfort limits in preference to any other.

Additional information on the effects of vibration on man can be found in Refs. 10, 16, 60, and 61.

4-5 VIBRATION CONTROL

When the vibration environment to which materiel is subjected becomes severe enough to cause malfunction or failure either in the short term or in the long term, then measures must be taken to permit the materiel to survive in such an environment. The process of reducing the effects of the vibration environment on materiel is known as vibration control. Essentially, vibration control consists of varying the structural properties of mechanical systems—such as inertial, stiffness, and damping properties—in order to attenuate the amount of vibration transmitted to the materiel or to reduce the effects of the vibration transmitted to the materiel.

A variety of techniques can attenuate vibration. Obviously, a very effective method is to reduce the vibration present in the environment, i.e., to reduce the vibration at its source. Although not practical in many applications, this method of control is sometimes much easier than modification of the materiel to achieve vibration resistance. If the vibration cannot be eliminated or reduced at the source sufficiently for the materiel to survive the environment, then it becomes necessary to reduce the effects of that environment on the materiel.

Damping is a term that refers to the process of producing a continuing decrease in the amplitude of the vibration. Such reduction of vibration amplitude is generally accomplished by employing frictional losses that dissipate the energy of the system with time or distance. Thus, damping is a very general term that can be applied to the use of any energy-absorbing mechanism or device when used to attenuate the effects of vibration on materiel. Structural damping is a more specific term that involves the modification of the elastic properties of the mechanical structure of the materiel. Structural damping is achieved by employing high energy-dissipating material or mechanical structures to reduce the amplitude of vibration (usually necessary in the neighborhood of structural sources). Structural damping techniques include the use of rigid or slip-friction damping, viscoelastic damped structural composites, and slip-friction, viscous shear, or viscoelastic shear damping structural joint assemblies. Viscoelastic damping materials have proved to be the most successful structural damping approaches.

Additional techniques, other than structural damping, that involve modification of the elastic properties of the mechanical structure of the materiel include making the structure more rigid, detuning, and decoupling the structure (Ref. 62). When the structure is rigidized, the result is a decrease in its deflection under load, an increase in its resonant frequency, and an increase in its overall strength. This technique, therefore, is useful only when the resonances of the structure have been raised sufficiently so that all structural resonances are higher in frequency than that existing in the vibration environment.

Detuning of a structure separates the resonant frequencies of structural members and components from other structural resonant frequencies by adjusting inertial and stiffness properties to eliminate coincident resonant frequencies. Decoupling decreases the number of coupled resonators that exist between the vibration environment and the component to be protected by designing the mechanical structure to possess a minimal number of resonances in the frequency range of the vibration environment.

For damping, in the general sense, several methods are used for dissipating energy in a vibrating mechanical system (Ref. 16). Some common methods are solid friction or hysteresis damping, environmental damping, viscous damping, coulomb damping, inertial damping, and electromechanical damping.

Solid friction (or hysteresis damping) occurs in all mechanical vibrating systems that have restoring forces derived from elastic elements such as springs. It seems to arise from slight relative displacements between adjacent crystals or minute elements of the spring material and is often referred to as internal friction.

Environmental damping is the dissipation of energy from a system vibrating in air or a fluid. As the mass vibrates, it displaces the surrounding air or fluid against the opposition of the fluid friction. In the majority of engineering applications, the force developed by environmental damping is approximately proportional to the square of the viscosity of the fluid.

In viscous damping, also called velocity damping, the damping force resisting the motion is a linear function of the velocity. It occurs where there is relative motion between two well-lubricated surfaces and where a viscous fluid is forced through a relatively long passage of small cross-sectional area.

Coulomb damping, also called dry friction damping, arises from the rubbing of dry surfaces with each other. The damping force is assumed to be independent of the velocity and acceleration of the oscillating mass and thus a function only of the materials involved and of the normal force acting on them. In friction damping the energy dissipated with each oscillation is directly proportional to the amplitude, whereas the vibratory energy is proportional to the square of the amplitude.

Inertial damping produces a damping force directly proportional to the acceleration of the vibrating mass. Its amplitude decay characteristics are similar to those of viscous damping, i.e., they result in a logarithmic decrease, thus making inertial damping suitable for large amplitude vibrations. Inertial damping is considerably more responsive than viscous damping since it is not only proportional to the accelerating force, but also acts in direct opposition to it. The viscous damping force lags the accelerating force since it is proportional to the velocity, not the acceleration.

Electromechanical and electromagnetic damping make use of interactions between electrical or electromagnetic phenomena and physical components of the vibrating system. Damping forces that are associated with magnetic hysteresis and eddy currents are examples of this type of damping.

In the paragraphs that follow, more detailed information is given on vibration isolators and absorbers as vibration control devices. In addition, several examples will be given of vibration control that employ damping techniques, detuning, and decoupling. Finally, the vibration control of rotating machinery is discussed in general terms.

4-5.1 ISOLATION AND ABSORPTION

Before discussing the various types of vibration absorbers and isolators, it is important to differentiate between the two classes of devices. A vibration isolator (see Fig. 4-59) is a resilient support that attenuates steady-state disturbances applied at the moving base. In the diagram, the mass constitutes the isolated item and the isolator is composed of stiffness and damping. A vibration absorber (see Fig. 4-60) is a device that dissipates energy to modify the response of the mass that houses a vibration source.

Generally speaking, vibration isolation is suitable for controlling harmonic, periodic, and broadband random vibration excitation. On the other hand, vibration absorption is effective over a relatively narrow frequency band and generally must be used to control vibrations at a single frequency. Vibration isolation and absorption systems are also characterized as active or passive. An active vibration isolation or absorption system is one in which external power is required for the system to perform its function.

4-5.1.1 Passive Systems

Classical passive isolation devices include a variety of springs and dashpots. Fig. 4-61 depicts various spring configurations employed in vibration isolation systems. Fig. 4-62 shows the construction of a typical liquid spring or more commonly called dashpot (Ref. 63). The liquid spring has inherent local damping and a high

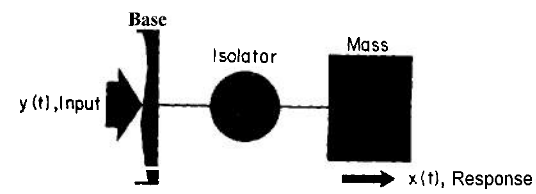


FIGURE 4-59. Shock and Vibration Isolator (Ref. 1).

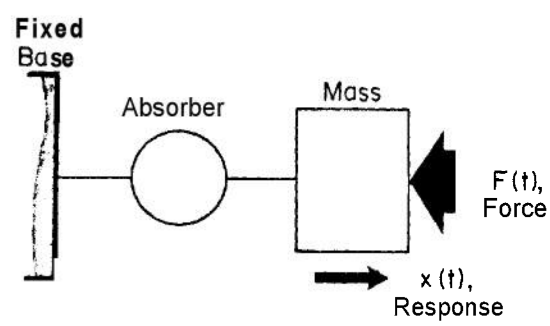


FIGURE 4-60. Shock and Vibration Absorber (Ref. 1).

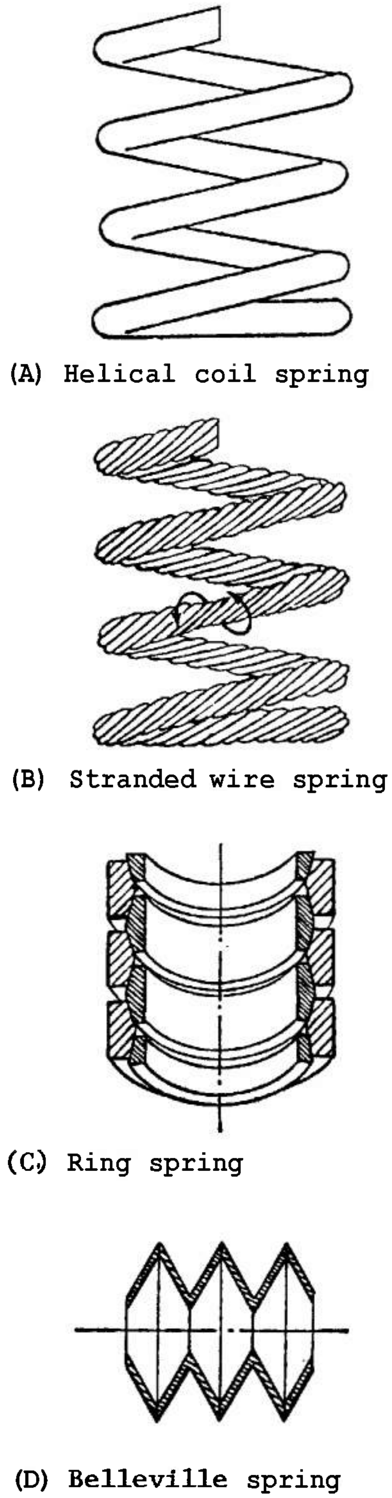


FIGURE 4-61. Springs Used for Vibration Isolation (Ref. 63).

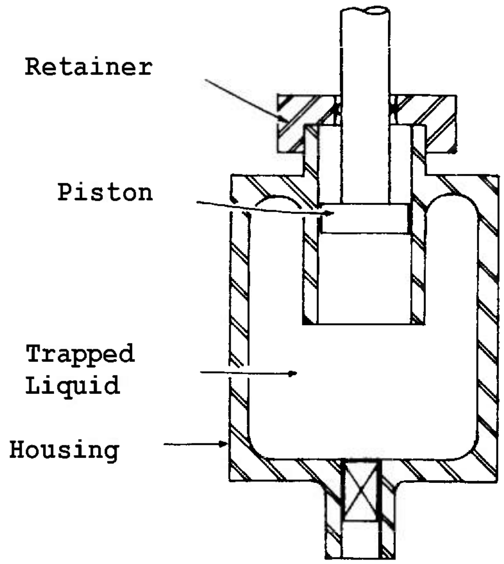


FIGURE 4-62. Liquid Spring or Dashpot (Ref. 63).

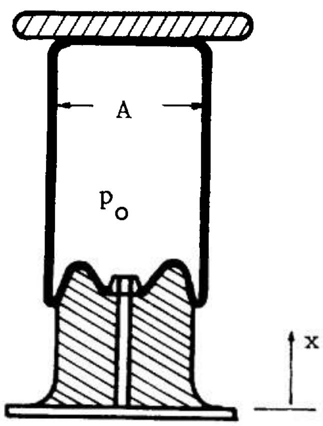


FIGURE 4-63. Pneumatic Spring (Ref. 63).

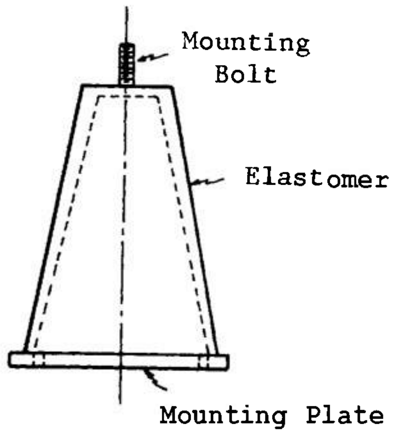


FIGURE 4-64. Solid Elastomer Isolator (Ref. 63).

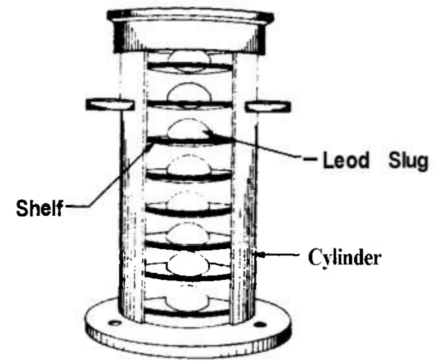
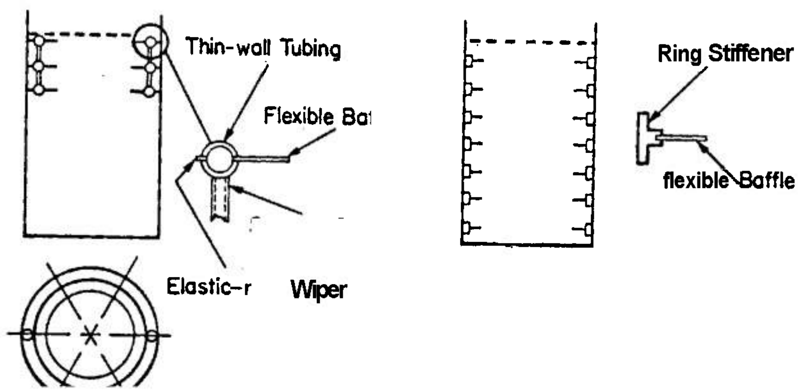


FIGURE 4-65. Flexible Ring Baffles (Ref 1).



(A) Self-positioning flexible-baffle configuration

(B) Flexible-baffle and structural-stiffener configuration

FIGURE 4-66. Viscous-pendulum Damper (Ref 1).

wave propagation velocity. Its basic operation is based upon fluid compressibility, and its stroke can be designed to be long or short depending upon the overall geometry and the fluid reservoir size. Fig. **4-63** shows the basic configuration of a pneumatic spring that is similar in characteristics and mechanism to the liquid spring except that the medium is air rather than a liquid. The flexibility of a pneumatic spring can be adjusted, of course, by variation of air pressure.

Another simple, commonly employed vibration isolator is the solid elastomer. A typical configuration for a solid elastomer isolator is shown in Fig. **4-64.** In this type of device, the elastomer is placed either in compression or in shear and can provide high damping of the vibration input.

In addition to their uses in detuning, decoupling, and structural damping, open cell foams are also attractive materials for use in vibration isolation. Open cell foam exhibits two separate phenomena that produce the resisting force to the vibration. One component of the force is due to the distortion of the porous elastomeric structure, which behaves as a nonlinear viscoelastic media. The other force component is caused by the air pressure generated as a result of distortion of the foam cell structure. Open cell polyurethane foam has large energy dissipation capacity and produces effective attenuation of high frequencies. One of its most attractive features is the ease with which it can be shaped. Since the use of such foams in shock and vibration isolation

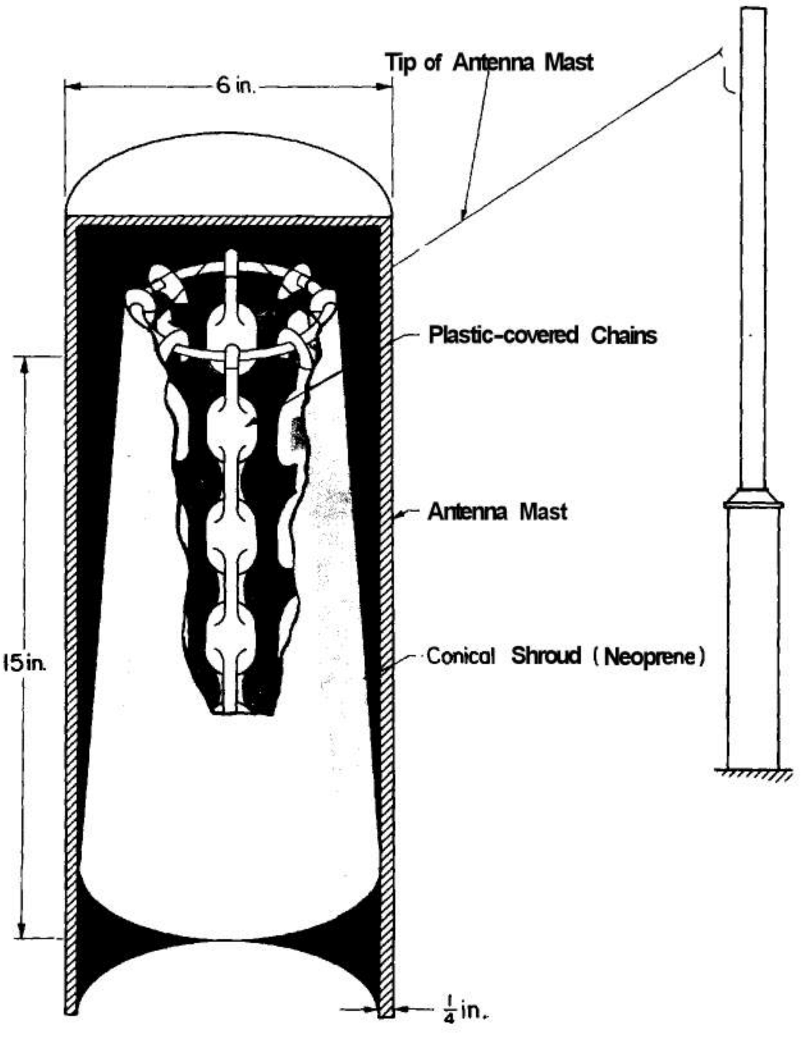


FIGURE 4-67, Suspended-chain Damper (Ref. 1).

systems is relatively new, some questions concerning their long-term behavior are still unanswered.

In addition to the classical spring or dashpot isolators, a number of unusual devices for shock and vibration isolation have been developed in recent years. For example, the liquid slosh problems in large tanks resulting from vibration have been solved by using flexible ring baffles (see Fig. 4-65). Fig. 4-66 shows a viscous-pendulum damper that can be used to suppress structural vibrations. Lead slugs moving in a pendulous motion in a viscous liquid are used. If the damping is used as a tuned absorber, the natural pendulum frequency of the lead slugs is designed to match the structural-excitation frequency.

A similar principle for tall flexible structures is the use of suspended plastic-covered chains (see Fig. 4-67) to damp wind-induced structural vibrations. Fig. 4-68 indicates the design of an elasto-plasto-viscous point vibration damper similar to that used on the Mariner IV spacecraft (Ref. 64). A variable-stiffness polymeric damper is shown in Fig. 4-69. In this design a heating element is embedded within the polymeric damping material. By varying the temperature of the polymeric material, the stiffness or energy absorption of the damper can be varied. Fig. 4-70 demonstrates the concept of the wire-mesh isolator.

Table 4-9 compares some of the various types of elastic elements on the basis of performance, cost, and maintainability.

4-5.1.2 Active Systems

Fundamentally, active vibration isolation and absorption systems consist of sensors, signal processors, and actuators. They are basically servomechanisms in which sensors detect the vibration environment and provide feedback signals that are proportional to the vibration. These signals are modified by signal-processing circuits and are used to control actuators that apply forces or induce motions in accordance with the sensed vibration environment. These systems have a basic disadvantage in their relative complexity. Fig. 4-71 demonstrates an automatically controlled air-spring suspension system that can be used as a vibration absorber. Basically, it consists of an air spring with variable stiffness (air pressure) and a closed-loop control of the air-spring height. The various components of the system are labeled on the diagram.

Fig. 4-72 is a block diagram of an active vibration isolator system. This active vibration isolator can isolate transient and steady-state disturbances and maintain a predetermined equilibrium position of an isolated body. The basic parts are the sensing elements, which measure the dynamic response of the flexible load and position of the actuator; the electrical control networks, which compare the signals of the sensing elements with preset standards to provide an output to the actuator; and the actuator, which applies a force to the isolated mass or structure to null its response and maintain a fixed equilibrium position.

Fig. 4-73 depicts an active (servo-control) base-motion isolation system that is controlled by gyroscopes and level sensors mounted on a massive conventional pneumatic isolator. For frequencies below 0.012 Hz, the system is controlled by the servo level; from 0.012 to 25 Hz the gyroscopes in the active system maintain control; and above 25 Hz the leveling system is locked out and the test device and massive frame act as an inertial system mounted on springs. This results in a 1.0-Hz damped vibration system that provides a stable seismically inactive test platform for instrument calibration and performance testing (Ref. 65).

A thorough discussion on the overall subject of the design of vibration isolation systems is given in a book prepared by the Society of Automotive Engineers (Ref. 66).

4-5.2 DAMPING

As already discussed, structural damping is used to reduce vibration in the neighborhood of structural resonances. A number of special structural assemblies have been designed to provide damping. Of these the most effective structural damping techniques have involved the use of viscoelastic damping techniques. Fig. 4-74 shows the configuration of viscoelastic shear-damped solid plates and viscoelastic shear-damped honeycomb plates. Such structural composites with viscoelastic shear-damped cores provide a large vibration attenuation capability. Structural composites with viscoelastic inserts can be used as frames and supports. The constrained viscoelastic material acts as a barrier against transmission of vibration. Since structural loss factors and stiffness values for these composites have been well documented, design data on damped structural shapes are available for use in electronic chassis and cabinet design (Ref. 67).

4-5.3 DETUNING AND DECOUPLING

Decoupling and detuning can be used in a variety of situations. One example in which these techniques are

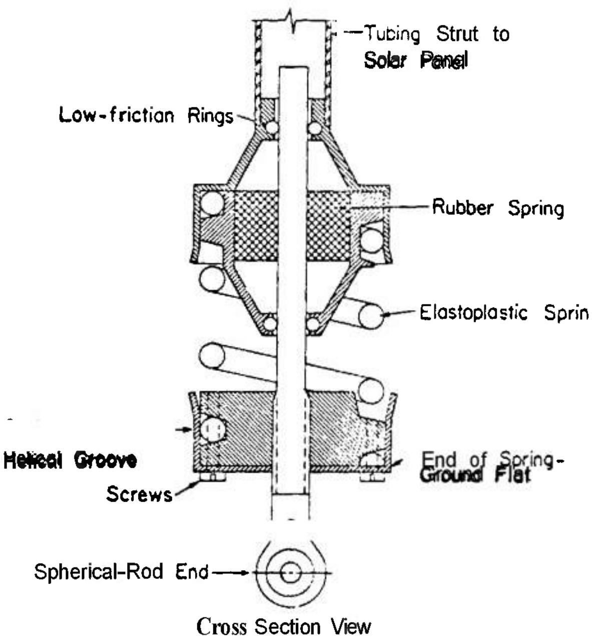
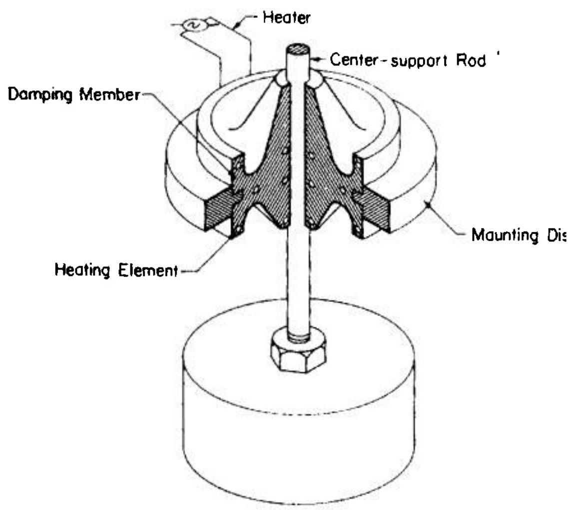


FIGURE 4-68. Elasto-plasto-viscous Point Damper (Ref. 1).



FIGWRE 4-69. Variable-stiffness Polymeric Damper (Ref. 1).

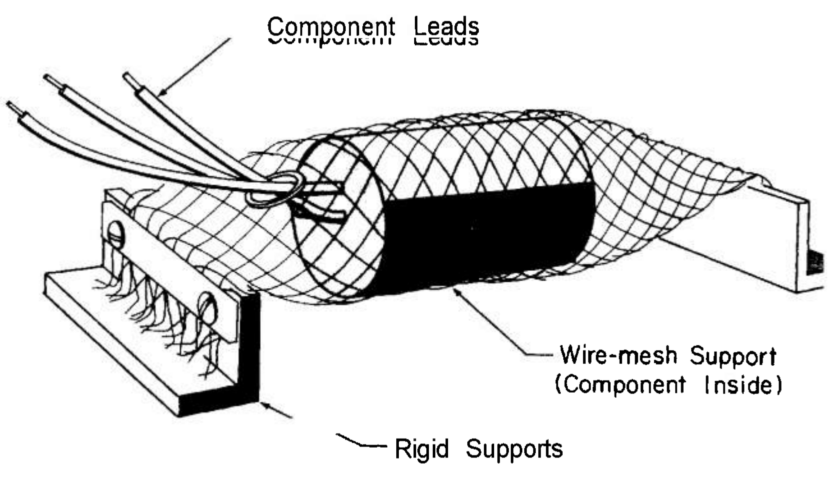


FIGURE 4-70. Wire-mesh Isolator (Ref. I).

TABLE 4-9. COMPARISON OF DIFFERENT TYPES OF ELASTIC ELEMENTS (Ref. 63)

Factor	Element type			
	Mechanical spring	Pneumatic spring	Hydraulic spring	Elastomeric spring
I Performance				
A. frequency				
Stiffness	Helical, torsional and Belleville, variable pitch linear or nonlinear	Stiffness automatically changes with load to maintain constant frequency	Stiffness is nonlinear and strong function of temperature	Stiffness is nonlinear, but can be linearized for small percent deflection
Higher harmonics	Surging and transients common	Almost never	Almost never	Limited
B. Damping				
Linear, nonlinear	Negligible internal damping (0.0005) needs auxiliary damper	Easily included in design, unusually nonlinear	Same as pneumatic	Inherent damping (0.05 to 0.2)
C. Adjustability				
Stiffness	Usually fixed by design	Easily varied	Fixed by design and fluid	None
Damping	None	Easily varied	Easily varied	None
Length	Usually difficult	Easily varied	Relatively fixed	None
D. Reliability				
Longevity	Excellent	Good	Fair	Good
Simplicity	Very simple	Simple	Complex	Very simple
E. Predictability	± 10 percent	± 1 percent	± 5 percent	± 15 percent
F. Envelope	Medium	Medium	Small	Medium
II cost				
A. Engineering				
Design	Low	Medium	Very high	Medium
Analysis	Low	Medium	Hard	Medium
Verification laboratory	Low	Medium	Medium	Low
Quality control	Low to medium	Low	Very high	Low
B. Fabrication	Low to medium	Medium	Very expensive	Low
C. Installation				
Initial	Low	Medium	Medium	Low
Tuning	High	Low	High	High
Verification	High	Low	High	High
Facility interface	Low	Low	Low	Low
D. Maintenance				
Inspection	Low	Medium	Medium	Low
Periodic displacement of components	Lor	Medium	High	Low
Performance verification	Low	Low	High	Medium
III Maintainability				
Accessibility and complexity	Virtually none required	Not as difficult as hydraulic but periodic maintenance definitely required	Difficult	None required except possible degradation check

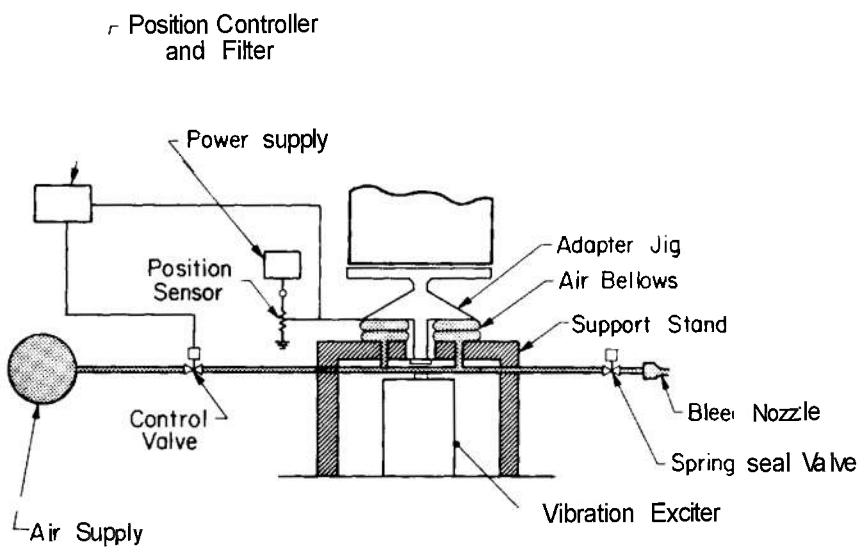


FIGURE 4-71. Automatically Controlled Air-spring Suspension System (Ref. 1).

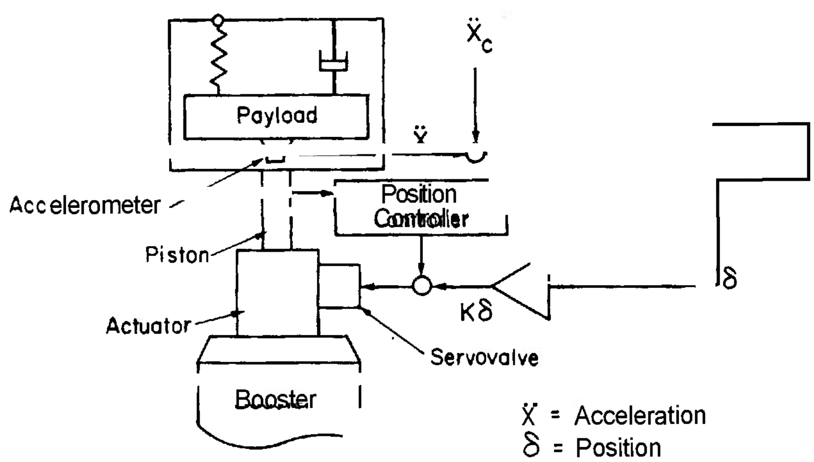


FIGURE 4-72. Active Vibration Isolator (Ref. 1).

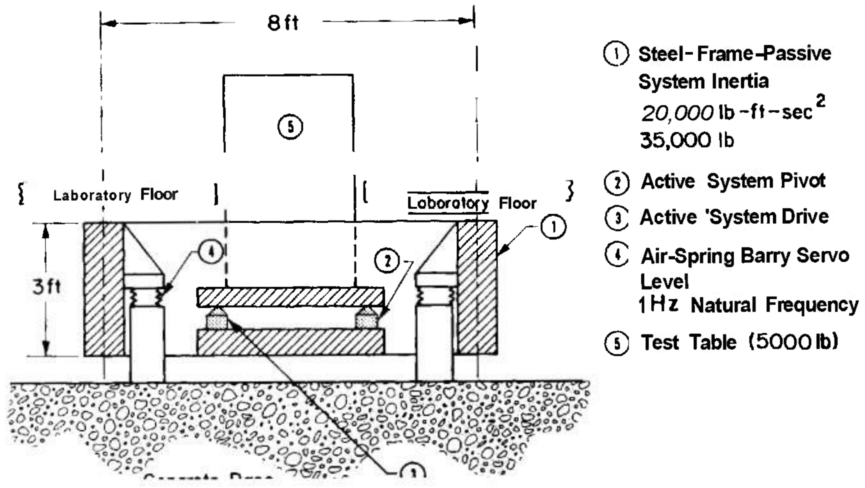


FIGURE 4-73. Active (Servocontrol) Base-motion Isolation System (Ref. 1).

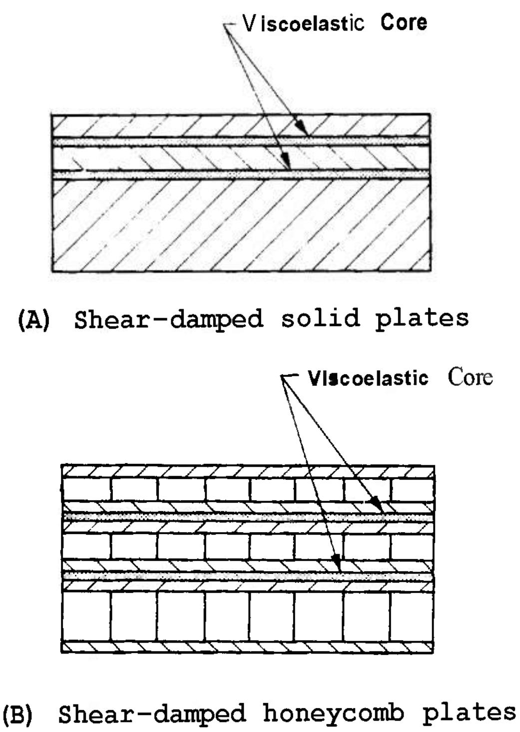


FIGURE 4-74. Viscoelastic Damping Plates (Ref 1).

effective is in the vibration protection of printed-circuit board components in electronic packages exposed to broadband vibration. By insuring that the components, circuit board, and chassis resonate at different frequencies, it is possible to reduce component vibration by this detuning technique. Additional vibration attenuation can be obtained by decoupling with the use of encapsulation compounds to reduce the number of coupled resonators. When encapsulation is employed, the components and the circuit board experience vibration as a mechanical system with distributed inertial and stiffness properties instead of the components vibrating at their various resonant frequencies, based on their individual inertial and stiffness properties. Fig. 4-75 shows some modes of printed-circuit-board vibration. Predicting printed-circuit-board response and designing printed-circuit boards for limited shock and vibration response are discussed by Derby and Ruzicka (Ref. 67) who have used structural composites with viscoelastic material layers to induce system damping. Encapsulated assemblies are generally more reliable than unencapsulated printed-circuit boards since the structural integrity is improved and the likelihood of component resonances that can cause lead breakage is reduced. An encapsulated assembly usually has a greater mass and can be susceptible to loosening and removal, however, particularly as a result of shock excitation.

4-5.4 VIBRATION CONTROL IN ROTATING MACHINERY

Rotating machinery is considered separately because, depending upon conditions, it can be a vibration source that either applies vibration to other materiel or applies sufficient vibration to its own components to cause its malfunction. For example, consider the case when a motor or a recorder generates vibration that does not interfere with the operation of the unit itself but transmits the vibration to other materiel in the surrounding environment. Three approaches are possible in such a situation: (1) isolation, (2) elimination of excitation, or (3) absorption of excitation. The use of vibration isolators for vibration control is similar to the other applications of vibration isolators; however, in this case the excitation originates within the machine and the forces transmitted to the base of the machine must be attenuated.

Certainly, the most straightforward method of controlling a vibration is to remove its source. In high-speed rotating machines, mass unbalance, gear inaccuracies, and belt fluctuations can be minimized .through careful design, machining specifications, and dynamic-mass balancing. Rotor balance is mandatory, of course, for high-speed rotating machines. Rotor unbalance is only one of the sources of vibration in high-speed rotating machinery, but all rotating machines are susceptible to vibration caused by unbalance. Static unbalance occurs when the rotor center of gravity is eccentric to the rotor centerline of rotation. The magnitude of rotor unbalance **is** consequently a weight (rotor weight) multiplied by the distance (eccentricity). Dynamic unbalance occurs when the total inertia (associated with the center of gravity) with reference to the rotational center line is nonzero. The balance problem becomes more difficult when rotors are flexible since the characteristics change with rotation speed. Unbalance can be caused by geometrical errors, nonhomogeneity of materials, or distortion due to speed, load, or temperature, in addition to simple mass unbalance. An extensive discussion of the balancing of rotating machinery is found in Chap. 39 of Ref. 10.

The third vibration control measure is the mass-vibration absorber, which can have either rotational or linear motion. The vibration absorber functions by introducing to a system an opposing excitation that cancels the vibration response of the original rotating system. Such a mass-vibration absorber can be designed to eliminate unwanted internal motion although it does not eliminate internal machine stress. Fig. 4-76 is a block diagram of a vibration absorber on an electric motor or drum recorder. The natural frequency of the absorber must coincide with the motor speed for maximum effectiveness. The main disadvantage of this system is that it is effective at only one frequency, and two resonant peaks are obtained. Fig. 4-77 shows the system response without the vibration absorber and with the vibration absorber. Synchronized gyroscopic vibration absorbers have been developed for multiple speed absorption.

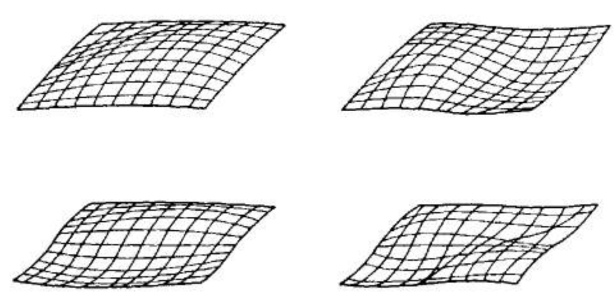


FIGURE 4-75. Modes of Printed-circuit Board Vibration (Ref. 1).

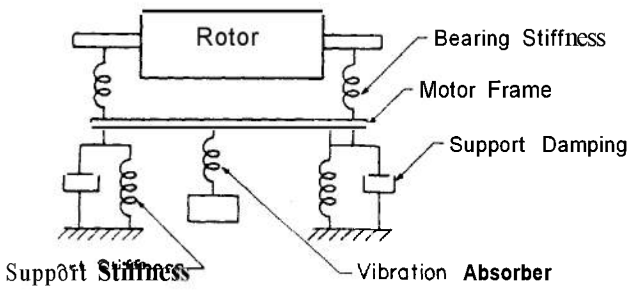


FIGURE 4-76. Vibration-absorber Application to Electric Motor (Ref. 1).

4-6 SIMULATION AND TESTING

4-6.1 GENERAL

Vibration can be simulated by the use of rotating eccentric weights or a crank-type mechanism that translates rotary, mechanical, or hydraulic motion into approximate sinusoidal vibration. However, such mechanical or hydraulic units are useful only up to about 800 **Hz.** The most widely used method of producing sinusoidal vibration employs an electrodynamic shaker, which operates on the same general principle as the radio speaker. This type of equipment has a useful frequency range of from approximately **5** to 2,000 **Hz.** The armature (or moving element) of the shaker is excited by an **AC** signal while in a **DC** magnetic field. The AC signal can be produced by a variable-speed motor-generator set or through the use of an electronic signal generator and amplifier. The latter technique provides the flexibility of being able to build up any waveshape at various frequencies.

Since most actual vibration environments are aperiodic or quasirandom, the validity of sinusoidal vibration testing has been questioned. Some form of shaped-spectrum, random vibration testing is a more accurate simulation of the environment. Investigations have shown no apparent correlation between sine wave and random vibration testing.

Fig. **4-78(A)** is a block diagram of a typical sinusoidal vibrator. A block diagram of the complex equipment required to generate random vibrations, to compensate for the various responses of test fixtures, and to assure proper inputs to test specimens is shown in Fig. **4-78(B).**

As already pointed out in the discussion of the vibrational environment, under most circumstances in real life situations, the vibration environment is extremely complex. For example, in the transportation environment, numerous sources of vibrational disturbances may exist in the transporting vehicle or vessel, the causes can be randomly distributed, and the mechanical connection to these vibration sources can be complex. Since the vibrational environment is so complex, a test to accurately reproduce such environments can be an expensive, time-consuming, and sophisticated endeavor. Only when equipment cost **is** very high or reliability is extremely important (such as in the aerospace program) are such tests carried out. Although sophisticated testing and simulation techniques are used routinely in many applications, most materiel is of such a nature that expensive testing is not feasible. Consequently, instead of trying to accurately simulate the

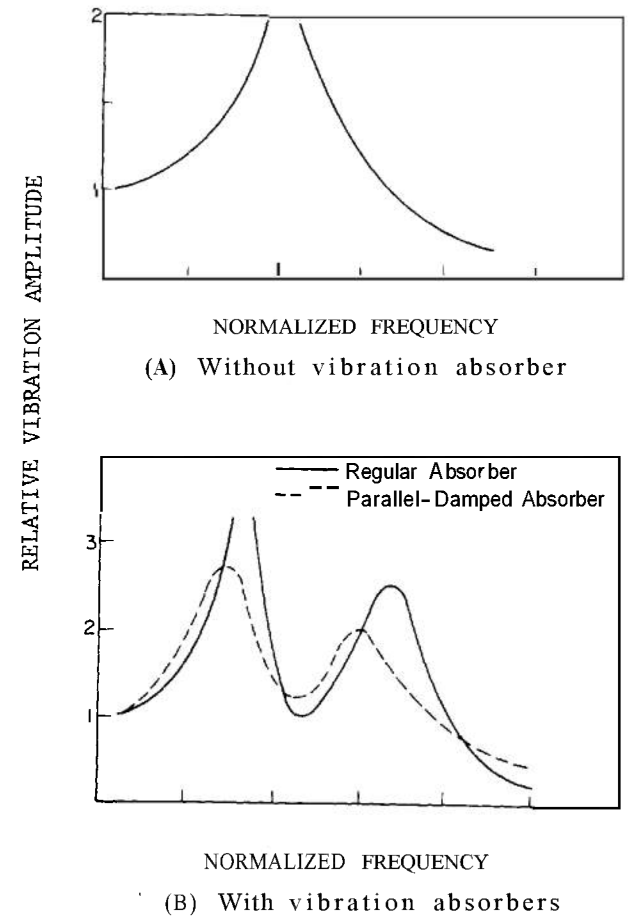
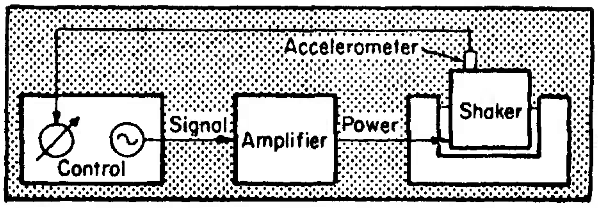
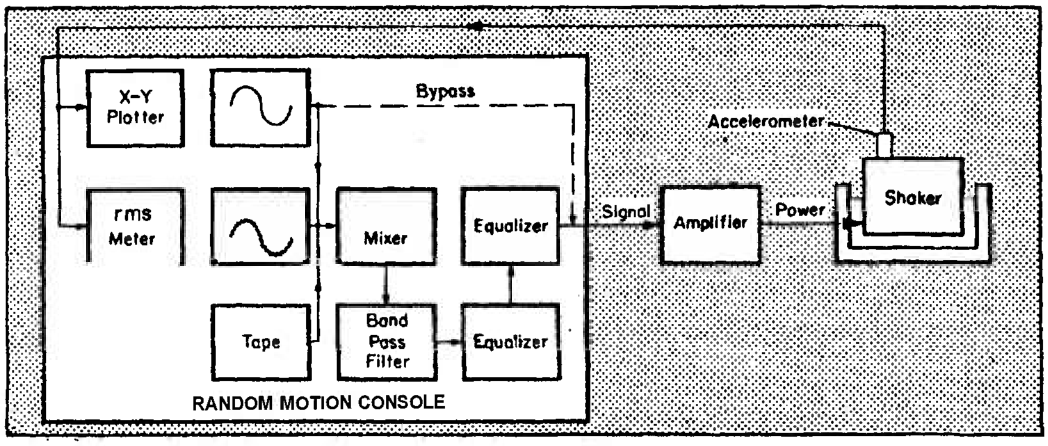


FIGURE 4-77. Effect of Absorber on Vibration of Electric Motor (Ref. 1).



(A) Sinusoidal vibrator



(B). Random vibrator

FIGURE 4-78. Block Diagrams of Vibration Test Systems (Ref. 37).

environment, a number of less sophisticated tests have been devised.

4-6.2 TESTS

In the testing of packages, three types of vibration tests are currently used for evaluating packages: the bounce test, the cycling test, and the resonance test (Ref. 68).

4-6.2.1 Bounce Test

The bounce test is intended as a loose cargo vibration test but is frequently employed as a general purpose vibration test. In this test the package is placed, unattached, on a sturdy wooden platform that is driven mechanically at constant frequency and amplitude for a specified period of time. The testing machines commonly used have a fixed peak-to-peak amplitude of 1 in. Some have circular motion in a vertical plane while others have simple vertical linear motion. The bounce test is specified in two ways: some specifications require that the vibrational frequency be adjusted so that a thin feeler can be passed between package and platform without difficulty while other specifications require a specific peak platform acceleration that defines a specific frequency.

4-6.2.2 Cycling Test

While the bounce test is not an attempt to simulate the environment, the cycling test represents the simplest attempt to simulate actual transportation vibrational environments. Basically, it requires a vibrational source that allows adjustment of amplitude as well as frequency (as noted previously, the bounce test is of fixed amplitude). In the cycling test the item to be tested is attached to the table of the vibrational source, and the test is conducted by sweeping a band of frequencies according to a specified amplitude versus frequency schedule. For simulation of transportation vibration environments, the schedule used is based directly on measured or expected vibrational spectra.

Three types of frequency sweep are commonly employed. The most widely used is the logarithmic sweep in which the total time per sweep is usually specified. The second method of sweeping the frequency range is a piecewise-linear sweep. This type of sweep is employed whenever the available testing apparatus does not allow a continuously variable or programmable sweep rate but rather provides several or many constant sweep rates. The piecewise-linear sweeps are arranged to best approximate the logarithmic sweep. The third and simplest technique of providing a frequency sweep consists of testing at a discrete number of frequency-amplitude pairs. A total time of dwell at each pair is chosen so that the net effect best approximates the logarithmic sweep, within the constraints imposed by the center frequencies available on the particular machine.

4-6.2.3 Resonance Test

Resonance tests consist of a single frequency sweep across a specified frequency spectrum in order to identify those frequencies at which the test item exhibits resonance. Following identification of the resonances of the test item, the unit is vibrated at some or all of the resonant frequencies. Specifications generally require a dwell of certain duration at each resonance, the amplitude being taken from a specific amplitude versus frequency schedule. Resonance is usually detected by means of an accelerometer fitted to the package and is indicated by a peaking of the ratio of package acceleration to table acceleration as the frequency is slowly swept.

4-6.3 SIMULATION OF FIELD RESPONSE

At least one aspect of vibration testing is concerned with evaluating the structural and/or functional integrity of a system. The success of such a test depends upon the accuracy of the simulation of the field environment that the materiel will experience during its service life. A number of vibration test techniques are employed in various kinds of vibration testing. Some of these techniques are motion control, motion-limiting, force-limiting the input to the test item, force-motion product control, reproduction of field responses, multipoint input control, and multiaxis input control (Ref. 69).

Briefly, motion-controlled vibration tests in which the input is maintained constant can be classified as infinite-apparent-weight testing since the test item is not allowed to affect its environment as it does in the field. Motion-limiting is a technique that prevents the vibratory response at various levels on the test item from exceeding specified levels. If the motion exceeds a specified limit, the input power is reduced. Force-limiting prevents the input force to the test item from exceeding specified levels. Reproduction of field response represents one of the greatest advancements toward realistic vibration testing. Laboratory reproduction of field data using computers is becoming an important testing method. The field data, recorded on magnetic tape and controlled by computer, are used as the input to the vibration devices that excite the item to be tested. The multipoint input control test technique utilizes two or more shakers to supply the vibratory input to the system. Each shaker is individually controlled, usually to a different input specification. This technique can be used to simulate field tests on equipments that employ multipoint mounts in the field. Multiaxis input control is a test technique in which all three axes of a test item are vibrated simultaneously. This technique is still in the early stages of development.

A rather unusual vibration environment is that which occurs during earthquakes. Vibration test criteria for evaluating the earthquake resistance and reliability of electrical switchgear are being developed (Ref. 70).

Further discussion of test methods is given in par. 4-8. The simulation capabilities of a number of rather complex vibration testing and simulation facilities are discussed in par. 4-7.

4-7 TEST FACILITIES

A large number of Government facilities, private companies, and independent testing laboratories have a capability for performing vibration testing of various kinds. These facilities range from the relatively simple and uncomplicated shakers maintained by small companies to extremely complex and expensive facilities maintained by large companies and the Government. In order to illustrate the variety of types of vibration facilities available, the discussion that follows contains some typical examples of a number of different types of facilities.

One of the largest facilities for vibration testing, particularly in the area of wheeled vehicles, is that operated by the U.S. Army at Aberdeen Proving Ground, Md. Facilities at this center permit performance of complete ground vehicle field tests. Specially constructed roads containing such hazards as embedded rock, staggered bumps, corrugations, and vertical walls are provided for evaluation of a complete ground vehicle under a shock and vibration service environment. Other facilities at the Aberdeen Proving Ground include a frame-twister road that imparts severe torsional stresses to the vehicle structure and a specially constructed 6-in. washboard road. This road consists of 6-in. waves 72 in. apart. The frequency of the vibration imparted to a vehicle may be varied by altering the speed of the vehicle as it travels over the washboard road. For example, a vehicle traveling at 5 mph will be subjected to a vibration frequency of 1.22 Hz. In addition to the rough roads, the facility has cross-country courses that embody hills, mud, and severe terrain. Fording and swimming tests are conducted in special troughs.

Extreme environmental tests are conducted at Yuma, Ariz. (desert environment) and Ft. Churchill, Manitoba, Canada (arctic environment). The desert course at Yuma has hills, sand dunes, and sloped sand and dust vehicle courses. The arctic course provides deep snow and frozen lakes for the operating areas. Temperatures on the order of $-35°F$ are frequent in the winter (Ref. 37).

The Naval Research Laboratory, Washington, D.C., has developed a rough-road simulator that employs rotating drums with detachable road profiles, or bumps, that are interfaced with a wheeled vehicle to provide a random shock and vibration environment (Ref. 71). The upper surfaces of the drums are at floor level with associated equipment mounted below floor level. The steel drums are driven by V-belt drives powered by two hydraulic motors to give a speedometer reading of approximately **38** mph for a 2-1/2-ton 6 X 6 military truck. The speed controls of each set of drums are independently adjustable. The fore and aft drums are not driven in phase. Heavy vehicles can be driven by the simulator at speeds up to 40 mph. Greater speeds are possible for powered vehicles if the engines are used to boost the driving power of the hydraulic motors. In testing vehicles on this simulator, three separate phenomena occur:

(1) At low speeds *(5* to 15 mph), forced vibration of the vehicle body on its springs takes place. This corresponds to a low frequency vibration with displacement amplitudes dependent on the spacing and heights of the road irregularities and on the speed of the vehicle. The input acceleration levels are substantially below 1 G.

(2) At higher speeds (15 to 40 mph), over the same irregularities as for the first phenomenon, a severe wheel bounce occurs, producing a random vibration.

(3) A single road discontinuity of large magnitude is traversed at sufficient speed to cause the body of the vehicle to strike the rubber pads (snubbers) on the axles. During the time the axle pad and the body are in contact, the suspension system is changed by the effective removal of the main springs from the system, thus giving the body of the vehicle **a** large acceleration or deceleration. This impact can produce **a** medium level shock pulse of 10 G maximum for a duration of several milliseconds.

The U S Army Armament Command (ARMCOM) at Rock Island, Ill., has a variety of facilities that permit the testing of vehicular armament systems under simulated field conditions. One such facility contains simulation equipment that can simulate the motion of various kinds of weapon mounts and also permits field firing of weapons on vehicles such as tanks, helicopters, and other armored vehicles. The variable-flexibility gun mount simulator consists of two rectangular load springs with hydraulic pressure pads to provide adjustable spring rates in a single degree of freedom (in the direction of gun recoil). Attached to the firing platform are two variable orifices that provide a variable damping ratio. With this equipment, it is possible to simulate present and future weapon mounting interfaces. The spring rate can be varied from 90 to 100,000 lb $in.^{-1}$ and the damping ratio can be changed from 0.05 to 0.80. This simulator is capable of supporting weapons up to and including 40-mm calibers, weighing up to 350 lb, and having a muzzle energy and impulse up to 120,000 ft-lb and 70 lb-s, respectively. Under these maximum conditions and with nominal damping (damping ratio equal to 0.10) the simulator is subjected to about 25,000 lb force and peak accelerations of 100,000 in. s^{-2}. The simulator is located in a facility 194 ft long which also contains a 1,000-in. range, target drop, sand butt, high bay area with overhead crane, and extra-high, double doors for equipment access. The simulator is located on a reaction mass at one end of the range. Hydraulic power supplies for the simulator, vibration excitation equipment, and other accessories are located near the reaction mass.

The ARMCOM simulator permits motions only in one direction (the line of fire); however, a more complex multiple-degree-of-freedom gun mount has also been installed. This gun mount consists of a flexible suspension system having spring and damping characteristics for six-degrees-of-freedom simulation—thus permitting translatory motion along and rotation about the three principal axes induced by the firing of the armament subsystem and resisted by the spring rate. and damping ratio that are characteristic of the vehicle in a particular condition. As originally conceived, the simulator actually supports sections of full-size helicopters and lightweight tank cupolas. With the help of this simulator, the weapon may be traversed, elevated, or depressed. The flexible suspension system, cantilevered from a concrete column, consists of six hydraulic actuators attached at both ends by universal joints. By proper excitation, simulation of the roll, pitch, and yaw effects of the helicopter, as well as the torque of its rotor, is possible (Ref. 72).

A variety of multiple-degree-of-freedom motion simulator systems for various environments are described in a report (Ref. 73). One system was a five-degrees-of-freedom railcar simulator that will excite entire vehicles and structures such as equipment shelters and transportation containers. The first test program using this system entailed simulation of the railcar shipping environment on automobiles to develop solutions to railcar shipping damage problems. The railcar simulator consists of:

(1) A platform constructed from a section of tripak railcar using minimum stiffening and restraint so that the test platform will exhibit high frequency local responses similar to those of the actual railcar platform.

(2) Six hydraulic actuators with associated servovalves, displacement feedback transducers, hydraulic power supply, and control electronics. Four actuators are positioned in the vertical axis and two are horizontally oriented to impart motion through the center of gravity of the platform in the lateral and longitudinal directions.

(3) Fixtures, air springs, spherical bearings, and a parallel cable assembly.

(4) Automobile tiedown devices to establish the proper relationship of the chain tiedown from the vehicle underbody to the tiedown track on the railcar deck.

The vertical and longitudinal actuator displacement capacities are 4.0 in., and the lateral actuator displacement capacities 8.0 in. Force requirements were 13,600 lb for the lateral and longitudinal actuators and 27,400 lb for the vertical actuators. Frequency response was 0.5 to 25 HZ. The structural beams used to react the actuator loads were preloaded with existing reaction masses and designed to be resonance free in the 0.5 to 25 Hz range. The system is capable of providing motion in three orthogonal directions as well as pitch and roll rotational directions (Ref. 73).

Another simulation system is the three-axis vibration test system. This is used to simulate helicopter flight environments and originated with a requirement by the U S Army Aviation Test Board to create a vibration environment that is representative of the vibration environment encountered by the AN/ARC-115 radio set when installed in an OH-58 helicopter. Other simulators being designed include a 50-ton tracked and wheeled vehicle-road simulator, a wheel-rail dynamics test facility, and a high force vibration test facility (Ref. 73).

A new spacecraft test facility, the launch phase simulator, has been developed by NASA (Ref. 74). The combined launch and environmental conditions of steady or sustained acceleration, acoustic noise, pressure profile, and mechanical vibration can be simulated. Physically, the facility is a large centrifuge (60-ft radius to the payload center of gravity) weighing approximately 500,000 lb. It has a cylindrical test chamber (12 ft in diameter and 22 ft long) mounted on the end of the centrifuge arm. The chamber houses the acoustic, vacuum, and vibration systems and can accommodate a payload or spacecraft configuration that weighs up to 5,000 lb and can be defined in an envelope 10 ft in diameter and 15 ft long. The centrifuge is located in an enclosure or rotunda 157 ft in diameter and 27 ft high. For the purposes of this discussion, only the vibration capabilities of this test facility are described. The vibrational capabilities are mechanical vibration having three degrees of freedom (longitudinal or thrust, lateral, and pitch) from 0.5 to 200 Hz with both sinusoidal and random capability. Multiaxis motion with this system may be either independent or simultaneous. The system is capable of being operated on the centrifuge arm or in an offboard condition mounted on a seismic reaction mass. The sinusoidal and random vibration schedules for the system are listed in Table 4-10.

At its engineering and research center in Denver, Colo., the U S Bureau of Reclamation has installed a vibration test system to study the effects of simulated earthquakes and other dynamic forces on test structures (Ref. 75). This test facility has been used primarily for determining the structural response of reinforced concrete specimens. The test facility is housed in a 53- by 42-ft building with a high ceiling of 28 ft 8.5 in. A major feature of the building is a 250-ton seismic mass. The reinforced concrete mass is 28 ft by 17 ft by 5 ft 8.75 in. with a 5- by 5- by 12-ft buttress at one end. Two hydraulic rams (or exciters) are used to produce static or dynamic forces. Characteristics of the rams are given in Table 4-11. Control equipment permits general sine wave dynamic testing using two oscillator systems. Both may be operated either individually or simultaneously to drive two exciters in a closed-loop configuration to maintain a preset acceleration, velocity, or displacement level. The oscillator produces a sinusoidal signal from 5 to 5,000 Hz or 5,005 to 10,000 Hz. Logarithmic sweep rates at 132 different speeds range from 0.3 to 335 deg min^{-1} on a circular 220-deg scale. Closed-loop control of acceleration from an accelerometer signal can be performed only above 10 Hz. Other oscillators capa-

TABLE 4-10. VIBRATIONAL TESTING CAPABILITIES OF LAUNCH PHASE SIMULATOR (Ref. 70)

Vibration	SCHEDULE	
	Motion	Force
Sinusoidal	Longitudinal or thrust	± 4 g, 1-in. double amplitude motion
	Lateral	± 2 g, 1-in. double amplitude motion
	Pitch	± 10 rad s^{-2} angular acceleration, 0.015 rad double amplitude motion
Random	Longitudinal or thrust	RMS 2.8 g(Peak 8.4), 1-in. double amplitude motion
	Lateral	RMS 1.4 g(Peak 4.2 g), 1-in. double amplitude motion
	Pitch	RMS 7 rad s^{-2} angular acceleration, 0.015 rad double amplitude motion (Ref. 74)

ble of producing sinusoidal, triangular, or square waveforms in five ranges from 0.005 to 50,000 Hz are available with either logarithmic or linear sweep rates. Random noise generators are also available to drive the system. Finally, a curve follower is available to generate arbitrary waveshape signals. The system is capable of performing most civil engineering tests in which the dynamic responses of structural elements or models are to be studied. Future projects envisioned for this facility include hydrodynamic effects on submerged structures, structure-foundation interaction, and the effects of nonstructural elements in frame structures.

It has not been possible to include all of the vibration facilities both governmental and private that are available within the United States. The examples were given for the purposes of illustration to demonstrate the spectrum of facility types among the more complex and extensive facilities. In no sense are these illustrations intended to be exhaustive of the vibration facilities available.

4-8 GUIDELINES AND SPECIFICATIONS

Vibration specifications are necessary in order to increase the capability of materiel for performing its intended function in the operational vibration environment and after exposure to the transportation vibration environment. As noted in par. 4-6, simulation of the field environment, or even the transportation environment, of materiel is a distinctly complicated, difficult, and expensive task. These two types of environmental conditions are distinct because, in the transportation environment, materiel is not actually operating and can be protected, while, in the operational environment, the equipment is in use.

A number of specifications detail the conditions under which materiel shall be transported. Basically, these specifications involve the manner in which the materiel shall be packaged for different kinds of transportation and storage environments. These are supported by engineering information such as is contained in AMCP 706-130, *Design for Air Transport and Airdrop of Materiel* (Ref. 15). This handbook presents general technical and operational air transport and airdrop requirements and provides detailed airdrop design criteria. Because materiel developed for air transport or airdrop must meet the limitations imposed by the characteristics of the aircraft, the handbook includes a chapter on the statistical-logistical data of Army and Air Force aircraft that transport or airdrop Army equipment. Selected commercial aircraft that may be utilized to transport equipment are also included.

Another engineering handbook involving the transport environment is AMCP 706-121, *Packaging* and

Pack Engineering (Ref. 14). This handbook discusses the fundamental principles, policies, and limitations of military packaging and pack engineering and is intended to serve as an introduction to military packaging and pack engineering, including protection from vibration. A major portion of the text is devoted to a broad treatment of the subject, emphasizing the rationale of military packaging and directing the user to other authoritative publications for information on how to perform a specific engineering task.

Another related document is TM 38-230-1, *Preservation and Packaging,* Vol. 1, *Preservation, Packaging and Packing of Military Supplies and Equipment* (Ref. 76). This manual presents the fundamental principles and approved methods employed in the protection of military supplies and equipment against deterioration and damage during shipment and storage. It emphasizes the importance of preservation and packaging of military supplies and equipment, and contains detailed information concerning the requirements to accomplish such operations.

Packing, which deals with exterior containers and the placing of supplies therein—together with blocking, bracing, cushioning, strapping, weatherproofing, marking, or other equivalent action to prepare material for shipment—is covered in TM 38-230-2 (Ref. 77); preparation of freight for air shipment is covered in more detail in TM 38-236 (Ref. 78), which should be consulted when known air transportation requirements exist. Also, a variety of other packaging specifications or criteria are published in the following publications:

(1) TM 38-250, *Packaging and Handling of Dangerous Materials for Transportation by Military Aircraft*

(2) AEC Regulation, Title 10 CFR, Part 71, *Packaging of Radioactive Material for Transport*

(3) DOD Regulation 4500.32R, *Military Standard Transportation and Movement Procedures (MILSTAMP)*

(6) AR 55-55, *Transportation of Radioactive and Fissile Materials Other Than Weapons*

(7) AR 55-56, *Transportation of Chemical Ammunition, Chemical Agents, and Other Dangerous Chemicals*

(8) AR 55-203, *Movement of Nuclear Weapons, Nuclear Components, and Related Classified Nonnuclear Material*

(9) AR 55-228, *Transportation by Water of Explosives and Hazardous Cargo*

(11) AR 220-10, *Preparation for Overseas Movement of Units*

(12) AR 70-44, DOD, *Engineering for Transportability Program*

(13) Safety Series No. 6, International Atomic Energy Agency, Vienna, 1967, *Regulations for the Safe Transport of Radioactive Materials*

(14) DOT Regulation, 49 CFR, Parts 170-190

(15) FAA Regulation, *Transportation of Dangerous Articles and Magnetized Materials by Commercial Air,* 14 CFR, Part 103

(16) Coast Guard Regulation, *Rules and Regulations for Military Explosives and Hazardous Munitions,* 46 CFR, Parts 146-149 (CG 108 and CG 187)

(17) U S Post Office Department, *Postal Laws* and *Regulations,* Title 39 CPR, Parts 14 and 15, U S Postal Guide, Parts 124 and 125

(18) IATA International Air Transport Association, Montreal, Quebec, *IATA Regulations Relating to the Carriage of Restricted Articles by Air,* 20th Edition, 1969

(19) Motor Carriers Explosives and Dangerous Articles Tariff, *Dangerous Articles Tariff No. 14,* December 1969, published by and available from American Trucking Association, Inc., 1616 P Street, N.W., Washington, D.C.

(20) *Official Air Transport Restricted Articles Tariff No. 6-D,* governing the transportation of restricted articles by air. Published by and available from Airline Pub-

TABLE 4-11. PERFORMANCE CHARACTERISTICS OF HYDRAULIC RAMS (Ref. 75)

Ram number	1	2
Vector force, lb	50,000	30,000
Stall force, lb	77,000	37,500
Stroke, in.	1	10
Maximum velocity, ips	18	30
Maximum frequency, Hz	400	100

lisher, Inc., Agent, Washington, D.C. These transportability regulations and specifications have been excerpted from Ref. 79.

Most vibration test specifications include some combination of bounce, cycling, or resonance testing as described in par. 4-6.2. The three most widely used vibration test standards today are MIL-STD-810, *Environmental Test Methods*, Method 514 (Ref. 51); Federal Test Method, Standard 101B (Method 5020 and Method 5019) (Ref. 80); and MIL-STD-331 (Test 104.1) (Ref. 81). MIL-STD-810 (Method 514) prescribes tests for many categories of equipment in aircraft and missiles and in addition has a separate category for packaged equipment transported by common carrier, land, and air. Separate tests are required for packages tied down during transport and for loose cargo. The test for tied-down cargo includes a combined cycling and resonance test, and the loose cargo test is comprised of a bounce test and a resonance search. Separate amplitude versus frequency schedules are prescribed for air transport and for three classes of land transport. Table 4-12 summarizes these tests.

The vibration tests of Federal Test Method, Standard 101B, are also widely used. Method 5020 includes low and high frequency range cycling tests and a resonance test. Method 5019 is a bounce test. Vibration tests

TABLE 4-12. PACKAGE VIBRATION TEST FROM MIL-STD-810 (Ref. 68)

CARGO TIED DOWN

1. Amplitude vs frequency schedules are as shown in this specification for four classes of transport: air; tracked vehicles; trucks, tractor-trailers, and railroad; and two wheeled trailers. Package weight is taken into account in the air transport schedule.

2. Test frequency range is 2-500 Hz, except for air transport of packages whose weight exceeds 100 lb. In the exceptional cases, the upper limit frequency is decreased with increasing weight.

3. Test time is 15 min per axis per 1,000 mi of land transport and 1 hr per axis per 1,000 mi of air transport. If both modes are included, the land transport test time shall apply only to the frequency range from 2 Hz to the intersection with the air transport schedule, and the air transport time applies to the frequency range from that intersection to the upper limit frequency.

4. Resonance search is conducted by a single sweep of the frequency range for each axis at amplitudes reduced from the schedules.

5. Resonant dwell is taken at the four most severe resonances along each axis if that many are clearly defined. Dwell time is 2.5 min per 1,000 mi of land transport or 10 min per 1,000 mi of air transport.

6. Cycling test is used for the remainder of the test time. A logarithmic sweep at the rate of 15 min per sweep is preferred, although a piecewise-linear sweep is acceptable.

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TABLE 4-13. VIBRATION TESTS FROM FEDERAL TEST METHOD STANDARD 101B (Ref. 68)

METHOD 5020

1. The low-frequency cycling extends over the range from 2-5 Hz. Test level. is 1-in. double amplitude and the test time is 15 min per axis. The sweep is to be a logarithmic sweep at 2 min per octave. However, a discrete frequency alternate is acceptable; 5 min each at 2, 3, and 5 Hz.

2. The high frequency cycling test schedule from 5-500 Hz is as illustrated in the specification, except that the upper limit frequency is taken as in the aircraft portion of the MIL-STD-810 test. Test time is 15 min per axis. Again a logarithmic sweep is preferred, and although the sweep rate is not specified, it is required that at least four 5-max freq. - 5 Hz sweeps be executed. Two alternates are allowed in the sweep:

	Time, s	Freq., Hz	Double amplitude, in.
	70	5-7.56	0.673
Piecewise-	70	7.56-11.44	0.295
linear	70	11.44-17.3	0.129
sweep	70	17.3-26.6	0.055
	105	26.6-50	0.036
	70	6.15	0.673
Discrete	70	9.3	0.295
freq.	70	14.07	0.129
sweep	70	21.6	0.055
	70	32.7	0.036
	70	49.5	0.036

3. The resonance test specifies a 15-min dwell at each resonant frequency.

LOOSE CARGO

1. Bounce test is taken at 1-in. double amplitude (i.e., peak-to peak displacement) at 284 rpm (4.73 Hz). Test time is 30 min on each face, for a total test time of 3 hr.

2. Resonant search is conducted over the range from 10-55 Hz with a minimum double amplitude of 0.003 in., by increments of 1-Hz steps and maintaining at least 10 s at each frequency. This test is run solely to establish that the resonant amplication factors do not exceed 2.0.

TABLE 4-14. VIBRATION TEST FROM MIL-STD-331 (Ref. 68)

PROCEDURE I

1. Cycling test is divided into two ranges, 10-60 Hz and 60-500 Hz. Ten sweeps per axis (10-60-10 Hz) are taken over the lower range and 14 sweeps per axis over the high range (60-500-60). A logarithmic sweep is specified such that each sweep requires 20 min. The amplitude schedules are given in the specification.

2. Resonance test consists of a 20-min dwell at each resonant frequency, the amplitude taken as in the cycling test. If no resonances are found, two extra 15-min sweeps are required in each of the cycling ranges.

3. A discrete frequency alternate is allowed. For the cycling test, this alternate requires 60-min dwells at each of the following frequencies:

   a. Longitudinal axis: 10, 17, 28, 46, 76, 128, 212, 350 Hz

   b. Transverse axis I: 12, 20, 33, 54, 91, 152, 250, 417 Hz

   c. Transverse axis II: 14, 24, 38, 65, 107, 178, 297, 500 Hz

   If no resonances are detected, the resonant dwells are replaced by 15-min dwells (each axis) at 10, 46, 152, and 500 Hz.

PROCEDURE II

1. Cycling test over range 10-60 Hz requires 16 logarithmic sweeps (10-60-10 Hz) of 15-min duration, following the schedule given in the specification.

2. The discrete frequency alternate requires 10 min each at the following frequencies:

   10, 11, 12, 14, 15, 16, 17, 18, 20, 22, 24, 26, 28, 30, 32,

   35, 38, 41, 44, 47, 51, 55, 60 Hz.

METHOD 5019

1. Bounce test is taken at 1-in. double amplitude at a frequency such that a 1/16-in. feeler may be slid freely between specimen and platform, or, alternatively at a 1-G peak acceleration. Test time is 2 hr if testing in only one position or 3 hr if tested in more than one position.

TABLE 4-15. BOUNCE TEST SPECIFICATIONS (Ref. 68)

Specification	Frequency adjustment	Test duration
Federal Test Method Standard 101B (Method 5019)	1/16 in. feeler or 1 g	Single position 2 hr Multiple position 3 hr
MIL-STD-810 (Method 514.1)	4.73 Hz (1.14 g)	30 min each face
MIL-T-4734	4.73 Hz (1.14 g)	15 min each face
ASTM D 999-68	1.0-1.1 g	Unspecified
National Safe Transit Committee Test Procedures	1/16 in. feeler	1 hr
MIL-W-21927 (outdated)	4.5 Hz (1.03 g)	30 min each axis, or 1 hr, single axis

TABLE 4-16. CYCLING TEST DURATIONS (Ref. 68)

Specification	Test duration per axis
MIL-STD-810	
Land	15 min/1,000 mi
Air	1 hr/1,000 mi
Federal Test Method Standard 101 B	105 min
MIL-STD-331	8 hr
USATECOM MTP 4-2-804	
Land	Trucks-tractor trailers-two-wheeled trailers, 15 min/1,000 mi Tracked vehicles, 20 min/1,000 mi
Air	Actual flight time or 3 hr (lesser)
MIL-E-4970	48 min

TABLE 4-17. CYCLING TEST SWEEP REQUIREMENTS (Ref. 68)

MIL-STD-810	Log sweep, 15 min for complete cycle (5-500-5 Hz)
Federal Test Method Standard 101B	Log sweep, 2 min/octave in 2-5 Hz range, minimum of 4 cycles in 5-500 Hz range
	Alternate I, piecewise-linear sweep in the 5-500 Hz range
	Alternate II, discrete frequency sweep in the 5-500 Hz range
MIL-STD-331	Procedure I, log sweep, 20 min for complete cycle (10-500-10 Hz)
	Alternate I, discrete frequency sweep
	Procedure II, log sweep, 15 min for complete cycle (10-60-10 Hz)
	Alternate III, discrete frequency sweep
MIL-E-4970	Constant sweep rate, 1 Hz/s
MIL-STD-167 (Type I)	Discrete frequency sweep in 1 Hz intervals, 5-min dwell at each.

TABLE 4-18. RESONANCE TEST SPECIFICATIONS (Ref. 68)

Specification	Frequency range	Dwell time
MIL-STD-810 (Method 514.1)	5-500 Hz	Land: 2.5 min/1,000 mi
		Air: 10 min/1,000 mi
Federal Test Method Standard 101B (Method 5020)	2-500 Hz	15 min
MIL-STD-331 (Test 104) Procedure I	10-500 Hz	15 min
USATECOM MTP 4-2-804	4.5-500 Hz	Two-wheeled trailers trucks, tractor-trailers: 2.5 min/1,000 mi
		Tracked vehicles: 3.3 min/1,000 mi
		Air: 17% of flight time or 30 min
MIL-E-4970	2-500 Hz	30 min
MIL-P-7936	2-60 Hz	1 hr
MIL-STD-167	5-33 Hz	2 hr total
MIL-W-21927 and WR-11	2-60 Hz	30 min

TABLE 4-19. TEST SPECIFICATIONS AND STANDARDS (Ref. 83)

Number	Title	Date of origin	Last revision
MIL-E-5272 (formerly 41065)	Environmental Testing of Aeronautical and Associated Equipment	12/7/45	1/20/60
MIL-E-5009	Turbojet and Turbofan Aircraft Engines	6/14/4	11/13/67
MIL-T-945	Test Equipment for Electronic Equipment	7/2/47	4/11/68
MIL-E-5400	Airborne Electronic Equipment	12/1/49	5/24/68
MIL-T-5422	Environmental Testing for Airborne Electronic Equipment	12/1/49	11/15/61
MIL-STD-202	Test Methods for Electronic and Electrical Component Parts	1/29/53	4/14/69
MIL-STD-167	Mechanical Vibrations of Shipboard Equipment	1/29/53	4/14/69
MIL-C-172	Vibration for Aircraft Electronic Equipment Cases	12/15/53	12/8/58
MIL-T-7743	Store Suspension Equipment Testing	12/5/56	3/22/62
MIL-T-4807	Ground Electronic Equipment Vibration and Shock Tests	10/7/58	10/7/58
MIL-STD-750	Test Methods for Semi-Conductor Devices	1/19/62	8/26/68
MIL-STD-810	Environmental Test Methods	6/14/62	6/15/67
MIL-STD-1311	Test Methods for Electron Tubes	4/19/68	7/10/69
MIL-STD-883	Test Methods for Microelectronics	5/1/68	5/1/68

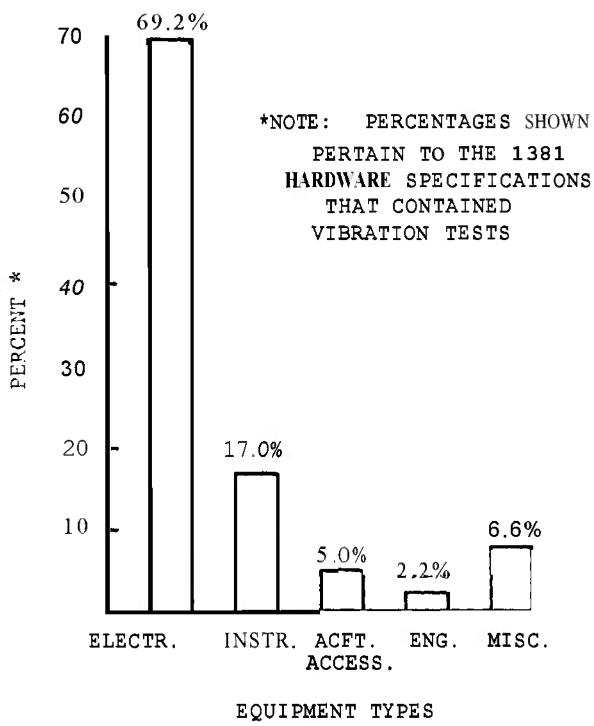

FIGURE 4-79. Types of Equipment Most Often Subjected to Vibration Test (Ref. 83).

of 5,917 detailed hardware or equipment specifications pertaining to Air Force materiel were selected at random. Of these 1,381 or approximately **23** percent contained vibration test specifications. Fig. 4-79 indicates the types of equipment most often subjected to vibration tests. It can be seen that electrical and electronic equipment comprises the bulk of major equipment that is subjected to vibration tests. In this survey a number of test specifications and standards are compared to determine the number and type of vibration tests presented in the specifications. Table 4-19 lists the test specifications along with their title, date of origin, and revisions as of 1971. Table 4-20 indicates the types of test procedures contained in the various specifications and standards. As can be seen resonance testing is a very common test procedure. The resonant dwell may be followed by cycling tests to check for equipment malfunction or for internal resonances that are difficult to detect. In early test procedures, only cycling tests are required. Table 4-21 shows a range of test parameters for typical cycling-type tests and for a variety of equipment locations.

One additional type of test with sinusoidal excitation is the endurance test, which is also listed in Table 4-20. This is a fatigue test and is generally of longer duration than the resonant or cycling test. Table 4-22 indicates

TABLE 4-20. TYPES OF TEST PROCEDURES IN TEST SPECIFICATIONS AND STANDARDS (Ref. 83)

Spec. No.	iesonance	Cycling	Endurance Steady	Endurance Cycling	Random Vib.	Temp. Vib.	Weight Allow Vib.	Total Vib. Tests
MIL-E-5272	4	4	1	1	0	1	1	12
MIL-E-5009	1	0	0	0	0	0	0	1
MIL-T-945	1	2	0	0	0	0	0	3
MIL-E-5400	0	4	0	0	0	0	0	4
MIL-T-5422	2	0	0	0	0	1	0	3
MIL-STD-202	1	5	0	0	1	0	0	7
MIL-STD-167	1	1	0	0	0	0	0	2
MIL-C-172	2	0	0	0	0	2	0	4
MIL-T-7743	0	0	1	0	0	0	0	1
MIL-T-4807	0	1	0	0	0	0	0	1
MIL-STD-750	0	1	1	0	0	0	0	2
MIL-STD-810	14	6	0	0	2	1	14	37
MIL-STD-1311	0	2	3	1	0	0	0	6
MIL-STD-883	0	1	1	0	0	0	0	2
TOTAL	26	27	7	2	3	5	15	85

TABLE 4-21. CYCLING TEST PARAMETERS (Ref. 83)

For equipment mounted on	Double ampl., in.	Accel., g	Freq., Hz	Total vib. time, hr
Recip. and gas turb. eng.	0.036-0.10	1-20	5-500	9
Turbojet engine	0.036-0.10	1-20	5-2,000	9
Aircraft structure on mounts	0.010	2	5-500	9
Helicop. structure on mounts	0.036-0.10	2-5	5-500	9
Helicop. structure, no mounts	0.10	2	5-500	9
Air-launched missiles, captive phase	0.036-0.10	1-10	5-500	6
Air-launched missiles	0.036-0.10	1-10	5-2,000	1.5
Grnd-launched missiles	0.06-0.20	1-50	5-2,000	1.5
Grnd. supt. vehicles	0.06-0.10	1-50	5-2,000	9

TABLE 4-22. ENDURANCE TEST PARAMETERS (Ref. 83)

Equipment type	Double amplitude, in.	Acceleration, g	Frequency range, Hz	Total test time, hr
Microelectronic	0.06	20	20-60	96
Suspended store	0.03	10	50	300
Engine mounted (on turbojet or turbofan)	0.01-0.05	20	15-250	36

TABLE 4-23. RANDOM VIBRATION TEST PARAMETERS (Ref. 83)

Equipment type	Power spectral density	Overall rms g	Total time
All equipment attached to structure of air vehicles and missiles powered by high thrust jets and rocket engines	0.02	5.2	3 min to 8 hr in one or three directions as specified in detail specification
	0.04	7.3	
	0.06	9.0	
	0.10	11.6	
	0.20	16.4	
	0.30	20.0	
	0.40	23.1	
	0.60	28.4	
	1.00	36.6	
	1.50	44.8	

TABLE 4-24. TEST SPECIFICATIONS MOST OFTEN REFERENCED

No.	Specification	Percentage
MIL-STD-202	Test Methods for Electronic and Electrical Component Parts	12.4
MIL-E-5400	Airborne Electronic Equipment	1.7
MIL-T-5422	Aircraft Electronic Equipment Environmental Testing	1.7
MIL-STD-810	Environmental Test Methods	10.7
MIL-E-5272	Environmental Testing of Aeronautical and Associated Equipment	51.3

parameters associated with some type of endurance test. Only two of the specifications, MIL-STD-810 and MIL-STD-202, recommend random vibration testing. Table 4-23 indicates typical parameters for random vibration tests.

Of the 14 general requirements documents reviewed in this summary, five were found to contain the majority (74 percent) of the vibration tests described. These documents are listed in Table 4-24. Of all the specifications, MIL-STD-810 is the most detailed, has been recently revised, and contains the most vibration tests presented. Further, MIL-STD-810 is the only test specification surveyed that describes a gunfire test and only one of two (the other is MIL-STD-202) that presents random vibration test procedures. MIL-E-5272, which was referenced far more frequently than MIL-STD-810, presents vibration tests formulated for the air vehicles and equipment of 15 to 20 yr ago. The apparent reason for such infrequent reference to an updated improved specification seems to lie in the regulations concerning automatic review of specifications at 5-yr intervals. The requirements of MIL-E-5272 appear to be based on 1950 to 1955 technology. On the other hand MIL-STD-810 is a much more recent document, having been available since 1962. It does seem clear that MIL-STD-810 in its latest revision represents the most complete and up-to-date vibration test specification currently in use by the military.

Virtually all of the specifications discussed previously are concerned with equipment that will be subjected to an external vibration environment. Yet, many types of materiel are themselves vibration sources. This is particularly true with respect to rotating machinery. Some basic guidelines have been published in the literature on the vibration levels in rotating machinery that are generally accepted. For example, Richart et al. discusses general machinery vibration severity (Ref. 84). The vibration severity is given in terms of horizontal peak velocity (in. s^{-1}) and compared with machine operation. For example, horizontal peak velocity of 0.005 in. s^{-1} is considered to be extremely smooth, 0.010 to 0.020 in. s^{-1} is considered smooth, 0.040 to 0.080 in. s^{-1} is considered good, 0.160 to 0.315 in. s^{-1} is considered slightly rough, 0.315 to 0.630 in. s^{-1} is considered rough, and anything greater than 0.630 in. s^{-1} is considered very rough.

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CHAPTER 5

SHOCK

5-1 INTRODUCTION AND DEFINITION

Materiel designed for military applications must be capable of surviving, without damage, the shock environment induced by transportation, handling, storage, and maintenance systems as well as that experienced in the operational environment of the equipment. Because of its ultimate application, some materiel is designed sufficiently strong to operate in extreme shock environments and thus requires no special considerations for the nonservice environments. However, other items, such as delicate instruments and electronic equipment designed to operate in a relatively shock-free environment, require some form of packaging or cushioning to prevent damage due to shock during the nonoperational phases of their life cycles.

In order to minimize materiel damage resulting from these nonservice environments effectively and efficiently, it is necessary to have a quantitative description of each environment. Such a description of the shock environments associated with the transportation, handling, storage, and maintenance systems is the primary objective of this chapter. The operational environment for a particular item is usually fully described in the design specifications and therefore will not be treated here.

Shock is often considered a special case of vibration wherein the excitation is a relatively short-term disturbance that has not reached or has ceased to be steady-state. The excitation is nonperiodic, usually in the form of a pulse, step, or transient vibration. The word "shock" implies a degree of suddenness and severity. For analytical purposes, the important characteristic of shock is that the motion of the object upon which the shock acts contains both the excitation frequency and the natural frequency of the object. Shock, then, may be defined as "a transient force or motion whose variation in time is sufficiently rapid to induce transient vibration at the natural frequencies of the object upon which it is imposed" (Ref. 1).

5-2 UNITS OF MEASURE[1]

Shock excitation is generally described by a time history of the rapid variation in the force applied to the system, or by displacement, velocity, or acceleration shock motions imposed upon a particular point in the system. A measurement of any one of these parameters, as a function of time, is sufficient for quantifying the shock environment. Acceleration is by far the most frequently measured parameter, and force is seldom, if ever, used as a shock measurement. In special situations, such as occur during handling operations, the shock levels are represented in terms of drop heights. By the use of known drop-height values, velocity shocks can be computed. Units applicable to acceleration, velocity, and displacement are as follows:

(1) Acceleration. The unit of linear acceleration is denoted by G and is equal in magnitude to the acceleration produced by the force of the gravity of the earth. Since the force of gravity varies with the latitude and elevation of the observer, the value of G has been standardized by international agreement as follows:

$$1\text{ G (standard)} = 980.665\text{ cm s}^{-2} = 386.087\text{ in. s}^{-2} = 32.1739\text{ ft s}^{-2}$$

The values used for most calculations are simplified to:

$$1\text{ G} = 981\text{ cm s}^{-2} = 386\text{ in. s}^{-2} = 32.2\text{ ft s}^{-2}$$

The unit of measure for angular acceleration is radians per second squared (rad s^{-2}). The conversion to other often used units of angular acceleration is as follows:

$$1\text{ rad s}^{-2} = 57.30\text{ deg s}^{-2} = 0.1592\text{ rev s}^{-2}$$

(2) *Velocity.* Linear velocity is expressed in a variety of units. The units used for any one occasion are usually determined by the magnitude of the velocities involved. For example, velocities relating to transportation are usually given in miles per hour, kilometers per hour, or knots. Impact velocities of dropped packages may be given in feet, inches, centimeters, or meters per second. Table 5-1 gives some of the common units and their respective conversion factors.

1. General references for this paragraph are Refs. 2 and 3.

	ft sec^{-1}	km hr^{-1}	m s^{-1}	mi hr^{-1}	cm s^{-1}	kt
1 foot per second =	1	1.097	0.3048	0.6818	30.48	0.5925
1 kilometer per hour =	0.9113	1	0.2778	0.6214	27.78	0.5400
1 meter per second =	3.281	3.6	1	2.237	100	1.344
1 mile per hour =	1.467	1.609	0.4470	1	44.70	0.8689
1 centimeter per second =	3.281 x 10^{-2}	3.6 x 10^{-2}	0.01	2.237 x 10^{-2}	1	1.944 x 10^{-2}
1 knot =	1.688	1.852	0.5144	1.151	51.44	1

Angular velocity is expressed in radians per second (rad/s) and in revolutions per minute (rpm). The following expression indicates their relationship:

$$1 \text{ rps} = 120\pi \text{ rad min}^{-1}$$

*(3) **Displacement.*** The meter is the standard unit of displacement. Table 5-2 gives the conversion factors for units commonly found in the literature.

5-3 DEFINITIONS AND ASSOCIATED TERMINOLOGY

The definitions that follow are given to introduce the terminology of mechanical shock and vibration. The definitions are based on recommendations of the USA Standards Institute (now American National Standards Institute) (Ref. *4*).

(1) ***Mechanical shock*** Occurs when the position of a system is changed in a relatively short time in a nonperiodic manner.

(2) ***Applied shock.*** Any excitation that, if applied to a mechanical system, would produce mechanical shock. The excitation may be either a force applied to the system or a displacement, velocity, or acceleration shock pulse imposed upon a particular point in the system.

*(3) **Shock pulse.*** A substantial disturbance characterized by the rise and decay of force, displacement, velocity, or acceleration excitation from a reference magnitude in a short period of time.

(4) ***Transient vibration.*** A temporarily sustained vibration of a mechanical system. It may consist of forced or free vibration, or both.

*(5) **Shockpulse duration.*** The time required for the excitation quantity represented by the shock pulse to rise from and decay to specified fractions of the maximum magnitude of the shock pulse.

*(6) **Shock pulse rise time.*** The interval of time required for the leading edge of the pulse to rise from some specified small fraction to some specified larger fraction of the maximum magnitude of the shock pulse.

(7) ***Impulse.*** The time integral of force over the interval during which the force is applied, where the force function is time dependent and equal to zero immediately before and after the force is applied.

(8) ***Impact.*** A single collision of one body upon another either in motion or at rest.

(9) ***Sustained acceleration.*** A constant level of acceleration, usually measured as a multiple of acceleration due to gravity, that is maintained for an extended length of time.

TABLE 5-2. CONVERSION FACTORS FOR DISPLACEMENT UNITS

	cm	m	km	in.	ft	mi
1 centimeter =	1	10^{-2}	10^{-5}	0.3937	3.281 x 10^{-2}	6.214 x 10^{-6}
1 meter =	100	1	10^{-3}	39.37	3.281	6.214 x 10^{-4}
1 kilometer =	10^5	1,000	1	3.937 x 10^4	3,281	0.6214
1 inch =	2.540	2.540 x 10^{-2}	2.540 x 10^{-5}	1	8.333 x 10^{-2}	1.578 x 10^{-5}
1 foot =	30.48	0.3048	3.048 x 10^{-4}	12	1	1.894 x 10^{-4}
1 statute mile =	1.609 x 10^5	1,609	1.609	6.336 x 10^4	5,280	1

(10) ***Displacement.*** A vector quantity that specifies the change of the position of a body or particle and is usually measured from the mean position or position of rest. In general, it can be represented by a translation or rotation vector, or both.

(11) ***Velocity.*** A vector that specifies the time rate of change of displacement with respect to a frame of reference.

(12) ***Acceleration.*** A vector that specifies the time rate of change of velocity with respect to a frame of reference.

(13) ***Jerk.*** A vector that specifies the time rate of change of acceleration with respect to a frame of reference.

(14) ***Oscillation.*** The variation with time of the magnitude of a quantity with respect to a specified reference, when the magnitude is alternately greater and smaller than the reference.

(15) ***Mechanical vibration.*** An oscillation wherein the oscillatory quantity is a mechanical parameter such as force, stress, displacement, velocity, or acceleration.

(16) ***Dynamic excitation.*** An external vibratory force (or other type of input such as acceleration, velocity, or displacement) applied to a system that causes the system to respond.

(17) ***Vibration response.*** The motion (or other type of output such as acceleration or velocity) resulting from dynamic excitation under specified conditions.

(18) ***Free vibration.*** Vibration that occurs in the absence of forced vibration.

(19) ***Forced vibration.*** Vibration that occurs if the system is caused to experience a dynamic response as a result of the imposed dynamic excitation.

(20) ***Amplitude.*** The zero-to-peak value corresponding to the maximum magnitude of the harmonic vibration time history.

(21) ***Instantaneous magnitude.*** The value (positive or negative) of the time history representing the vibration or shock phenomenon at a given instant of time.

(22) ***Continuous spectrum.*** A spectrum whose components are continuously distributed over a frequency region.

(23) ***Combined spectrum.*** A spectrum representing a superposition of a discrete and a continuous spectrum.

(24) ***Power density spectrum.*** A graphical presentation of values of power density displayed as a function of frequency. It represents the distribution of vibration energy with frequency.

(25) ***White noise.*** A type of random vibration for which the spectral density has a constant value for all frequencies from zero to infinity.

(26) ***Stationary vibration.*** That type of vibration for which properties—such as the mean magnitude, the root mean square (rms) magnitude, the spectral density, and the probability distribution of the random vibration magnitude—are independent of time. The condition of stationarity for random vibration is analogous to the steady-state condition for periodic vibration.

(27) ***Periodic vibration.*** An oscillation having a waveform that is repeated at certain equal increments of the independent time variable.

(28) ***Period T.*** The smallest increment of time t for which the waveform of a periodic vibration is repeated.

(29) ***Cycle.*** The complete sequence of magnitudes of a periodic vibration that occurs during a complete period.

(30) ***Frequency f.*** The reciprocal of the period of vibration; i.e., $f = 1/T$ Hertz (Hz) is the accepted unit of cyclic frequency.

(31) ***Angular frequency (circular frequency)*** ω in radians per unit time. The cyclic frequency f multiplied by 2π; i.e., $\omega = 2\pi f$.

(32) ***Phase of a periodic vibration.*** The fractional part of a period through which the periodic vibration has advanced, measured from an arbitrary reference. The phase angle $\phi = \omega t_L$, where t_L is the time lag or lead that exists between the periodic vibration and the reference.

5-4 SHOCK ENVIRONMENTS

One of the major problems in transporting materiel between any two locations is the shock environment to which it is exposed. For military operations that may be worldwide, these problems in transporting materiel are magnified greatly because any particular item of cargo may be subjected to a number of different packaging techniques and to mixed modes of transportation. Also, the increasing variety of both military cargoes and transport vehicles with their differing size, mass, and internal cushioning has compounded the effort required to define adequately the shock environment that a piece of materiel is likely to encounter during the nonservice phases of its life cycle.

The four major modes of transporting materiel are by air, rail, water, and highway. Other relevant shock environments are handling, storage, and maintenance.

5-4.1 TRANSPORTATION

Shocks associated with the transportation environment are discussed in the subparagraphs that follow:

(1) *Air.* Shock forces on cargo-hat"ng aircraft typically result from runway surface roughness, landing impact, braking (including propeller reversal), wind gusts and buffet loads, and jet-assist or catapult takeoff (Ref. 5). The aircraft shock environment may be characterized by shock pulses or forces of magnitudes up to 12 G with durations of less than about 0.1 s (Ref. 6). The most severe and most frequently occurring shocks are in the vertical direction. It is recommended in TB 55-100 that the shock acceleration normally encountered during landing should be based on a velocity (not stated but assumed to be vertical velocity) at touchdown for the aircraft of 10 ft s^{-1}.

(2) *Rail.* The primary source of shock excitation in rail vehicles is impact resulting from switching, humping, braking, and slack runouts in the coupling system (Ref. 7). The shock environment associated with humping and coupling operations is predominantly one of large longitudinal and vertical shock forces resulting from impact of two cars at speeds ranging up to about 12 mph (Ref. 5). Maximum shock accelerations resulting from humping operations have been as high as 30 to 50 G, depending on cargo type (Ref. 6). Braking and slack runouts result in high-amplitude transient vibrations having frequency components predominantly in the range of 1 to 200 Hz (Ref. 8).

During normal running conditions (i.e., relatively constant speed), longitudinal shocks in trains are the result of road contour, engineer ineffectiveness, and type of draft gear (a device used to isolate shock in the longitudinal direction in railroad cars) on the particular car. The magnitude of the shock is a function of train speed and length as well as the location of the car in the train. Under normal operating conditions, these shock accelerations are less than 2 G (Ref. 7).

Vertical forces imposed on cars when switched or humped depend on the type of draft gear and the type of snubbing employed. For normal running conditions, vertical force depends on speed, track condition, spring travel, and snubbing.

(3) Water. The shock environment experienced by cargo aboard ship is generally much less severe than that for the other three modes of transport. Shock excitations occur primarily during emergency maneuvers, slamming in rough seas, and docking operations. The acceleration shocks are very seldom greater than 2 G and are, of course, a function of the size of the ship.

(4) Highway. Typical sources of shock forces encountered by truck cargo include road surface roughness, wind loads, starts, stops, and impacts from collision (e.g., when the truck strikes the loading dock). Examples of road surface roughness include cattle and railroad crossings, abrupt changes in the type of road (e.g., paved to gravel or dirt), and bridges. The truck environment is characterized by relatively small shock forces in comparison to the train environment and by forces of about the same magnitude as those experienced by air cargo. The maximum shocks measured in either vertical, longitudinal, or lateral directions are nearly always less than 10 G and are usually much smaller, falling in the range of from 1 to 2 G (Ref. 9). In developing a shock index classification for highway vehicles, Kennedy (Ref. 10) concludes that for a specific vehicle the percent of loading relative to the rated load factor has the largest effect on the magnitude of shock forces experienced for a fixed set of conditions. The maximum allowable load (percent rated load factor of 100) results in the smallest shock forces.

5-4.2 HANDLING

The handling shock environment includes those shocks resulting from the loading and unloading of transport vehicles and from depot handling operations. Results from a number of test shipments indicate that the severest environment, regardless of mode of transportation employed, occurs during the handling operations (Ref. 11). Handling shocks are usually generated by flat drops on a hard surface—such as dropping a package on a concrete surface from the tailgate of a truck during unloading operations; by the fall of a package from a conveyor to a handcart during loading, unloading, or depot handling; or by rotational corner-drops of a large package being maneuvered during loading or unloading (Ref. 5). Handling shocks usually are described by the impact velocity or the drop height and angular orientation at impact. The shocks are generally less severe than a 36-in. drop on concrete, which corresponds to a velocity change of approximately 165 in. s^{-1}.

5-4.3 STORAGE

The storage shock environment includes those shocks experienced by materiel while in warehouses or storage areas for any extended period. Shocks typically occur from being moved by forklift and from being struck by other packages during stacking operations. Although few data are available for evaluating the severity of the shock environment associated with materiel storage, one isolated sample involving the overseas shipment of electronic shelters resulted in the maximum shock excitations being recorded when the shelters were skidded on a warehouse floor (Ref. 12). The values of the accelerations were 3.18 G vertically and 2.55 G longitudinally.

5-4.4 SERVICE

The service shock environment includes those motions experienced while the item is in the repair shop. Service shocks consist primarily of impacts by tools or dropped articles, and by rotational drops about the corner of a piece of equipment during servicing on the work bench (Ref. 5). Although the shock levels are not in general as severe as those encountered in the handling environment, it must be remembered that during service and repair operations the equipment is usually not packaged or protected against the shock forces. Thus, equipment is more susceptible to low-level shock forces during service and repair activities than it is in any of the other nonoperational environments.

5-5 SHOCK CHARACTERISTICS

Basically, two methods are used to describe a shock environment. One method is to describe the inherent properties of the shock phenomenon. This may be accomplished in the time domain by obtaining a time history of a shock parameter—such as acceleration, velocity, or displacement—over the period that the shock is active or in the frequency domain by a Fourier spectrum (Ref. 13). The Fourier spectrum defines a shock pulse in terms of the amplitude and phase of its frequency components and is typically given graphically as a plot of acceleration in units of G versus frequency.

The second method of describing shock is by measuring the response of a system to the shock excitation. This method may also be used in the time domain or in the frequency domain; i.e., the system response can be expressed in terms of a time plot of acceleration, velocity, or displacement of the system over the duration of the pulse or in the form of a shock spectrum. The shock spectrum, sometimes referred to as the response spectrum, is a plot of acceleration in units of G versus frequency as measured at a point on the system. It differs from the Fourier spectrum in that the natural frequencies of the system are involved (Ref. 14).

5-5.1 INHERENT

5-5.1.1 Time Domain

Impact of objects having various elastic-plastic deformation properties results in shock waveforms that vary in shape from an impulse (i.e., rectangular pulse of short duration) to a step function. Typical shock waveforms commonly encountered in cargo transportation and handling systems are illustrated in Fig. 5-1 (Ref. 15). The most frequently used means of describing or specifying a shock pulse is by use of the acceleration time history. However, in some instances, a velocity or a displacement time history may be desirable and is therefore included in Fig. 5-1. Common shock waveforms are characterized as follows:

(1) ***Impulse or rectangular.*** The rectangular pulse shape results from the impact of a rigid body with a deformable pad of uniform cross section. The acceleration time history is expressed mathematically by[2]

$$a(t) = A \text{ for } (0 < t < T_0) \tag{5-1}$$

and

$$a(t) = 0 \text{ for } (t < 0,\ t > T_0) \tag{5-2}$$

where the amplitude of the acceleration $a(t)$ abruptly changes from zero to A at the initiation $(t = 0)$ and from A to zero at the termination $(t = T_0)$ of the shock pulse.

In the situation where $T_0 \to 0$, the mathematical expressions for the acceleration, velocity, and displacement time histories as shown in Fig. 5-1(A), respectively

$$a(t) = V\delta(t) \tag{5-3}$$

where $\delta(t) = 0$ when $t \neq 0$, $\delta(t) = \infty$ when $t = 0$, and $\int_{-\infty}^{\infty} \delta(t)dt = 1$, and V is an acceleration impulse function.

$$v(t) = V \text{ for } (t > 0) \tag{5-4}$$

2. **Acceleration, velocity, and displacement are represented by a, v, and x, respectively. Constant values are represented by A, V, and X, respectively.**

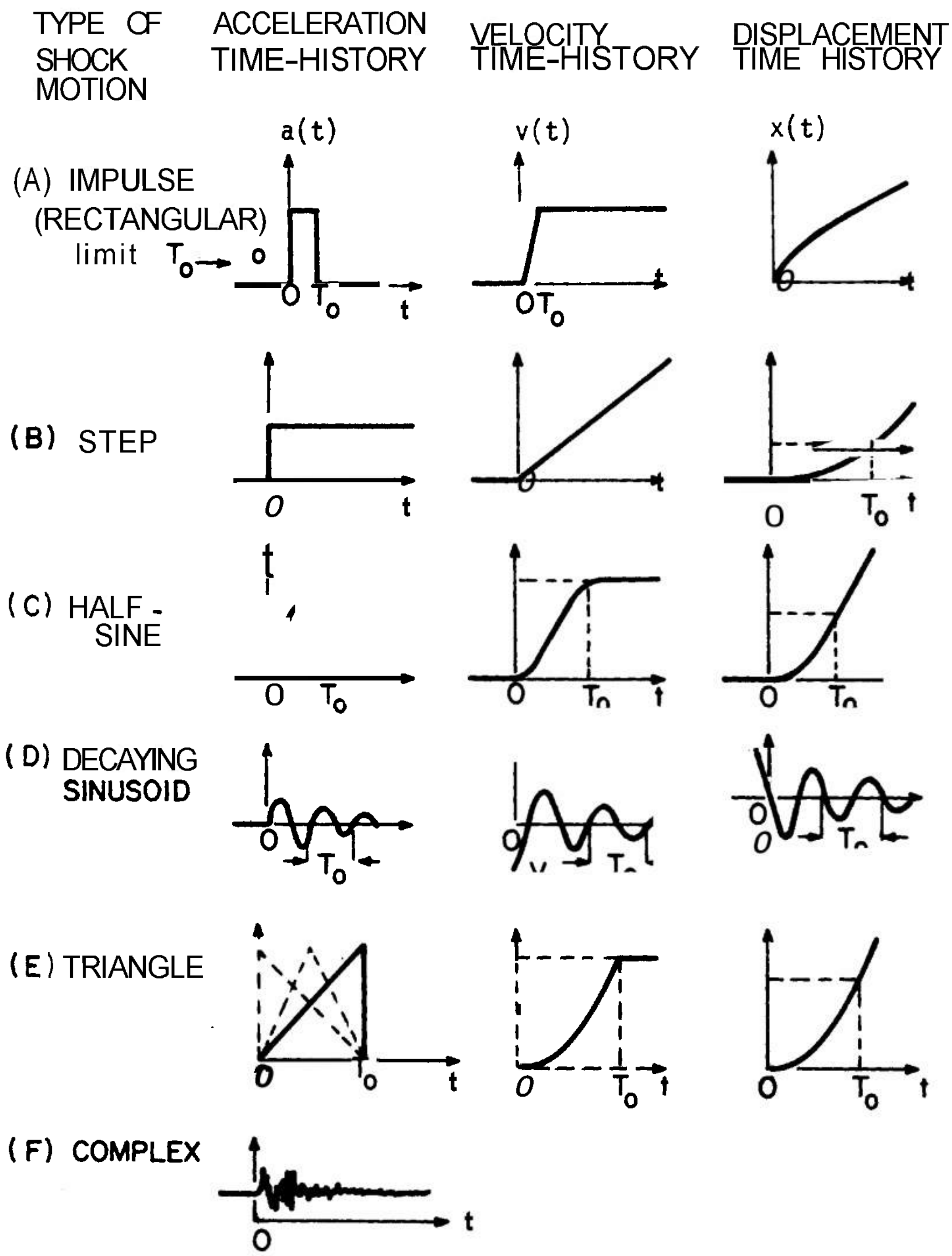


FIGURE 5-1. Six Examples of Shock Motions (Ref. 5).

and

$$x(t) = Vt \text{ for } (t > 0) \qquad (5\text{-}5)$$

(2) Step. The acceleration step and accelerating impulse waveforms represent the classical limiting cases of shock motions (Ref. 15). To mathematically describe the step pulse, the unit step function $1(t)$ is first defined as a function that has a value of zero for all $t < 0$ and a value of unity for all $t > 0$. The mathematical expressions describing the acceleration step as shown in Fig. 5-1(B) are:

$$a(t) = A[1(t)] \qquad (5\text{-}6)$$

$$v(t) = At[1(t)] \qquad (5\text{-}7)$$

and

$$x(t) = At^2[1(t)]/2 \qquad (5\text{-}8)$$

(3) Half-sine. When a rigid carriage, on which a test specimen is rigidly mounted, impacts a linear spring, the specimen encounters an acceleration half-sine shock pulse, provided that the spring is stressed within its elastic limit. This situation is approximated by transport vehicles such as truck and train cars in which the shock forces act through the spring system of the vehicle.

An acceleration half-sine pulse of duration T_0 and magnitude A_0 as shown in Fig. 5-1(C) can be represented mathematically by the expression

$$a(t) = A_0 \sin(\pi t/T_0) \text{ for } (0 < t < T_0) \qquad (5\text{-}9)$$

and zero at all other times. By successive integrations, the corresponding velocity and displacement functions are:

$$v(t) = (A_0T_0/\pi)[1 - \cos(\pi t/T_0)] \text{ for } (0 < t < T_0) \qquad (5\text{-}10)$$

and

$$v(t) = 2A_0T_0/\pi \text{ for } (t \geq T_0) \qquad (5\text{-}11)$$

Also,

$$x(t) = (A_0T_0^2/\pi^2)[\pi t/T_0 - \sin(\pi t/T_0)] \text{ for } (0 < t < T_0) \qquad (5\text{-}12)$$

and

$$x(t) = (2A_0T_0/\pi)(t - T_0/2) \text{ for } t \geq T_0 \qquad (5\text{-}13)$$

(4) Decaying sinusoid. Vibrations that do not persist long enough to be treated as a stationary process are called transients, and a transient vibration whose duration is shorter than the decay time associated with the natural resonances of the system to which it is applied is classified as a shock. Transient vibrations encountered in the transportation environment are frequently of the form that can be represented mathematically as a decaying sinusoid. A graphical illustration is given in Fig. 5-1(D). For the initial condition as illustrated (i.e., acceleration is zero for $t = 0$), the appropriate mathematical expression is of the form:

$$a(t) = A \exp(-kt) \sin \omega t \text{ for } t > 0 \qquad (5\text{-}14)$$

Generally, the decaying sinusoid is the waveform used to represent the response motion of a system to shock excitation. The waveform, then, is a function of the damping and natural frequencies of the system as well as the shock pulse characteristics. The velocity and displacement time histories are further governed by the initial conditions of the system. For these reasons, only a general equation representing the acceleration time history is given with no treatment of the velocity and displacement curves. A detailed treatment of the decaying sinusoid as the response of a damped single-degree-of-freedom system is given by Pennington (Ref. *13).*

(5) Triangular pulses. Triangular shock waveforms are frequently encountered in the transportation system. The exact forms vary from a leading-edge sawtooth through the isosceles triangle to the terminal-edge sawtooth. These three forms are illustrated in Fig. 5-1(E). The terminal-edge sawtooth pulse will be discussed here because it is one of the easiest waveforms to produce; consequently, it is utilized in many shock tests. A waveform shaped as an isosceles triangle has approximately the same characteristics as a half-sine pulse, and the leading-edge sawtooth waveform is less frequently encountered and is difficult to generate; therefore, these two pulse shapes will not be treated at this time.

The terminal-edge sawtooth pulse with corresponding velocity and displacement functions can be represented by the following expressions:

$$a(t) = mt \text{ for } (0 < t < T_0) \qquad (5\text{-}15)$$

and zero at all other times where m is the slope of the rising sawtooth. If A is the maximum acceleration, then

$$A = mT_0 \qquad (5\text{-}16)$$

$$v(t) = mt^2/2 = At^2/(2T_0) \text{ for } (0 < t < T_0) \qquad (5\text{-}17)$$

$$v(t) = AT_0/2 \text{ for } t \geq T_0 \qquad (5\text{-}18)$$

$$x(t) = mt^3/6 = At^3/(6T_0) \text{ for } (0 < t < T_0) \qquad (5\text{-}19)$$

and

$$x(t) = (AT_0/6)(3t - 2T_0) \text{ for } t \geq T_0 \qquad (5\text{-}20)$$

(6) Complex shock motion. Transient vibrations of a system may be in the form of a complex motion similar to the diagram in Fig. 5-1(F). Because of its highly complex nature, a shock motion of this type cannot be defined by an analytical function; therefore, the corresponding velocity and displacement time histories must be obtained by numerical or graphical techniques, or by analog integration of the acceleration function.

5-5.1.2 Frequency Domain

The Fourier spectrum of a nonperiodic transient wave is a continuous function and is obtained by integration. The Fourier integral $F(\omega)$ of a shock wave is as follows:

$$F(\omega) = \int_{-\infty}^{\infty} a(t) \exp(-j\omega t)\,dt \qquad (5\text{-}21)$$

with the requirement that $a(t)$ is finite, or

$$\int_{-\infty}^{\infty} |a(t)|\,dt < \infty \qquad (5\text{-}22)$$

where

t = time
ω = angular frequency
$j = \sqrt{-1}$
$a(t)$ = acceleration
$F(\omega)$ = Fourier integral, i.e., acceleration expressed as a function of frequency

A Fourier spectrum shows the frequencies or frequency ranges that are important in terms of the instrumentation necessary for measuring the shock as well as estimating system response to that particular type of excitation.

Examples of a rectangular, terminal-edge sawtooth, and half-sine shock pulses and their Fourier transforms are given in Fig. 5-2.

As seen from the graphs, the magnitude of the transform is zero at certain frequencies for the rectangular and half-sine pulses. In contrast, the transform of the terminal-edge sawtooth has a continuous and finite value for all frequencies with a gradual and somewhat linear decay rate. These differences in Fourier spectra are important for estimating the response of a given system to a shock pulse type. For example, it is obvious that the response of a system with natural frequencies of $1/T_0$, $2/T_0$, etc., would be more drastic when subjected to a terminal-edge sawtooth pulse than it would be for either of the other two pulse types. The significance of these differences will be discussed in greater detail in par. 5-5.2.

5-5.2 RESPONSE

5-5.2.1 Time Domain

Response characteristics of a given system to a shock pulse are described in the same manner as are the inherent characteristics of a shock pulse in the preceding paragraph; i.e., time history plots of acceleration, velocity, or displacement. In the case of response characteristics, the measurements are made at some point on the system; whereas, in describing inherent characteristics, the measurements represent the input to the system. For example, the response of a system to shock is influenced by the magnitude, duration, and shape of the input shock pulse as well as by the structural properties of the system itself.

5-5.2.2 Frequency Domain

In representing the response of a system to a shock pulse by means of a shock spectrum, the system is hypothesized as an array of single-degree-of-freedom elements (Fig. 5-3) whose natural frequencies are continuously distributed over a wide range (Ref. 17). The single-degree-of-freedom system is restricted to displacement in only one coordinate and is completely defined by its natural frequency ω_n and damping factor ζ as follows:

$$\omega_n = \sqrt{k/m} \quad \text{and} \quad \zeta = C/(2\sqrt{km}) \qquad (5\text{-}23)$$

where

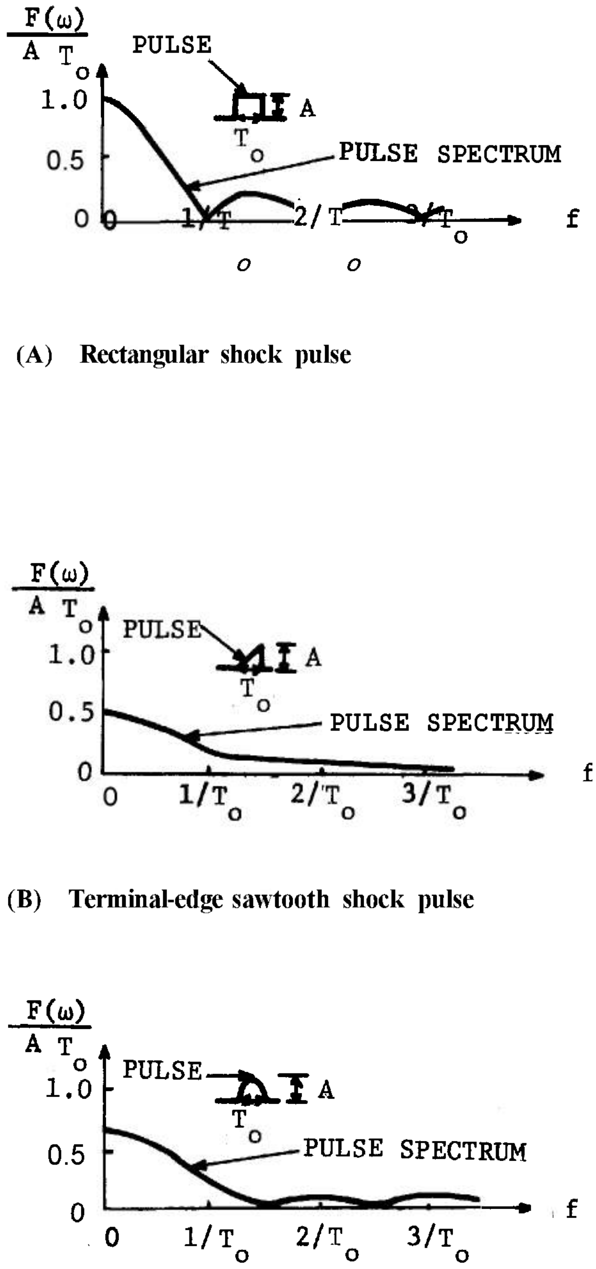
ω_n = natural frequency, Hz
m = mass, g
k = spring constant, dyn cm^{-1}
ζ = damping factor, dimensionless
C = system damping, dyn s cm^{-1}

The effect of a particular shock pulse, then, is to excite the system to vibrate over the frequency range indicated by the Fourier spectrum of the pulse with the magnitude of the vibrations controlled by the natural frequencies and damping of the system. A shock spectrum incorporates all the preceding parameters. The shock spectrum as discussed here is a two-dimensional graph showing for each frequency the maximum acceleration that occurred in the system subjected to the shock. In other words, if several single-degree-of-freedom elements-each with a different natural frequency—were mounted at a point on the system and subjected to the same shock input, a graph of the maximum response of each element as a function of resonant frequency is the response or shock spectrum for that shock input.

In most cases it has become customary to include, along with the maximum or primary spectrum (maximum response during shock input), the residual spectrum (response after shock input). The shock spectra of several shock pulse types are given in Fig. 5-4 (Ref. 18).

Important characteristics of the maximum response shock spectrum as gained from studying the examples given in Fig. 5-4 are:

(1) A shock spectrum is always zero at zero Hz.



(A) Rectangular shock pulse

(B) Terminal-edge sawtooth shock pulse

(C) Half-sine shock pulse

FIGURE 5-2. Examples of Shock Pulse Time Histories and Their Fourier Transforms (Ref. 16).

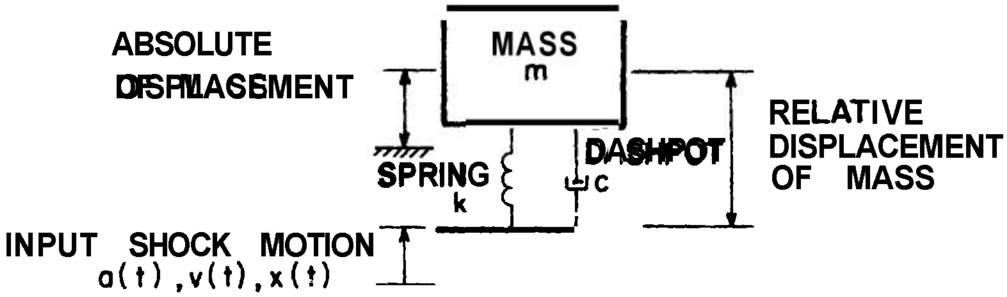


FIGURE 5-3. ***A Single-degree-of-freedom System*** *(Ref* ***17).***

(2) It rises to an initial maximum amplitude that is not exceeded at higher frequencies.

(3) Within certain limits, it remains relatively flat as the frequency increases.

(4) The pulse shape has comparatively little effect on the maximum response spectrum. This is also seen in Fig. 5-5 where the effect of pulse shape on spectra is shown.

The undamped residual spectrum $R(\omega)$ is related to the Fourier spectrum $F(\omega)$ by the following relationship:

$$\omega_n \cdot R(\omega_n) = |F(\omega_n)| \quad (5\text{-}24)$$

where ω_n is the natural frequency of an undamped single-degree-of-freedom system. It is a plot of the maximum response of a single-degree-of-freedom element after the shock pulse has been completed. The residual spectrum provides important information pertaining to dynamic loading and fatigue loading due to flexural motion.

An important characteristic of the residual response spectrum is that for both the square pulse and the half-sine pulse the spectrum goes to zero at certain frequencies, indicating that there is no "ringing" at these frequencies upon termination of the pulse. However, the residual response spectrum of a terminal-edge sawtooth pulse is the same as the primary response spectrum and, therefore, imposes an equally severe loading at all frequencies.

5-6 TYPICAL SHOCK LEVELS

5-6.1 TRANSPORTATION

The measurement of the shock environment of transportation and handling systems is still a rather crude science. Differences in methodology, instrumentation, and data interpretation can result in considerably different sets of data taken from nearly identical environmental conditions. Also, the shock motions encountered in transportation—whether by air, rail, water, or highway—depend greatly upon the characteristics of the cargo and loading geometry (Ref. 19). The lack of consistency in measuring and reporting in the same shock parameters and/or units makes it difficult to compare the testing results.

In order to adequately define the shock environment and to be of maximum use to future users, the data should (1) be graphical in format, (2) be statistical in nature, (3) represent those parameters that can be controlled in the laboratory as well as measured in the field, and (4) lend themselves to alternative means of combination or analysis (Ref. 20).

In any new measurement program, the first effort is generally directed toward evaluating the worst case conditions. Much of the data presented herein is representative of such conditions. In general, the lack of adequate data limits the drawing of meaningful conclusions.

5-6.1.1 Aircraft

A great deal of data exists on the vibration levels of different aircraft, but only a very limited amount on shock levels. The curve in Fig. 5-6 envelopes the maximum shock levels recorded in field studies conducted by the Transportation *Corps*. These data are from tests in which short recording periods were used and high

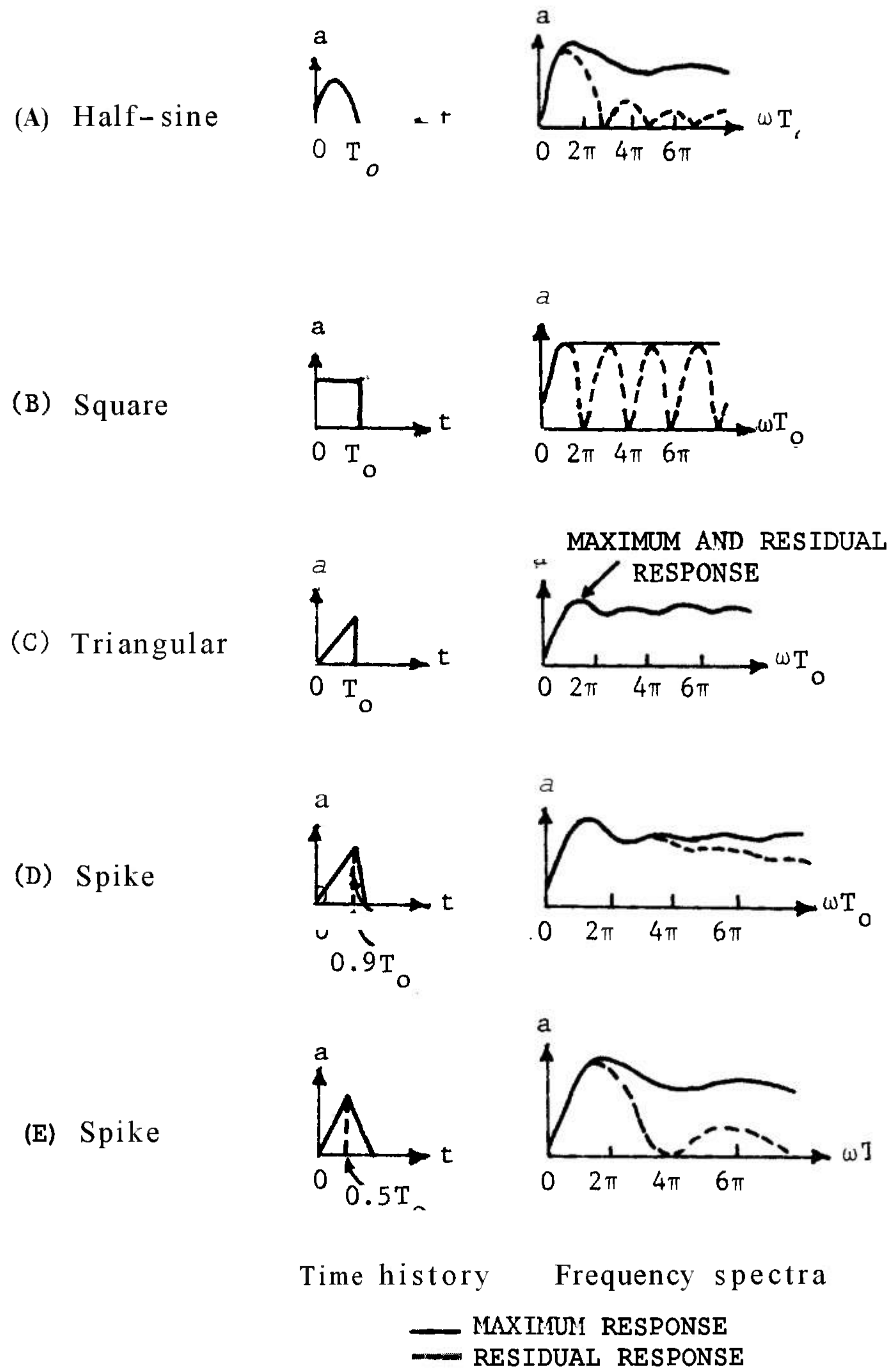


FIGURE 5-4. Shock Spectra of Several Typical Shock Pulses (Time t is given in terms of the natural period T_0. Acceleration a is in arbitrary units. Frequency is given in terms of ωT_0, dimensionless.) (Ref. 18).

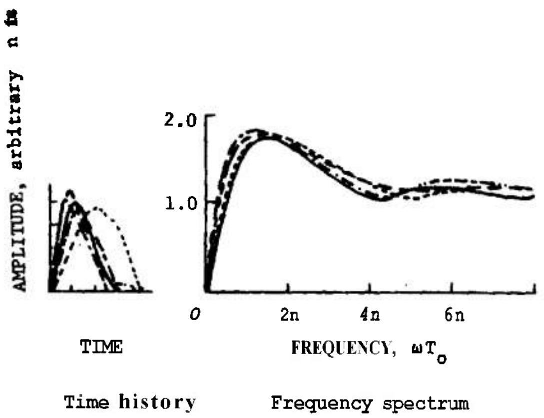


FIGURE 5-5. Effect of Pulse Shape on Shock Spectra (Ref. 18).

input loadings were simulated consistent with test safety. These data cover both helicopters and fixed-wing aircraft. Shock levels encountered under emergency conditions would probably exceed those represented here.

Shock and vibration measurements made on a Saturn S-IV stage during air transport aboard a modified Boeing 377 Stratocruiser indicate about a 1-percent probability of the **S-IV** stage experiencing an acceleration as great as **4** G (Ref. 21).

Measurements made in the aft passenger compartment of an NC-135 jet aircraft show acceleration peaks of approximately 1 G during braking after touchdown (Table **5-3**) and values **as** high **as 4** G during takeoff (Table **5-4**). The data are given **as** the percentage of accelerations at the corresponding magnitude. In order to find the number of times that a given level was recorded, the percentage given in the table is multiplied

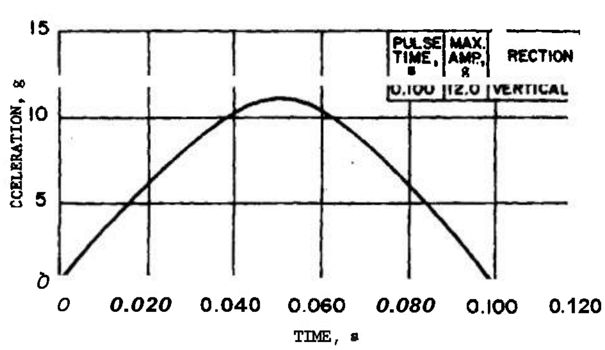


FIGURE 5-6. Cargo Shock Environments for Air Transport (Ref. 6).

by the samples per channel for that channel. The data in these two tables are predominantly for vibration; however, it is assumed that the highest readings are representative of the shock levels encountered.

5-6.1.2 Rail

The major portion of the data presented here is reported by Schock and Paulson (Ref. 8) in a paper summarizing the results of a project wherein all the available information and test data pertaining to the transportation shock environment are evaluated. Over 300 reports were reviewed and **55** agencies that are active in the transportation field were contacted by Schock and Paulson in preparation of the paper. The data are presented in the form of acceleration versus frequency graphs. The magnitudes represent values that had been reported in the literature prior to 1966. In some of the original reports, the data were in the form of peak acceleration versus duration. For these data, unless the pulse shapes were given, a half-sine wave was used to compute a frequency spectrum.

Fig. **5-7** represents the high-amplitude transient vibrations that occur during starts, stops, slack runouts, and run-ins. This graph was constructed by enveloping all reliable data (pre-1966) for all types of railroad cars, rail conditions, directions, and speeds. Therefore, it represents the maximum values encountered in over-the-road operations.

The largest shock excitations occur during coupling and/or humping operations. Figs. ***5-8*** through 5-20 contain shock spectra data in the form of peak acceleration versus frequency graphs for different coupling-humping speeds, damping factors, and types of draft gear used. The damping factor is defined as

$$\zeta = C/C_c$$

where

C = **actual damping of system, dyn s cm^{-1}**
C_c = **smallest value of C that prevents system oscillation (critically damped)**

Values of actual system damping **used** here are: $C = 0$, $C = 0.005\ C_c$, and $C = 0.05\ C_c$. Equivalent damping factors are: $\zeta = 0$, $\zeta = 0.005$, and $\zeta = 0.05$, respectively.

As can be seen from the graphs, the maximum shock levels occur at frequencies above approximately 100 **Hz.** For a fixed set of conditions, vertical shocks are the most severe, followed by longitudinal (fore/aft), then lateral. The percent of critical damping (% C/C_c) shows a significant inverse relationship to the shock levels. A comparison of Figs. **5-8** and ***5-20*** indicates

TABLE 5-3. DISTRIBUTION OF VERTICAL ACCELERATION PEAKS, BRAKING AFTER TOUCHDOWN, NC-135 AIRCRAFT (*Ref.* 22)
(Distribution in percent)

Acceleration, g	Frequency band of channel, Hz											
	20-40	40-80	80-120	120-180	180-240	240-350	350-500	500-700	700-1,000	1,000-1,400	1,400-1,900	1,900-2,500
1.00–1.40									0.36			
0.72–1.00									0.46			
0.52–0.72									0.72	0.21		
0.37–0.52								0.06	0.77	0.82		
0.27–0.37							0.23	0.18	1.39	0.62	1.97	
0.19–0.27						0.20	0.62	0.43	1.65	1.65	0.56	
0.14–0.19						0.90	0.77	0.91	1.34	2.47	21.71	
0.10–0.14		1.85		3.53	2.13	2.59	1.93	1.95	3.36	6.80	73.68	
0.0–0.10	100.00	98.15	100.00	96.47	97.87	96.32	96.37	96.46	89.93	87.42		
	Samples per channel											
	132	54	89	510	609	1,005	1,295	1,640	1,937	485	152	4

TABLE 5-4. DISTRIBUTION OF VERTICAL ACCELERATION PEAKS TAKEOFF, NC-135 AIRCRAFT (*Ref.* 22)
(Distribution in percent)

Acceleration, g	Frequency band of channel, Hz											
	20-40	40-80	80-120	120-180	180-240	240-350	350-500	500-700	700-1,000	1,000-1,400	1,400-1,900	1,900-2,500
3.70–5.20					0.19	0.14	0.05		0.05	0.17		
2.70–3.70												
1.90–2.70						0.14			0.02			
1.40–1.90						1.43			0.90		0.23	
1.00–1.40				1.11	0.09	9.60	1.11	0.63	6.40	0.05	1.31	
0.72–1.00				11.93	1.97	25.14	9.40	4.87	18.61	0.56	2.71	
0.52–0.72			0.20	21.36	12.96	23.77	20.87	15.91	24.25	2.77	6.19	
0.37–0.52			2.82	22.05	26.10	17.57	24.39	27.04	21.53	7.92	9.78	
0.27–0.37			13.71	19.97	22.25	11.17	19.04	22.00	12.90	16.86	13.06	
0.19–0.27		6.91	17.14	10.54	14.46	4.77	10.80	12.77	6.76	19.69	15.50	
0.14–0.19		17.11	24.40	5.55	9.11	2.52	5.88	7.41	3.79	17.42	29.44	
0.10–0.14		36.18	25.81	4.58	8.26	2.32	4.19	5.46	3.11	19.13	21.54	
0.0–0.10	100.00	39.80	15.93	2.91	4.60	1.43	4.29	3.90	1.68	15.42	0.23	
	Samples per channel											
	155	304	496	721	1,065	1,468	2,075	2,873	4,218	6,032	7,772	0

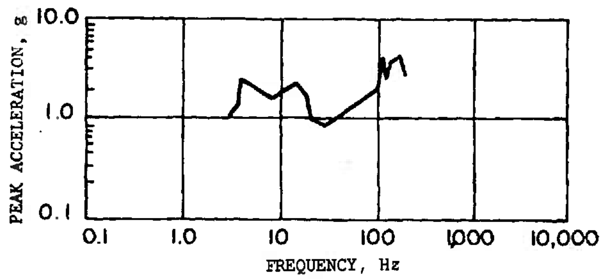


FIGURE 5-7. Maximum Railraod Transient Acceleration Envelopes, Over-the-road, Standard Draft Gear (Ref. 8).

that the shock level is less for a railroad car equipped with a cushioned draft gear at a coupling speed of 12 mph than it is at 3.4 mph for a car using a standard draft gear.

Fig. 5-21 envelopes the maximum shock levels encountered under three different conditions during a railroad shipment extending over 500 mi. The top curve, representing the most severe condition of humping operations with an impact velocity of 11 mph, shows a range in intensity from 10 to approximately 450 G. Gens estimates (Ref. 23) that the probability of these shock levels being encountered in a typical railroad shipment is about 0.01.

The middle curve represents values measured during switching and coupling operations at speeds of 2 to 5 mph. These values are, on the average, a factor of 10 lower than those for 11-mph humping operations at a given frequency. Gens estimates that there is a probability of 0.95 of these shock levels being encountered by rail cargo.

Data for the bottom curve were recorded while the train, traveling at about 45 mph, crossed tracks perpendicular to its own, or switched from one set of tracks to another.

One general observation made by Gens from this test is that transverse shocks are the most severe at the lower frequencies, but that the vertical shocks become most severe at the high frequencies.

Fig. 5-22 shows the distribution of coupling speeds based on 3,369 measured impacts. Data are presented in terms of percent of total impacts versus coupling speed. The data show that 50 percent of the couplings are made at impact speeds greater than 5 mph. Pulse shape, duration, and magnitude as determined by Transportation Corps studies are given in Fig. 5-23. These are envelopes of the maximum values recorded while using standard commercial railcars impacted at 10 mph.

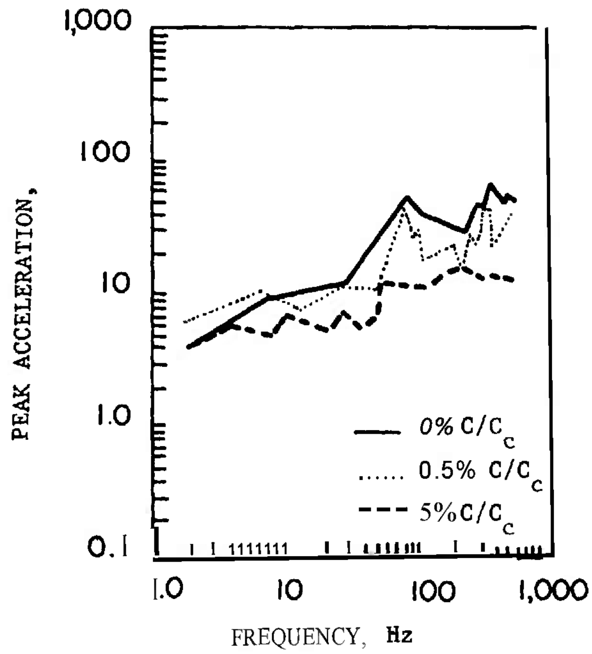


FIGURE 5-8. Railroad Coupling Shock Spectrum, 3.4 mph, Fore/Aft, Standard Draft Gear (Ref. 8).

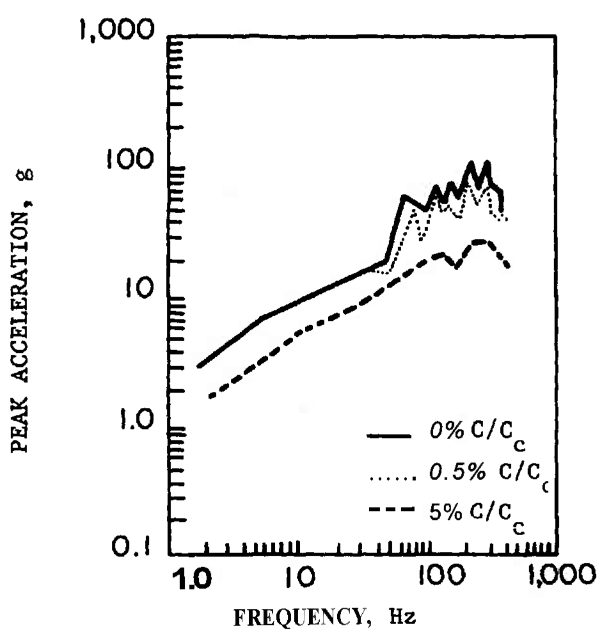


FIGURE 5-9. Railroad Coupling Shock Spectrum, 3.4 mph, Vertical, Standard Draft Gear (Ref. 8).

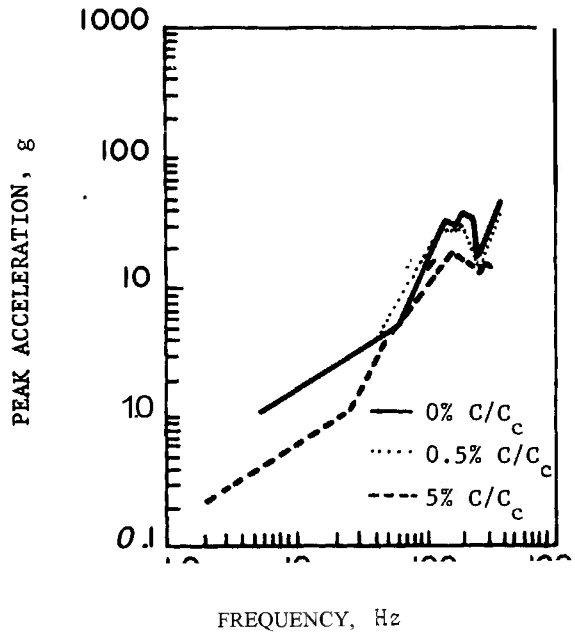


FIGURE 5-10. Railroad Coupling Shock Spectrum, 3.4 mph, Lateral, Standard Draft Gear (Ref. 8).

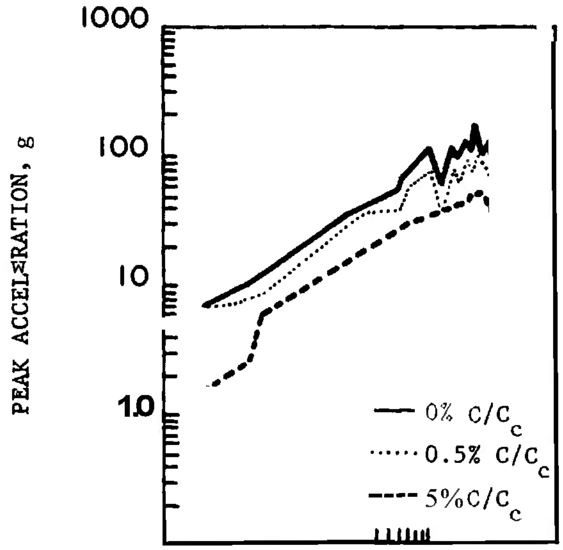


FIGURE 5-11. Railroad Coupling Shock Spectrum, 6 mph, Fore/Aft, Standard Draft Gear (Ref. 8).

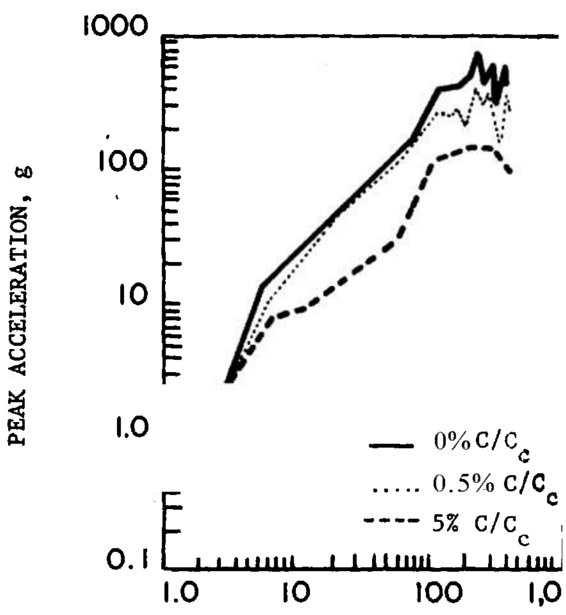


FIGURE 5-12. Railroad Coupling Shock Spectrum, 6 mph, Vertical, Standard Draft Gear (Ref 8).

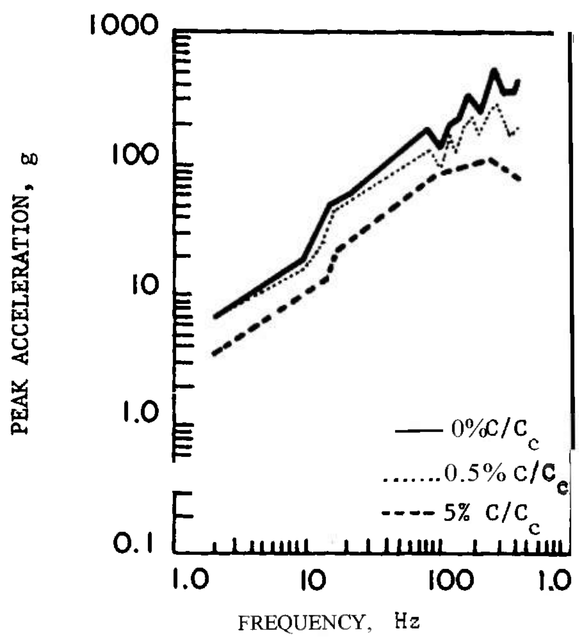


FIGURE 5-13. Railroad Coupling Shock Spectrum, 8 mph, Vertical, Standard Draft Gear (Ref 8).

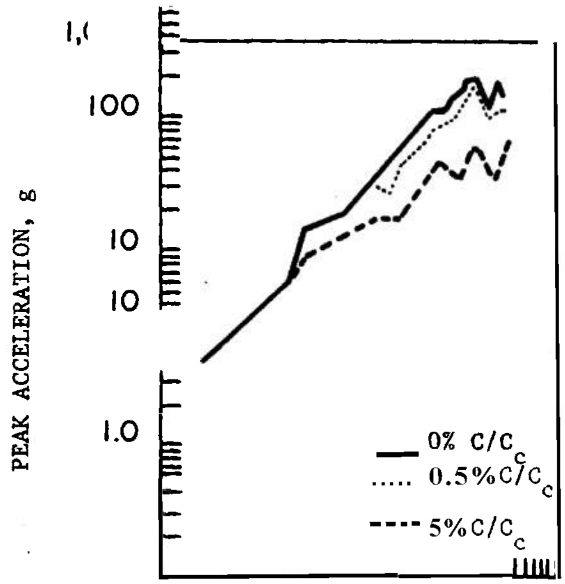


FIGURE 5-74. Railroad Coupling Shock Spectrum, 70 mph, Vertical, Standard Draft Gear (Ref. 8).

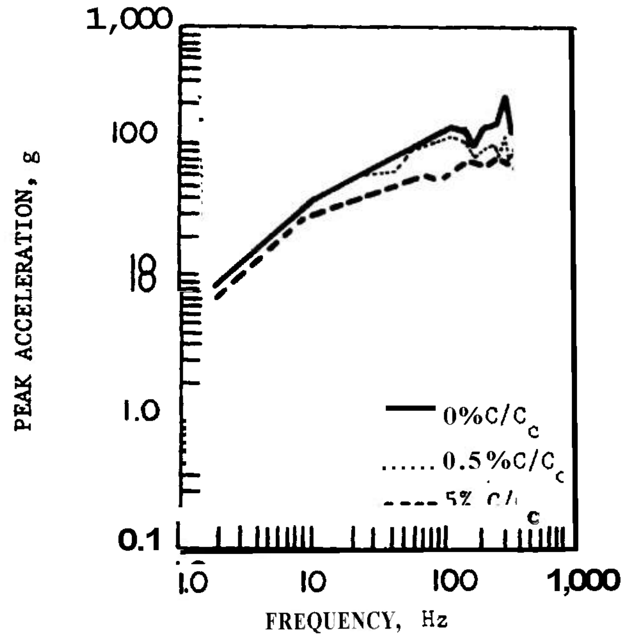


FIGURE 5-75. Railroad Coupling Shock Spectrum, 70 mph, Fore/Aft, Standard Draft Gear (Ref. 8).

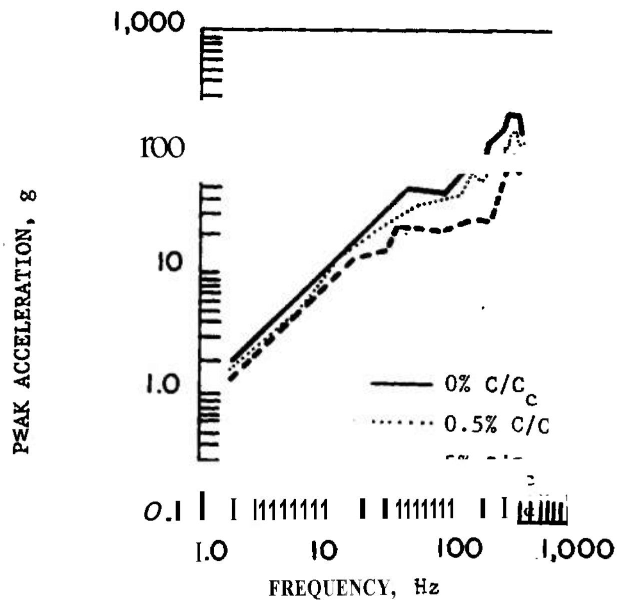


FIGURE 5-76. Railroad Coupling Shock Spectrum, 70.0 mph, Lateral, Standard Draft Gear (Ref. 8).

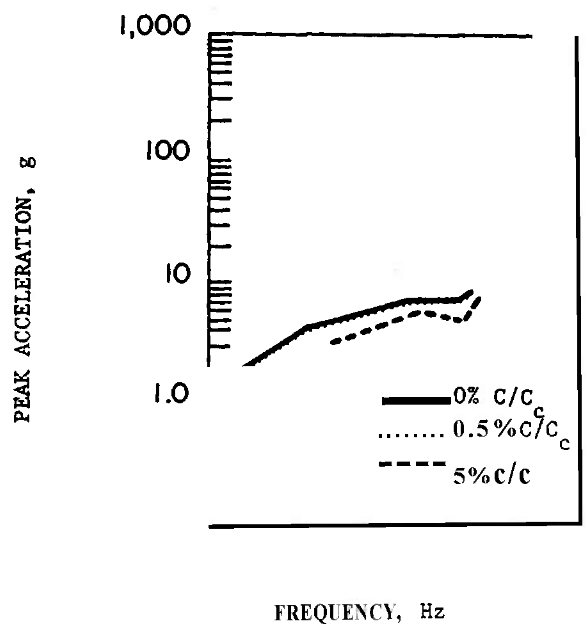


FIGURE 5-17. Railroad Coupling Shock Spectrum, 3.7 mph, Fore/Aft, Cushioned Draft Gear (Ref. 8).

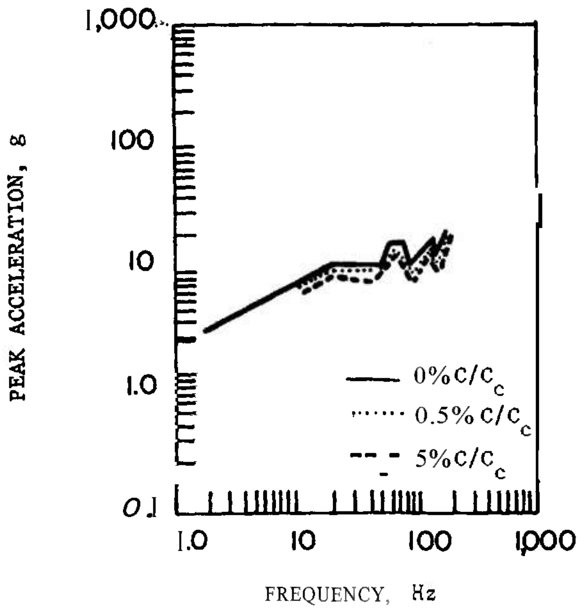


FIGURE 5-18. Railroad Coupling Shock Spectrum, 6.8 mph, Fore/Aft, Cushioned Draft Gear (Ref. 8).

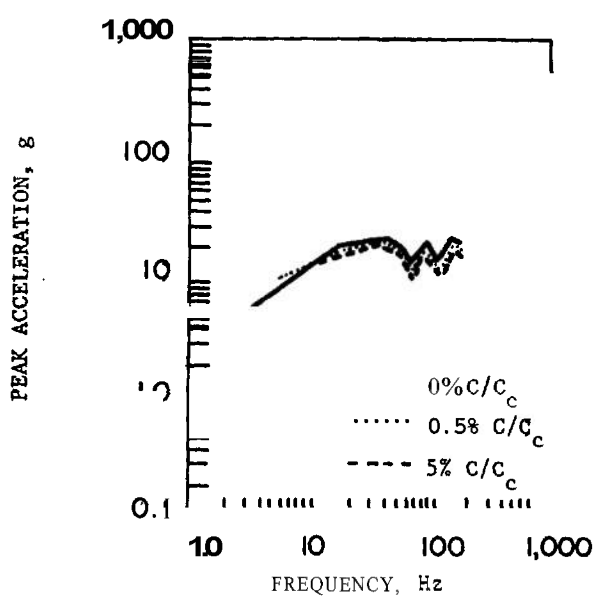


FIGURE 5-19. Railroad Coupling Shock Spectrum, 9.8 mph, Fore/Aft, Cushioned Draft Gear (Ref. 8).

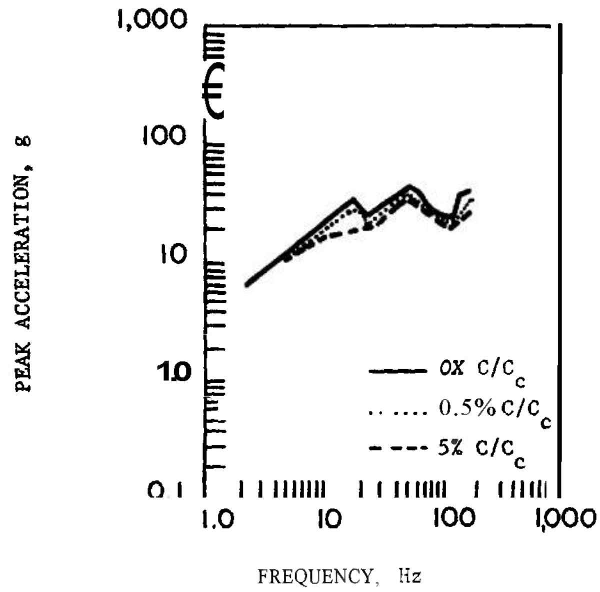


FIGURE 5-20. Railroad Coupling Shock Spectrum, 12 mph, Fore/Aft, Cushioned Draft Gear (Ref. 8).

5-6.1.3 Water

The shock environment associated with sea transport is not as severe as those of rail, highway, and air transport. This is perhaps the reason for the scarcity of data in this area. One set of data defines the shock environments experienced by a Saturn s-IV stage while aboard (1) a seagoing barge, and (2) a seagoing freighter (Ref. 21).

The seagoing barge is towed from place to place at the end of a 1,000-ft cable. The data given in Figs. **5-24, 5-25,** and **5-26** were recorded during heavy seas (8- to 10-ft chops). The shock excitations resulted from the "spanking" action of the barge. The distribution of transient durations is given in Fig. **5-24.** *Also,* probability distributions of the shock levels are given in Fig. **5-26** for measurements made on the transporter that supported the missile stage while on the barge and in Fig. **5-25** for measurements made on the barge deck.

The freighter was of the Victory type, approximately 500 ft long with a 10,000-ton displacement and a 28-ft draw. Normal cruise speed is about 17 kt. Fig. 5-27 gives the maximum acceleration levels measured aboard the freighter. These maximum accelerations were recorded during rough weather and had periods ranging from 4 to 10 s. These accelerations, then, are

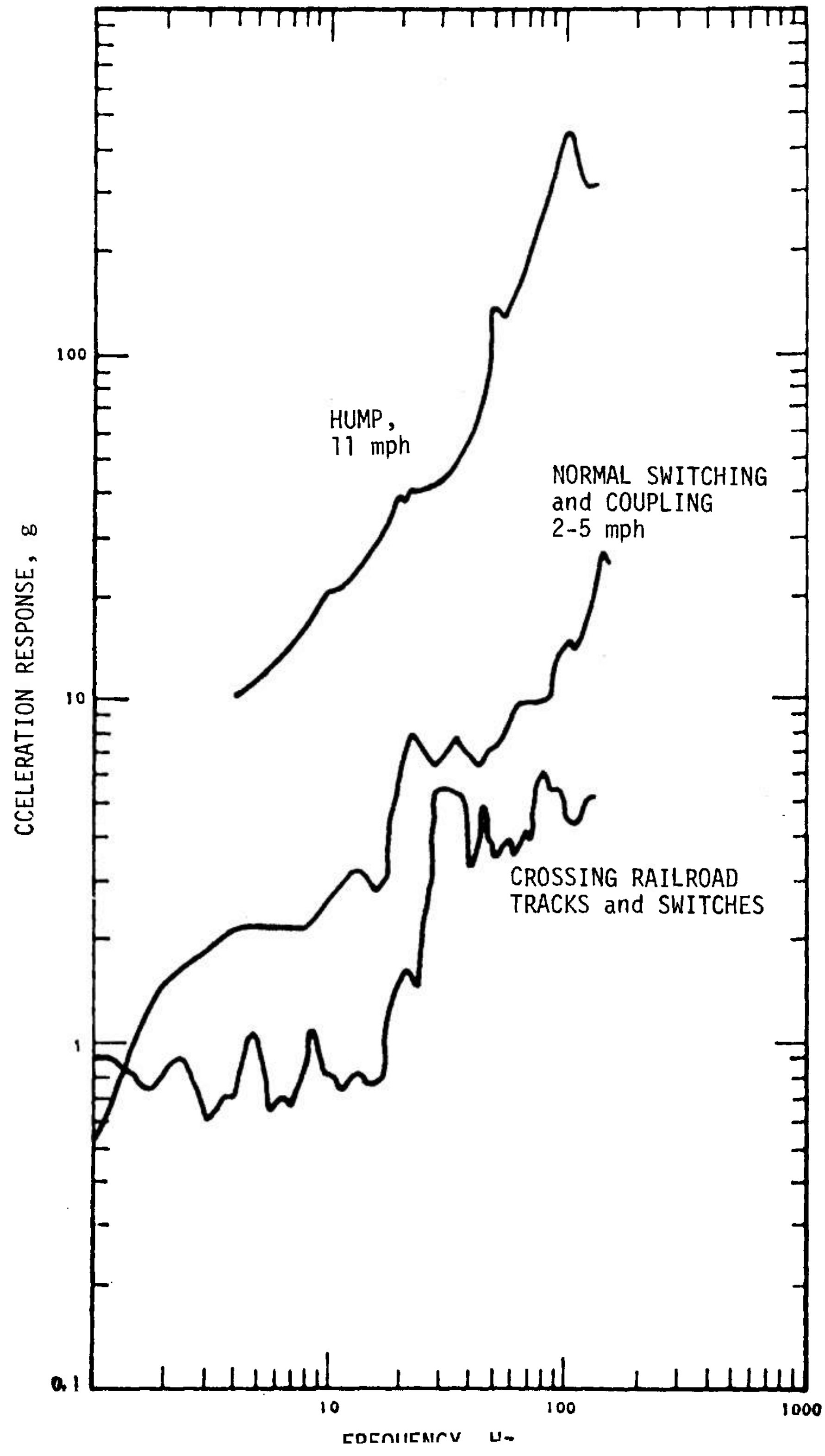


FIGURE 5-21. Rail Transport Shock Spectra (Ref. 23).

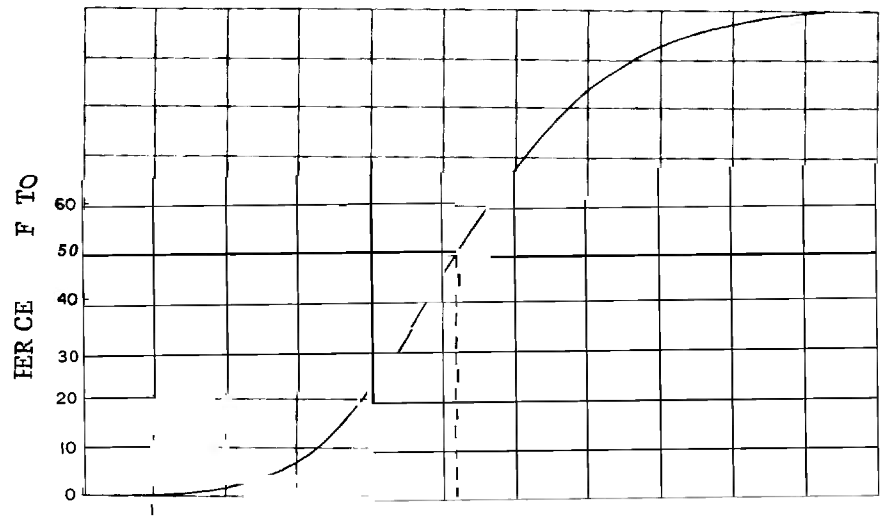
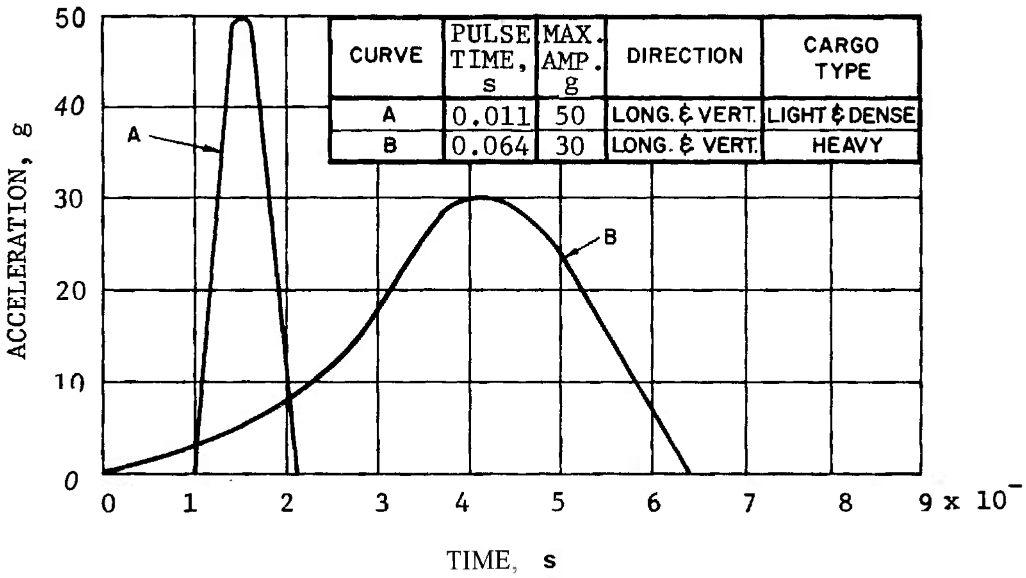


FIGURE 5-22. Field Survey of Impact Speeds (Cumulative Impacts) (Ref 7).



CURVE	PULSE TIME, s	MAX. AMP. g	DIRECTION	CARGO TYPE
A	0.011	50	LONG. & VERT.	LIGHT & DENSE
B	0.064	30	LONG. & VERT.	HEAVY

FIGURE 5-23. Cargo Environments for Rail Transport (Ref. 6).

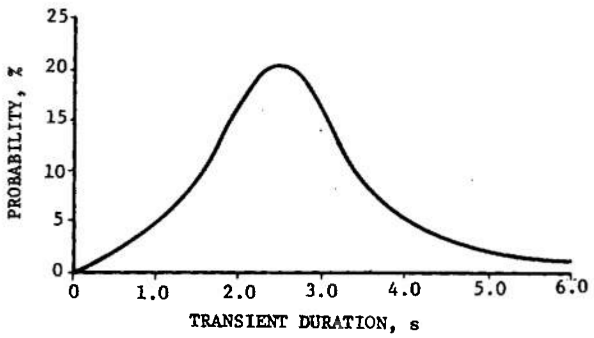


FIGURE 5-24. Duration of Transients, S-IV Transporter on Barge, Heavy Seas (Ref. 21).

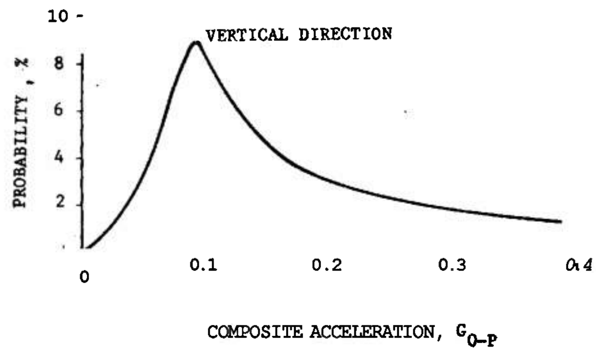


FIGURE 5-25. Transient Vibration Levels, S-IV Barge Deck, Heavy Seas (Ref. 21).

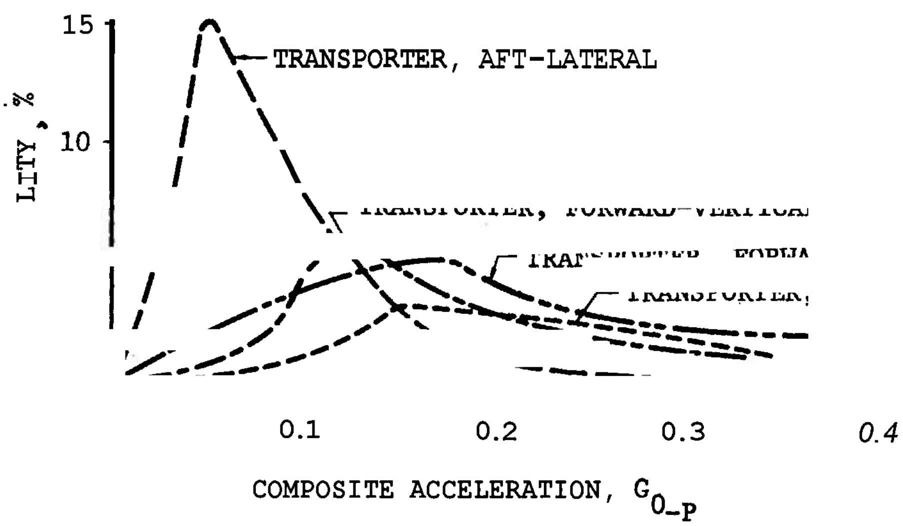


FIGURE 5-26. Transient Vibration Levels, S-IV Transporter on Barge, Heavy Seas (G_{O-P} = the acceleration in g measured from the baseline to the peak whether negative or positive) (Ret 21).

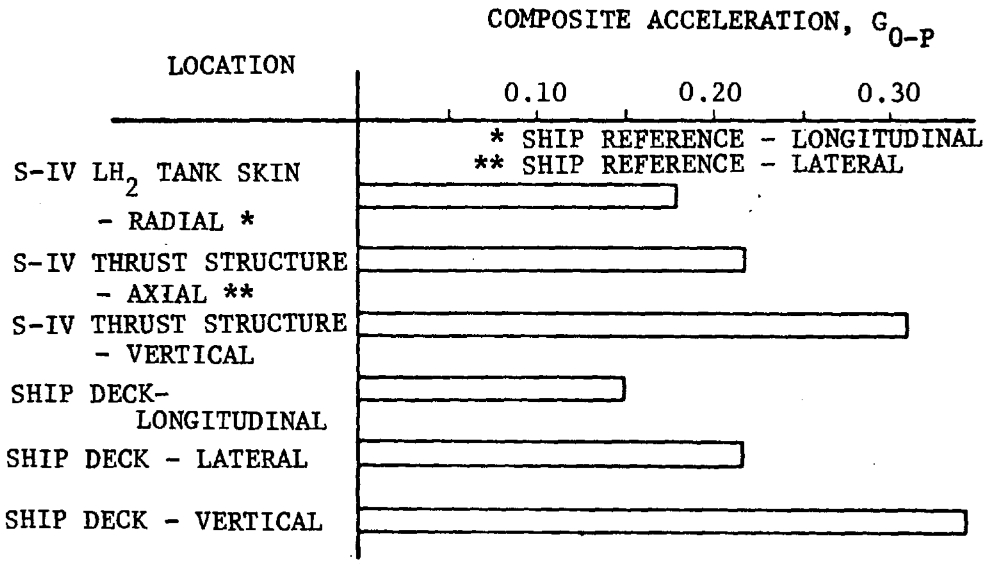


FIGURE 5-27. Maximum Acceleration Levels, S-IV Stage on Freighter (Ref. 21).

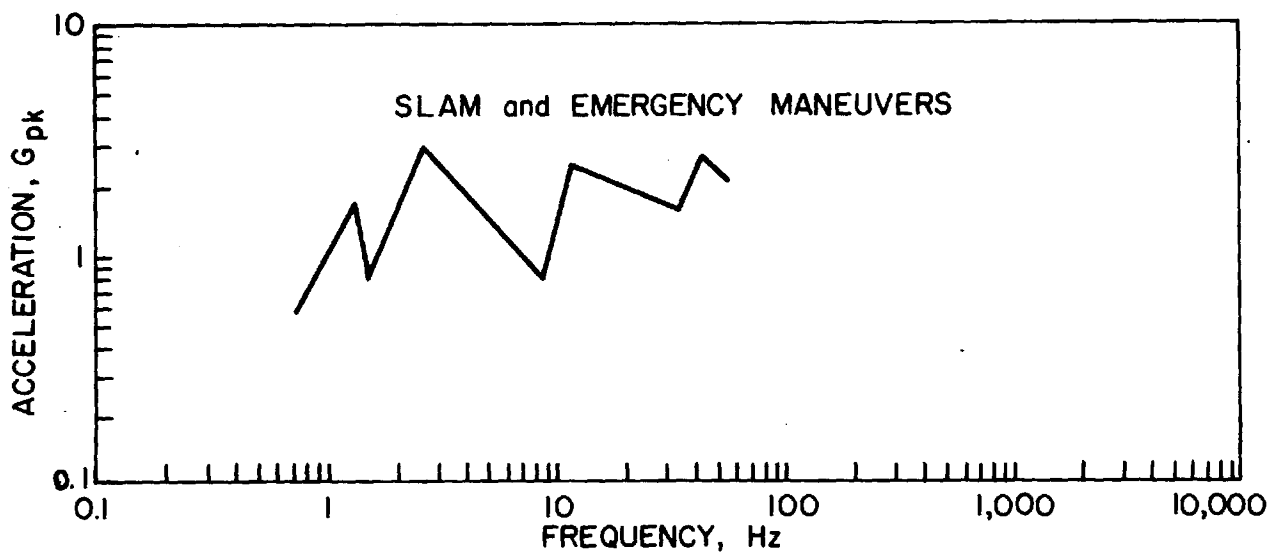


FIGURE 5-28. Ship Transient Acceleration Envelope (Ref. 8).

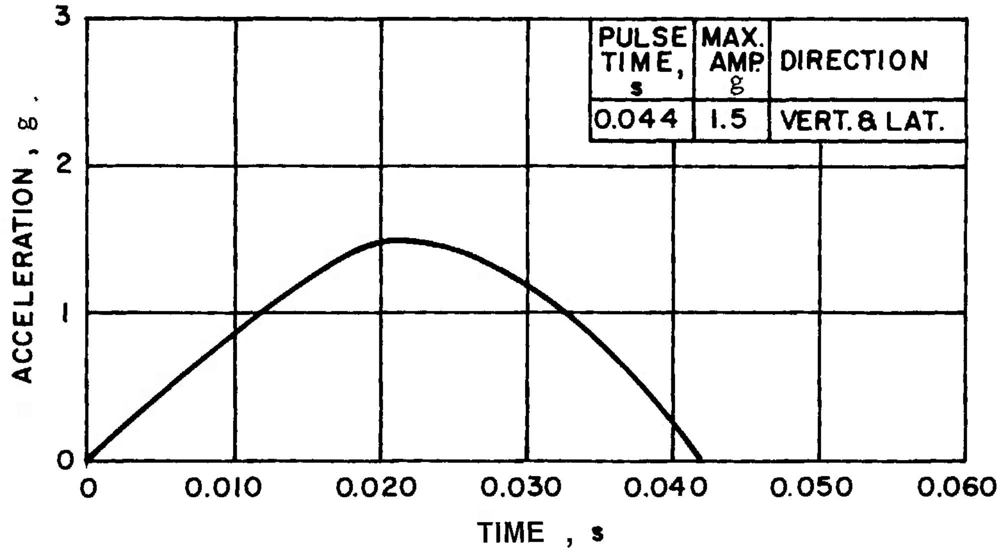


FIGURE 5-29. ***Cargo Environments for Sea Transport (Ref. 6).***

TABLE 5-5. USHAPED FLAT-BED TRAILER DATA

Station	Location of accelerometer*	Direction	Truck speed, mph	Road condition	Predominant fund. freq. Hz	Peak shock, g
1	Center of flat bed	Vertical	7	Ditches & potholes	2-5	1**
2	On wood near tire	Vertical	7			1
1			12			No signal
2			12			2
1			18			No signal
2			18			2.5
1			25			2.1
2			25			1.7

*The accelerometers remained in the same location for all tests.
**These data were obtained on a stretch of hard-packed-sand road, approximately 120 yd long, with a random distribution of ditches and potholes.

not shock excitations; however, since they are the maximum values measured, it may be assumed that there were no shock levels exceeding these values.

Fig. 5-28 was constructed by enveloping all available test data (up to 1966) pertaining to slamming and emergency operations. Some of the data may not have been recorded in cargo areas but should represent an upper limit for the cargo environment.

A time history envelope of the maximum ship shock environment as measured by the Transportation Corps is given in Fig. 5-29.

5-6.1.4 Highway

Lahood (Ref. 7) made shock and vibration measurements using two different types of Army trucks during a series of rough-road tests. One of the trucks was a 6-wheel conventional cab with a U-shaped flat-bed trailer (M390). The testing component was mounted on the trailer. The other was an M36 (10-wheel) truck. In both tests the cargo specimen was rigidly tied down by means of steel cables or chains.

The shock levels recorded on the flat-bed trailer as given in Table 5-5 are maximum values measured at the peak of one cycle. The measured waveforms are quasi-sinusoidal with the amplitude decaying to a negligible level in 5 to 10 cycles. Table 5-6 contains the data for the M36 Truck. The levels reported are averages of two cycles of vibration. Shock excitations measured on the M36 decayed to zero amplitude in two to four cycles.

Results from a series of tests, in which a 2-1/2-ton flat-bed truck was loaded with cargo consisting of a distributed-mass dummy mounted on an isolated pallet

TABLE 5-6. ARMY M36 TRUCK DATA

Station	Location of accelerometer*	Direction	Truck speed, mph	Road condition	Predominant fund. freq., Hz	±, g
1	Specimen floor, 2-3 ft left of CG	Vertical	25	Hard-packed sand-and-gravel road	1.5-3.5	0.3
2	Specimen floor, 2-3 ft right of CG	↓	↓	↓	↓	0.5
3	Specimen floor, CG	↓	↓	↓	↓	0.5
4	Truck bed, back end	↓	↓	↓	↓	0.6
1		↓	13	9-in. potholes	2.0-4.0	1.0
2		↓	↓	↓	↓	1.0
3		↓	↓	↓	↓	0.5
4		↓	↓	↓	↓	1.2
1		↓	14	Cobblestone hill	4.0-5.0	0.65
2		↓	↓	↓	↓	0.4
3		↓	↓	↓	↓	0.4
4		↓	↓	↓	↓	0.7
1		↓	36	8-in. x 8-in. x 4-ft wooden block under each wheel	2.0-7.0	1.0
2		↓	↓	↓	↓	1.0
3		↓	↓	↓	↓	1.0
4		↓	↓	↓	↓	1.4
1		↓	35	Railroad track	2.0-4.0	1.4
2		↓	↓	↓	↓	0.9
3		↓	↓	↓	↓	1.1
4		↓	↓	↓	↓	0.8
1		↓	40	Railroad track	2.0-4.0	1.1
2		↓	↓	↓	↓	0.9
3		↓	↓	↓	↓	1.0
4		↓	↓	↓	↓	0.7

*The accelerometers remained in the same station location for all tests.

with piezoelectric transducers located ahead of and behind the truck/load interface on main members of the truck bed, are reported by Foley (Ref. **24**). The cargo was tied down with chains so that the shock response of the truck bed would be the shock input to the cargo. Several environments were sampled. Four events sufficiently transient to warrant analysis in terms of shock spectra were (1) backing into loading docks, (2) crossing railroad tracks at low and high speeds, **(3)** crossing a cattle guard at high and low speeds, and **(4)** hitting potholes at high speed. Figs. 5-30 through **5-33** give the acceleration time history of each event and the associated shock spectrum. The shock spectra are the response spectra of single-degree-of-freedom systems with critical damping ratios of 0.0, **0.03**, and 0.10, respectively. Foley interprets the damping ratios as follows: the 0.0 damping spectrum represents the upper limit of response severity, the 0.03 spectrum is an estimate of the response severity produced on nonisolated cargo systems, and the 0.10 spectrum is an estimate of the response severity produced on isolated or cushioned cargo systems.

In all instances the vertical shocks were the most severe, with the one exception being that of backing into the loading dock, in which case shocks along the longitudinal axis were the most severe. One of the conclusions drawn from the test results is that the location of the cargo on the truck bed has a significant effect on the severity of vertical inputs, with cargo located directly above or near the rear wheels experiencing the most severe excitations. Location has no effect on longitudinal shock levels.

Fig. 5-34 gives the maximum shock spectra as measured at three different positions on a van during a cross-country shipment. The most severe shocks were recorded at the aft position with the maximum value being about 4 G.

An envelope of maximum shock excitations recorded during field studies conducted by the Transportation Corps is given in Fig. **5-35.** No explanations of the test conditions or equipment were given.

5-6.2 HANDLING

A comprehensive literature survey and search of the cargo-handling shock environment was conducted by Ostrem, who published a summary in 1968 (Ref. 11). Over 150 reports and articles were reviewed, and over ***50*** organizations were contacted during the conduct of the project. Much of the data presented herein is from that report. The original publications are referenced by Ostrem and are not repeated here. His findings are summarized as follows:

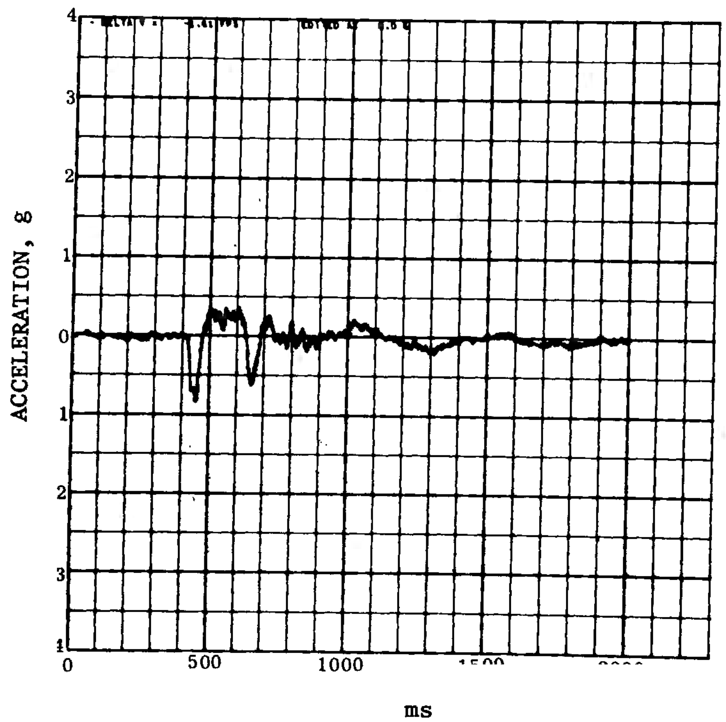
(1) Peak ***accelerations.*** Thirty-three shipping containers of various shapes and weights, instrumented with Impact-O-Graph[3] accelerometers, were shipped by air, truck, and ship within a radius of 200 mi of Washington, D.C. The results, given in Table **5-7** as peak accelerations, show that the smaller containers (60 to 90 lb) experienced the largest peak accelerations. Fig. **5-36** shows the maximum shocks recorded during a test shipment involving many handling operations and different modes of transport. Both longitudinal and vertical shocks were monitored by using two impact recorders. The test specimen was a wooden box having a total weight of 73 lb. Results from this test show clearly that shock excitations recorded during handling operations are much more severe than those encountered during transport by air or road.

*(2) **Drop heights.*** Drop height distributions have been developed for various package weights and configurations, handling operations, and distribution systems.

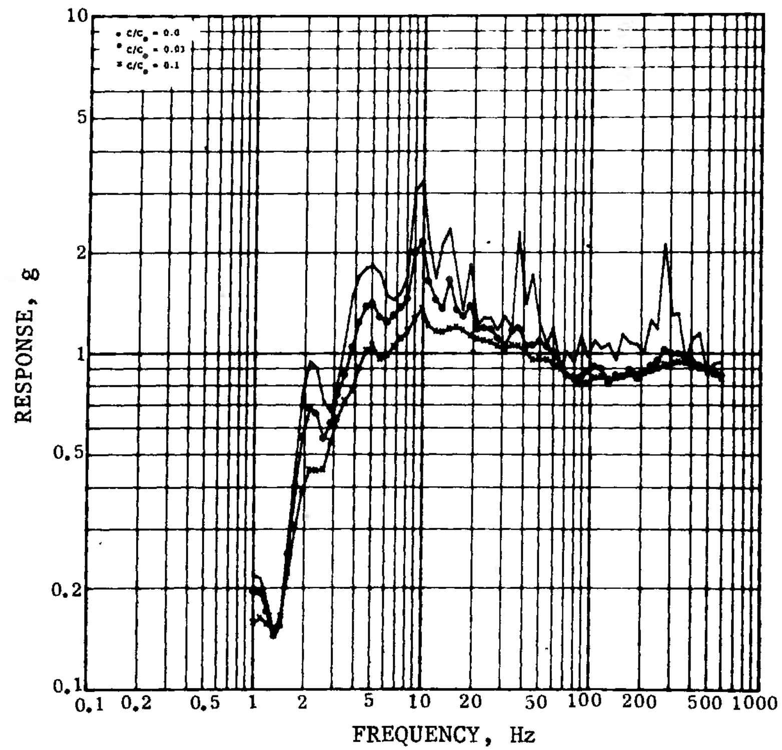
Results from a series of tests involving the shipment of 43-lb plywood boxes via Railway Express and air freight are given in Fig. 5-37. The tests were conducted by the Wright Air Development Center, Wright-Patterson AFB, Ohio, and involved 13 boxes, each instrumented with an Impact-O-Graph accelerometer. From a total of 862 recorded drops, 5 percent were from heights greater than 21 in. and 50 percent were above 8 in. A somewhat similar test was conducted by the Packaging and Allied Trades Research Association, Surrey, England, whereby instrumented fiberboard boxes weighing 22 lb were shipped by railroad in mixed-goods consignments. The results from 1,479 recorded drops showed that 5 percent were greater than 20 in. and 50 percent were above 6 in.

Fig. **5-38** demonstrates the effect of horizontal loading distance on drop height. These data were obtained from observational studies. Curve 1 represents the handling procedure for transferring packages from a conveyor to a handcart. Data were taken only during the loading of the first layer on the extreme end of the cart. Curve 2 represents the less severe handling procedure for transferring packages from a railroad car to a handcart. As before, the packages loaded on the bottom layer received the highest drops, and were the only ones

3. **Impact-0-Graph is a trademark of the Impact-0-Graph Corporation.**

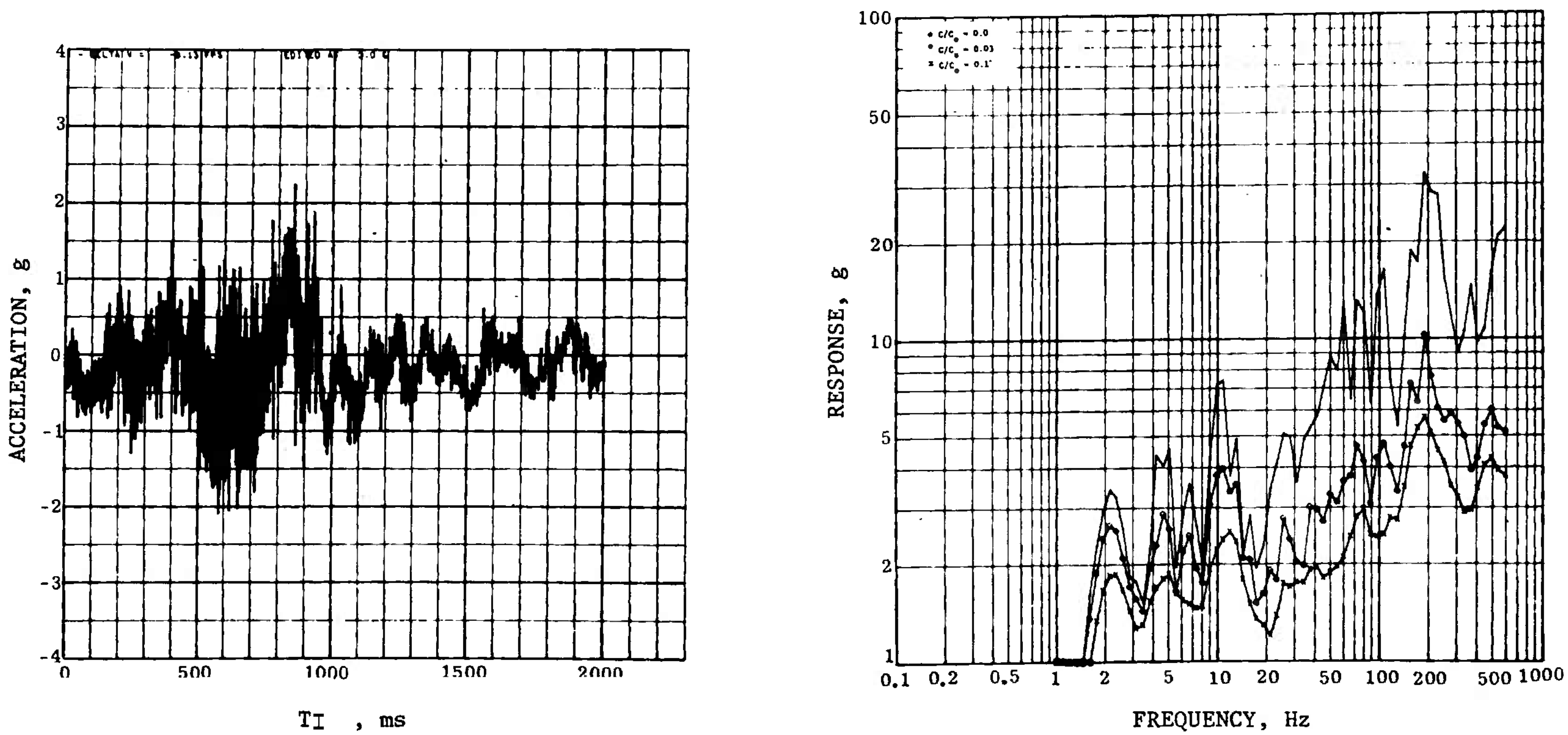


(A) Acceleration time history



(B) Shock spectrum

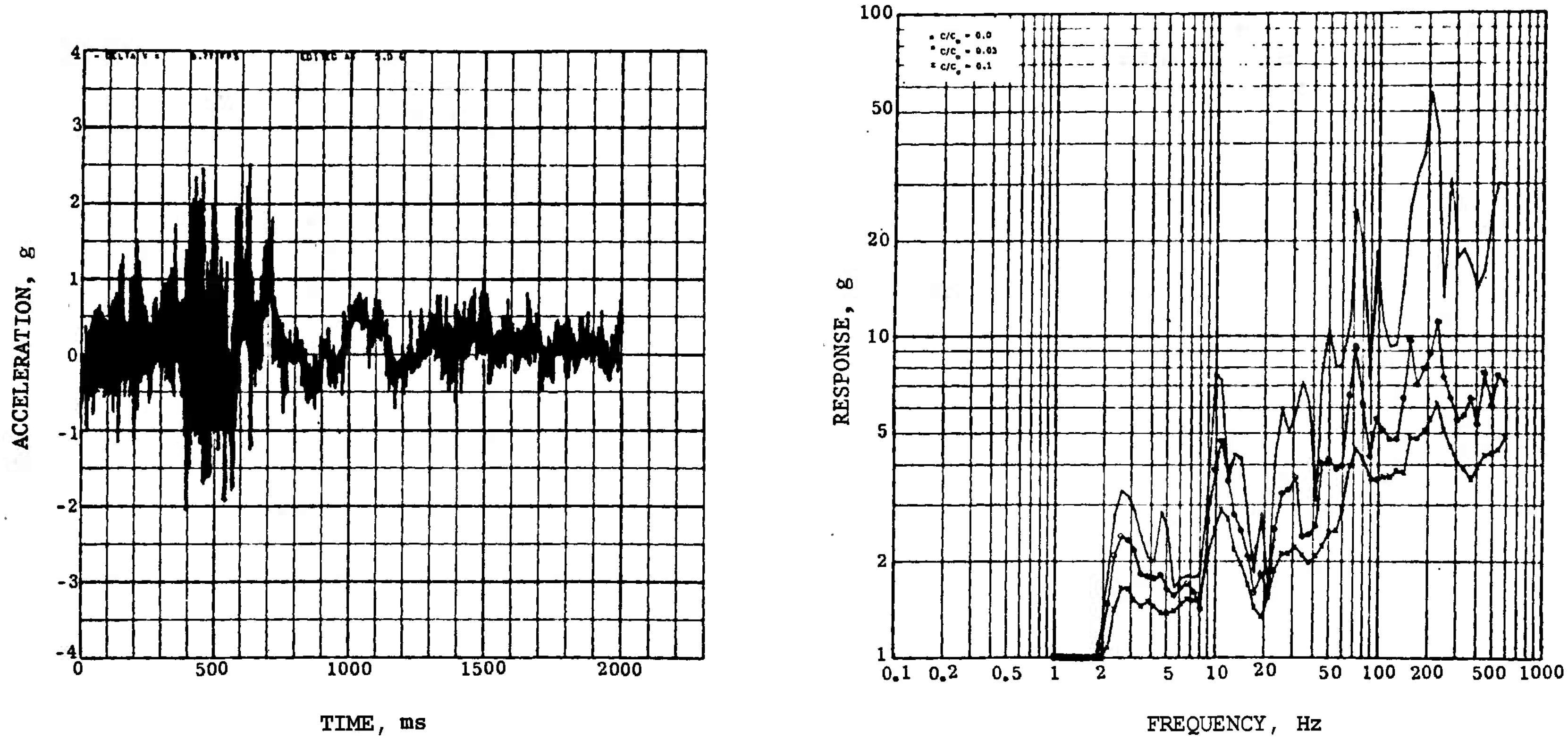
FIGURE 5-30. Shock Data--Truck Backing Into Loading Dock, Longitudinal, Forward on Truck Bed (Ref. 24).



(A) Acceleration time history

(B) Shock spectrum

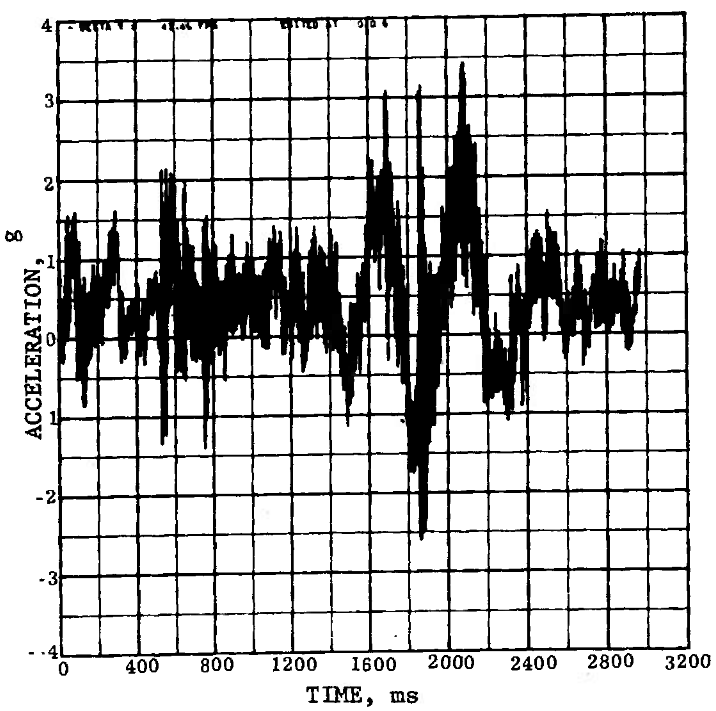
FIGURE 5-31. Shock Data--Truck Driving Across Railroad Tracks at 45 mph, Vertical, Aft on Truck Bed (Ref. 24).



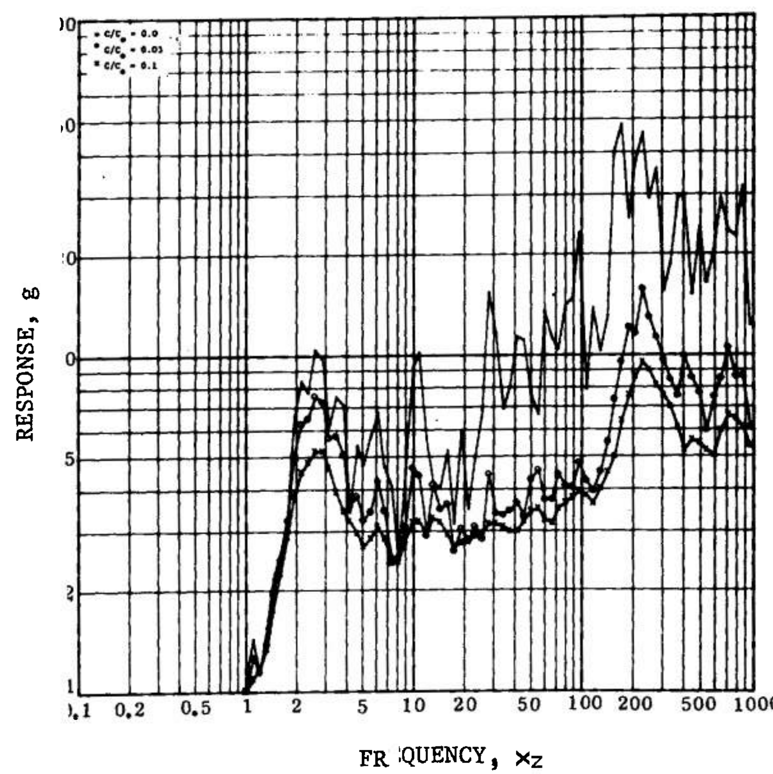
(A) Acceleration time history

(B) Shock spectrum

FIGURE 5-32. Shock Data--Truck Driving Across Cattle Guard at 45 mph, Vertical, Aft on Truck Bed (Ref 24).



(A) Acceleration time history



(B) Shock spectrum

FIGURE 5-33. Shock Data--Truck Driving Across Potholes at Truck Stop, Aft on Truck Bed (Ref. 24).

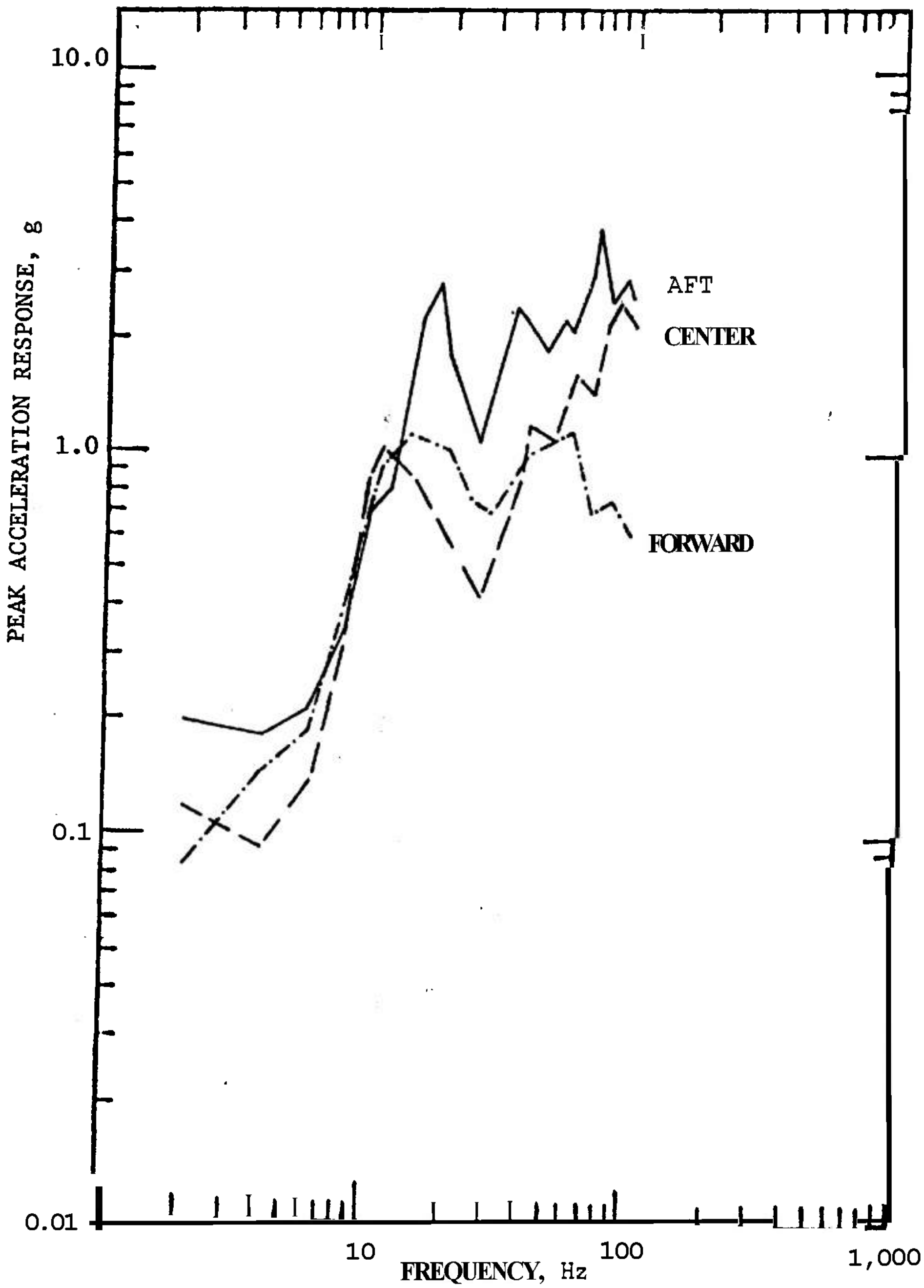


FIGURE 5-34. Maximum Shock Spectra for Various Shocks Encountered During a Cross-country Shipment, Van, Air Ride Suspension (Ret 25).

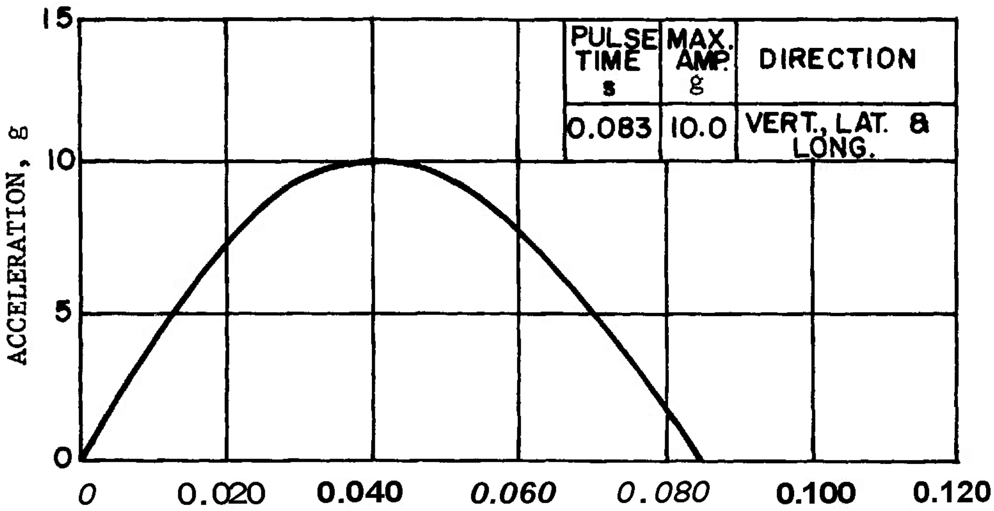


FIGURE 5-35. Cargo Shock Environments for Highway Transport (Ref. 6).

recorded. All observations for Curve 1 and Curve 2 were made at two transfer points in a large railroad depot where express freight weighing less than 80 lb is handled.

Drop height as a function of package weight for the handling operation of loading a handcart from a conveyor is indicated in Fig. 5-39. The maximum drop height recorded was 24 in. for a 2-lb package. The data show that, in general, drop height decreases with an increase in package weight.

The effect of package height on drop height is shown in Fig. 5-40. These results apply to the same handling operation as described in the previous paragraph. The data show that drop height decreases with an increase in package height.

(3) Number of drops. Shock damage to cargo items can be cumulative; therefore, a knowledge of the number of drops at different heights that an item is likely to encounter may be as important as the knowledge of maximum drop heights. Figs. 5-41 and 5-42 show the number of drops above different heights for boxes shipped via Railway Express and by rail, respectively, as mixed goods. Data for Fig. 5-41 were taken from the same tests as described for Fig. 5-37. Fig. 5-42 was constructed from data obtained by the shipment of instrumented, 22-lb, fiberboard boxes by rail as mixed goods. These results show that 10 percent of the 43-lb boxes experienced at least 30 drops of 3 in. or higher and approximately 3 drops of 24 in. or higher. In con-

TABLE 5-7. CARGO-HANDLING FIELD TEST RESULTS: PEAK ACCELERATION, g (Ref. 11)

Container shape	Container weight, lb			
Length: width: height,	Small, 60-90	Medium, skid-mounted, 150-250	Medium, skid-mounted, 250-500	skid-mounted, 500-1,500
Average (?:2:2)	3-144 (41)	4-131 (31)	3-24 (14)	3-43 (21)
Long (3:1:1)	4-50 (30)	3-38 (20)	4-35 (19)	3-14 (18)
Tall (1:1:2)	3-76 (29)	3-41 (22)	3-50 (17)	3-17 (9)

Data presented are ranges, followed by means (in parentheses).

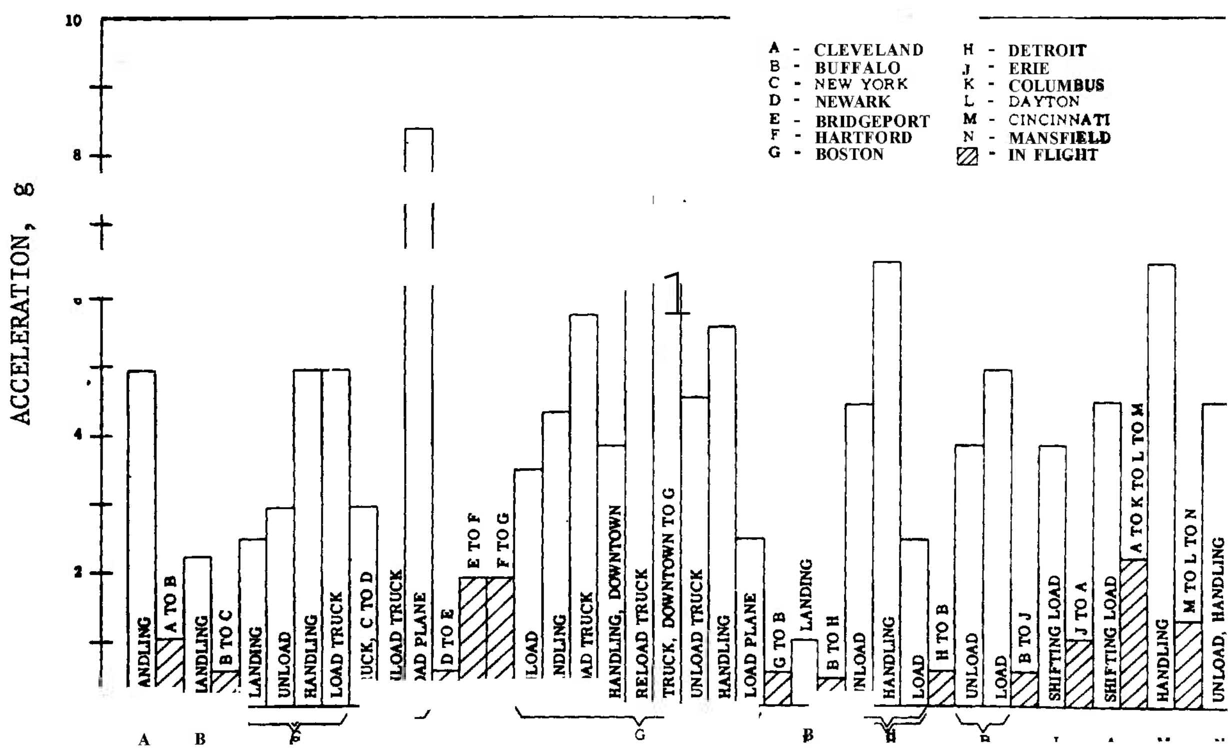


FIGURE 5-36. Maximum Shocks Recorded During Airline Test Shipment (Ref. 26).

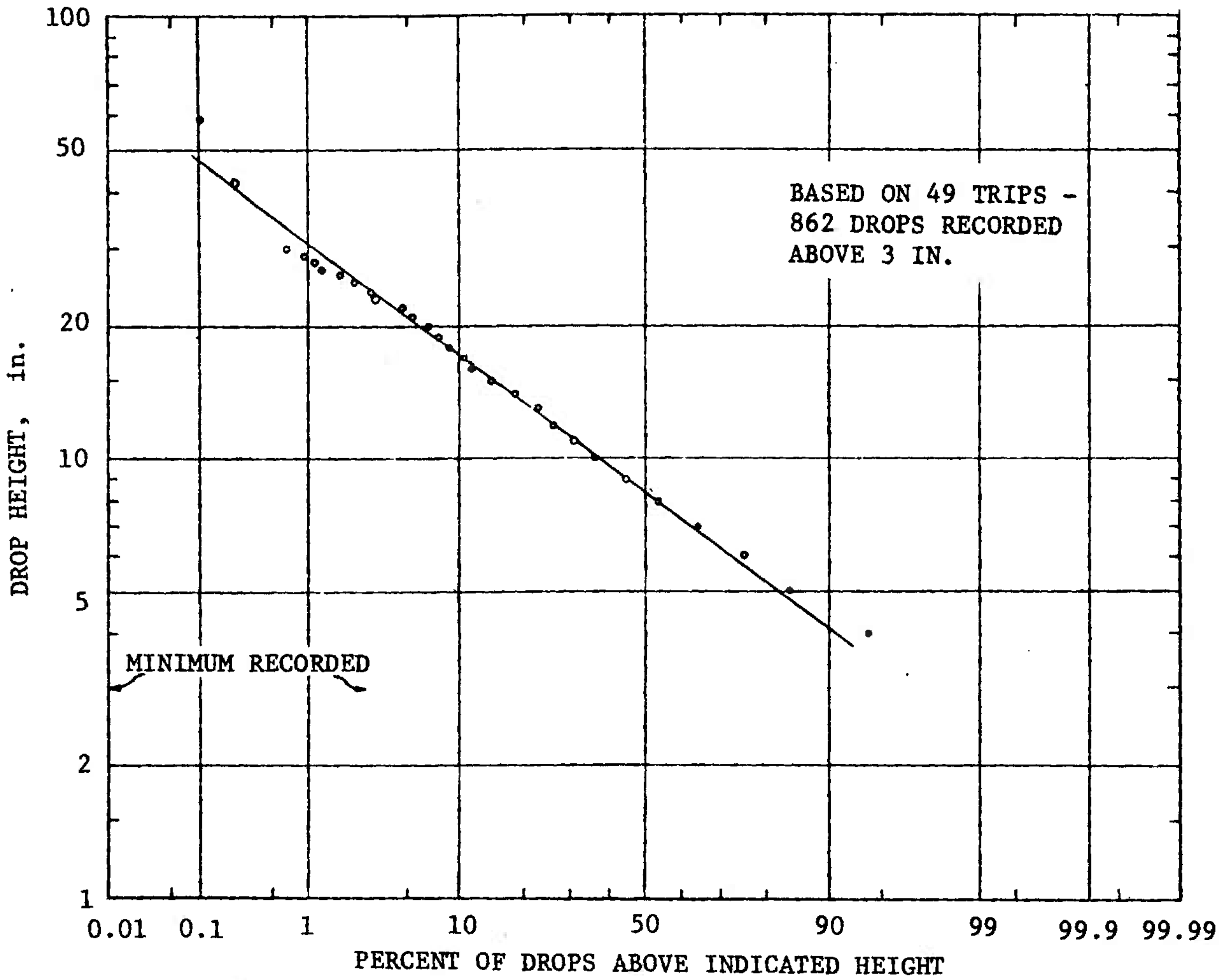


FIGURE 5-37. Drop Height Distribution Cubical Cleated Plywood Box Sent by Railway Express (43-lb, 19 x 19 x 19 in.) (Ref. 11).

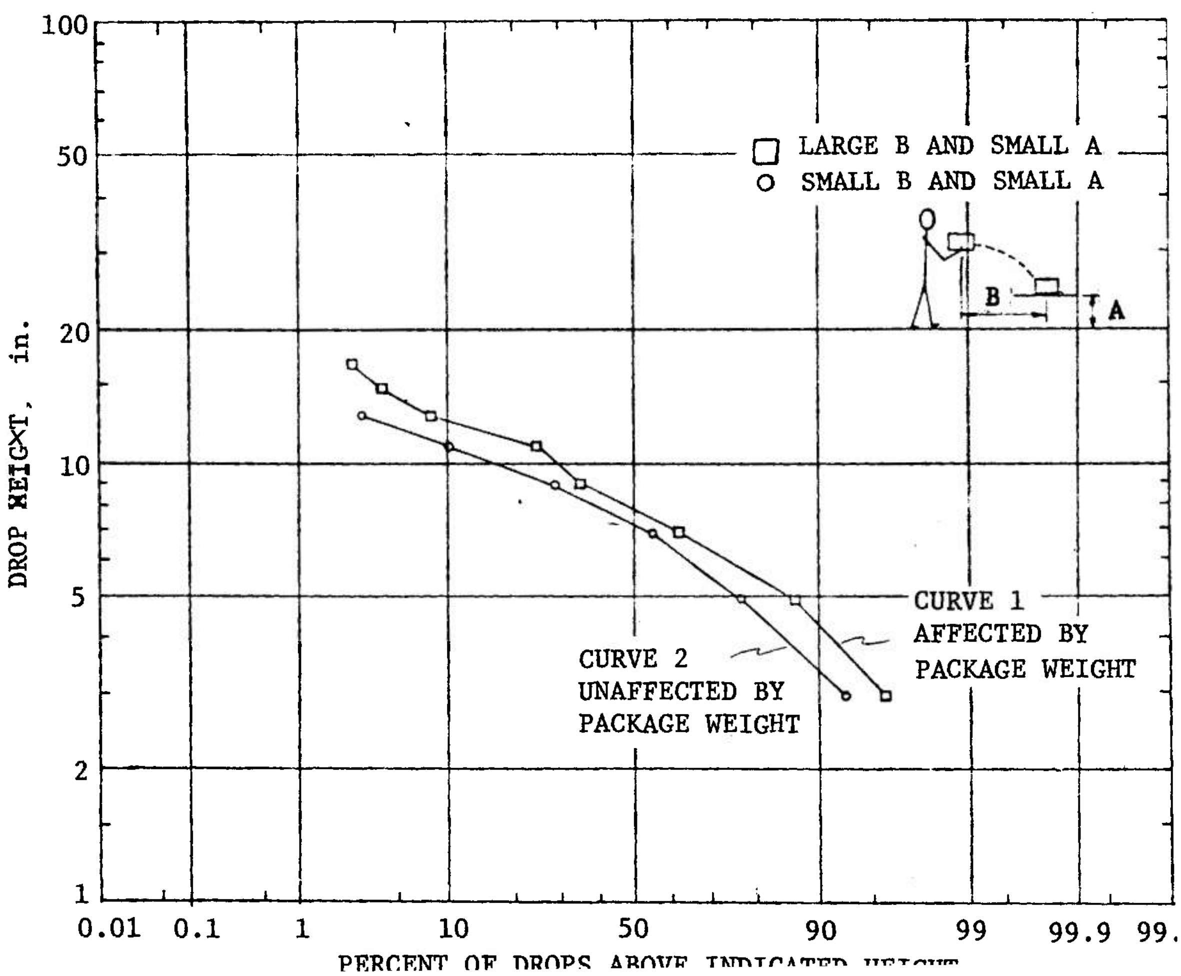


FIGURE 5-38. Drop Height Distribution, Railroad Depot Loading Operation, Severest Handling Operation (Ref. 11).

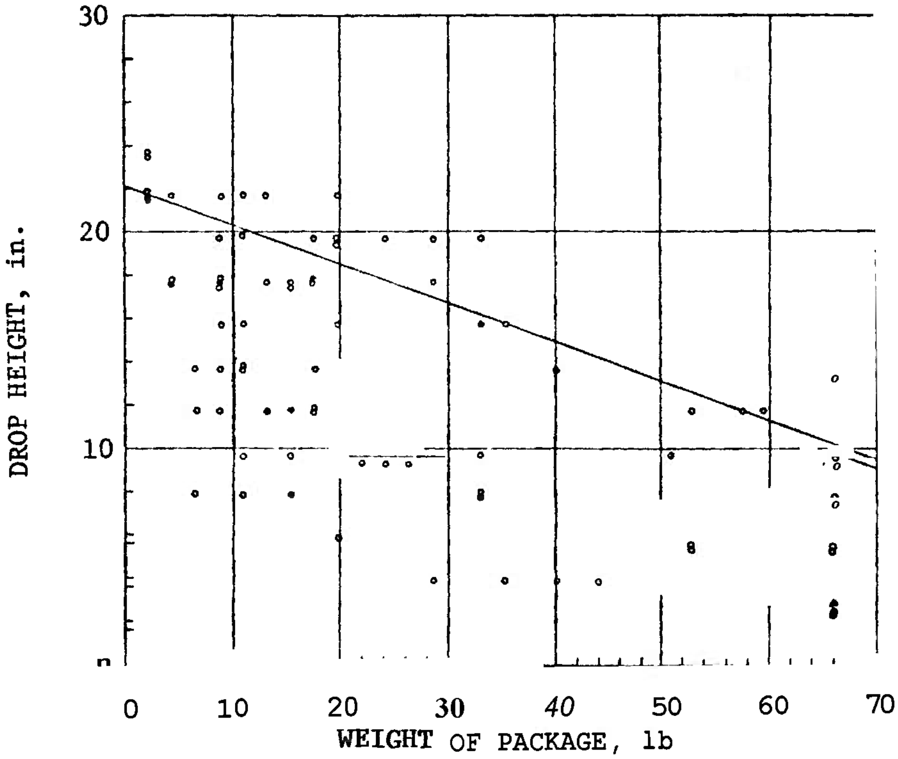


FIGURE 5-39. Drop Height vs Package Weight, Railroad Depot, Severest Handling Operation (Ref. 71).

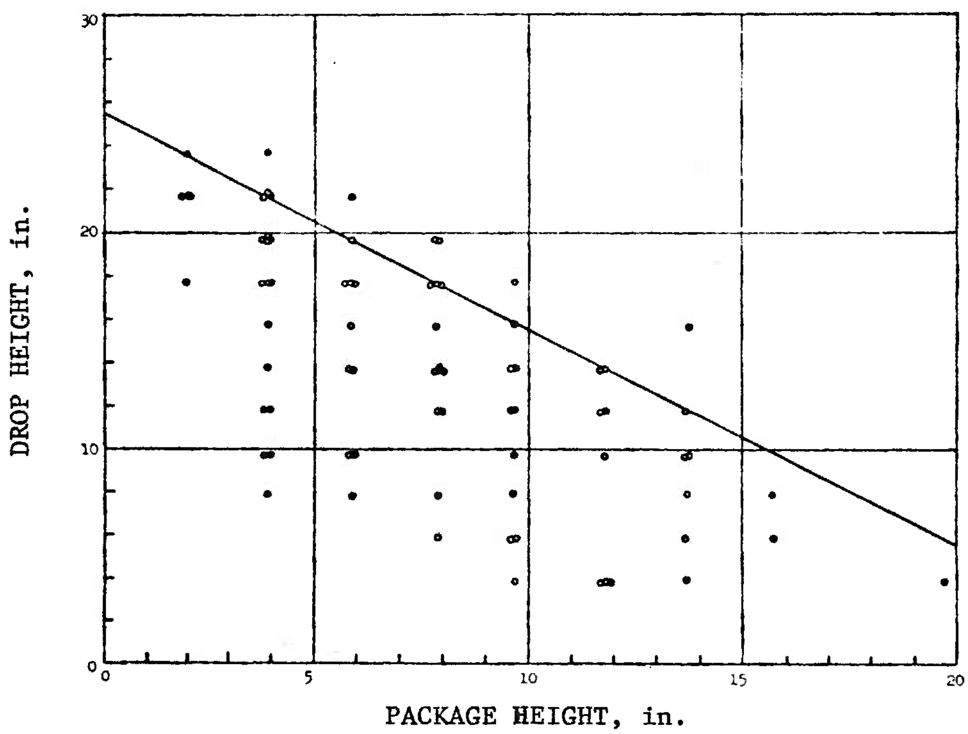


FIGURE 5-40. Effect of Package Height on Drop Height, Railroad Depot, Severest Handling Operation (Ret 71).

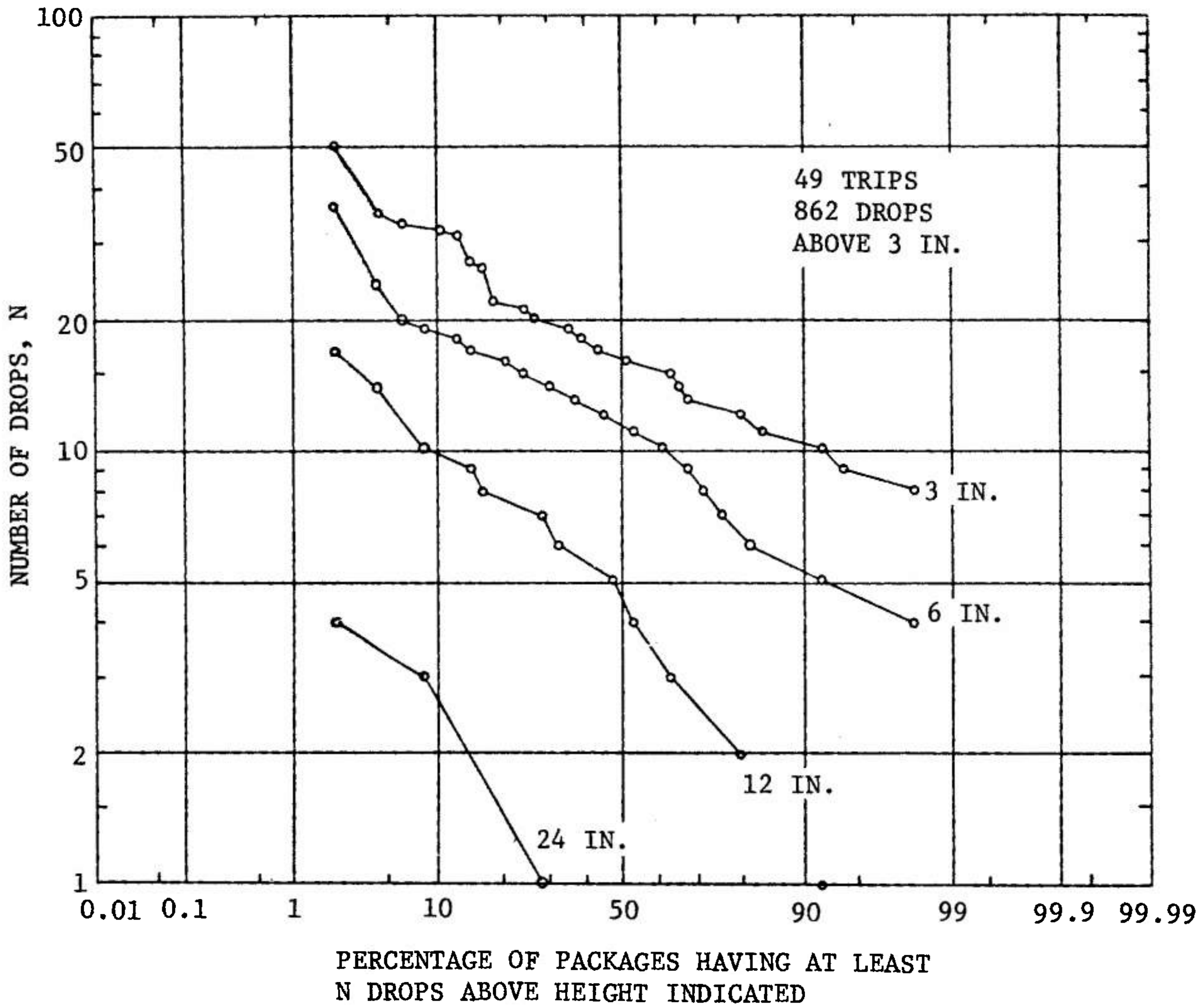


FIGURE 5-41. Number of Drops by Drop Height of Package Sent by Railway Express (Mixed Goods) (43-lb Cleated Plywood Box, 79 x 19 x 19 in.) (Ref. 11).

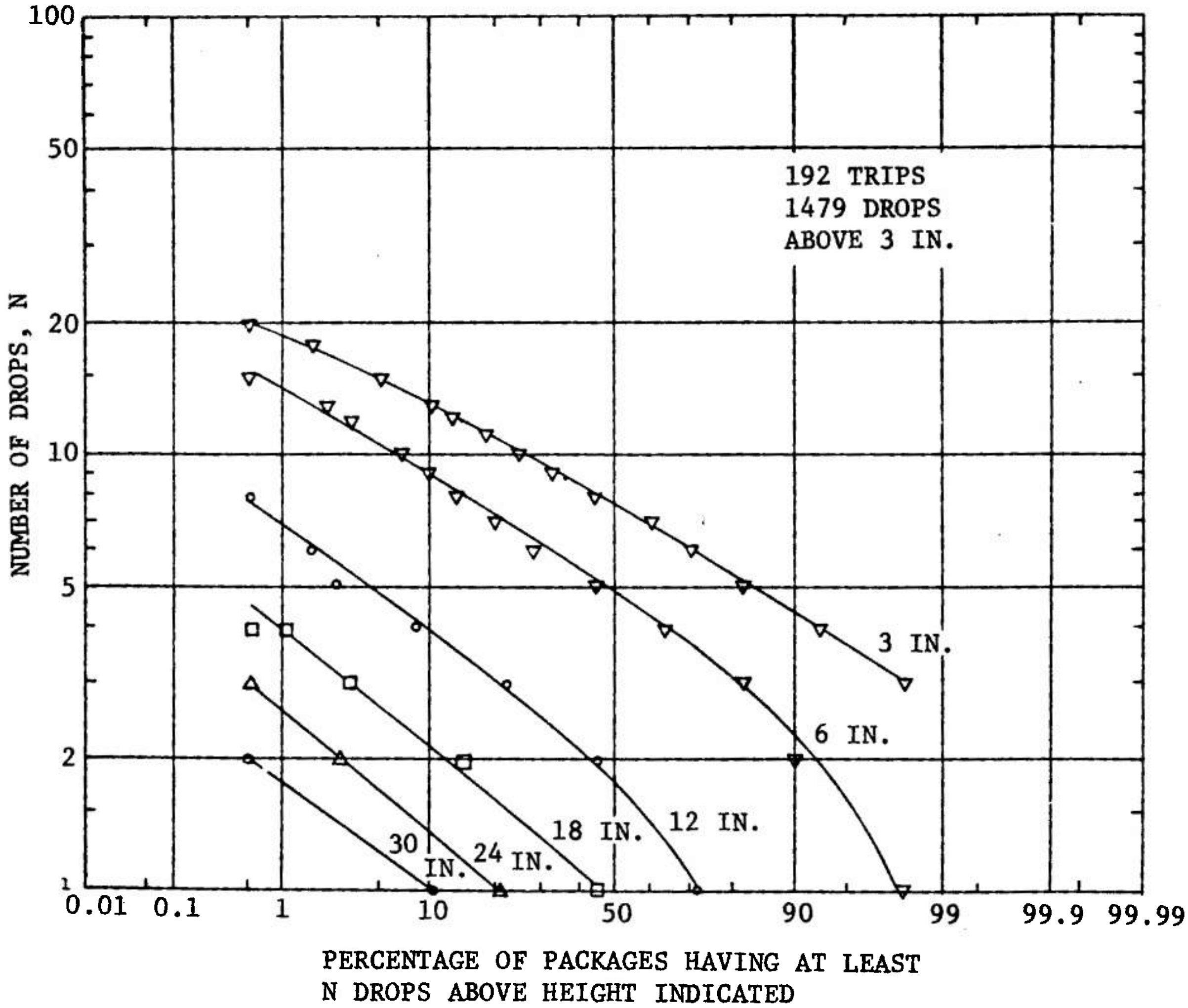


FIGURE 542. Number of Drops by Drop Height of Package Sent by Rail (Mixed Goods) (22-lb Corrugated Fiberboard Box, 17.5 x 12 x 11.5 in.) (Ref. 11).

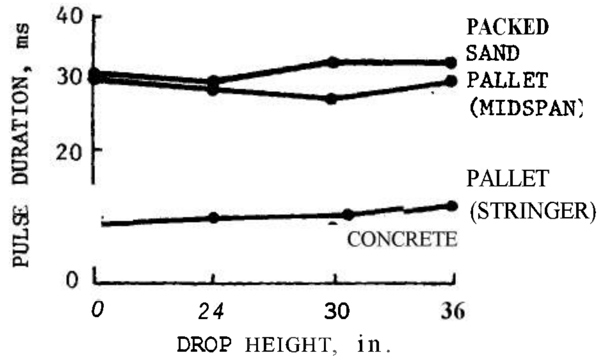


FIGURE 5-43. Impact Pulse Durations for Container Corner Drops on Typical Stacking Surfaces (Ref. 27).

trast, 10 percent of the 22-lb boxes received fewer than 15 drops higher than 3 in. and fewer than 2 drops above 24 in.

(4) Shock pulse duration. In designing against shock damage to certain types of equipment, both the magnitude and duration of the shock excitation are important. Fig. 5-43 shows the pulse duration for container corner drops from several drop heights and for different impact surfaces. Fig. 5-44 shows the results of flat drops on different impact surfaces. The results in both cases show that the pulse duration is practically independent of drop height. It is, however, very sensitive to the type of impacting surface. Corner drops are characterized by much longer pulse durations than are flat drops. The longest pulse duration, approximately 31 ms, was recorded for a corner drop on packed sand. The test container used in this study weighed 45 lb and measured 16-1/4 X 12-3/16 X 9-3/8 in.

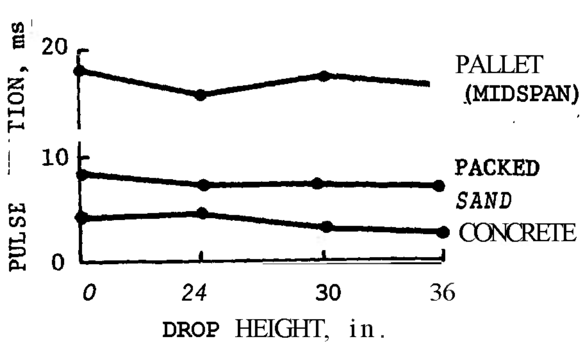


FIGURE 5-44. Impact Pulse Durations for Container Flat Drops on Typical Stacking Surfaces (Ref. 27).

5-6.3 STORAGE

Handling operations characteristic of the storage environment are probably the source of the most severe shocks encountered in this environment. Although there were no data pertaining to the storage environment per se, it seems evident that the severity of the shocks resulting from the normal handling activities of storage would be on the same order of magnitude as those reported for the handling environment. Many operations-such as loading a handcart or forklift truck from a stack of packages, railroad car, or truck-are common to both environments.

Until more definitive data are available for the storage environment, it is recommended that the handling environment data be used as a guide for design requirements.

5-6.4 SERVICE

Data are not available for defining the service environment. The shocks are those received as a result of drops or bumps during servicing on the work bench. Also, in cases where the piece of equipment has to be transported across base or over short distances for repair, the shock levels encountered would be related to the particular mode of transport employed. Under these conditions the equipment would in all probability be insufficiently packaged or protected from shock forces.

Shocks encountered on the work bench would probably be no more severe than a 2- to 3-in. comer drop. When the equipment is transported over short distances from its operational station to the repair facility, the unpackaged equipment that is placed unrestrained in the back of a small truck may be representative of the worst case conditions.

5-7 MEASUREMENTS

5-7.1 GENERAL

The need for accurate and reliable shock data has increased greatly in recent years. This increase is a direct consequence of the increased mobility of the field army and the increased use by the Army of fragile and sensitive materiel.

The measurement of shock forces involves measuring the position, velocity, or acceleration of a point on the test item as a function of time. Devices used for making such measurements range from a purely mechanical system that indicates the resulting motion by means of a mechanical pointer, to transducers that provide a usable electrical output in response to a specific stimulus. The type of transducer most commonly used in shock measurements is electromechanical, i.e., one that converts the energy of mechanical motion into electrical energy (Ref. 28).

Although shock excitations and response can be described in terms of velocity, displacement, or force, the vast majority of measurements are made of acceleration as a function of time. The shocks that are encountered vary from less than 1 G to several thousand G with durations of from a few to over 100 ms (Ref. 29). This wide dynamic range makes it difficult to have a single measuring system capable of recording all the shock encountered by an item of cargo during intermodal transport, for example. The transducer most often used because of its wide dynamic range and high natural frequency is the piezoelectric accelerometer. If frequencies above about 400 Hz are of interest, the piezoelectric accelerometer nearly always is used (Ref. 2).

5-7.2 ACCELEROMETERS

An accelerometer is a transducer whose output quantity varies in proportion to the acceleration that it experiences. A seismic system consisting of a mass suspended from a base by a spring and usually constrained to move in only one direction is employed in accelerometers as the sensing element (Ref. 2). In the operating frequency range of the transducer, which is below its resonant frequency, the mass undergoes nearly the same acceleration as the body of the transducer. The mass exerts a force on the support that is directly proportional to the magnitude of the component of acceleration, and the output is a known function of the force. The types of accelerometers most generally used for shock measurements are described in the paragraphs that follow.

5-7.2.1 Piezoelectric Accelerometers

Piezoelectric (crystal) accelerometers utilize the ability of certain crystalline materials to generate electrical charge motion when subjected to mechanical stress. These piezoelectric materials contain crystal domains comprising electric dipoles oriented either by natural or artificial polarization. The slight relative motion of these domains, resulting when a load is applied, causes a charge flow to be generated. The material, under a varying load, functions electrically as a charge-generating capacitor. One type of crystal accelerometer consists of a seismic mass compressed between a spring and a wafer of piezoelectric material. The inertial force experienced by the mass causes a proportional change in strain within the crystal. This change in strain causes an electrical potential to be developed across the crystal in proportion to the inertial force or acceleration experienced by the mass. The compression spring is preloaded in such a way that the crystal wafer is always maintained in compression. The resulting mechanical system exhibits a high resonant frequency and virtually no damping. A typical crystal accelerometer is shown in Fig. **5-45.**

Crystal accelerometers are available with or without an electrically isolated case. Some models are constructed with the seismic mass compressed between two crystal elements. Accelerometers of improved design, with the crystal bonded to a button- or mushroom-shaped mass, avoid the influence of case distortion.

Due to the high resonant frequency (on the order of 30 kHz) of crystal accelerometers, they are well suited for the measurement of both vibration and shock. They can be used to measure shock on the order of 10,000 G (peak) and sinusoidal vibration up to 1,000 G (peak). Instrumentation for shock measurement usually includes low pass filters to avoid falsification of data by "ringing" at resonant frequencies. Some progress has been made in the damping of piezoelectric accelerometers. This decreases the ringing and extends the linear frequency response. The range of linear frequency response ($\pm$5 percent) is on the order of 10 Hz to 10 kHz. The operational temperature range of crystal accelerometers is approximately $-67°$ to 500°C. However, models that will operate down to -220°C and measure

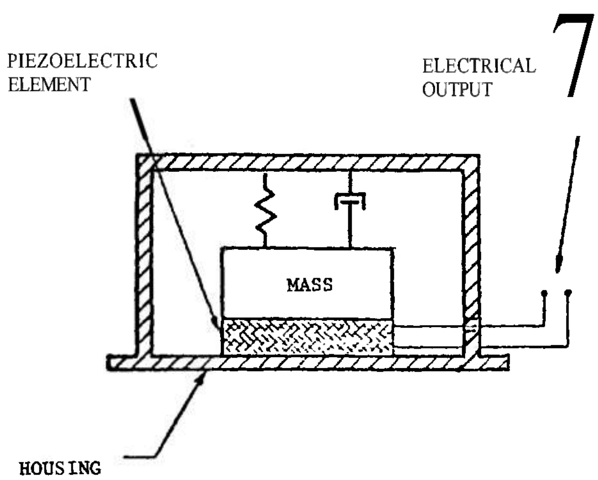


FIGURE 5-45. Piezoelectric (Crystal) Accelerometer (Ref. 30).

the motion of surfaces at temperatures to +2,200°C using liquid cooling are available. Instruments designed for extreme temperature environments are generally supplied with calibration curves obtained at various temperatures.

5-7.2.2 Strain Bridge Accelerometers

The electrical resistance of a wire increases when it is stretched, and decreases when it is compressed axially or when an initial tension is relieved. The operation of strain bridge accelerometers is based upon this principle. One type of bridge accelerometer consists of a mass suspended by a strain wire spring and a damper. The inertial force experienced by the mass when it is accelerated induces a change in the strain on the supporting wires, and thus a change in their electrical resistances. Damping of the strain bridge accelerometer varies somewhat with temperature. The accelerometer case is generally filled with a viscous fluid that constitutes the damping medium. If part of the damping fluid is lost, the decrease in damping can be detected by measuring the frequency response. This response will be peaked at the resonant frequency when damping is low. Since the electrical circuit is passive, it must be powered externally. The power supply can be either a direct current or an alternating current source. To obtain adequate sensitivity, the strain wires are arranged electrically in the form of a Wheatstone bridge. The bridge is balanced externally. The electrical unbalance of the bridge circuit is then proportional to the acceleration experienced by the instrument. An illustration of a strain bridge accelerometer is shown in Fig. 5-46.

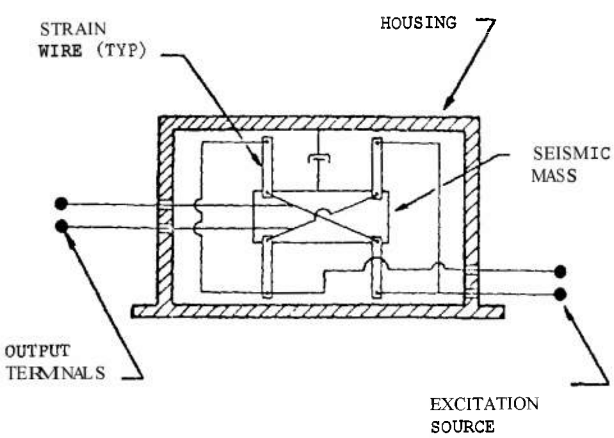


FIGURE 5-46. Strain Bridge Accelerometer (Ref. 30).

Unlike crystal accelerometers, the strain bridge type can be used to measure low acceleration levels at frequencies down to zero. The relatively low natural frequency of strain bridge accelerometers (on the order of 500 **Hz**) limits the frequency range of linear response (±5 percent) to approximately 0 to 300 **Hz.**

These instruments are generally used for measuring accelerations to approximately 2,000 G (peak). Strain bridge accelerometers can be used for low-level shock measurement when high frequency information is not desired. The higher frequencies will be mechanically attenuated by the instrument. Strain bridge accelerometers, calibrated over a temperature range of approximately −65° to +250°F, are available.

5-7.2.3 Potentiometer Accelerometers

The potentiometer accelerometer consists of a mass-spring-damper system and a potentiometer circuit (Ref. 31). The potentiometer wiper is connected to the seismic mass. A constant voltage is maintained across the resistance element of the potentiometer. When the instrument experiences an acceleration, the mass is displaced, causing a proportional change in the output voltage of the potentiometer circuit. The mass-spring system for some models is the form of a cantilever beam. Viscous fluid is generally used for the damping medium. A potentiometer accelerometer is illustrated in Fig. 5-47.

To obtain adequate sensitivity, the mass-spring system generally has a natural frequency of approximately 15 Hz, and the system is usually damped from 70 to 140 percent critical. The low natural frequency limits the frequency range of linear response to approximately 0 to 10 Hz. These instruments are generally used for measuring very low accelerations at low frequencies. A typical instrument might be calibrated for a range ± 0.5 G with a sensitivity of 5 V per G.

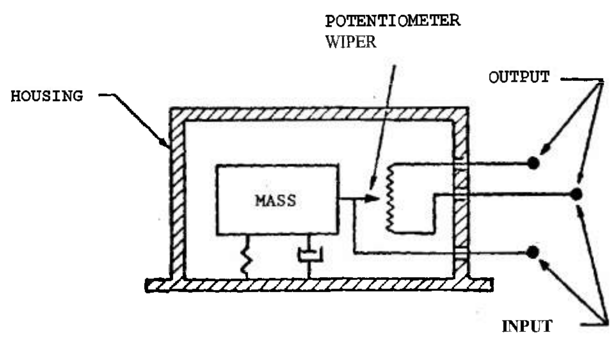


FIGURE 5-47. Potentiometer Accelerometer (Ref. 30).

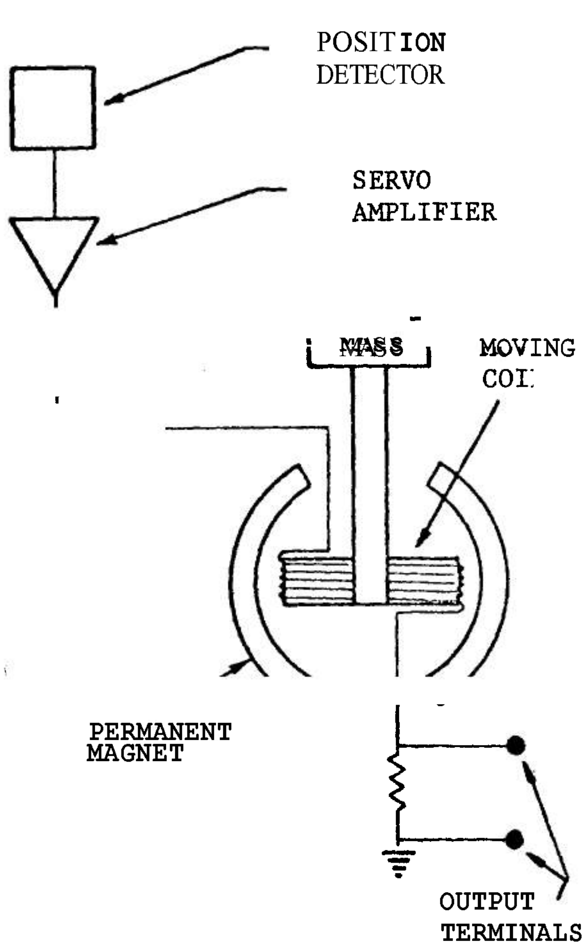


FIGURE 5-48. Force Balance Accelerometer (Ref. 30).

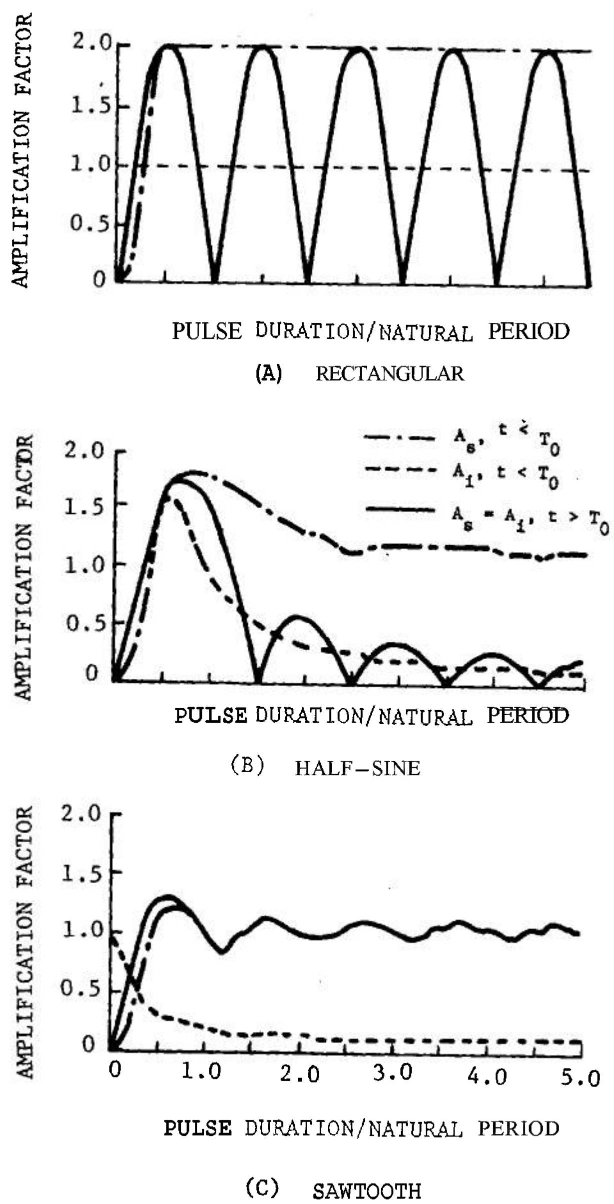


FIGURE 5-49. Amplification Factors Resulting From Three Fundamental Pulse Shapes (Ref. 32).

5-7.2.4 Force Balance Accelerometers

The force balance accelerometer is basically an electromechanical feedback system actuated by a seismic mass. The essential components of the instrument are illustrated in Fig. **5-48.** When the instrument is excited along its sensitive axis, the seismic mass tends to move. This causes a change in the output current of a small servoamplifier. The output current is passed through a moving coil, inducing a torque on the mass support arm which is equal to, and opposite from, the torque due to the inertia force experienced by the mass. Therefore, the current output of the amplifier is proportional to the acceleration experienced by the seismic mass. The acceleration is measured as a voltage drop across a resistor in series with the output of the amplifier.

The force balance accelerometer is generally used for measuring low-level accelerations at low frequencies. The instrument has a low natural frequency and is damped considerably. The frequency range of linear response is on the order of 0 to 100 Hz. Force balance accelerometers can be operated over a temperature range of approximately −40° to 200°F. A typical instrument might be calibrated for a range of ± 10G with a sensitivity of 0.8 V per G.

5-8 EFFECTS ON MATERIALS

Equipment subjected to shock loads responds in a complex way. The shock load can overstress and deform the basic equipment structure (structural response) and/or damage fragile components attached to the structure (inertial response) (Ref. 32). Both responses exist together, with their relative intensities being a function of the shape, duration, and intensity of the shock pulse; the geometrical configuration; total mass; internal mass distribution; stiffness distribution; and damping of the item or equipment (Ref. 26).

In the case of a completely resilient, single-degree-of-freedom system with negligible damping, the structural response varies from a small fraction of the shock pulse magnitude to twice the magnitude depending on the shape of the pulse. Gain or amplification factors for the structural response A, and inertial response A_i are given for the rectangular, half-sine, and sawtooth pulse shapes in Fig. 5-49.

A common, characteristic response to all three pulse shapes is, for a structure or object whose natural period is long compared to the pulse duration (the ratio of pulse duration T_0 to the natural period T is less than 1/4), that the amplification factor for the structural response is less than 1 and becomes smaller as the above ratio decreases. This implies that a structure with a low resonant frequency may withstand a large short-duration pulse because the structural amplification factor is low. However, as the ratio T_0/T becomes smaller than about 1/4, the inertial amplification factor becomes equal to or greater than the structural amplification factor. For this situation, then, the load on the structure is less significant than the load on the components within the structure.

As can be seen from Fig. 5-49, no oscillation occurs after the termination of the pulse when T_0/T is an integer (even or odd) in the case of a rectangular pulse and an odd integer for a half-sine pulse. The sawtooth pulse results in an amplification factor that is approximately 1 after the pulse termination for all values of T_0/T greater than about 1/4. This relates to the damage resulting from transportation shock in that the package or container may act as the structural element while the contents of the package would experience shocks as governed by the inertial amplification factor.

In keeping with the preceding discussion, the effects on materials can be treated in terms of structural or inertial effects. Shock can contribute to or cause fatigue failure of metals, reinforced plastics, and other structural materials. During a sufficiently violent shock excitation, structural components can be overstressed and permanently deformed. In the shipment of military equipment, perhaps the most costly damage along these lines is the weakening or destruction of packages or containers. This renders the contents susceptible to damage when exposed to future shocks, vibrations, or any number of other undesirable environments. In intermodal transport, for example, the high shock forces encountered in the railroad environment could have such an effect on the container and packing material as to reduce their shock isolating capabilities to a point where even the much lower shock levels common to ship transport would result in equipment damage.

Effects of shock resulting from inertial response vary from reduced reliability to malfunction or complete failure of equipment. Forms of damage include breakage of brittle or fragile components, displacement of massive components, and a change in the geometrical relationship between components.

5-9 PROTECTING AGAINST SHOCK

In the shipment of military cargo, it is impossible to eliminate the sources of shock excitations. The alternatives, then, are (1) isolation of the equipment from the shock forces through proper packaging and stowing techniques, or (2) design of the equipment in such a fashion as to render it unsusceptible to the shock environment. Economic factors generally favor the use of isolation techniques rather than overdesigning the equipment.

The resistance of an item to shock constitutes its ability to withstand impact without damage. The fragility rating of an item is a quantitative decription of this ability. Fragility rating is expressed as an acceleration in G units. Specifically, it is a measure of the maximum shock levels that an item can withstand yet still function properly. Therefore, if the estimated shipping and handling shock environment is greater than the fragility rating of the item, some form of shock mitigation system must be employed. Fundamentals of package design, barrier, cushioning, and container materials are discussed in AMCP 706-121 (Ref. 26) and in TM 38-230-1 (Ref. 33).

Cushioning is the generic name applied to several methods of packaging to prevent shock damage as well as for other purposes. It is summarized in the paragraphs that follow.

5-9.1 FUNCTIONS OF CUSHIONING

Cushioning is the protection from physical and mechanical damage afforded an item by means of compressible and resilient materials, known as cushioning materials, designed to absorb the energy of shocks and vibration caused by external forces. In order to utilize properly the many cushioning materials, it is necessary to understand the functions of cushioning. Among these functions, the more important are—

(1) ***Minimize movement and vibration.*** Cushioning, when properly applied, controls the movement of the item within the barrier or container and dampens vibration.

(2) ***Protect fragile or delicate components.*** When fragile or delicate components form a part of an otherwise rugged item, they may be disassembled and packaged separately. If disassembly is not permitted and they must be left in place, cushioning is applied to give them protection.

(3) ***Prevent rupture of barriers and containers.*** Many items have sharp corners or projections that could puncture the barriers or containers in which they are packaged, resulting in the entry of moisture or water. Cushioning is applied to these projections or corners to insure that waterproof or water-vaporproof barriers are not rendered useless by such damage.

(4) Distribute forces. Cushioning materials reduce the effects of shock to an item by distributing the damaging forces over a large area thus lowering the energy concentration at any one point on the surface of the item.

(5) ***Prevent abrasion.*** Items with highly finished surfaces that may be marred by blocking or strapping, or by contact with other items in the container must be protected against abrasion by cushioning. Usually, lesser amounts and thicknesses of cushioning materials are employed to accomplish this cushioning function.

(6) ***Absorb shocks.*** Perhaps the most frequent and important use of cushioning is to absorb the energy resulting when a container is subjected to impact. This shock energy is absorbed as the cushioning material is compressed by the item.

(7) ***Multipurpose cushioning.*** The foregoing functions of cushioning should not be considered separately because cushioning is often used for more than one purpose in the same package. Material selected to protect an item against shock may at the same time minimize movement, prevent abrasion, protect barriers, and cover sharp projections. Many cushioning materials also act as good insulation to protect items against drastic temperature changes. Cushioning may be required to absorb liquids and, consequently, must have liquid-absorbing qualities to prevent liquid flow in case of breakage of the containers.

When cushioning materials are used within waterproof or water-vaporproof barriers, they must be as dry as practicable, noncorrosive, and, if the item is coated with a preservative, the preserved item must first be wrapped in a greaseproof barrier.

5-9.2 CUSHIONING SELECTION FACTORS

Several factors must be considered in selecting the appropriate cushioning material for a given application. The nature and physical limitations of the item, the favorable and unfavorable characteristics of the cushioning material, the destination of the packages, and the means of transportation must all be taken into consideration before an item can be properly cushioned.

(1) ***Nature of the item.*** In planning to cushion an item, the nature and physical limitations of the item must first be considered. .The shock resistance, size, weight, shape, surface finish, and the degree of disassembly permitted will influence the way an item is to be cushioned (Fig. 5-50).

(a) Shock resistance or fragility. Fragility cannot be determined by eye alone. The tendency is to overcushion seemingly fragile items and to undercushion seemingly sturdy items. Fragility—the greatest amount of energy an item can withstand without destruction—can be measured with scientific instruments. The term 'G-factor' has been accepted as the indicator of the shock resistance of an item. This resistance is determined by measuring the acceleration of an item during a specific fall and dividing this by the acceleration due to gravity. This is expressed as: G-factor = Acceleration/Gravity. The G-factor values of many military items are being determined. In the absence of known G-factor values, the determination of the right cushioning must be based on the history of previous shipments and, whenever practicable, on actual drop testing of the completed package.

(b) Size. A large item may require a thinner layer of cushioning than a smaller item of the same weight because less load per square inch is applied to the cush-

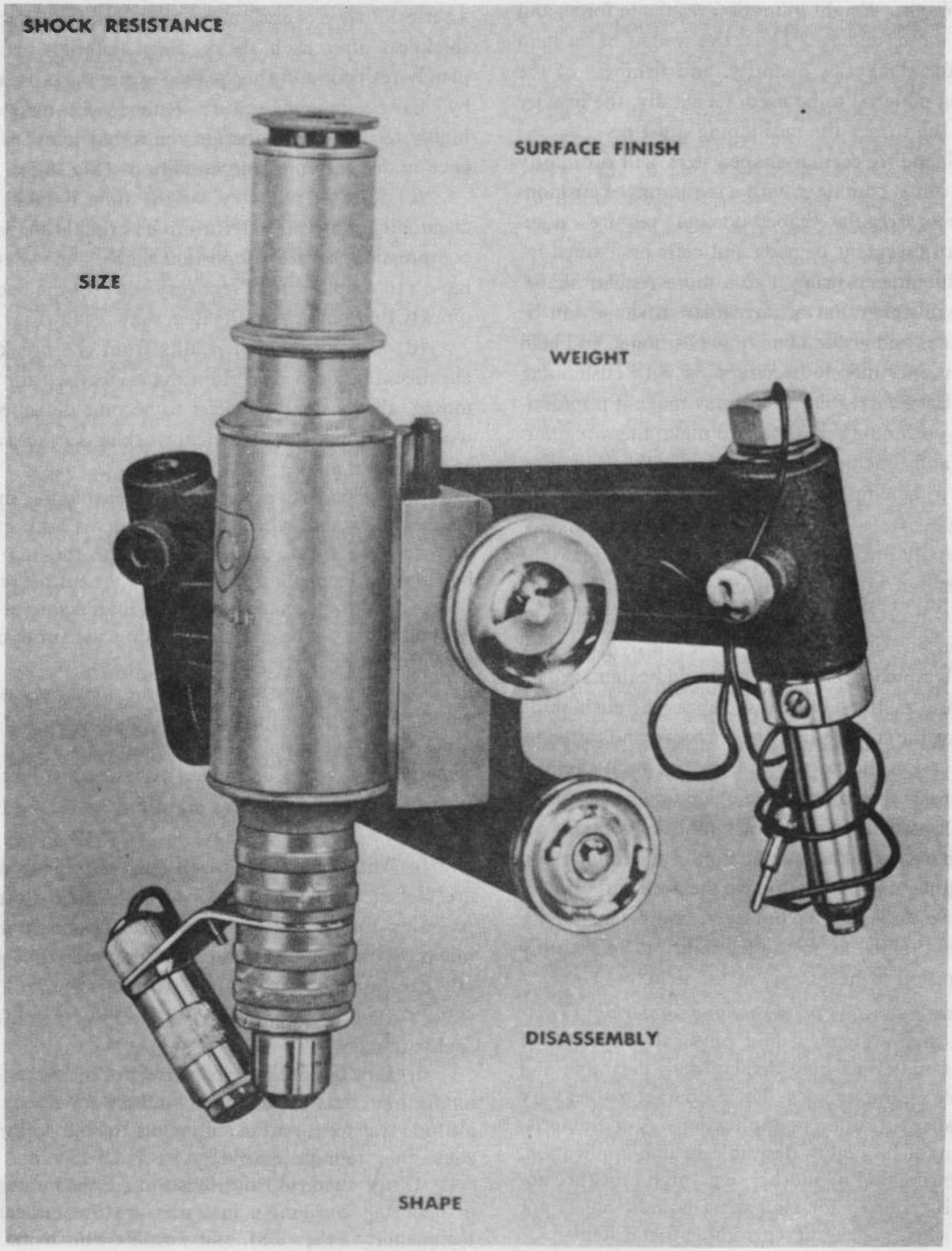


FIGURE 5-50. Item Characteristics That Determine The Selection Of Cushioning Material (Ref. 33).

ioning. This should be kept in mind when an item is irregular in shape—more cushioning may be required at the small end than at the large end.

(c) Weight. Weight in motion results in force, and force can cause damage. Thus, the weight of an item controls the thickness, quantity, and firmness of the cushioning material to be used. Generally, the heavier the item, the firmer the cushioning must be.

(d) Shape. A regular-shaped item will ordinarily fit snugly into a container with a minimum of cushioning, while an irregular-shaped one may require a complicated arrangement of pads and cells or foamed-in-place cushioning to bring it to a more regular shape. Light, small items that are irregular in shape can be made regular and at the same time positioned and held in the container merely by wrapping with cushioning material. Large, irregular items may make it impractical to use cushioning materials to make them regular. Blocking and bracing in conjunction with cushioning will have to be employed to protect such items.

(e) Static stress. Tables of cushioning performance factors usually present data based on static stress (the weight per unit area). This is determined by dividing the weight in pounds by the area in square inches.

(f) Surface finish. An otherwise sturdy item may have highly finished surfaces that could be damaged by the rubbing action of harsh abrasive cushioning material, or the surfaces may be corroded and pitted by chemical action due to the presence of moisture and acidic or basic elements in the cushioning material.

(g) Disassembly. The disassembly of a highly irregular item may allow a reduction in its volume and permit simpler cushioning to give the necessary protection. Before disassembly, however, competent advice should be obtained as to the feasibility of reassembly and calibration, if necessary, in the field.

(2) *Characteristics of cushioning materials (Table 5-8).* The many chemical and physical properties of cushioning materials may display both desirable and undesirable characteristics. These characteristics vary in importance for different applications. A characteristic that might be highly desirable in one application, may be detrimental in another; e.g., high moisture absorbency is required for packaging liquids, but is not desirable when packaging corrodible metal items.

(a) Compression set is the difference between the original thickness of a cushioning material and the thickness of the same material after having been released from compression. Compression set is undesirable since it creates free-moving space in the container (Fig. 5-51).

(b) Resilience is the ability of a material to absorb a series of shocks and return to its original shape and thickness after each shock. Few materials are completely resilient and this quality is often greatly altered by changes in temperature. Rubber, for instance, is highly resilient in temperate zones, but loses its resilience under extreme cold conditions (Fig. 5-51).

(c) Rate of recovery, or the time it takes for a cushioning material to return to its original shape after compression, is also important since some materials have a too rapid rate of recovery and "spring back" so quickly that damage to the item may result (Fig. 5-51).

(d) Dusting, which results from the breakdown and disintegration of certain materials used for cushioning, allows small particles to become detached and work into crevices and critical working surfaces of the cushioned item.

(e) The corrosive effect of some cushioning materials is undesirable when packaging items with critical surfaces. When this cannot be avoided, the item must be shielded from such materials by a neutral wrap or liner. Cushioning materials with a high acidic or basic content must not be enclosed within waterproof or water-vaporproof barriers.

(f) Fungus resistance of some materials is low, which allows for the growth of mold, mildew, and other fungi. Many materials can be treated to inhibit such growth. However, such treated materials are often very corrosive to metal surfaces and must be isolated from them.

(g) The abrasive characteristics of some materials are factors that must be considered when protecting precision surfaces such as the lenses of optical instruments. Some soft-textured cushioning materials generally can be placed in contact with easily marred surfaces. Coarse-textured materials should not be used on such surfaces.

(h) Low temperature performance of certain cushioning materials makes them suitable for use in high altitude transport and in shipments to cold regions because they remain relatively soft and resilient.

(i) Other characteristics that should not be neglected in choosing cushioning materials are fire resistance or flammability (Fig. 3-23), and possible skin irritation to personnel who come in contact with it.

(3) Destination of the item. The destination of the item is a factor in cushioning. Many cushioning materials change their characteristics under extreme climatic

TABLE 58. PROPERTIES OF SELE

(Ref.

Material	Compres-sion set	Damping shock absorption[1]	Density	Dusting	General corrosive effect	Moisture Absorp-tion	Moisture content	Fungus resistance[4]	Low-tem-perature function
Animal hair, bondedsheet molded	**Slight** **Slight**	**Good** **Good**	Average Varies	Slight Slight	Slight Slight	Slight Slight	Low High	Poor Poor	Fair Fair[5]
Foam rubber, molded	Slight	**Good**	High	Some	Slight	Much	High	Poor	Good
Blown vinyl flexible foam	Some	Good	High	None	Slight	Much	Low	Good	Poor
Air pillow—vinyl cradle	**None**	Fair	**Low**	None	None	None	None	Excellent	Good
Vinyl cradles in suspension	**None**	Fair	**Low**	None	None	None	None	Excellent	Good
Springs	**Neglig.**	**Poor**	----------	None	None	None	None	Excellent	Good
Canvas slings	Neglig.	Fair	----------	None	None	Some	Varies	Poor	Good
Honeycomb, Kraft paper	**Much**[3]	Excellent[a]	Low	None	Slight	Medium	Low	Poor	Good
Excelsior	**Much**	Excellent	Average	Very high	Much	High	High	Poor	Poor
Shredded paper	Much	Excellent	Average	Very high	Much	High	Varies	Poor	**Good**
Corrugated fiberboard[2]	Much	Excellent'	Low	Slight	None	High	Varies	Poor	Good
Plastics foams:									
Polyethylene, molded	Slight	Excellent	Average	Slight	None	Low	None	Good	Good
Polystyrene, Molded	Varies	Good	Low	Slight	None	Slight	Low	Good	Good
Strands	Slight	Excellent	Low	Slight	None	Slight	Low	Good	Good
Resilient sheet	Slight	Excellent	Low	Slight	None	Slight	Low	Good	Fair
Polyurethane, rigid	Much	Excellent	Varies	High	None	Low	Low	Good	Good
Polyurethane, flexible	Slight	Excellent	Varies	Slight	None	High	High	Good	Good
Cellulose wadding:									
Creped	Much	Excellent	Average	Much	None	Varies	Low	Poor	Good-
Homogeneous	Varies	Excellent	Varies	Varies	None	Varies	Low	Poor	Good
Cotton	**Much**	**Excellent**	**Low**	Much	None	Much	Varies	Poor	Good
Plant fibers, rubber bonded	**Slight**	**Fair**	Average	Slight	Slight	Slight	Low	Poor	Fair
Fibreglas	Slight	Fair	Average	Slight	Slight	Slight	Low	Good	Good

* Ratings shown are general. Properties differing from those given here can vary producers regarding specific requirements.

[1] Capacity of cushion to absorb and not transmit shock.

[2] Values for flutes in column or flat.

[3] Shock absorption declines as material crushes under repeated shock.

[4] Many treatments are used to avoid problem of poor fungus resistance.

[5] Good when treated.

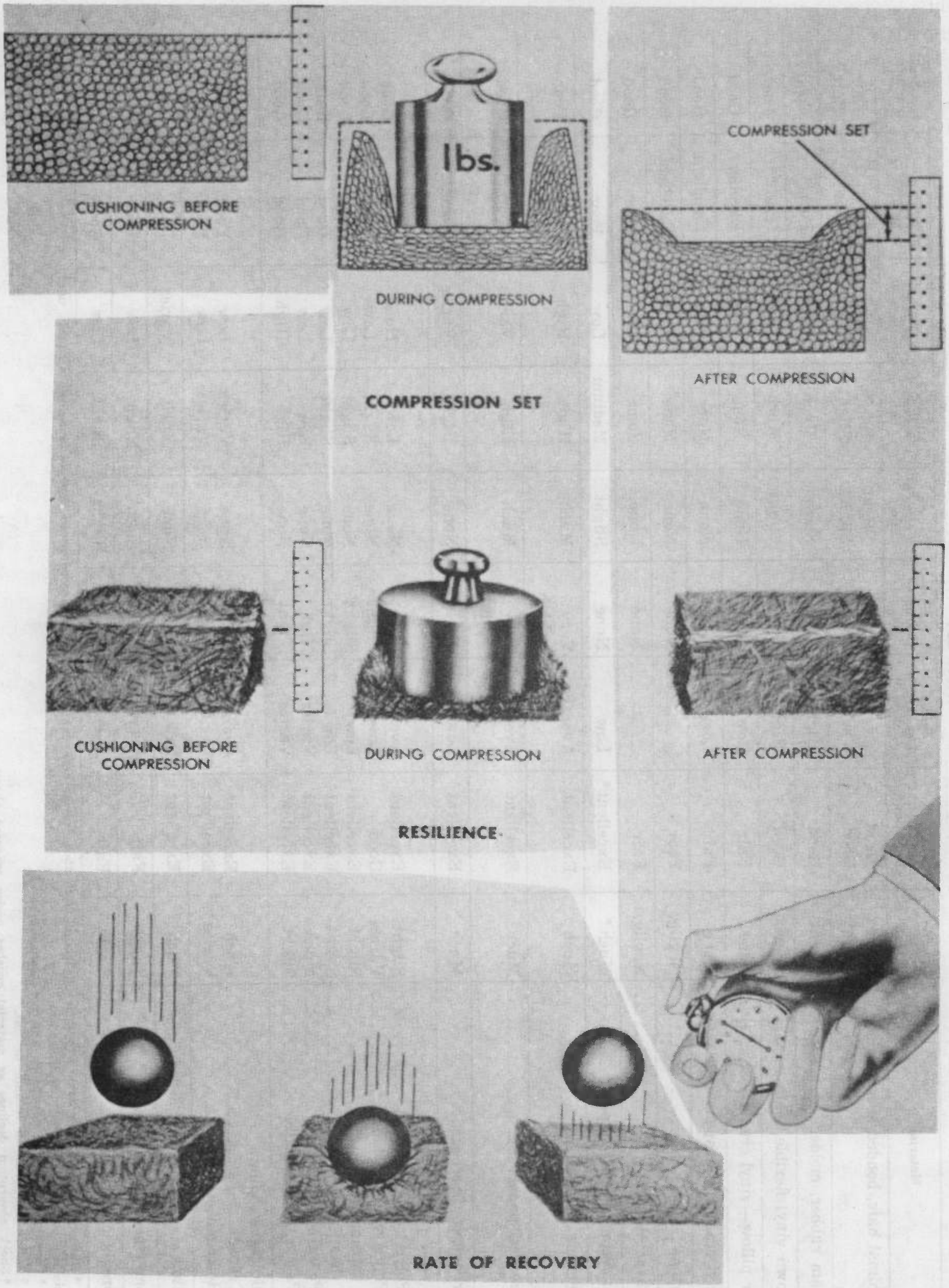


FIGURE 5-51. Characteristics of Cushioning Materials (Ref. 33).

conditions. Some materials become so rigid or brittle at extremely low temperatures that they are useless as cushioning materials. In tropical climates, some materials soften and lose their cushioning qualities. In jungles or rainy locations, some materials will pick up excessive moisture, resulting in the loss of resilience and leading to growth of fungus and accelerated corrosion.

(4) *Means of transportation.* The means of transportation must not be overlooked. Hazards and handling situations vary greatly between air, motor, rail, and ship. For example, considerable difference may exist between the amount of handling that an item being transshipped from truck, to rail, to ship would get and one that is being shipped by air freight. Likewise, an item to be delivered by air drop would require different protection from one that would be delivered by truck.

5-9.3 REPRESENTATIVE CUSHIONING MATERIALS

Representative cushioning materials for shock protection are described as follows:

(1) *Bound fiber cushioning materials.* These materials may consist of any suitable natural hair, vegetable fiber, or synthetic fiber bound with an elastic material. Horse hair, sisal, and cactus fibers sprayed with latex are common examples. The materials are furnished in four types according to firmness from soft (capable of supporting loads up to 0.01 lb in.$^{-2}$) to firm (capable of supporting loads up to 1.3 lb in.$^{-2}$). They may be supplied as noncompressed flat sheets for general cushioning applications, or in molded forms shaped to fit the contours of the item. The materials have a high degree of resilience, low compression set, and fair damping quality, and they do not disintegrate easily. They are neutral and have a low water-soluble acidity so that their corrosive effects are slight. Moisture content and moisture absorption are both low; however, the materials may need to be treated to improve fungus resistance. Their performance is reduced at low temperature. They are intended to protect items against vibrational and impact shocks where resilient and water-resistant cushions are required.

(2) *Cellulosic cushioning material.* This material may be made of any kind of cellulosic matter that will result in a product that meets specification requirements. The cellulosic matter used may be cotton, bonded fibers, natural fibers, or creped wadding. The material is furnished in two types—Type I, water absorbent, and Type II, water-resistant. It is available in two classes—Class A, low tensile strength (filler material), and Class B, high tensile strength (wrapping material). The material is required to be noncorrosive. However, even when it is water-resistant, water may be absorbed and retained within its pores. Cellulosic cushioning material is readily moldable and fairly resilient. Its compression set is high, its damping ability excellent, but dusting is great enough to require an excluding wrap around items susceptible to dust damage. Its performance in cold temperature is good. This material is intended for use in packaging lightweight, fragile items; as a protection against abrasion; and Type I, specifically, for absorbing liquids from containers broken in transit.

(3) *Fibrous glass cushioning material.* This material consists of glass fibers matted, bonded, or otherwise treated to meet specification requirements. The surface of Type II material is coated with an elastomeric material to prevent dusting. This material can be supplied in various classes of density ranging from a very soft material with a load range from 0.2 to 0.5 lb in.$^{-2}$ to a very firm material with a load range from 50 to 100 lb in.$^{-2}$. The resilience of the material is high, its compression set low, its damping fair, and its dusting slight, especially in the Type II material. It is highly flame-resistant and water-resistant. The material is neutral and will produce no corrosive effects. Moisture content and moisture absorbency qualities are low. The material is fungus-resistant and performs well at low temperatures. Fibrous glass cushioning is intended for use in protecting packaged or installed equipment against shock and vibration. A temporary skin irritation may occur as a result of handling the uncoated type (Type I). Minute fibers sticking to the skin are readily removed by ordinary washing. Suitable precautions and adequate ventilation should be used when there is any possibility of particles getting into the eyes or of accumulation of glass dust in the air.

(4) *Cellular, plasticized, polyvinyl chloride cushioning material.* This material consists of plasticized, lead stabilized, nonhygroscopic polyvinyl chloride, supplemented with dyes, pigments, and fillers as necessary to meet the specification requirements. The surface of Type I is coated with a permanently bonded flexible material for abrasion resistance. It is furnished in four densities, ranging from low (8 to 12 lb ft^{-3}) to high density (20 to 30 lb ft^{-3}). The material may be coated or uncoated, as specified, and supplied in a standard commercial grade or a special low temperature grade. It is furnished in either flat sheets or in molded forms,

as required. The compression set is low, resilience high, damping good, and dusting low. The material is neutral and does not produce corrosive effects. Its moisture absorbency is nil and moisture content low. It is fungus-resistant and fire-resistant. The low temperature performance is poor for the commercial grade and good for the low temperature grade.

(5) Paper honeycomb cushioning material. This material consists of kraft fibers constructed into sheets of paper board that resemble honeycomb. This material is primarily used as an energy-dissipating medium for the landing shock to which air-dropped objects are subjected. It may also be used for special packaging requirements.

(6) Wood excelsior in fabricated pads and bulk form. **Excelsior is made of shredded, straight-grained soft wood, free from mold, decay, and pitchy accumulations. It is furnished as bulk excelsior or as pads. The pads may be either waterproof or nonwaterproof. The bulk excelsior is obtainable in six grades, from superfine wood wool to coarse or ribbon excelsior. The pads are obtainable in 12 weights, from light to extra heavy. The material has a high compression set, medium resilience, and excellent damping qualities. Its moisture content and absorbency are high and the corrosive effects are considerable because of the wood acids present. It has poor fungus resistance, is highly flammable, and has poor low temperature performance. Its dusting characteristics are high and, if the moisture content gets too low, the material disintegrates into fine particles. It is abrasive and should not be used against finished surfaces that may be marred by scratching. Excelsior is best used for packaging in the waterproof pad form or as a cushioning layer between the walls of an inner and an outer container, with a waterproof liner to keep out excess moisture. The finer grades of excelsior are for cushioning the lighter, more fragile items, and the coarser grades are best adapted for cushioning rugged items.**

(7) Hair felt. Hair felt consists of cleaned, washed, and sterilized cattle hair. It is finished in five types based on the fabrication process. It is available in rolls of 3-, 6-, or 9-ft width. It is also available in a variety of thicknesses and densities. It has an average degree of resilience, low compression set, poor damping, and some amount of dusting. It will withstand repeated compression and abrasion without disintegrating. The felt must be free from acids. It will retain moisture and is subject to fungus attacks unless treated. It is used mainly as cushioning and padding of cradles for large articles. It should be glued in place and kept dry.

(8) *Solid and corrugated fiberboard.* Both solid and corrugated fiberboard are used in cushioning, but corrugated is more frequently used because it has greater cushioning value. The most common forms of fiberboard applications are die-cuts, open end cells, trays, pleated pads, and flat pads. Generally, cells and trays should be held in shape with tape. Those surfaces of the cell or tray that are perpendicular to the contracting surface of the item are called bracing supports and are the load-bearing members. To utilize all of the strength of these bracing supports, they should bear directly on the item. Pleated pads have greater resistance to breakdown than open end cells because the load is spread over a large area rather than on bracing supports. Therefore, they should be used to cushion heavier loads (up to 2 lb in.$^{-2}$). Flat pads are used to block shallow projections, to level off projecting screw heads, and to separate items within a container. They can be slotted to form partitions, or may be die-cut or punched to fit articles of irregular shape as shown in Fig. 5-52.

(9) *Solid fiberboard.* This fiberboard is made from cane, wood, or other vegetable fiber by a felting or molding process that incorporates a sizing agent to form uniform solid sheets, blocks, or special fabricated shapes. The board is made in two types—single ply and laminated multiple ply. The single ply is furnished in 1/2- and 3/4-in. thicknesses. The material is available in a density of between 14 and 19 lb ft^{-3}. It has average resilience, low compression set, low damping quality, and performs fair in cold weather. Its dusting qualities are low. The material is required to be neutral and low in water-soluble acid content. The moisture content and moisture retention qualities are low, and it has a low corrosive effect. It is also treated to improve moisture resistance.

(10) *Waxed, shredded paper.* This is a commercial-quality paper composed of cellulosic fibers coated with a petroleum-based wax. The waxed paper is supplied in two types—long shreds and short shreds—and is compressed in bales and furnished by the pound. The material has a high compression set, low resilience, excellent damping, low density, very high dusting, and high corrosive effect. Hence, it cannot be used against critical metal surfaces without isolation by a neutral wrap. Its moisture content is low, moisture absorption high, fungus resistance poor, but its low temperature performance is good. This material is used to position items in containers and to offer limited shock protection. Because of the wax present, the material should not be utilized in containers that are exposed to unlimited outdoor storage in tropical climates.

(11) *Cushioning, wrapping paperboard.* This is a paperboard composed of a corrugated sheet or a solid molded pulp sheet firmly cemented to a backing flat

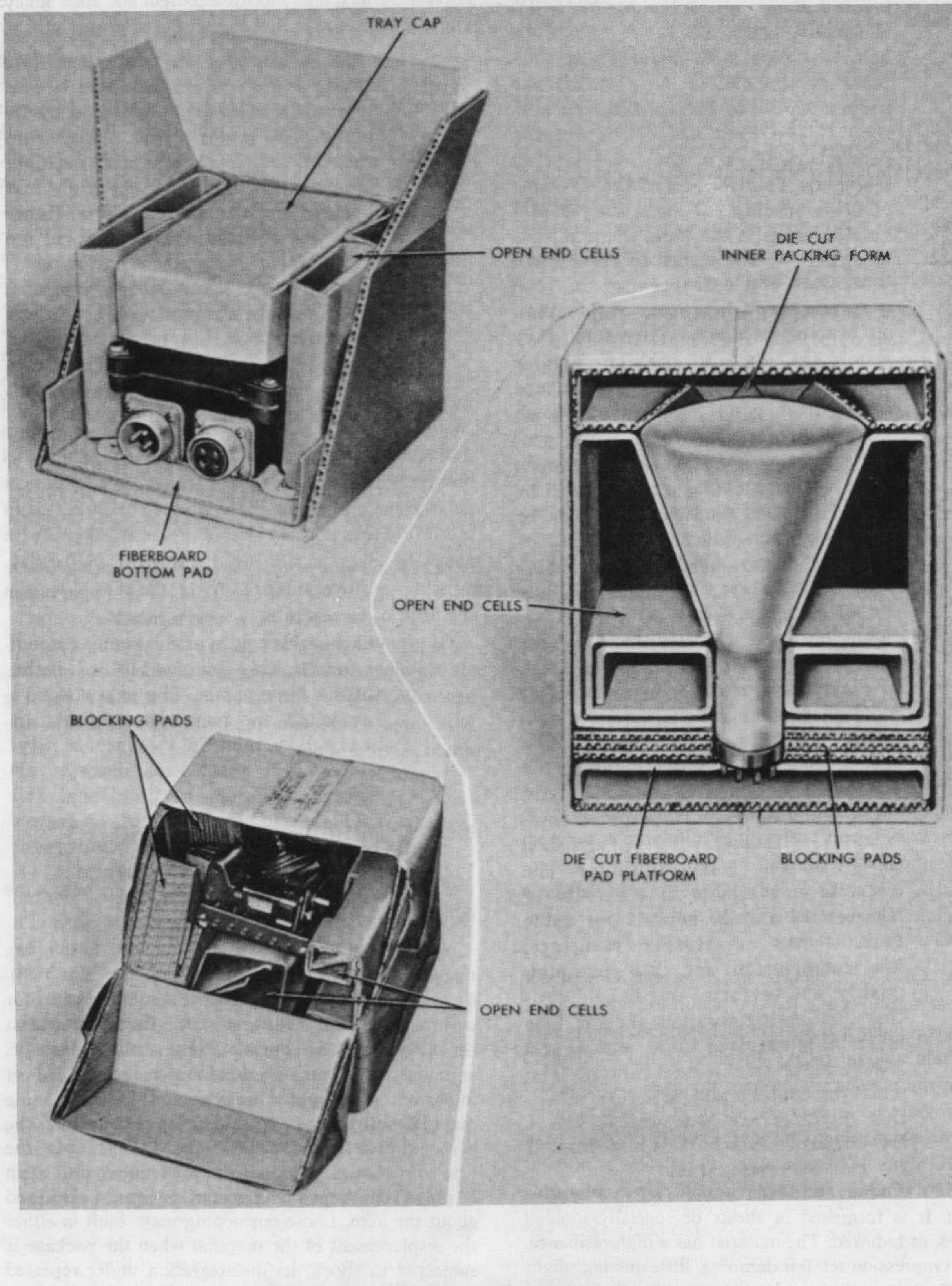


FIGURE 5-52. Application of Fiberboard (Ref. 33).

sheet of unbleached sulfate fiber paper. The paperboard is furnished in two types—light and heavy-duty, and in two styles: Style 1—backing sheet, mandatory; and Style 2—backing sheet, optional. It is furnished in sheets or rolls, as desired. This material has high compression, low resilience, excellent damping, and some dusting. The moisture content and moisture absorption are high. The material is not neutral and, hence, has a high corrosive effect. Its performance in cold weather is poor, and it is neither fungus- nor flame-resistant. Critical metal items must first be wrapped in a chemically neutral or greaseproof barrier.

(12) ***Rigid or elastic polyurethane foam.*** This material consists of both rigid and elastic types of foamed products obtained through the proper blending of complex synthetic chemical compounds. By proper combinations, reaction mixtures can be poured or pumped into various shaped cavities. Carbon dioxide is given off by the reactions, causing the rapidly stiffening resin to expand, completely filling the space. The material then sets rapidly to a lightweight, solid, porous structure that has excellent cushioning properties. The material is furnished in a form suitable for foaming-in-place application or it may be preformed and supplied in rolls, flats, sheets, or molded shapes. Strong rigid foams, tough elastic foams, soft flexible foams, and spongy water-absorbent foams can be obtained by the choice of ingredients. Foams with densities as low as 2 to 3 lb ft^{-3} may be obtained. These foams can be adjusted to give a high or low compression set, excellent or poor damping, and high or low resilience. In other words, the material can be tailored to meet the requirements of any type of cushioning required. Dusting is no problem, moisture content is exceedingly low, absorption capacity can be varied, and the corrosive effect is negligible. The material is flame- and fungus-resistant. It stiffens in cold climates.

(13) ***Chemically blown, cellular rubber.*** This rubber is made by subjecting the compound to a gas, such as nitrogen, under high pressure. Under these conditions, a certain amount of gas dissolves in the compound. When the pressure is lowered, the mass expands and the product becomes a myriad of individual nonconnected gastight cells. This material may be obtained in soft, medium, and firm classes; oil-resistant or non-oil-resistant grades; and fire-retardant or combustible kinds. It is furnished in sheets or specially molded shapes, as required. The material has a high resilience, low compression set, fair damping, little dusting, slight corrosive effect, high moisture content and absorbency, and poor-to-average low temperature performance.

(14) ***Resilient, expanded, polystyrene cushioning material.*** This is a resilient cushioning material of expanded polymers or copolymers of styrene for use in cushioning and packaging applications. It is available in two types: Type I—sheet form, classed as soft, medium, firm, and extra firm; Type 11—roll form, with the same classes as Type I. The material is nonabrasive, and fungus- and mold-resistant. It is used as a cushioning material within packages to protect items from damage due to shock, vibration, abrasion, and concentrated forces during handling and shipment. It is especially suited to packaging problems where a high degree of energy absorption is required in a minimum space and with a minimum weight of cushioning; to packaging problems in which the cushioning material should also provide temperature insulation; and to packaging problems in which the cushioning material must perform at extremely low temperatures. Resilient polystyrene cushioning material may be furnished in special converted forms, sizes, and shapes, such as with paper backing, paperboard backing, cloth backing, pressure-sensitive adhesive surface, die-cut holes, or in the form of corner pads of special shapes.

Caution: Expandable polystyrene cushioning materials contain gaseous hydrocarbons, which are explosive. Seven days exposure to the atmosphere after expanding is required to dissipate the hydrocarbons so that the products are no longer dangerous.

5-9.4 METHODS OF CUSHIONING

Cushioning is generally accomplished by one of the following methods:

(1) ***Floated item.*** The item is floated in cushioning material and placed within a unit container (Fig. 5-53). This is perhaps the method most commonly used for cushioning small, lightweight, fragile items against shock, vibration, and abrasion. In this case the dryness and noncorrosiveness of cushioning materials are most important since both the item and the cushioning material will be enclosed in the unit container. The accepted practice today is to make the cushioning the first wrap. Grease proof barriers are required if the item is preserved. 'Cushioning materials must be secured about the item. Loose cushioning may result in either the displacement of the material when the package is subjected to shock, its disintegration under repeated

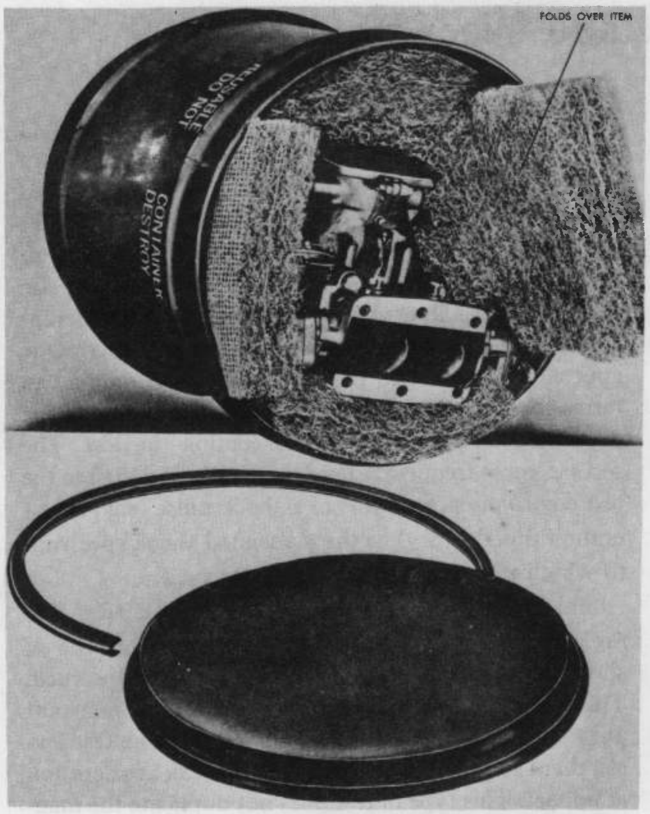


FIGURE 5-53. Methods of Cushioning--Floated Item (Ref. 33).

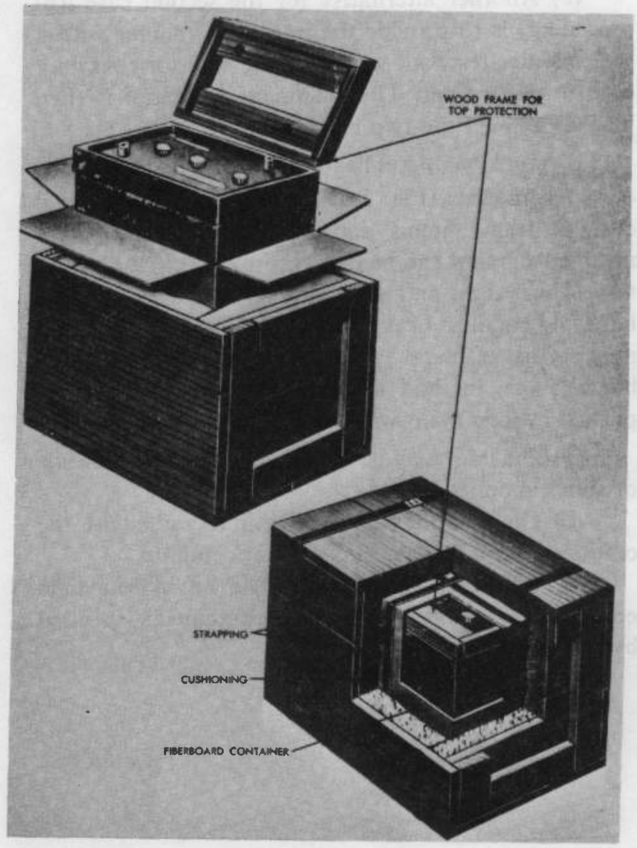


FIGURE 5-54. Methods of Cushioning–Floated Package (Ref. 33).

vibration, or the production of dust or loose particles, which will be entrapped within the package. Since a container may be dropped on any one of its faces, edges, or comers, the cushioning material must be designed to withstand the full impact of the ent e weight of the item in any direction.

(2) ***Floated package.*** The item is packaged in an interior container, which in turn is floated in cushioning material (Fig. 5-54). This method is generally used in connection with semifragile items of medium size and weight. The item is initially packaged (which may include cushioning or blocking) in an interior container, then floated in cushioning and placed into an exterior container. In this method, the noncorrosiveness and moisture content of the cushioning materials are not critical since the materials will not come in contact with the item. The use of absorbent cushioning materials, when used in this method, should be governed as follows:

(a) When both the interior and exterior containers are water-resistant, the cushioning material may simply be placed between the two containers.

(b) When either container is nonwater-resistant, the cushioning material must be placed in the form of pads wrapped in a water-resistant barrier material.

(c) Another alternative for the second case ((b) preceding) is to provide the interior container with a sealed water-resistant wrap and the exterior container with a sealed liner. The cushioning material is then placed between the two barriers.

(3) ***Shock mounts.*** The item is cushioned by means of shock mounts (Fig. 5-55). This method is used to cushion fragile items and sensitive instruments or mechanisms that can be damaged by shock and vibration. The weight and size of the item may vary from light and small to heavy and large. The shock mounts may consist of metal springs with damping or rubber blocks. This method of cushioning may be accomplished in four main ways:

(a) The item may be suspended directly by means of shock mounts.

(b) The item may be blocked in a cradle with the cradle suspended by means of shock mounts.

(c) The item may be boxed in an intermediate container with the intermediate container suspended by means of shock mounts.

5-10 SHOCK TESTS

5-10.1 SPECIFICATIONS

Shock testing is performed to evaluate the ability of an item or piece of equipment to survive undamaged the transportation and handling environments: The problems involved in defining the shock environment and simulating this environment in the laboratory are very complex. Due to this complexity, two different approaches to shock test definition have evolved. One approach has been to define the test environment in terms of the type of shock machine to be used and the procedure to be followed in executing the test. The second, most frequently used approach, is to define the test environment in terms of a shock pulse (e.g., acceleration time history) or the associated shock spectrum to which the specimen must be subjected.

Shock tests as specified in MIL-STD-202 (Ref. 34) are examples of the first approach; i.e., the type of shock machine and the test procedures are specified. This is a drop test and as such has a nearly constant pulse duration regardless of drop height. The test levels, then, are given as drop heights or peak acceleration at impact. This type of test does not duplicate the magnitude-time duration relationship of the different shock waveforms encountered in the handling and transportation environments.

The shock test as specified in Method 516 of MIL-STD-810 (Ref. 35) is designed to determine that the structural integrity and the performance of equipment are satisfactory with respect to the shock levels that may be encountered in handling and transportation activities. In this test the pulse shape, peak value, and duration are specified. Fig. 5-56 shows the terminal-edge sawtooth and half-sine pulses with tolerance limits as specified in the test procedure. All points of the measured acceleration waveform must fall within the area enclosed by the tolerance limit lines. The only restriction on the type of shock machine used for this test is that it be capable of producing the input shock pulse as specified.

A shock spectrum (i.e., acceleration level in G units vs frequency) is another means of specifying shock test requirements (Ref. 18). The advantages of this method over pulse shape specification are (l) the shock spectrum correlates with a theory of damage, (2) it is easier

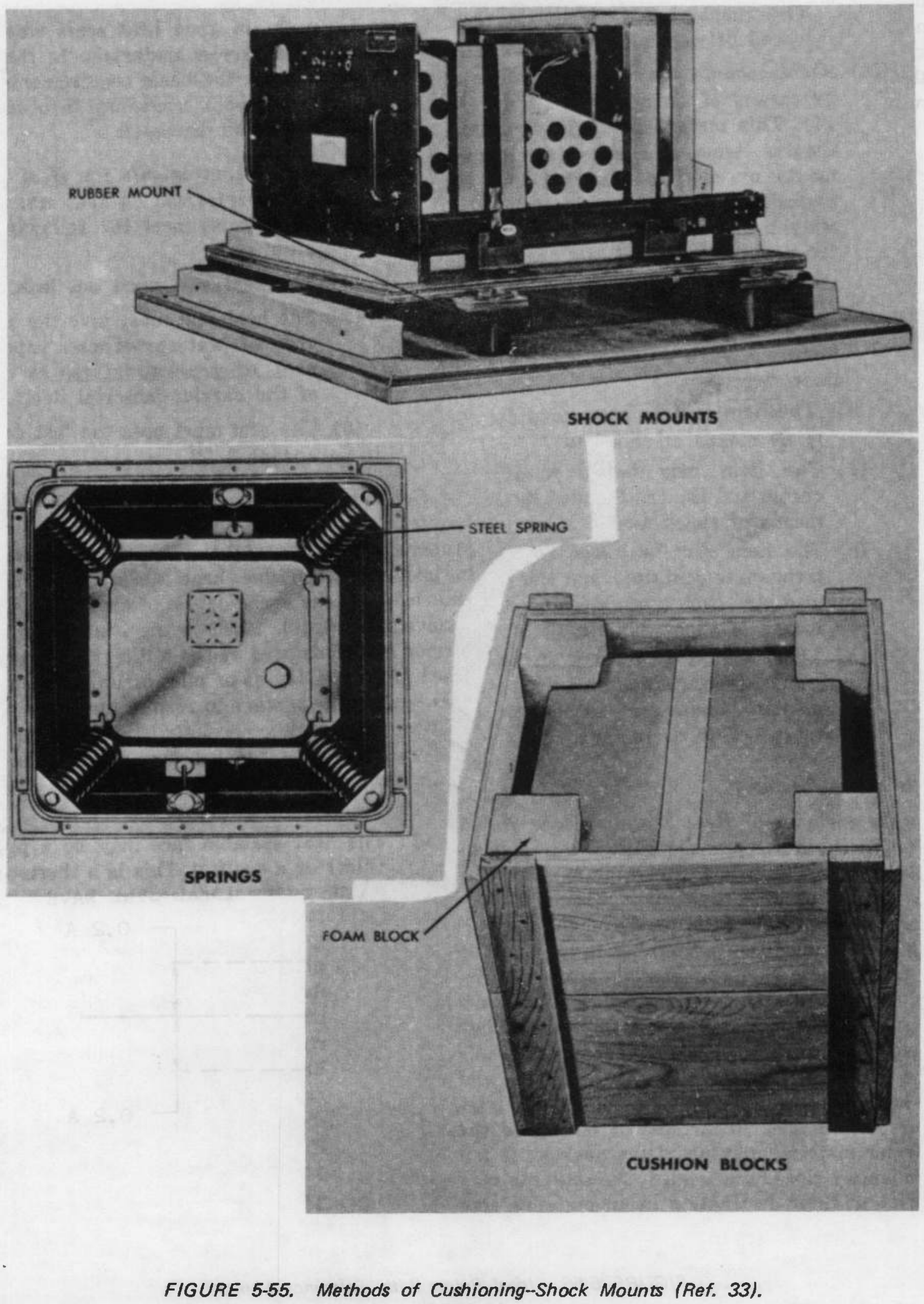


FIGURE 5-55. Methods of Cushioning--Shock Mounts (Ref. 33).

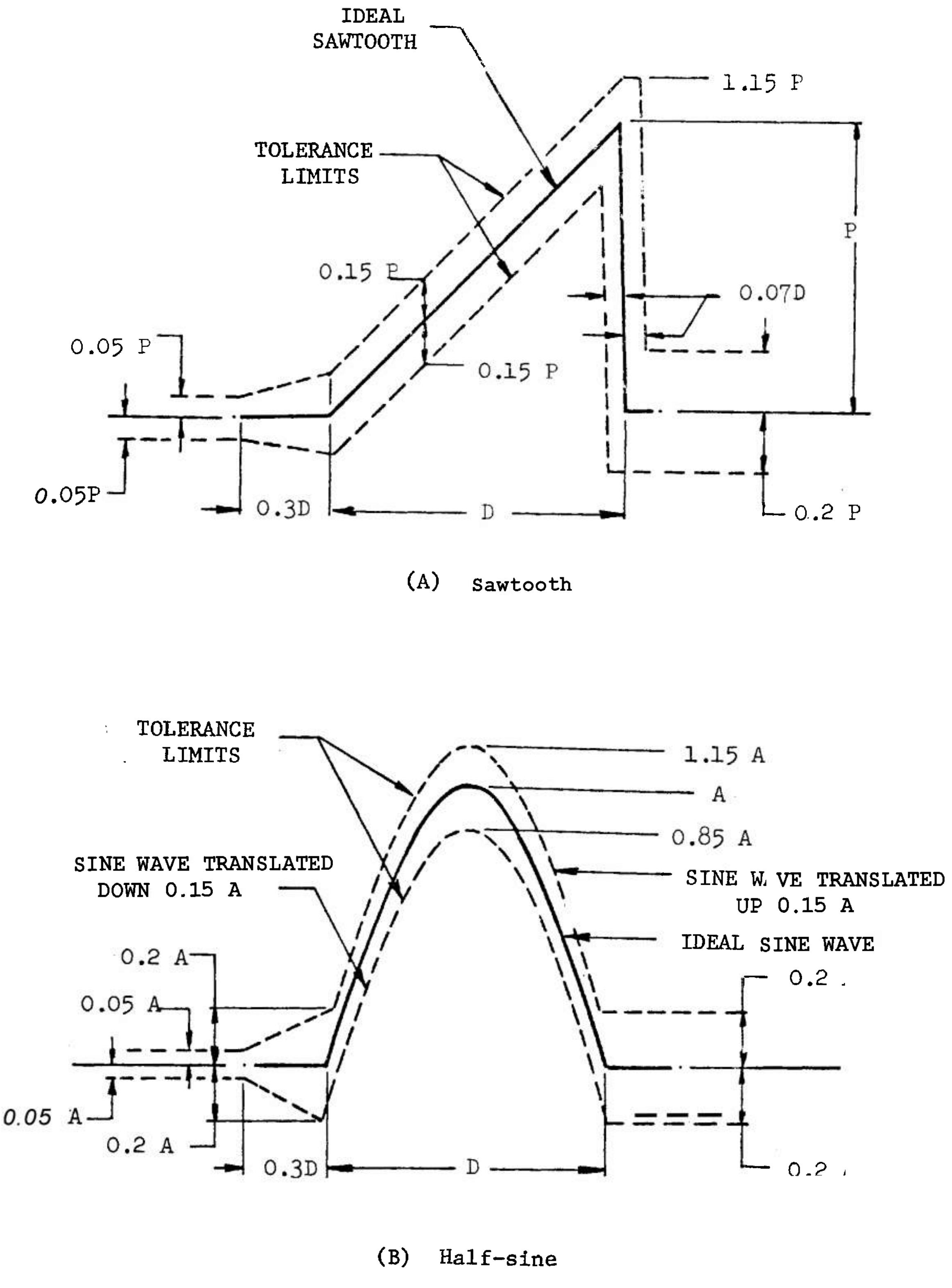


FIGURE 5-56. Ideal Pulses With Tolerance Limits (Ref. 35).

to define tolerance limits, and (3) actual service conditions can be reproduced (Ref. 13). On the other hand, Schell (Ref. 36) favors the pulse shape definition because he believes that spectra specification can lead to large errors. He states that small changes in the spectrum can yield very large changes in the acceleration time signature. Shock spectra specification gives the test engineer the option of using any pulse shape that will produce the required spectrum.

5-10.2 METHODS

Railroad humping operations represent the source of the most severe shocks encountered in the transport phase. Therefore, most transportation shock tests have been developed for the purpose of simulating this environment. The most frequently used methods are the incline impact test, the pendulum impact test, the railcar impact test, and the shock machine tests.

The incline impact test is conducted using a wheeled dolly running on a steel track inclined at some fixed angle to the floor with a sturdy barrier perpendicular to the track and located at the lower end of the track. The test specimen is placed on the dolly, which is raised a certain distance up the track, then released to impact against the barrier (Ref. 25).

The pendulum impact test may also be used to simulate rail humping shocks. In this test the package or test item is either placed on a platform that can swing through an arc, or slung to a single support with cables. In both cases the platform and/or package is raised a specified distance through the arc, then released to impact the package against a solid barrier.

The railcar impact test is conducted by first placing the test items onto a railcar. By means of a humping ramp or a switch locomotive, the test car is then accelerated to a specified speed and impacted into a stationary car.

Mechanical shock machines used for equipment testing are of two basic types. One type is referred to as an impulse machine in which the test item is mounted to a moving object, called the hammer, which impacts against a stationary object called the anvil. The second type, an impact machine, has the test item mounted on the anvil. In this case, the anvil is struck by the moving hammer.

One type of impulse machine is pictured in Fig. 5-57 (Ref. 30). This machine employs a drop table (hammer) whose fall is arrested in a sandbox. By attaching a variable number of hard wooden blocks to the underside of the table and adjusting the drop height, shock pulses varying from 30 to 100 G in magnitude and 8 to 10 ms in duration can be achieved. In some impulse machines of this type, spring or elastic cords are used to aid in accelerating the drop table. One such machine allows the equivalent of a 100-ft drop in just 11 ft.

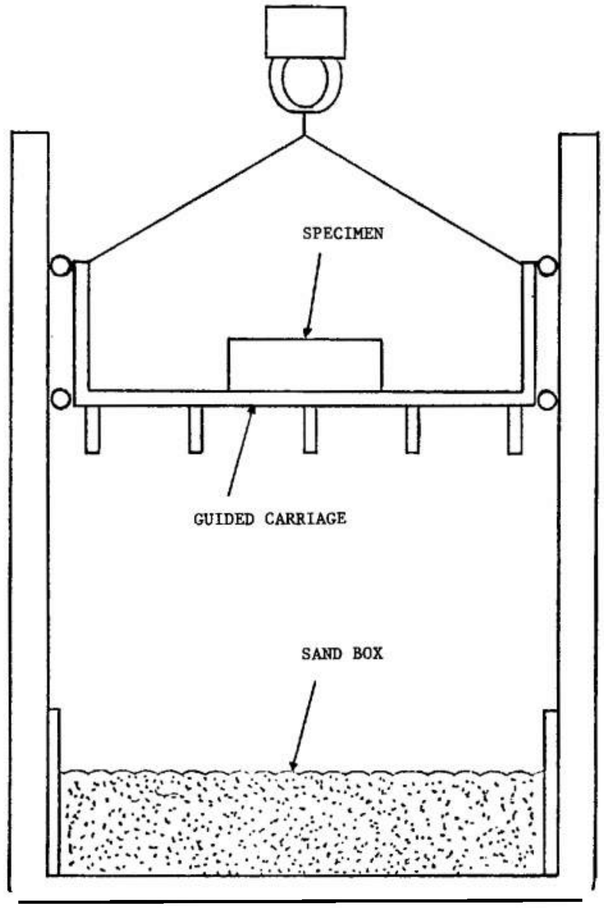


FIGURE 5-57. Impulse-type Shock Test Machine (Ref. 30).

Impact machines consisting of heavy pivoted hammers capable of swinging through wide arcs and impacting against an anvil can produce complex shocks of magnitudes up to 2,000 G (Ref. 25).

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CHAPTER 6

ACCELERATION

6-1 INTRODUCTION

Army materiel subjected to relatively long periods of acceleration suffers the same types of damage which result from exposure to shock and vibration environments but with much less frequency and severity. Acceleration is defined as the time rate of change of velocity with respect to a reference system (Ref. 1). Whereas acceleration is the parameter most often used to describe the vibration and shock environment, the term as used in this chapter refers to accelerations that are of longer duration than shock pulses and that differ from vibration in that they are either nonperiodic or, if periodic, of very low frequency. It includes but is not restricted to sustained acceleration, defined as a constant level of acceleration that is maintained for an extended length of time (Ref. 2). In terms of the materiel itself, any acceleration whose period is long compared to the resonant period of the materiel upon which it acts satisfies the definition of acceleration as given in this chapter.

Acceleration causes a mechanical force to act on an item so that its ability to survive acceleration is a measure of its structural strength and integrity. Failures are similar, therefore, to those observed under static loads, or for operating mechanical devices, to those observed under high dynamic loads or excessive friction.

'Army equipment designed to perform reliably under static conditions may, if not properly protected during shipping and handling, experience acceleration levels sufficient to reduce equipment reliability or, in some cases, to make it inoperable upon reaching its destination. Fragile or sensitive equipment transported by aircraft, missile, or rocket must be protected against damage from acceleration as well as shock and vibration.

Equipment designed to operate in shock and vibration environments will in most cases survive the operational acceleration environment with no ill effects. However, certain devices such as panel meters, electromechanical time-delay relays, and accelerometers may be affected more seriously by acceleration than by shock or vibration.

6-2 UNITS, DEFINITIONS, AND LAWS

6-2.1 UNITS

Linear acceleration is commonly expressed in units of feet per second per second (ft s^{-2}) or meters per second per second (m s^{-2}). However, the most frequently used unit of measure is the acceleration due to gravity, or G. The standard value of G is 32.1740 ft s^{-2} (9.80665 m s^{-2}). Conversion factors for units of linear acceleration are given in Table 6-1 (Ref. 3).

Angular acceleration is expressed as radians per second per second (rad s^{-2}) or as revolutions per minute per second (rpm s^{-1}) (Ref. 4).

6-2.2 DEFINITIONS

The following definitions are necessary in the treatment of acceleration (Refs. 2,5).

(1) ***Displacement.*** Displacement is a vector quantity that specifies the change of the position of a body or particle and is usually measured from the mean position or position of rest. In general, it can be represented by a translation or rotation vector, or both.

(2) ***Velocity.*** Velocity is a vector that specifies the time rate of change of displacement with respect to a frame of reference.

(3) ***Acceleration.*** Acceleration is a vector that specifies the time rate of change of velocity with respect to a frame of reference.

(4) ***Jerk*** Jerk is a vector that specifies the time rate of change of the acceleration with respect to a frame of reference.

(5) ***Sustained acceleration.*** Sustained acceleration is a constant level of acceleration that is maintained for an extended length of time.

(6) ***Rectilinear motion.*** The motion of an object is rectilinear when it is confined to a straight-line path.

(7) ***Curvilinear motion.*** The motion of an object is curvilinear when it travels in a curved path.

(8) ***Circular (rotary) motion.*** Circular motion is a

TABLE 6-1. LINEAR ACCELERATION CONVERSIONS (Ref. 3)

	$m\ s^{-2}$	$m\ min^{-2}$	$m\ hr^{-2}$	$m\ hr^{-1}s^{-1}$	$in.\ s^{-2}$	$in.\ min^{-2}$	$in.\ hr^{-2}$	$ft\ s^{-2}$	$ft\ min^{-2}$	$ft\ min^{-1}s^{-1}$	$mi\ s^{-2}$	$mi\ min^{-2}$	$mi\ hr^{-2}$	$mi\ hr^{-1}s^{-1}$
1 $m\ s^{-2}$ =	1	3.6000×10^{3}	1.29600×10^{7}	3.6000×10^{3}	3.9370×10^{1}	1.41732×10^{5}	5.10235×10^{8}	3.28083	1.18110×10^{4}	1.9685×10^{2}	6.21373×10^{-4}	2.23694	8.05299×10^{3}	2.23694
1 $m\ min^{-2}$ =	2.77778×10^{-4}	1	3.6000×10^{3}	1	1.09361×10^{-2}	3.93700×10^{1}	1.41732×10^{5}	9.11343×10^{-4}	3.28083	5.46806	1.72604	6.21373	2.23694	6.21373
1 $m\ hr^{-2}$ =	7.71605×10^{-8}	2.77778×10^{-4}	1	2.77778×10^{-4}	3.03781×10^{-6}	1.09361×10^{-2}	3.93700×10^{1}	2.53151×10^{1}	9.11343×10^{-4}	1.51890×10^{-5}	4.79454×10^{-11}	1.72604×10^{-7}	6.21373×10^{-4}	1.72604×10^{-7}
1 $m\ hr^{-1}s^{-1}$ =	2.77778	1	3.60000×10^{3}	1	1.09361×10^{-2}	3.9370×10^{1}	1.41732×10^{5}	9.11343×10^{-4}	3.28083	5.46806	1.726035	6.21373	2.23694	6.21373
1 $in.\ s^{-2}$ =	2.54000×10^{-2}	9.14400×10^{1}	3.29184×10^{5}	9.14400×10^{1}	1	3.6000×10^{3}	1.29600×10^{7}	8.33333×10^{-2}	3.00000×10^{2}	5.00000	1.57829×10^{-5}	5.68183×10^{-2}	2.04546×10^{2}	5.60966×10^{-2}
1 $in.\ min^{-2}$ =	7.055556×10^{-6}	2.54000×10^{-2}	9.14400×10^{1}	2.5400×10^{-2}	2.77778×10^{-4}	1	3.60000×10^{3}	2.31481×10^{-5}	8.33333×10^{-2}	1.38889×10^{-3}	4.38413×10^{-9}	1.57829×10^{-5}	5.68183×10^{-2}	1.57829×10^{-5}
1 $in.\ hr^{-2}$ =	1.95988×10^{-9}	7.05556×10^{-6}	2.54000×10^{-2}	7.05556×10^{-6}	7.71605×10^{-8}	2.77778×10^{-4}	1	6.43004×10^{-9}	2.31481×10^{-5}	3.85803×10^{-7}	1.21781×10^{-12}	4.38413×10^{-9}	1.57829×10^{-5}	4.38413×10^{-9}
1 $ft\ s^{-2}$ =	3.04800×10^{-1}	1.09728×10^{3}	3.950208×10^{6}	1.09728×10^{3}	12	4.32000×10^{4}	1.55520×10^{8}	1	3.60000×10^{3}	6.00800×10^{1}	1.89394×10^{-4}	6.81820×10^{-1}	2.45455×10^{3}	6.81820×10^{-1}
1 $ft\ min^{-2}$ =	8.46667×10^{-5}	3.04800×10^{-1}	1.09728×10^{3}	3.04800×10^{-1}	3.33333×10^{-3}	12	4.32000×10^{4}	2.77778×10^{-4}	1	1.66667×10^{-2}	5.26096×10^{-8}	1.89394×10^{-4}	6.81820×10^{-1}	1.89394×10^{-1}
1 $ft\ min^{-1}s^{-1}$ =	5.08000×10^{-3}	1.82880×10^{1}	6.58368×10^{4}	1.82880×10^{1}	2.0000×10^{-1}	7.20000×10^{2}	2.5920×10^{6}	1.66667×10^{-2}	60	1	3.15657×10^{-6}	1.13637×10^{-2}	4.09092×10^{1}	1.13637×10^{-2}
1 $mi\ s^{-2}$ =	1.60934×10^{3}	5.79364×10^{6}	2.71931×10^{10}	5.79364×10^{6}	5.33600×10^{4}	2.28096×10^{8}	8.211456×10^{11}	5.28000×10^{3}	1.90080×10^{7}	3.16800×10^{5}	1	3.6000×10^{3}	1.29600×10^{7}	3.6000×10^{3}
1 $mi\ min^{-2}$ =	4.47040×10^{-1}	1.60934×10^{3}	7.55364×10^{6}	1.60934×10^{3}	1.76000×10^{1}	6.33600×10^{4}	2.28096×10^{8}	1.46667	5.28000×10^{3}	8.8000×10^{1}	2.77778×10^{-4}	1	3.6000×10^{3}	1
1 $mi\ hr^{-2}$ =	1.241778×10^{-4}	4.47040×10^{-1}	2.09823×10^{3}	4.47040×10^{-1}	4.88889×10^{-3}	1.76000×10^{1}	6.33600×10^{4}	4.07407×10^{-4}	1.46667	2.44444×10^{-2}	7.71605×10^{-8}	2.77778×10^{-4}	1	2.77778
1 $mi\ hr^{-1}s^{-1}$ =	4.47040×10^{-4}	1.60934×10^{3}	7.55364×10^{6}	1.60934×10^{3}	1.76000×10^{1}	6.33600×10^{4}	2.28096×10^{8}	1.46667	5.28000×10^{3}	8.80000×10^{1}	2.77778×10^{-4}	1	3.60000×10^{3}	1

special case of plane curvilinear motion in which the object moves in a path of constant radius.

(9) ***Tangential acceleration.*** In curvilinear motion, the tangential acceleration is that component of the total acceleration taken in the direction of the velocity tangent to the path of travel.

(10) ***Normal acceleration.*** In curvilinear motion, the normal acceleration is that component of the total acceleration, taken in a direction perpendicular to the velocity, directed toward the center of curvature of the path of travel.

Displacement, velocity, and acceleration are related as follows (Ref. 1):

(1) Linear (rectilinear):

$$v = dx/dt \tag{6-1}$$

$$a = d^2x/dt^2 = dv/dt \tag{6-2}$$

(2) Angular (rotational):

$$\omega = d\theta/dt \tag{6-3}$$

$$\alpha = d^2\theta/dt^2 = d\omega/dt \tag{6-4}$$

where

x = linear displacement
θ = angular displacement
v = linear velocity
ω = angular velocity
a = linear acceleration
α = angular acceleration
t = time

Newton's second law relating force, mass, and acceleration is expressed as follows:

$$f = ma \tag{6-5}$$

where

f = force (resultant of all forces acting on mass m)
m = mass

6-2.3 LAWS

Objects seldom move with constant velocity. In almost all cases, the velocity of an object is continually changing in magnitude and/or direction. Motion in which the velocity is changing is called accelerated motion, and the time rate at which the velocity changes is by definition acceleration.

(1) ***Acceleration in rectilinear motion.*** The motion of an object is rectilinear when it is confined to a straight-line path. Acceleration then results from a change in the magnitude of the velocity and not in the direction. Under these conditions the acceleration is parallel to the direction of motion with a magnitude given by

$$a = dv/dt \tag{6-2a}$$

where dv/dt is the time derivative of velocity.

(2) ***Acceleration in curvilinear motion.*** The velocity of an object moving along a curved path changes in direction from point to point and may also change in magnitude. It follows, then, that acceleration is always present when an object is undergoing curvilinear motion even though the speed remains constant.

If the velocity of an object undergoing curvilinear motion changes in direction only, the resulting acceleration is perpendicular to the direction of motion and directed toward the center of curvature. Acceleration in any direction other than perpendicular to or parallel to the direction of motion is the result of velocity changing in both magnitude and direction (Ref. 6).

For convenience the total acceleration is usually resolved into two components. One component, a_t, taken in the direction of motion, is tangent to the path of travel and is referred to as the tangential acceleration. The second component, a_n, taken perpendicular to the direction of motion and directed toward the center of curvature, is called the normal or centripetal acceleration.

Treating a short segment of the curvilinear path as an arc of a circle with radius r as diagrammed in Fig. **6-1**, the values of a_n and a_t are given by the following equations:

$$a_n = v^2/r \tag{6-6}$$

where

a_n = normal acceleration
v = linear velocity
r = radius

and

$$a_t = dv/dt \tag{6-7}$$

where a_t = tangential acceleration.

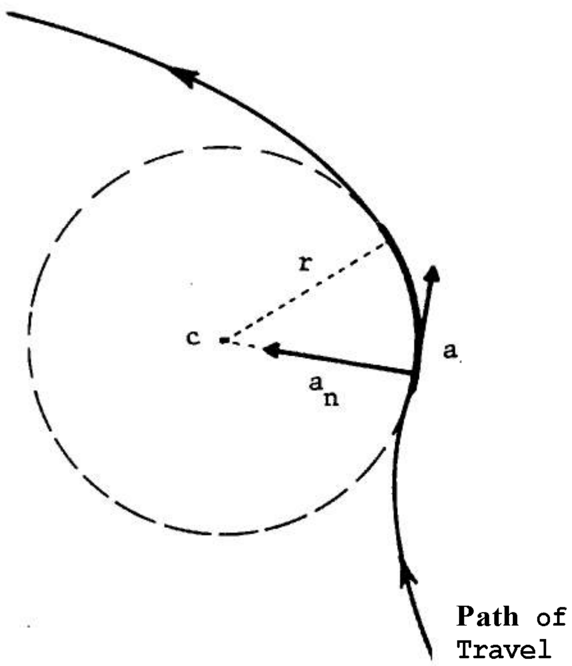

FIGURE 6-1. Tangential and Normal Components of Acceleration.

The total acceleration is the vector sum of the normal and tangential components as illustrated in Fig. 6-2. The magnitude and direction of the acceleration are given by the following equations:

$$a = \sqrt{a_t^2 + a_n^2} \tag{6-8}$$

and

$$\tan \theta = a_t/a_n \tag{6-9}$$

The two extremes of acceleration in curvilinear motion can be stated thusly: (a) when the total acceleration is equal to the tangential acceleration (i.e., the normal acceleration is zero), the object is moving in a straight line, and (b) when the total acceleration is equal to the normal acceleration, the object is in rotary or circular motion.

(3) Acceleration in circular motion. The motion of an object moving in a circle is usually described in terms of angular units. Angular acceleration is the time rate of change of angular velocity as given by the relationship

$$\alpha = d\omega/dt \tag{6-4a}$$

where

α = angular acceleration
$d\omega/dt$ = time rate of change in angular velocity

When radians are used as the unit of angular measure, the relationship between angular acceleration and the tangential component of the linear acceleration is given by the equation

$$a_t = r\alpha \tag{6-10}$$

The normal component of the linear acceleration is given by

$$a_n = r\omega^2 = v^2/r \tag{6-11}$$

since $\omega = v/r$.

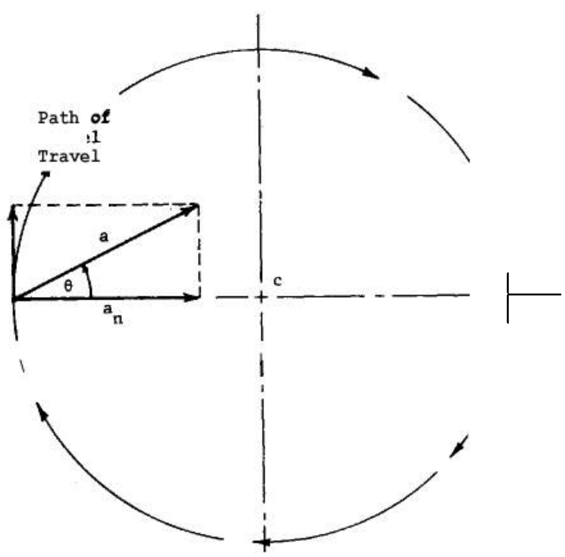

FIGURE 6-2. Total Acceleration as the Vector Sum of the Normal and Tangential Components.

(4) *Accelerationforces.* According to Newton's second law of motion, an object subjected to the action of an unbalanced force will experience an acceleration a proportional to the force f and inversely proportional to the mass m of the object (Ref. 6). This relationship can be expressed by rearranging Eq. 6-5,

$$a = f/m$$

Both a and f are vector quantities. Since the unbalanced force, in this equation, is the resultant of all the unbalanced forces acting on the individual particles of mass composing the object, it must act through the center of gravity of the object (Ref. 5). Rearranging this equation to a form more pertinent to the objectives of this chapter, we can state that an object of mass m constrained to undergo an acceleration a will experience a force f acting through its center of mass, given by Eq. 6-5,

$$f = ma$$

Substituting in Eqs. 6-6 and 6-7 we see that for an object having curvilinear motion there must be a normal effective force given by:

$$f = mv^2/r \quad \textbf{(6-12)}$$

and a tangential effective force

$$f_t = m(dv/dt) \quad (6\text{-}13)$$

6-3 TYPICAL ENVIRONMENTAL LEVELS

When a vehicle accelerates from 0 to 60 mph in 30 s, the acceleration is approximately 2.9 ft s^{-2}; to do so in 10 s, the acceleration is 8.8 ft s^{-2}. In terms of G, these accelerations are 0.09 and 0.27 **G,** respectively. This gives some indication of the nature of the acceleration environment since a high performance automobile can reach 60 mph in 10 s. Commercial aircraft do not exceed these G levels in normal operation. To reach a takeoff speed of 120 mph in 30 s, the acceleration is approximately 0.18 G; in normal flight, the maximum acceleration is from 0.04 to 0.06 G; and in maneuvers such as a turn with a 30-deg bank angle, the maximum acceleration is 0.25 G. Thus, normal accelerations on land vehicles and commercial aircraft will fall below 0.3 G.

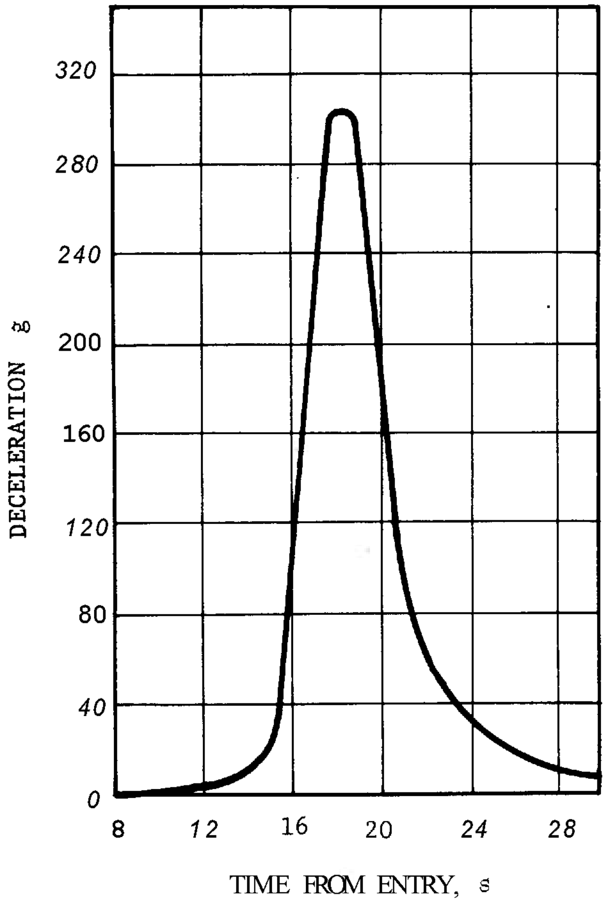

FIGURE 6-3. Venus Entry Deceleration (Ref. 7).

High performance military aircraft experience larger accelerations; e.g., a fighter plane may experience accelerations in excess of 6 G, and space vehicles and missiles similarly experience high sustained acceleration or deceleration. Unmanned rockets can experience greater loads. The deceleration time-history computed for a probe entering the atmosphere of Venus (as per NASA Specification SP 3016) is given in Fig. 6-3 (Ref. 7). The maximum deceleration is approximately 310 G and is sustained for about 1 s; the deceleration is greater than 160 G for about **4** s.

Approximate maximum longitudinal accelerations for the Able series of rockets as derived from engine thrust and vehicle mass characteristics are given in Table 6-2. The data show that the maximum accelerations occur at the end of burning of the third stage boosters. The maximum acceleration experienced by the payload is 30 G for Able-1. Maximum lateral accelerations of 2 to 3 G with accelerations due to vehicle spin of up to 13 G were expected for the Able series of multistage space vehicles (Ref. 8).

TABLE 6-2. ACCELERATION CHARACTERISTICS OF THE ABLE SERIES OF ROCKETS (Ref. 8)

	First stage	Second stage	Third stage	Payload
Able-1 (Pioneer 11)	11 G	7 G	30 G	30 G
Able-3 (Explorer VI)	11	7	13	4
Thor Able-4 (Space)	11	8	20	--
Atlas Able-4 (Lunar)	6	5	7	--

The inability of man to withstand high G values limits the permissible accelerations in manned spacecraft. Values as high as 10 *G* for 10 *s* have been sustained by man in a supine position. For short periods of time, as much as 14 G can be tolerated by conditioned individuals with specialized supporting clothing (Ref. 9). This value is sufficiently high to permit travel into space.

The important loadings to consider when shipping equipment by air transport are the dynamic loadings that occur during turbulent atmospheric conditions. These are differentiated from shock loadings in that they consist of fairly high magnitude accelerations imposed for a prolonged period of time. These accelerations can be as high as 2 to 3 G during normal operation of large transport aircraft (Ref. 10). During evasive actions and emergency landings, higher accelerations can be expected.

6-4 MEASUREMENT

The measurement of acceleration, either to determine the environmental levels of the different modes of transportation or to monitor the acceleration levels applied to a piece of equipment or component during evaluation or acceptance testing, demands a measuring system that is not only rugged, but also meets many other criteria. For example, an ideal measuring system should be able to operate over a wide dynamic range. It must not be significantly affected by spurious inputs. Its characteristics must be stable with time and use, and it must be able to withstand the extreme temperature variations inherent in military applications, such as the testing of missiles and aircraft.

6-4.1 TRANSDUCERS

Requirements of a transducer, in addition to the criteria previously described, are that (a) it must not significantly alter the motion of the structure or component to which it is attached, (b) it must not produce significant errors due to nonacceleration mechanical effects, and (c) it must be convenient to mount on the. **test structure or a component (Ref. 11).**

Most accelerometer transducers measure the force needed to prevent a seismic mass (proof mass) from being accelerated relative, to the case within which it is mounted. The force and acceleration are proportional and, of necessity, in the same direction. Although this principle is common to most accelerometers, a difference exists in their performance in terms of accuracy, sensitivity, frequency response, stability, and consistency in adverse conditions; e.g., humidity, heat, and magnetic fields.

An excellent reference that lists and describes the large variety of acceleration transducers available has been published by the Instrument Society of America (Ref. 12). The more important of these are discussed in the following subparagraphs:

(1)-Potentiometric accelerometers. In this type of transducer, displacement of the force-summing device causes a wiper arm to sweep across a resistance winding. The resistance change produced may be linear, sine, cosine, logarithmic, exponential, etc., depending on the manner in which the resistance wire is wound. Fig. 6-4 illustrates this principle.

Potentiometric-type accelerometers offer high output voltage and, consequently, no signal amplification or impedance matching is necessary. These devices require a large displacement and have a relatively low frequency response of 10 to 20 **Hz.** The unit has high mechanical friction, with the resolution usually represented by a finite number (Ref. 4).

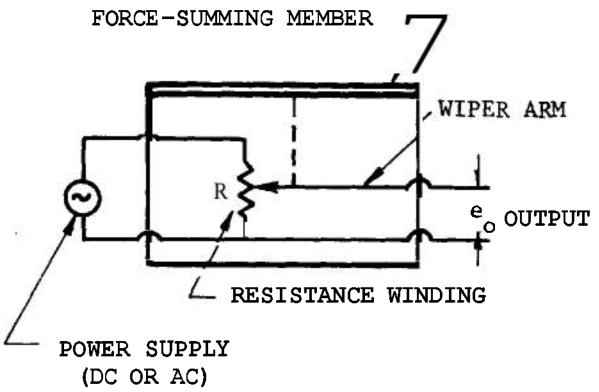

FIGURE 6-4. Potentiometric Accelerometer.

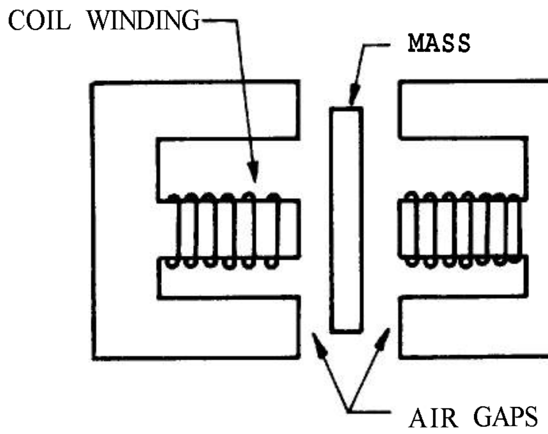

FIGURE 6-5. Inductive Accelerometer.

(2) Inductive accelerometer. A schematic representation of a typical inductance-bridge type of inductive accelerometer is shown in Fig. 6-5. Inductive accelerometers employ a pair of coils connected as a half-bridge (the other half can be a matched pair of resistors) and a magnetically coupled mass. When acceleration acts on the mass, the armature deflects so that the inductance of one coil increases and that of the other coil decreases, making the two inductance changes additive in creating a bridge imbalance.

Inductive accelerometers are used to measure static or dynamic accelerations with high output and essentially continuous resolution (Ref. 4). They have a low frequency response and are susceptible to error in magnetic fields. Inductive accelerometers are used in applications where the upper frequency is 80 Hz or less.

(3) *Vibrating string accelerometer.* A vibrating string accelerometer as illustrated in Fig. 6-6 is sensitive to accelerations along the string axis. Tension differences result, and the natural frequencies (f_1 and f_2) of the two supporting strings vary accordingly (Ref. 13). A transducer using this principle has been used for space booster acceleration telemetry where an overall measurement-system accuracy within ±0.25 percent of full scale was required (Ref. 1).

Elaborate instrumentation is required to obtain insensitivity to cross-axis acceleration and, because the accelerometer is difficult to design and manufacture, it is costly. However, the transducer itself measures the applied acceleration with an error of less than ±0.1 percent of full scale.

(4) *Cantilever beam accelerometer.* A cantilever beam accelerometer as illustrated in Fig. 6-7 has four strain gages bonded to the cantilever beam and is sensitive to acceleration perpendicular to the beam in the bending plane of the beam. The gages are connected as four legs of a Wheatstone bridge, generating an electrical output proportional to acceleration. In actual instruments the housing containing the beam and proof mass is often filled with a damping fluid. Piezoelectric elements such as barium titanate bonded to the beam are as effective as the conventional wire strain gages (Ref. 13).

This type of strain gage accelerometer may be excited by either AC or DC voltage. It offers continuous resolution, and can be used to measure either static or dynamic phenomena.

(5) Piezoelectric accelerometers. The piezoelectric effect is utilized in a variety of transducer designs. The self-generating accelerometer illustrated in Fig. 6-8 uses a piezoelectric crystal in compression to self-generate an output voltage proportional to acceleration. In the spring-mass system consisting of a proof weight pressed against the top of the crystal, a highly compressed soft spring reduces creep instability. Linearity is good over a wide range of accelerations (Ref. 13).

Quartz is the only natural material used extensively in acceleration transducers. Ceramic crystals are used much more frequently than natural crystals (Ref. 1). The first ceramic material used in commercial transducers was barium titanate. Ceramic materials such as lead metaniobate can operate at temperatures up to 570°C. Generally, piezoelectric accelerometers are used when the desired frequency range extends above about 400 Hz.

6-4.2 CALIBRATION METHODS

Constant linear acceleration can be developed by two methods. The first uses the constant gravitational field of the earth; the second uses a horizontal rotary accelerator (Ref. 14). These static methods are commonly used for calibrating linear-acceleration transducers.

Gravitational calibrations use the gravitational field of the earth to apply acceleration levels from 0 to ±1 G to the accelerometer by turning the sensitive axis of the accelerometer through ±90 deg. Fig. 6-9 illustrates the mounting of an accelerometer on a rotatable platform for calibration using gravity. The component of acceleration applied along the sensitive axis of the accelerometer is

$$a = G \sin \theta \qquad (6\text{-}14).$$

where θ is the angle of inclination of the platform.

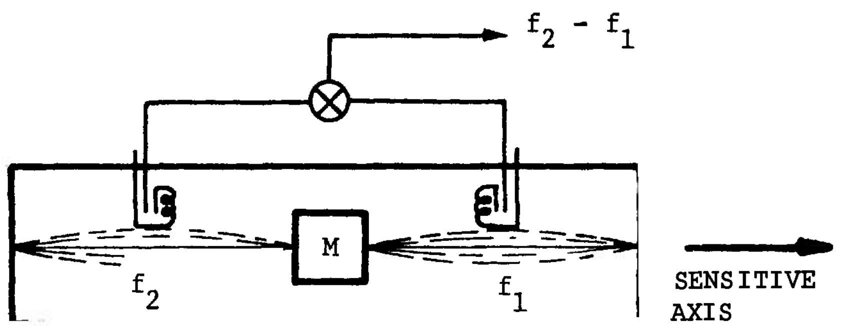

FIGURE 6-6. Vibrating String Accelerometer.

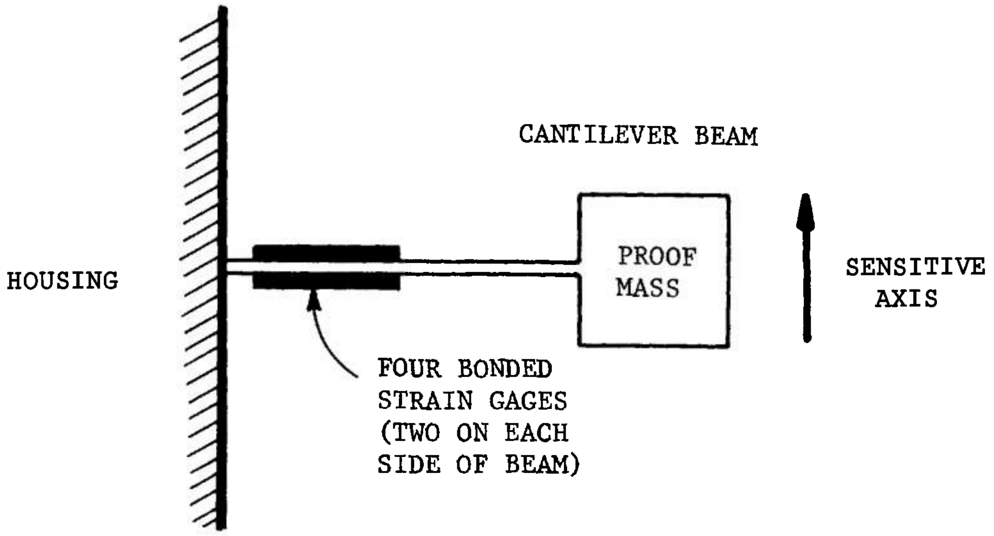

FIGURE 6-7. Cantilever Beam Accelerometer.

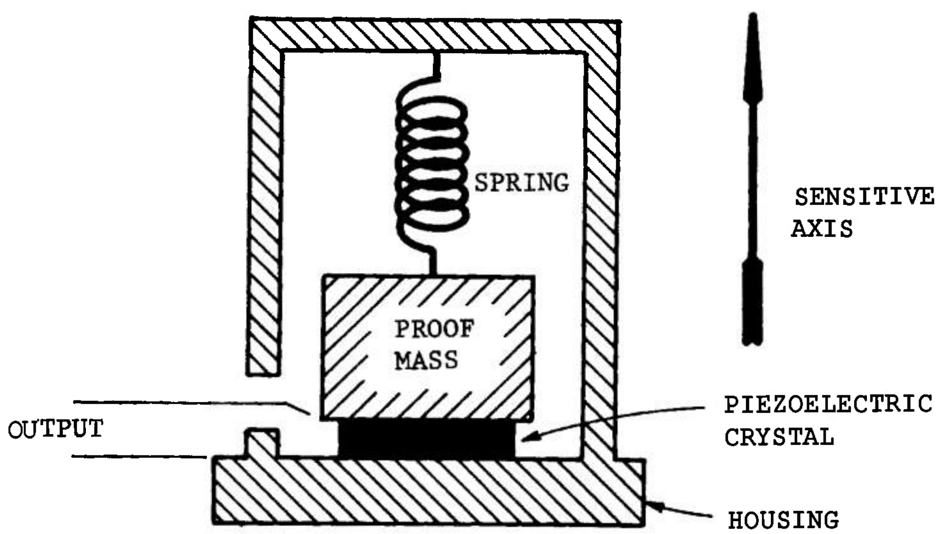

FIGURE 6-8. Piezoelectric Accelerometer.

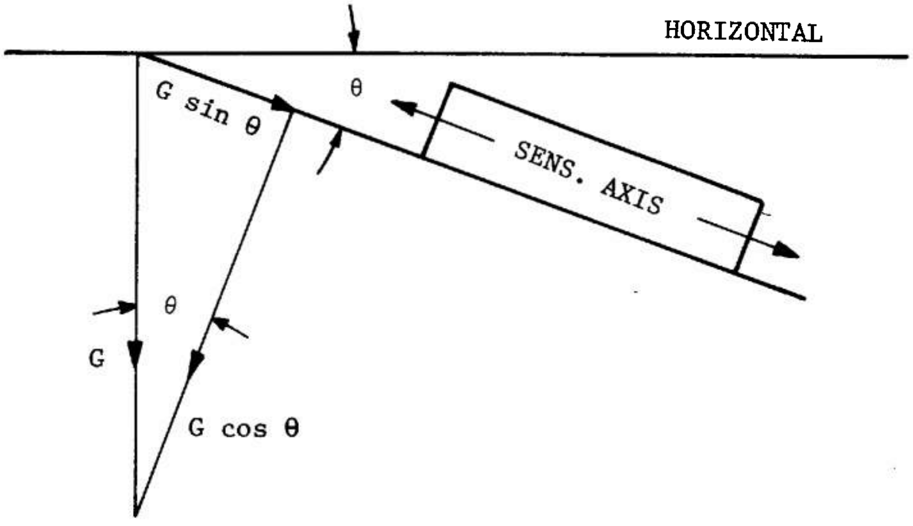

FIGURE 6-9. Gravitational Calibration of Accelerometer.

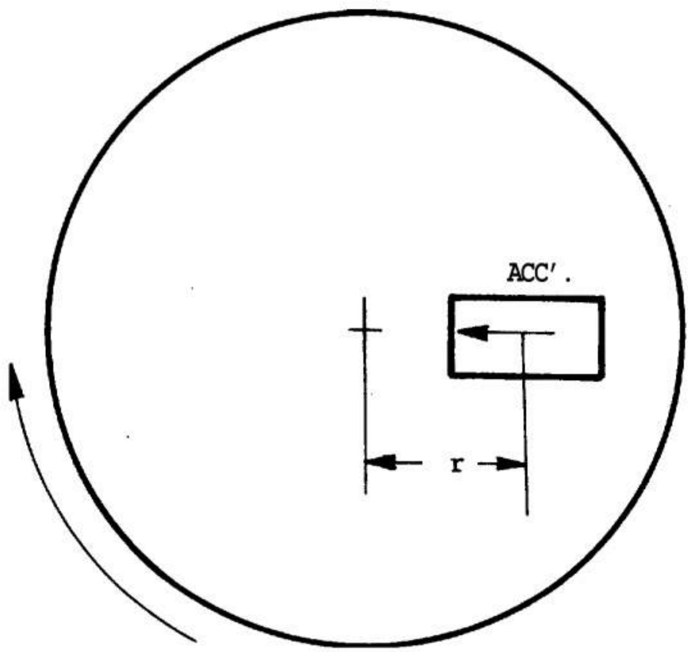

FIGURE 6-10. Accelerometer Mounted on Centrifuge for Calibration.

The second method of applying constant linear acceleration is by a horizontal rotary accelerator or centrifuge. The accelerometer is mounted on the centrifuge (see Fig. 6-10) and subjected to a centripetal (normal) acceleration given by the equation

$$a_n = \omega^2 r \tag{6-15}$$

where

a_n = the centripetal acceleration
ω = the angular velocity
r = the radial distance between the center of the proof mass of the accelerometer and the center of the centrifuge

6-5 EFFECTS OF ACCELERATION

Most items of materiel are designed to operate within a narrow band of acceleration forces centered on the normal gravitational force of 1 G. Many items are designed to utilize this acceleration force—mechanical linkages, liquid transfer systems, friction drive systems, and liquid manometers. When the acceleration differs appreciably from 1 G, these items fail to function properly. Considerable stresses may be set up in the structure of a guided missile system by the acceleration forces resulting from the environmental conditions encountered. These stresses usually determine the strength requirements and thus, ultimately, the type and amount of material used in the construction of the system. However, these requirements imposed by acceleration are normally taken into account in design.

The effects of large acceleration on equipment include structural and mechanical failures, abnormal operation of electron tubes, characteristic changes in vibration isolators, and malfunctions due to deformation of parts (Ref. 9). Typical effects of acceleration on different types of equipment and components are listed in Table 6-3.

Sustained acceleration exists in a dynamic environment when a constant level of acceleration is maintained for an extended length of time. Spacecraft and satellites experience quasi-sustained acceleration while in orbit about the earth, moon, or other celestial bodies. Sustained acceleration forces can range from zero to several G and are for many purposes indistinguishable from an increase or decrease in gravitational fields.

The direction in which acceleration occurs relative to an item is of importance in many cases. An acceleration that reduces G to a value less than 1 can be as important as one that increases it. Deleterious effects of reducing gravity below 1 G are continuous and increase in severity as zero gravity is approached. The effects of zero gravity on equipment include (Ref. 9):

(1) Springs assume new equilibrium positions when their normal preload is due to a supported mass. Shock and vibration isolators change characteristics. Mechanical devices depending on a pendulum or a spring-weight mechanism malfunction.

(2) Gas bubbles will not tend to rise in liquids, normally due to density differences. Hydraulic system may become vapor-locked and pumps may malfunction due to the absence of hydraulic head. Gas bubbles generated in batteries will remain in contact with the plates, thus contaminating active surfaces and degrading electrochemical action.

(3) Liquid-level devices will malfunction. Manometers, for example, will be totally inoperative due to the absence of weight in the indicating fluid.

(4) The convective movement of air due to thermal density gradients will cease. This lack of convective heat transfer presents serious problems in the heating and cooling of equipment (Ref. 16).

(5) Complex mechanisms with direction-sensitive components may malfunction due to the absence of component weight. Thus, equipment that will not function properly in an inverted attitude at 1 G may malfunction in a zero gravity environment.

Materiel requirements are also affected by the biological effects of acceleration forces. Normally, the effects of acceleration on man are described in terms of a coordinate system such that the z-axis is down the spine, the x-axis is front to back, and the y-axis is right to left. Thus, a positive z-axis acceleration, $+G_z$, displaces the heart toward the feet, $+G_x$ displaces the heart against the spine, and $+G_y$ displaces the heart to the left. In Fig. 6-11, the average acceleration tolerance for human subjects is plotted for x- and y-accelerations. It is interesting that the impulse required to achieve earth orbit—measured in G-seconds or G multiplied by seconds (10 G for 30 s is 300 G-s)—is 820 G-s while that required to achieve an escape velocity of 25,000 mph is 1,140 G-s. The actual magnitude and duration of G varies with mission profile (Ref. 16).

The effects of acceleration on human subjects are cardiopulmonary in nature; they are related to heart and lung function and to the displacement of blood in the body and are evidenced by grayout, blackout, or unconsciousness. As can be seen in Fig. 6-11, the body

TABLE 6-3. EFFECT OF ACCELERATION ON MILITARY EQUIPMENT
(Ref. 15)

Item	Effect
Mechanical: moving parts, structures, fasteners	Pins may bend or shear; pins and reeds deflect; shock mounts may break away from mounting base; mating surfaces and finishes may be scoured.
Electronic and electrical	Filament windings may break; items may break away if mounted only by their leads; normally closed pressure contacts may open; normally open pressure contacts may close; closely spaced parts may short.
Electromagnetic	Rotating or sliding devices may be displaced; hinged part may temporarily engage or disengage; windings and cores may be displaced.
Thermally active	Heater wires may break; bimetallic strips can bend; calibration may change.
Finishes	Cracks and blisters may occur.
Materials	Under load, materials may bend, shear, or splinter; glue lines can separate; welds can break.

is very sensitive to the direction of the acceleration, being able to endure five times the acceleration forward compared to downward (Ref. 16).

At the low G forces to which Army personnel are normally exposed, most of these physiological effects are minor, although in aircraft operations accelerations up to 5 G may be encountered.

6-6 METHODS OF PREVENTING ACCELERATION DAMAGE

The primary means of protecting materiel against damage from the acceleration environment is through proper packaging. In order to effectively package an item for shipment or on-board use, the fragility rating

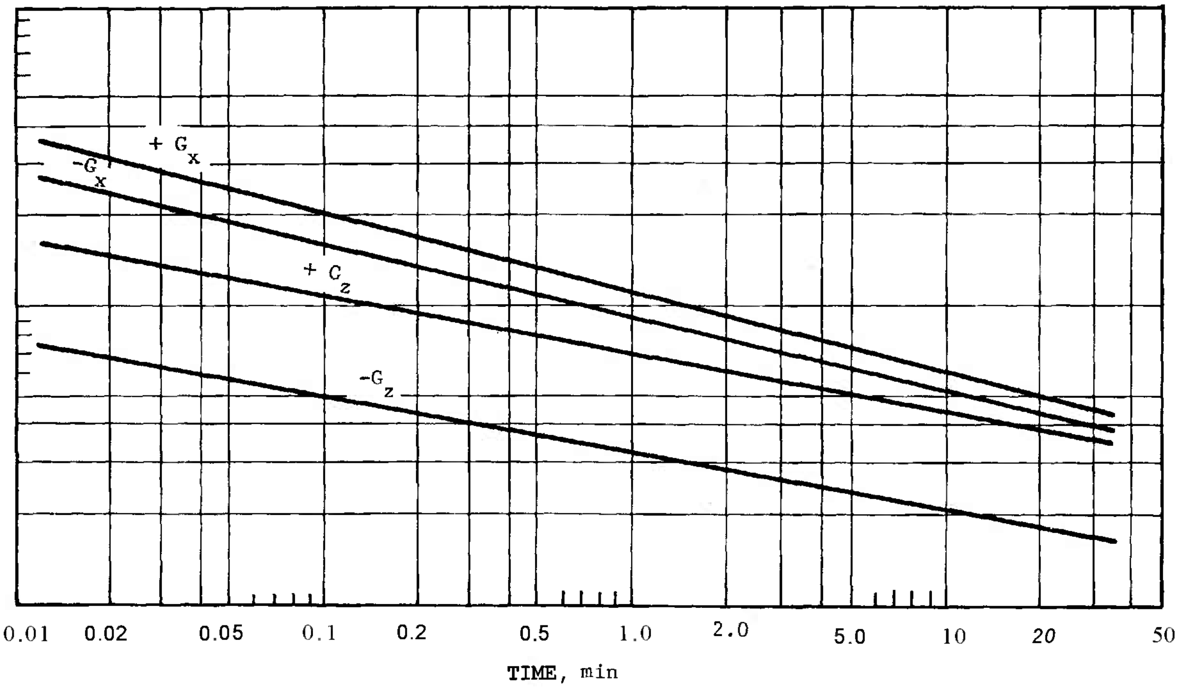

FIGURE 6-11. Crude Comparison of G-tolerances for Human Subjects in Four Vectors of G (Ref. 16).

of the item must be known as well as the environmental levels that are likely to be encountered. The fragility rating of a piece of equipment should be available from the designer or manufacturer. Military packaging techniques and packing requirements are prescribed in AMCP 706-121 (Ref. 10).

Equipment that is a part of or is being transported by space vehicles, where packing per se is not practical, must be designed sturdy enough to survive the environment. One example is that vibration isolators under a high acceleration field can be driven to the limit of their travel, thus rendering them ineffective against the vibration environment. In this situation vibration isolators with nonlinear characteristics should be employed to protect against vibration and/or acceleration.

In general, any design techniques used to preclude damage from the shock environment will also aid in preventing damage due to the acceleration environment. Such techniques include the use of shock mounts, the selection and use of the correct types of materials in terms of weight, strength and flexibility, and proper structural mounting of component parts. For a more detailed discussion see Chap. 5 of this handbook.

As rockets, satellites, and space vehicles become larger, more powerful, and more numerous, the importance of designing equipment to operate in a zero-G environment will increase. The designer of such equipment must be aware of and compensate for the fact that weight forces do not exist; hence, liquids with a free surface, or ullage, have no hydrostatic head and, consequently, buoyancy and natural connections do not exist. This poses a multitude of problems of design in the many systems of a space vehicle that utilize fluids. Some of these are pumping fluids from point to point, restarts of propulsion devices with partially filled tanks, lubrication systems that require a constant flow of a cooling fluid. In short, all the effects given in par. 6-5 must be compensated for or designed out of the system.

6-7 ACCELERATION TESTS

Acceleration tests are necessary to insure that equipment (packaged or unpackaged) will survive the handling, transportation, and service acceleration environments that it is likely to encounter during its life cycle. Acceleration tests are carried out on centrifuges or track and rocket sled. Because it is not possible, in all cases, to reproduce the exact natural environment with either a rocket sled or centrifuge alone, it may be necessary to employ a combination of tests for a full investigation of the physical processes leading to the degradation or failure of the equipment being tested. The test parameters that may affect the type and degree of failure are (1) acceleration level, (2) time duration of the test, (3) jerk, i.e., rate of change of acceleration, and (4) direction of acceleration.

Perhaps the simplest means of simulating a zero-G environment is by placing the specimen in free fall (Ref. 17). However, simply dropping the specimen through the atmosphere is inadequate since the buildup of air drag rapidly results in the disappearance of the force. To surmount this problem, the specimen container is placed in a second container or blast shield. Most such facilities are limited to approximately 10 s, which restricts the specimen volume to a few cubic centimeters.

To increase the duration of the zero-G periods, aircraft flying a parabolic flight path have been utilized. The aircraft goes into a shallow dive to build up airspeed, then makes a 2.5-G pullup to start the zero-G portion of the flight which continues over the top of the parabola and downward until the airspeed builds up to certain limits at which time a 2.5-G pullout is executed and the aircraft resumes normal flight. Periods of weightlessness in excess of 40 s have been achieved in this manner (Ref. 18).

For packaged equipment, insofar as the package exterior is concerned, acceleration loads could be represented by static loading. However, for complex packages and containers and for packages with isolation systems, a static load test cannot simulate the relationship between package and contents (Ref. 19). If this relationship is believed to be critical to the performance of the package, an acceleration test must be performed to evaluate the transportability of the package. Of course, the test must be conducted on the complete package (i.e., with the actual or simulated contents in place) to achieve valid results.

In simulating a linear acceleration by means of a rotary accelerator or centrifuge, the test item must be mounted so that the resulting force will be in the proper direction. A component, package, or system mounted or stored in a vehicle whose direction of motion is as shown in Fig. 6-12, must be mounted on the centrifuge as shown in Fig. 6-13 in order to achieve a valid test (Ref. 20).

Two disadvantages hinder the simulation of a linear acceleration with a Centrifuge. One is that any deviation in angular velocity results in a tangential acceleration, which in effect changes the magnitude and direc-

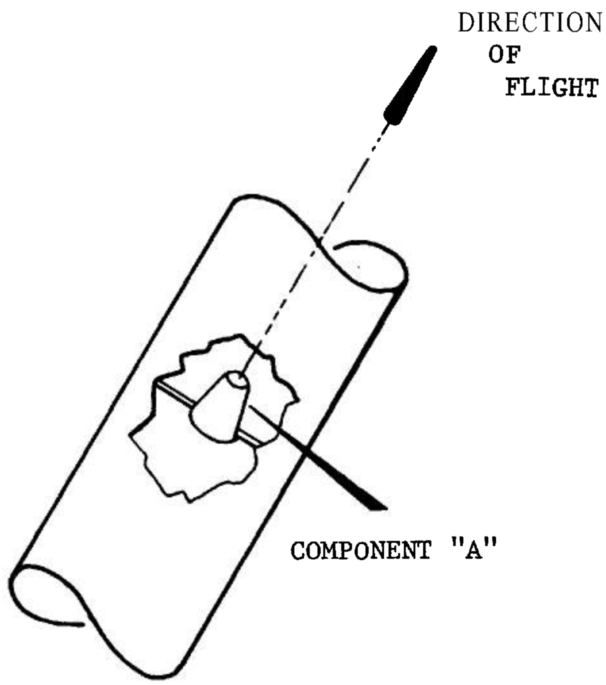

FIGURE 6-12. Component Mounted on a Vehicle in Motion (Ref. 20).

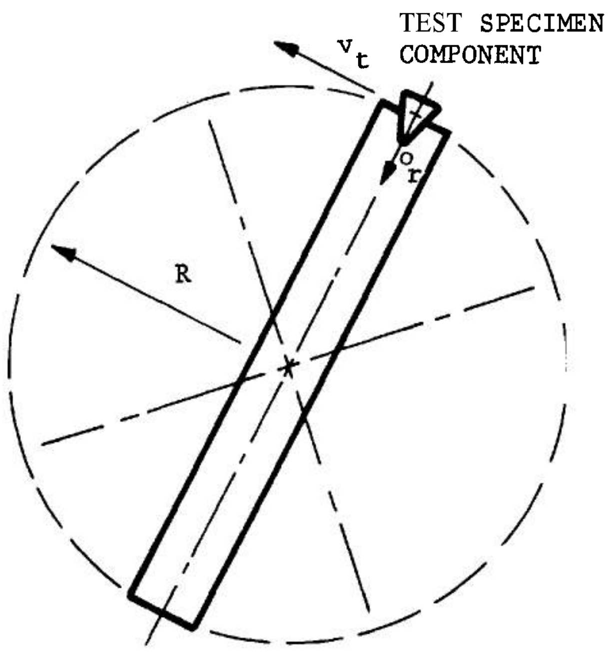

FIGURE 6-13. Proper Mounting of Test Specimen on Centrifuge (Component "A" in fig. 6-12) (Ref. 20).

tion of the resultant acceleration force on the test item. The second and perhaps the most serious disadvantage is that an acceleration gradient develops across the test specimen as a result of the increasing radius arm from front to rear of the test item.

In testing equipment such as gyroscopes, inherently sensitive to angular rotation, a counter-rotated centrifuge is particularly useful. It consists of a small satellite platform, mounted on the main arm of the centrifuge and arranged so that the angular velocity of the small turntable is zero relative to the earth while it orbits about the vertical axis of the centrifuge. This machine can be used to subject test items to an acceleration field that varies sinusoidally in amplitude at relatively low frequencies and is used for dynamically calibrating test instruments.

An alternate method of developing sustained acceleration for relatively short periods is to use one of the linear acceleration test devices, such as the rocket-powered sled at Holloman Air Force Base (Ref. 9). These devices permit linear acceleration and deceleration with relatively large payloads and have the advantage of a zero acceleration gradient across the test package. This advantage is outweighed for most applications by the short acceleration periods available, the large space requirements, and the cost of the test apparatus. For example, the test vehicle must include space for all sled-borne measuring equipment and provision must be made for instrument protection against shock, heat, windblast, and other extreme environmental conditions. Vibration isolation of the instrumentation is often necessary as well.

In some instances it may be desirable to perform acceleration and vibration testing simultaneously. This can be accomplished in either of two ways: a vibrator can be mounted on a centrifuge, or a specially designed centrifuge may be placed on a vibration table.

TABLE 6-4. G LEVELS FOR STRUCTURAL TEST (Ref. 21)

Vehicle category		Direction				
		Fore	Aft	Up	Down	Lateral
Aircraft and helicopters		9.0	3.0	4.5	13.5	6.0
Manned aerospace vehicles		9.0 to 18.0	3.0 to 6.0	4.5 to 9.0	13.5 to 27.0	6.0 to 12.0
Air launched missiles		13.5 to 45.0	4.5 to 15.0	7.0 to 23.0	20.0 to 23.0	4.5 to 30.0
Ground launched missiles	Liquid boosters	9.0 to 18.0	3.0 to 6.0	--	--	6.0 to 12.0
	Solid boosters	9.0 to 45.0	3.0 to 15.0	--	--	6.0 to 30.0

TABLE 6-5. G LEVELS FOR OPERATIONAL TEST (Ref. 21)

Vehicle category		Direction				
		Fore	Aft	Up	Down	Lateral
Aircraft and helicopters		6.0	2.0	3.0	9.0	4.0
Manned aerospace vehicles		6.0 to 12.0	2.0 to 4.0	3.0 to 6.0	9.0 to 18.0	4.0 to 8.0
Air launched missiles		9.0 to 30.0	3.0 to 10.0	4.5 to 15.0	13.5 to 45.0	6.0 to 20.0
Ground launched missiles	Liquid boosters	6.0 to 12.0	2.0 to 4.0	--	--	4.0 to 8.0
	Solid boosters	6.0 to 30.0	2.0 to 10.0	--	--	4.0 to 20.0

6-8 SPECIFICATIONS

MIL-STD-810 Method 513.1 (Ref. 21) requires that the item be tested either on a centrifuge or on a track and rocket sled facility. If the peak forward acceleration A of the particular vehicle is known, and the specific orientation of the item relative to the vehicle is known, the item is tested for 1 min in each of six directions. If A is unknown, a value of 2.0 G is to be assumed for A and, if the orientation is unknown, all six directions are to be tested at the most severe level (i.e., 6.75 A for airplanes and 5.25 A for helicopters). The required acceleration levels for nonoperating structural testing are given in Table 6-4. Those for operational testing are given in Table 6-5.

MIL-STD-202, Method 212 (Ref. 22), requires that electronic and electrical components be tested on a centrifuge. The item is subjected to one of three possible test conditions as specified for that item. One test condition specified 5-min acceleration in each sense of three mutually perpendicular directions for a total of 30 min at either 17, 50, or 100 G. Another test condition specifies a 1-min acceleration at nominally 10,000 or 20,000 G. The third test condition specifies that the specimen be subjected to the value of acceleration specified in the individual specification for 10 min in each sense of three mutually perpendicular directions.

6-9 TEST FACILITIES

Numerous acceleration test facilities are located throughout the United States. The trend in recent years has been toward combined environmental testing. The following five acceleration facilities were listed as representing the ultimate combined environmental capability in the country by Begg and Sando (Ref. 23) in 1966.

(1) ***Edwards Air Force Base, Calif. Combined Environmental Test Facility***

Arm radius = 22-ft radius
Max. acceleration = 55 G
Max. payload = 30,000 lb
Vibration = 5,000 ft-lb, 20 to 3,000 Hz sine and random, at 32 G radial

Environmental chamber = Temp. range of –300" to +500°F, 300,000 ft altitude 3 X 3 X 4 ft test specimen
Main drive = Hydraulic (400 HP)
G-lb rating = 1,000,000 G-lb
Humidity = 50 to 95% RH

(2) ***Goddard Space Flight Center, Greenbelt, Md. Launch Phase Simulator***
Arm radius = 60.0-ft radius (178.0-ft pit diameter)
Max. acceleration = 30.0 G
Payload = 5,000 lb 10.0 ft D X 15.0 ft L Agena-Centaur and Titan Class satellite packages upgrading capability for newer systems.
Main drive = Two 1250 HP DC direct drive motors. Capability of adding two additional 1250 HP motors.
Acoustic = 150 dB, 100 to 12,000 Hz Air modulator type sound generator
Vibration = Hydraulic in 3 deg of freedom

(3) ***Manned Spacecraft Center, Houston, Tex. "The Flight Acceleration Facility"*** (A Man-Rated System)
Arm radius = 50.0-ft radius
Max. onset = 10 G-s
Max. acceleration = 30.0 G
Payload = Three Apollo astronauts with full flight equipment (3,000 lb)
1st axis gimbal = 30 rpm, Static load on 1st axis is in excess of 27,000 lb
2nd axis gimbal = 30 rpm
Gondola size = 12.0-ft diameter
Environments:
Temp. = 40° to 200°F
Altitude = 125,000 ft
Humidity = 5 to 95% RH
Vibration = None at present. Study has been made to add 1 or 2 axis vibration.
Main drive = 6,700 HP DC direct drive continuous duty
Control = Two 4,000 word, 24 bit digital computers with memory exchange unit.
Data acquisition = 630 sliprings and pulse coded modulation for environmental and physiological monitoring.

(4) ***Sandia Corporation, Albuquerque, N. Mex. 25-ft Radius, 300-G Centrifuge Facility***
Arm radius = 25-ft radius
Max. acceleration = 300 G
Main drive = Hydraulic, 1300 HP
Vibration capability = Two 7,500 electrodynamic exciters physically coupled and driven push-pull. A hydrostatic bearing slip table supports exciters' coupling and reacts acceleration load. The gross weight of the vibration system is 15,000 lb and the system is designed to take 100 lb package to 50 G sine in 100-G constant acceleration field.
Test specimen size = 18 X 18 X 18 in.
Other environments = None
G-lb rating of centrifuge = 1,600,000 G-lb

(5) ***Wright Field, Dayton, Ohio Dynamic Escape Simulator*** (A Man-Rated System)
Arm radius = 19.5-ft radius
Max. acceleration = 20 G (55 rpm)
Onset capability = 10 G-s (20 G max.)
Main drive = 330 HP DC
1st axis gimbal = 30 rpm max
2nd axis gimbal = 150 rpm max
Degrees of motion within cab = 6 deg of freedom, hydraulic drive

		±6.0 in. vertical
		±3.0 in. horizontal
		±3.0 in. longitudinal
		±18 deg roll
		±30 deg pitch
		±3 deg yaw
Type of control	=	Digital, 18 bit, 4,000 word memory, minimum cycle time 10 μs. Pilot is passive element only in control system.
Cab environments	=	5-95% RH 40° to 12°F 3 psig to 12 psia

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CHAPTER 7

ACOUSTICS [1]

7-1 INTRODUCTION

Acoustics is the science of sound. In the broadest sense, acoustics deals with the production, control, transmission, reception, and effects of sound. Each of these aspects of acoustics is an important subject area, but full treatment of any one of them is beyond the scope of this chapter. The content of this chapter is restricted to airborne sound, its measurement, and its effects on man and materiel, i.e., acoustics as an induced environmental factor.

By far the most significant aspect of sound to man is its relationship to communication by speech and hearing. Speech and its accurate perception are absolutely essential to the normal existence of man; that speech perception is adversely affected by excessive noise or by hearing loss is obvious. Consequently, every reasonable effort must be made to insure that the probability of inadvertent hearing loss is minimized. Much of this chapter is concerned with this aspect of acoustics—the effects of unwanted (and often intense) sound on hearing and the possible ways to limit exposure to unwanted sound.

Above certain sound intensity limits, exposure to sound has physical and physiological effects in addition to its effects on hearing. Sufficiently intense airborne sound can destroy materiel and kill exposed personnel; this is not surprising since sound consists of rapid variations in air pressure. These nonaural effects of sound are discussed in par. 7-6.

7-1.1 DEFINITIONS AND UNITS

Airborne sound refers to a rapid variation in ambient atmospheric pressure. By definition, noise is unwanted sound. ***Steady-state*** sound is a periodic or random variation in atmospheric pressure having a duration in excess of 1 s. An impulse sound is a nonperiodic variation in atmospheric pressure having a duration of less than 1 s, and a peak to root-mean-square (rms) pressure ratio greater than 10 dB. *Blast* is a poorly defined term most frequently used to describe very large amplitude, long-duration pressure waves accompanying the discharge of large-caliber weapons, the ignition of rocket motors, or the detonation of conventional and nuclear explosives. Taken together, sound, noise, and blast all refer to airborne acoustical phenomena whose energy may be described both in terms of their physical characteristics (amplitude, frequency content, and duration) and their effects on human physiology and behavior. Some common terms and units used in physical and psychological acoustics are shown in Table 7-1.

Definitions of physical characteristics follow:

(1) Amplitude. The amplitude of sound at any given point is expressed as sound-pressure level (SPL). Its physical unit is the decibel (dB), given as:

$$SPL = 20 \log (p/p_0), \text{ dB} \qquad (7\text{-}1)$$

where

p = sound pressure being measured, $\mu N\ m^{-2}$

p_0 = a reference pressure, usually 20 micronewtons per square meter, $\mu N\ m^{-2}$

The reference pressure of 20 $\mu N\ m^{-2}$ is approximately equal to the lowest pressure that a young person with normal hearing can barely detect at a frequency of 1,000 Hz. Other measures of sound pressure are encountered in the literature, such as dynes per square centimeter (dyn cm^{-2}), microbars (μbar), and pounds per square inch (psi). Table 7-2 shows the relationship between four such measures.

Common examples of representative SPL include:

(2) *Speed*. The speed of sound is dependent only upon the absolute temperature of the air, assuming that air behaves as an ideal gas. The equation for the speed of sound C in metric units is

$$C = 20.05\sqrt{T}, \text{ m sec}^{-1} \qquad (7\text{-}2)$$

where

T = absolute temperature in kelvins (273.2 plus the temperature in degrees Celsius). Thus the speed of sound at 21.1°C is about 344 m s^{-1}

1. **This chapter is based on a report on noise and blast by D. C. Hodge and G. R. Garinther of the Human Engineering Laboratory, Aberdeen Proving Ground, Md. (Ref. 1).**

TABLE 7-1. TERMS AND UNITS USED IN ACOUSTICS

Physical		Psychological	
Term	Unit	Term	Unit
Frequency	Hertz (Hz)	Pitch	Mel
Amplitude	Decibel (dB) re 20 μN m^{-2} Newtons/meter^2 (N m^{-2}) Dynes/centimeter^2 (dyn cm^{-2}) Microbar (μbar) Pounds/inch^2 (psi)	Loudness	Phon Sone
Duration	Seconds; minutes	Duration	Seconds; minutes

In English units

$$C = 49.03\sqrt{R}, \text{ ft sec}^{-1} \qquad (7\text{-}3)$$

where

R = temperature in degrees Rankine (459.7 plus the temperature in degrees Fahrenheit). At 70°F the speed of sound at sea level is about 1,128 ft s^{-1}.

(3) Wavelength. The wavelength λ of a sound is the distance the wave travels during one period or cycle. It is related to the speed of sound and to frequency by the equation

$$\lambda = C/f \qquad (7\text{-}4)$$

where

C = speed of sound, m s^{-1} or ft s^{-1}
f = frequency, Hz

For example, during one period a 100-Hz wave would move 3.44 m or 113 ft at 70°F (21.1°C). From Eq. 7-4, as frequency increases, wavelength becomes shorter.

(4) Frequency. The unit of frequency is hertz (Hz); i.e., cycles per second. Nominally, the human range of aurally detectable sounds is 20 to 20,000 Hz. Pressure oscillations at frequencies above this range are called ultrasonic waves or ultrasound. These frequencies cannot be heard by man, but at high SPL they produce some biological effects and are discussed in a later paragraph. The effects of infrasonic frequencies (< 20 Hz) are also covered briefly. The terms "supersonic" and "subsonic", which are related to the speed of sound, should not be confused with those terms when used to describe frequency range.

When describing sound, measuring only the overall SPL is not sufficient. The sound must also be analyzed to determine how the sound energy is distributed over the frequency range. A sound is usually analyzed by passing it through a constant-percentage bandwidth filter, such as an octave-band analyzer, in which each passband has upper and lower limiting frequencies having a ratio of 2:1. An octave-band analysis is usually sufficient to determine the effect of steady-state noise upon human beings and the surrounding community. A 1/3-octave (or narrower) analysis is required when localizing the component in a system that is the major contributor to a noise problem, or if the noise contains a pronounced narrow-band frequency component.

The "preferred" series of octave bands for acoustical measurements is identified as multiples and submultiples of 1,000 Hz, which describe the center frequency

TABLE 7-2. RELATIONSHIP BETWEEN UNITS OF SOUND PRESSURE*

dB	N m^{-2}	μbar†	psi
0	0.00002	0.0002	2.94 x 10^{-9}
14	0.0001	0.001	14.70 x 10^{-9}
34	0.001	0.01	1.47 x 10^{-9}
54	0.01	0.1	1.47 x 10^{-6}
74	0.1	1	14.70 x 10^{-6}
94	1	10	147.0 x 10^{-6}
114	10	100	1.47 x 10^{-3}
134	100	1,000	14.70 x 10^{-3}
154	1,000	10,000	147.0 x 10^{-3}
174	10,000	100,000	1.47

*All quantities in same row are equal.
†Also note that 1 μbar = 1 dyn cm^{-2}.

of each band. Another series of octave bands that has been widely used in the past is the "commercial" octave bands. These are normally described by their band-limiting frequencies. Table **7-3** compares the commercial and preferred octave bands in terms of their center and limiting frequencies.

Another type of frequency analysis that is gaining importance is the "weighting network", included in all sound-level meters that meet the requirements of the ANSI Standard for Sound Level Meters (Ref. **2).** The weighting networks consist of three alternate frequency-response characteristics, designated A-, B-, and C-weighting, as illustrated in Fig. **7-1.**[2] These characteristics are implemented by electronic filters that for a constant amplitude sound level give the indicated relative sound level measurements as are presented in the figure. Whenever one of these networks is used, the reading obtained must be identified properly. For instance, if an, A-weighted sound level of 90 is obtained, it would be reported as 90 dBA. The A-weighting network is particularly valuable if a quick estimate of the interference of noise upon speech communication is required (Ref. 5). Also, a trend has recently developed toward using the A-weighting network for evaluating the hearing hazard of steady-state noise when it is not possible or practical to perform a complete octave-band analysis (Refs. 6,7).

2. These frequency response curves are derived from the sensitivity characteristics of the normal ear as functions of frequency and loudness level; see Ref. 8 for details.

(5) Definitions peculiar to impulse noise and blast:

(a) Peak pressure level. The highest pressure level achieved, expressed in dB (*re* 20 μN m^{-2}) or in psi.

(b) Rise time. The time taken for the single pressure fluctuation that forms the initial or principal positive peak to increase from ambient pressure to the peak pressure level.

(c) Pressure wave duration (A-duration). The time required for the initial or principal pressure wave to rise to its positive peak and return momentarily to ambient.

(d) Pressure envelope duration (B-duration). The total time that the envelope of pressure fluctuations (positive and negative) is within **20** dB of the peak pressure level. Included in this time is the duration of that part of any reflection pattern that is within 20 dB of the peak level.

(6) ***Psychological*** terms. The measures of loudness are the ***phon*** and the ***sone.*** Sones are obtained by a conversion of eight octave bands into sones from an appropriate table. The phon is merely a transformation of the sone into a logarithmic scale. Sounds that are perceived as equally loud to the human ear will have the same sone or phon value. The *mel* is used as a subjective measure of the pitch differences in frequency between sounds.

7-1.2 PROPAGATION OF SOUND

In an ideal, homogeneous, loss-free atmosphere, SPL decreases, through spherical divergence, inversely with distance in the far field. That is, a 6-dB decrease in SPL occurs for each doubling of distance from the source. In addition, when sound travels through still, homogeneous air, a significant amount of energy is extracted through "molecular absorption", a phenomenon related to the relaxation behavior of gas molecules. This "excess attenuation" depends not only on frequency, but also on temperature and humidity, and is in addition to losses resulting from spherical divergence. Fig. **7-2** shows engineering estimates of excess attenuation as a function of distance and frequency for air temperatures ranging from 0° to 100°F and over a relative humidity range from 10 to 90 percent. Data are given for the preferred octave bands ranging from 500 to 8,000 Hz. While some absorption occurs in the lower bands, it can usually be neglected. A more nearly complete discussion of atmospheric absorption is given in a report by the Society of Automotive Engineers (Ref. 9). In certain cases, "classical absorption" should also be considered. This encompasses those losses due to

TABLE 7-3. CENTER AND LIMITING FREQUENCIES FOR OCTAVE-BAND ANALYZERS

Commercial frequencies ANSI 224.10 (Ref. 3)		Preferred frequencies ANSI S1.6 (Ref. 4)	
Octave-band limits, Hz	Center frequency, Hz	Octave-band limits, Hz	Center frequency, Hz
37.5 - 75	53	44 - 87	63
75 - 150	106	87 - 175	125
150 - 300	212	175 - 350	250
300 - 600	425	350 - 700	500
600 - 1,200	850	700 - 1,400	1,000
1,200 - 2,400	1,700	1,400 - 2,800	2,000
2,400 - 4,800	3,400	2,800 - 5,600	4,000
4,800 - 9,600	6,800	5,600 - 11,200	8,000

*Higher or lower preferred frequencies are obtained by successive multiplication or division by a factor of 2.

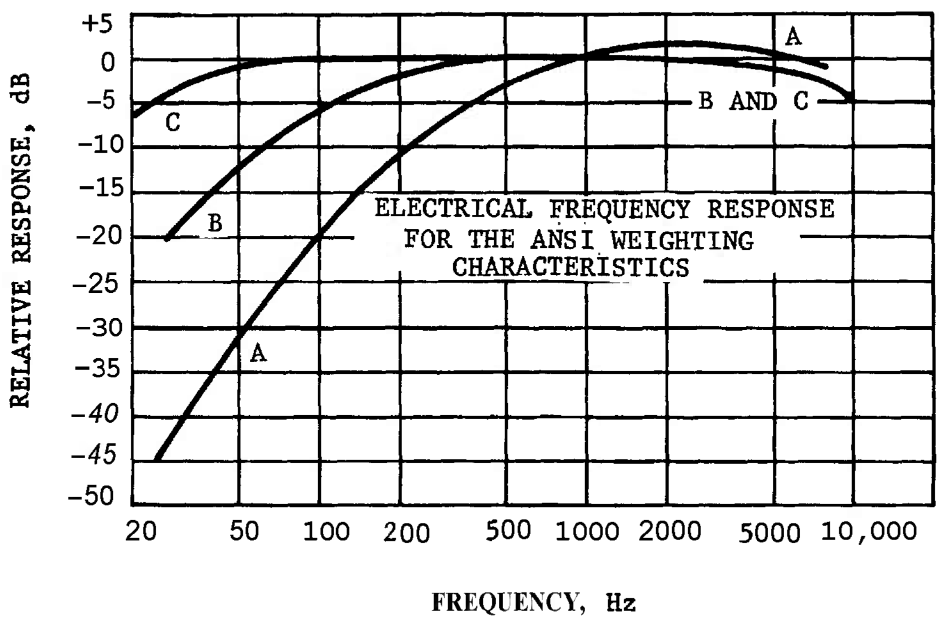


FIGURE 7-1. Frequency-response Characteristics for Standard Sound-level Meters (Ref. 2).

inertial and frictional forces involved in molecular motion. Classical absorption is proportional to the frequency squared, is independent of humidity, and, typically, has many fewer effects than those of molecular absorption (Ref. 10).

In addition to the preceding, the refraction of sound waves produced by meteorological conditions between the surface of the earth and altitudes of 3 to **4** km is sometimes significant. This phenomenon may cause sound waves produced at or near the surface of the earth to be focused in areas removed some distance from the sound source. This refraction is due to changes in speed of sound with altitude resulting from variations in temperature, humidity, and wind with altitude. The SPL for various refraction conditions and their focal points may be calculated by a modified ray-acoustic method if the directivity characteristics of the source are known. Experience has shown that the effects of refraction and focusing do not often occur (except in regions where thermal inversions occur frequently), and the SPL approaches that predicted for a homogeneous medium. For example, although the conditions causing focusing do sometimes occur in the Cape Kennedy, Fla., area, they are not prevalent (Ref. 11).

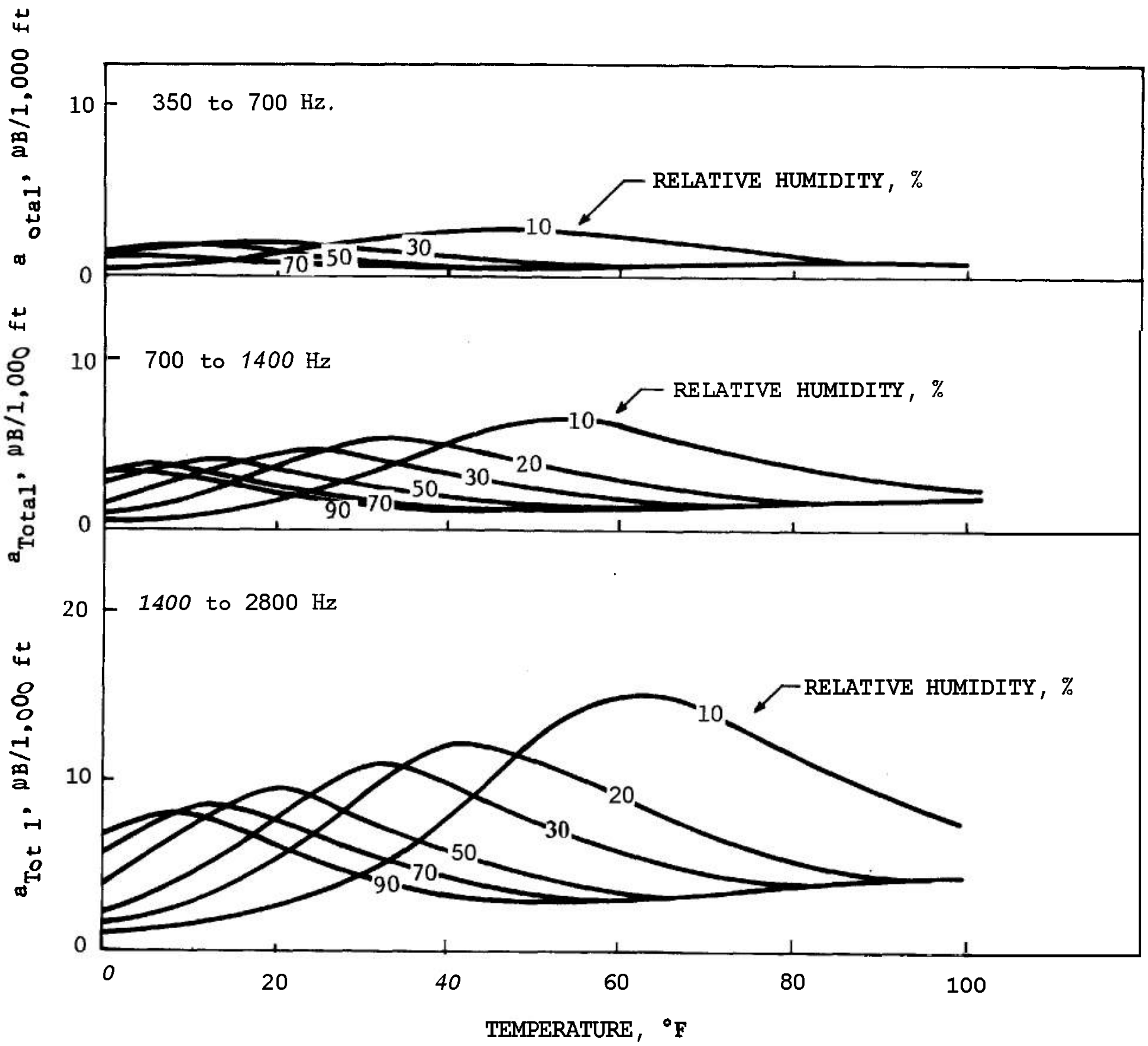


FIGURE 7-2. Atmospheric Absorption Coefficients for Octave Bands of Noise for Different Temperatures (Ref. 9).

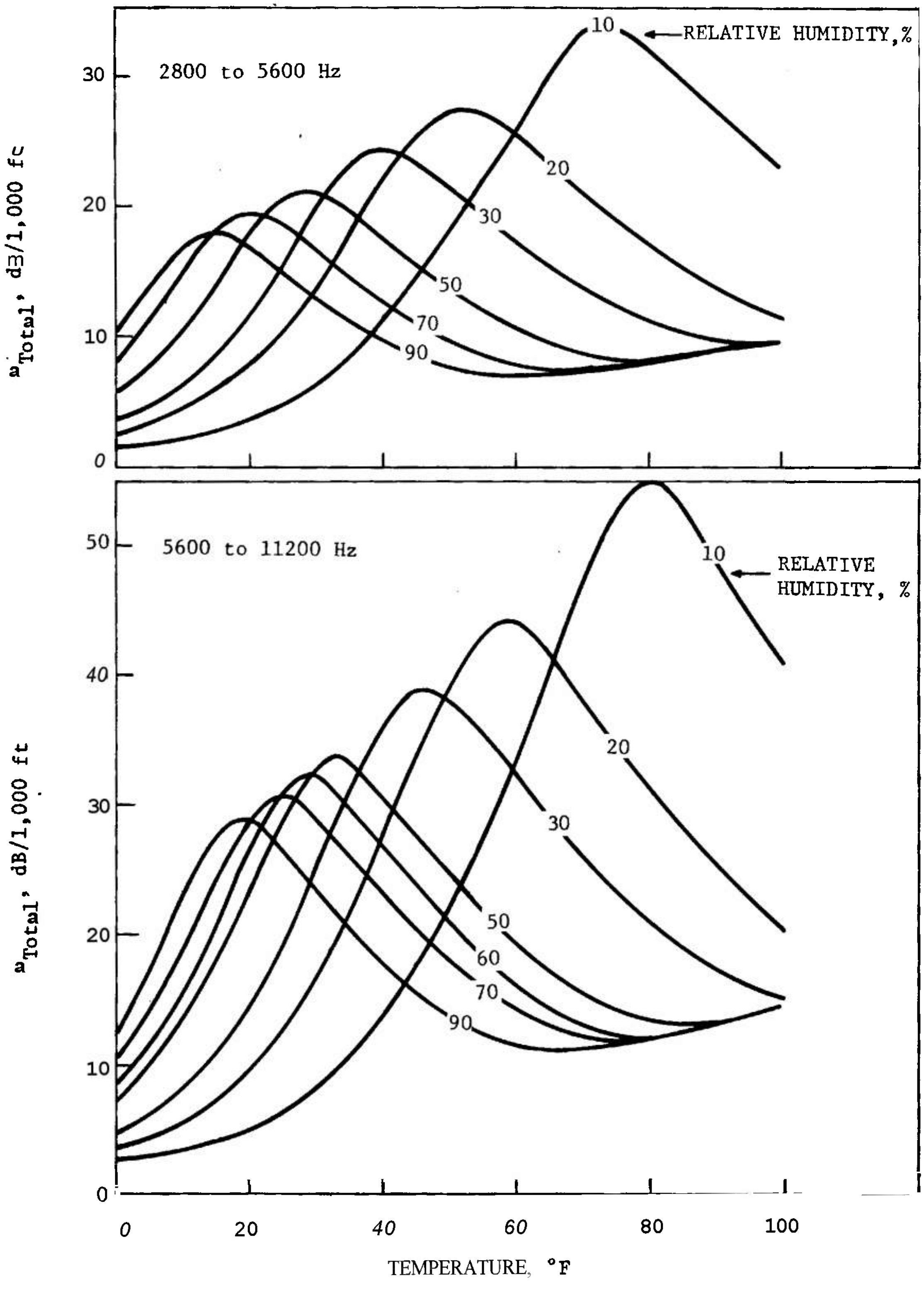


FIGURE 7-2 (continued). Atmospheric Absorption Coefficients for Octave Bands of Noise for Different Temperatures (Ref 9).

7-1.3 THE ARMY'S ACOUSTIC ENVIRONMENT

Sound-pressure levels of interest in the Army's acoustic environment cover roughly 20 decimal orders of magnitude, i.e., a 200-dB range. Extremely low environmental SPL's, in the range 0 to 20 dB, are of interest in nighttime clandestine operations in remote areas, while the firing of a large artillery piece will produce peak pressures in the crew area near 190 dB SPL. The hearing threshold of some young adults at certain frequencies (around 2,000 Hz) is — 10 dB SPL; such acute hearing is a substantial asset for night sentry duty in a war zone.

Any common Army ***small arm*** (all arms up to and including cal .60 and shotguns) produces impulse noise levels in excess of 140 dB SPL (see Ref. 12). That such levels of impulse noise constitute a potential hazard to hearing is well established. Most if not all of the mechanized equipment in the Army produces steady-state noise environments that can interfere with direct person-to-person communication, i.e., sounds in the speech frequency range that are over 60 dB SPL at the listener's ears. Many mechanized items produce sufficient steady-state noise to be potentially hazardous to hearing. Table 7-4 summarizes some sound levels and their sources in the Army setting. The significance of the various sound levels is also indicated.

7-2 MEASUREMENT OF SOUND[3]

The basic measuring system for evaluating the physical characteristics of sound consists of the following elements:

(1) Transducer (microphone)
(2) Electronic amplifier and calibrated attenuator
(3) Octave-band or other acoustic spectrum analyzer
(4) Readout and/or recorder.

Taken together, Items (1), (2), and (4) make a sound-level meter, the system most widely used for basic sound measurements. Item (3) must be added whenever the sound contribution from a particular frequency band must be determined.

7-2.1 MICROPHONE CHARACTERISTICS

Acoustical measurements start with the transducer (microphone), which converts audio sound pressure into an electrical signal. Ideally, the microphone distorts neither the sound field by its very presence in the field nor the electrical signal due to any inherent nonlinearities in the microphone. The ideal microphone, including any required preamplifier, must therefore satisfy the following requirements:

(1) Cause negligible diffraction of the sound field, i.e., its dimensions must be small compared to the shortest wavelength of interest

(2) Have a high acoustic impedance (more nearly accurate, acoustic driving-point impedance) compared to the medium to which it is coupled (usually air) and so absorb no acoustic energy

(3) Have a flat frequency response

(4) Introduce zero phase shift (or a phase shift that varies linearly with frequency) between the sound-pressure signal and the electrical output

(5) Have a pressure response independent of the pressure level

(6) Have a 0-dB noise figure

(7) Be independent of the environment; i.e., stable with respect to time, temperature, humidity, and static air pressure.

While these requirements cannot be met by any microphone, they do form a basis against which microphone performance can be evaluated. Specifications have been established for laboratory standard microphones and are described in an ANSI (American National Standards Institute) Standard (Ref. 13).

7-2.1.1 Types of Microphones

The variety of functions required of microphones has necessitated the development of various types. For example, for intelligible voice communication by telephone, a microphone of only limited frequency range is required; however, it must be rugged and sensitive and require no preamplifier. The carbon granule microphone more than fulfills these requirements. The broadcast industry, on the other hand, needs microphones that not only have a broad frequency range for good fidelity but also are highly directional to reduce interference from unwanted sounds. The ribbon microphone handles this job well. Although microphones such as these play important roles in their specific areas and do, indeed, convert sound pressure to voltage, their relatively loose operating characteristics make them unsuitable for accurate sound measurements. The three most widely used microphones for sound measurements are the ceramic, high frequency condenser, and condenser microphones.

(1) ***Ceramic microphone.*** The ceramic microphone gets its name from its ceramic cartridge, which exhibits piezoelectric properties. Thus the cartridge produces a

3. **Much of this paragraph is based on the Hewlett-Packard *Acoustics Handbook* (Ref. 8).**

TABLE 74. SOUNDS ENCOUNTERED IN ARMY ENVIRONMENT

SPL, dB re 2×10^{-4} μbar	Typical source	Impulse or steady-state	Significance/action required
0	-----------	Steady-state	Threshold of hearing at 1,000 Hz
30	Rustling of leaves by light breeze	Steady-state	Good sleeping environment
50	Office noise	Steady-state	Little interference with mental tasks
65 - 70	Speech at 3 ft	Steady-state	Normal voice-level communication
75	Auto interior at 60 mph	Steady-state	Voice must be raised for conversation
80	Typewriter at 6 ft	Impulse	Concentration difficult/close office door to reduce annoyance.
85	Interior of jeep at 45 mph, rough road	Steady-state	High vocal effort for reliable speech reception
90	-----------	Steady-state	Maximum allowed at 2,000-4,000 Hz for Army Materiel Command equipment without hearing protection
95	Heavy truck interior at 60 mph	Steady-state	One hour exposure will cause temporary 25 dB hearing loss at 4,000 Hz.
110	Jet aircraft, full power at 500 ft	Steady-state	Hearing protection is essential for other than brief (takeoff-landing) exposures.
140	-----------	Steady-state	Threshold of pain
150	Atlas launch at 150 ft	Steady-state	Hearing protection alone (plugs, muffs, or both) is not adequate to prevent temporary hearing loss, even for brief exposures.
140-170	Small arms fire	Impulse	Hearing protection required for repeated exposure
175-190	Artillery	Impulse	Hearing protection essential; body protection desirable

voltage as a result of strain caused by sound pressure. Unlike the high frequency condenser and condenser microphones, the ceramic microphone requires no polarization voltage, an advantage in circuits designed for portable operation. However, the ceramic microphone has some disadvantages as well. Its upper frequency range is somewhat limited, about 10 to 12 kHz; its frequency response, ±8 dB for frontal field and ±4 dB for random and parallel fields, is not as good as that of the condenser microphone, although most of the variation occurs above about 8 kHz; and it is about 14 dB less sensitive than a condenser microphone of the same dimensions.

(2) ***High frequency condenser microphone.*** The high frequency condenser microphone gets its name from the fact that (1) it utilizes a condenser (capacitor) as the transducer, and (2) the condenser forms part of the frequency-determining network of a high frequency (about 10 MHz) oscillator. Since the diaphragm of the microphone is one plate of the condenser, the sound pressure varies the spacing of the condenser plates and, thus, the capacitance. As a result, the oscillator frequency is modulated by the sound, and the audio is recovered by detecting the FM signal. The high frequency condenser microphone has somewhat better characteristics than the ceramic microphone. Its greatest advantage is that its low frequency limit can be extended to zero Hz. However, compared to the condenser microphone, the typical high frequency condenser microphone is 10 dB less sensitive, and its frequency response (±6 dB for frontal field) is not as good. The high frequency condenser microphone requires only a low polarization voltage.

(3) ***Condenser microphone.*** The condenser microphone's flat frequency response (±1 dB from 20 Hz to 20 kHz for a 0.5-in. diameter version) and high sensitivity (=1.5 mV/μbar for **0.5** in., **5** mV/μbar for 1 in.) are advantages that more than outweigh its one disadvantage: the requirement for a high polarization voltage (≈200 V).

The condenser microphone also gets its name from the fact that it utilizes a condenser to convert sound pressure to voltage. The general physical construction of a condenser microphone consists of a membrane (diaphragm) forming one plate of the condenser or capacitor, and a polarization electrode forming the other plate of the capacitor. The membrane is attached to the housing, at ground potential, while the 200-V polarization voltage is applied to the polarization electrode. A quartz insulator supports the polarization electrode as well as insulates it from the housing. With the polarization voltage applied, the spacing between the membrane and polarization electrode is about 0.6 mm. Air holes in the polarization electrode relieve the air that otherwise would be trapped behind the membrane. These holes lower the resonant frequency of the microphone cartridge, increase its sensitivity, and improve its frequency response. A small capillary,hole through the housing allows some airflow so that the static pressure within the capsule always equals the ambient atmospheric pressure. However, the hole is small enough so that it permits only long-term pressure equalization. Thus, the acoustic loading is the same on both sides of the membrane even at frequencies well below 20 Hz.

(Thus far the term "microphone" has been used rather loosely, sometimes meaning the entire microphone assembly, including the associated preamplifier electronics, and sometimes just the microphone cartridge. Henceforth, the term "microphone" will mean the entire assembly; "microphone cartridge" and "preamplifier" will be used where necessary to distinguish these from the assembly. This definition of terms has no bearing on the preceding discussion because microphone characteristics are determined primarily by the cartridge.)

The condenser microphone cartridge generates a voltage because the voltage across a capacitor having a given charge is proportional to the distance between the plates. The charge is supplied by the polarization voltage. If the polarization voltage source has an impedance high enough to prevent significant current flow even at the lowest frequency, then the charge on the condenser can be considered constant. Since one plate of the condenser is the microphone membrane, and the displacement of the membrane from its rest position is proportional to sound pressure, the generated voltage is also proportional to sound pressure.

Because the transducer is a condenser or capacitor, its impedance is frequency dependent. In a typical 0.5-in. condenser microphone, the value of capacitance is 27 pF. At 20 Hz, the source impedance of this microphone is approximately 300 megohms. Thus the condenser must be connected to as high a load resistance as possible. On the other hand, the capacitance shunting the load resistance must be as small as possible to avoid attenuating the output from the cartridge. These factors require that the microphone cartridge be connected directly to an impedance converter or preamplifier. Furthermore, the preamplifier must not interfere with the sound field; to do so would degrade the accuracy of the measurements. For this reason, most preamplifiers are designed to fit into a cylindrical housing having the same diameter as the cartridge.

7-2.1.2 Calibration of Microphones

In order to make sound measurements, the sensitivity of the microphone over the frequency range of interest must be known. That is, the sound pressure to voltage conversion factor must be determined. At present the most widely used method for absolute calibration of microphones is the so-called reciprocity method. This method is described in detail in ANSI Standard S1.10 (Ref. 14). Generally, the reciprocity method is used to calibrate only the cartridge, but, since the cartridge is the primary factor in determining the characteristics of the microphone assembly, for all practical purposes the entire assembly is also calibrated. Calibration in the laboratory and in the field to a secondary standard is often satisfactory, in which case a pistonphone may be used. A pistonphone is a small, battery-powered precision sound source that attaches to the microphone to be calibrated. Although the pistonphone typically calibrates only at a single sound-pressure level and a single frequency, this calibration is very accurate (better than ± 0.5 dB), rapid, and convenient.

7-2.2 MICROPHONE SELECTION

Microphones are available in a variety of sensitivities. When very low sound levels are to be measured, the minimum SPL to which a microphone can respond should be the determining factor in selection. The self-noise of the microphone (and the entire measuring system for that matter) must be at least 10 dB below the sound that is to be measured in each frequency band of interest. On the other hand, for measuring high-level noises such as those produced by gas turbines or rocket engines, the choice of microphone to be used will be limited by the maximum SPL to which the microphone can respond without excessive distortion or failure. After these two considerations have narrowed the selection, the microphone that should be selected is the one having the smoothest frequency response over the frequency range of interest.

The frequency response of microphones typically varies with the direction of arrival of the sound wave. At low frequencies (below 1 kHz), where the size of the microphone is small in relation to the wavelength of sound, most microphones are omnidirectional. However, at higher frequencies the direction in which the microphone is pointed, often specified as its incidence angle,[4] must be carefully considered. The manufacturer's specifications should be consulted to obtain the incidence angle that provides the smoothest frequency response.

If a moving sound source is to be measured, a microphone that has its best response at 0-deg (normal) incidence should not be used since the measured spectrum will change with sound-source location. In this case, a microphone with good response at 90-deg (grazing) incidence should be selected and positioned so that the moving sound source is always at 90-deg incidence to the microphone.

The principal limitations in the measurement of impulse noise lie in the ability of the transducer and its associated equipment to respond to the pressure pulse accurately (Refs. 15,16). The minimum qualities of the transducers and associated equipment for such measurements are:

(1) A good phase response

(2) A uniform amplitude response characteristic over a wide frequency range. A bandwidth of from 100 Hz to 70 kHz is adequate for measuring most short-duration impulses such as from small arms, but longer-duration impulses such as from large-caliber weapons and sonic booms require an extension of the low frequency response and may permit relaxation of the upper limit (Ref. 17)

(3) Less than 1.5 dB ringing and overshoot at the pressure being measured (ringing should be completely damped after 100 ps)

(4) Rise-time capability of 10 μs or less at the pressure being measured

(5) Sufficient robustness to withstand damage from the pressure pulse being measured

(6) Sufficient sensitivity to allow a signal-to-noise (S/N) ratio of 25 dB or greater

(7) Minimum drift caused by temperature instability.

The *angle of microphone incidence* is even more important for measuring impulse noise than for measuring steady-state noise. At 0-deg (normal) incidence the measured peak pressure level of various microphones may differ by as much as 10 dB (Ref. 15). Since the peak readings obtained from various microphones should theoretically be, and are in fact found to be, in good agreement at 90-deg incidence, the transducer should be oriented for impulse measurements at an angle of 90 deg (grazing incidence) between the longitudinal axis of the transducer and the direction of travel of the pressure pulse or shock wave.

With the transducer positioned at grazing incidence, rise-time characteristics will be affected by the transit time of the wave across the sensing element. Therefore, the transducer selected must have a sensitive diameter of about 4 mm or less.

4. The incidence angle for a microphone is that angle subtended between its longitudinal axis and a line drawn between the sound source and the microphone.

7-2.3 MICROPHONE LOCATION AND MEASUREMENT ACCURACY

Using the proper microphone for a given measurement does not insure that good data will be obtained. The placement of the microphone, the existence of interference, and a number of other factors affect measurement accuracy. These are discussed in the following subparagraphs:

(1) ***Placement and orientation of the microphone.*** This paragraph is concerned with measuring sound in terms of man's reaction to it. The sound a listener would have heard, had he been present, must therefore be measured. This condition requires that the microphone be placed at the normal location of a listener's head, i.e., at a height of 80 cm (31.5 in.) above the seat for sitting locations and 165 cm (65 in.) above the floor for standing locations and at an appropriate distance from the source.

The orientation of the microphone is immaterial in a *diffuse* acoustic field.[5] However, since even omnidirectional microphones exhibit some directional qualities, orientation is important in a field that is wholly or partly directional. In this case, the microphone should be oriented so that the directional part of the field is frontally incident, because, for most microphones, frequency response is flattest for such incidence. The transition from a directional sound field to a diffuse field in a room can be estimated from the formula

$$r_G = 0.14\sqrt{\bar{a}A} \qquad (7\text{-}5)$$

where

r_G = distance from the source at which the sound field changes from directional to diffuse

$\bar{a}$ = acoustic absorption coefficient of the walls

A = surface area of the walls, floor, and ceiling

5. A *diffuse* acoustic field is one in which sound comes from all directions equally (with random phase relationships). As a general rule, indoor acoustic measurements should assume a diffuse field (because of reflections). In outdoor measurements, a *free* field—in which sound propagates by spherical divergence and is directional—is more often encountered.

For a factory room 30 X 40 X 5 m (98 X 130 X 16 ft) in size, r_G is about 2.5 m or 8 ft. In some special measurement situations, the microphone may be located very close to the sound source. If the sound includes very high frequencies, standing waves may exist between the microphone and source, greatly influencing the measurement results. For such situations, the microphone should be oriented at some small angle, say 5 deg, with respect to the direction of the sound to avoid the creation of standing waves. This angle has virtually no effect on microphone frequency response.

Many measurement procedures are standardized, and many other standards are being considered. In these the location and orientation of the microphone are specified, and these instructions should be followed to obtain meaningful results. Examples include measurement of aircraft and motor vehicle noise, determination of characteristics of loudspeakers, measurement of noise emitted by machines, and determination of noise rating numbers with respect to annoyance and to conservation of hearing and speech communication. These are described in more detail and references are given in par. 7-7.

(2) ***Interference.*** Interference can be defined as those factors that are not normally associated with a sound field and that affect the accuracy of its measurement. For the most part, interference is caused by objects introduced into a sound field in order to measure it. Such objects include the microphone, its supporting structure, associated measuring instruments, and even the observer himself. Furniture, machines, and walls affect the sound field, but are not considered interference factors because they are permanent structures in the field. Outdoor measurements can be complicated further by wind, temperature, and humidity, so these factors must be accounted for when they differ from the norm for the area.

In general, a diffuse field is affected much less by interfering objects than is a free field. However, it is often difficult to judge whether a field is free or diffuse, even with the aid of Eq. 7-5. As a general rule for such cases, indoor measurements should be treated as diffuse-field measurements, outdoor measurements as free-field measurements. These interference factors can be quantified, based on the knowledge that the numbers apply primarily to free-field measurements.

As the transducer, the microphone is the only part of the measuring system that must actually be located in the sound field, and, since its dimensions are often significant compared to the wavelength of the sound signal being measured, it does indeed affect the nature of the field. However, as noted previously, the design of a microphone usually accounts for this interference, and the output of the microphone very closely approximates that of an ideal microphone.

A microphone can be supported in a number of ways. Because of its small size and light weight, it can easily be mounted on a tripod or held in the hand; moreover, sometimes it is an integral part of the indicating equipment. The first of these, a tripod, generally includes, in addition to the legs, a vertical cylindrical rod to which the microphone is attached. Assuming this rod is 1 in. in diameter and the microphone is suspended 6 in. (150 mm) from it, between it and the sound source, the maximum free-field measurement error under such circumstances exceeds 2 dB above 4 kHz, diminishing with frequency below 4 kHz as the dimensions of the rod become less significant with respect to the wavelength of the sound signal. In reality, the microphone is “suspended” at one end of the rod, a position that diminishes its effect somewhat. However, the legs of the tripod add additional reflected signals that add vectorially to that of the vertical support. The net effect is a maximum expected error of about 2 dB for frequencies of 4 kHz and above. In the case of the hand-held microphone, the observer is a reflecting object that affects the sound field. The degree to which a measurement is affected cannot be stated with any precision because of the unpredictability of the observer’s size and dress. Nevertheless, a measurement error greater than 3 dB is a virtual certainty, with 4 or 5 dB quite likely.

When the microphone is an integral part of the indicating instrument, the effect of the instrument must be considered. In some cases, the instrument is square; in others, tapered. If the instrument case is a sphere 6 in. in diameter and the microphone is suspended 6 in. from the sphere between it and the sound source, the maximum error would be about ± 2 dB at frequencies of 1 kHz and above. The instrument with a tapered case behind the microphone reduces this figure somewhat. The square case does not. To improve the situation, microphones associated with square-case instruments are often mounted on an arm that is pivoted where it connects to the instrument. The microphone can then be suspended above the instrument rather than between its flat front surface and the source. Although the disturbance of the field is less at this point, the angle of incidence is 90 deg, so the directional characteristics of the microphone must then be taken into account. Of course, any additional supporting structure must also be considered.

Based on these considerations, accuracy is improved if the observer and the measuring equipment are some distance from the microphone, particularly when larger instruments are used.

*(3) **Measurement accuracy.*** A number of factors in addition to interference affect measurement accuracy. When these are considered together, the overall measurement accuracy can be predicted. These additional factors include:

(a) Equipment setup. The first, and perhaps most important, step toward accurate sound measurements is the proper setup of the equipment. Both the measuring instruments and the observer can have considerable effect on free-field measurements, and, while the effect is much less for diffuse-field measurements, good practice dictates the use of care here as well. If the indicating instruments are well out of the way, only the microphone support need be considered. In the case of a tripod, measurement accuracy is affected by less than 2 dB for free-field measurements, negligibly for diffuse-field measurements.

(b) Microphone correction factor. Acoustic measuring equipment is calibrated on the basis of the nominal sensitivity of a given size of microphone, e.g., 5 mV/μbar for 1-in. condenser microphones. However, due to manufacturing tolerances of the cartridge itself, plus the attenuating effect of the input capacitance of the associated preamplifier (small compared to the manufacturing tolerances), the sensitivity of the microphone assembly is seldom the same as the nominal sensitivity. Deviation from nominal sensitivity ranges from +1 to - 4.5 dB. Fortunately, this deviation is independent of frequency. The deviation typically is noted in a calibration report that is fumished with precision microphones, indicating the correction that must be made to the measurement. After this correction is made (some manufacturers add a microphone correction factor switch to their various acoustic instruments), the residual error is typically less than 0.2 dB. This figure is useful for determining overall accuracy.

(c) Frequency response. Frequency-response curves, as well as the microphone correction factor, are supplied with each microphone assembly. Use of these curves implies a knowledge of the frequency distribution of the sound being measured either because of its limited frequency range or because of the use of filters. For broad-band measurement, the full variation of microphone response must be considered. For a typical 0.5-in. condenser microphone, this variation is only ± 1 dB from 20 Hz to 20 kHz; for a 1-in. microphone, ± 1.5 dB from 20 Hz to 16 kHz.

(d) Type of field and orientation. The discussion of frequency response deals only with frontal free-field measurements. However, many measurements, particularly those indoors, are in diffuse fields, and not all free-field measurements are with frontal incidence. Since even omnidirectional microphones exhibit some directional qualities at higher frequencies, these must be accounted for in measurements. At those frequencies requiring corrections, the best accuracy that can be expected is about ± 2 dB. Again, this applies to single frequency or narrowband measurements. For broadband measurements, the error can be up to the full value of the correction indicated by the manufacturer's curve for diffuse-field versus free-field response, perhaps a 5 dB error.

(e) Absence of the observer. The effect of an observer on a sound field is sufficient to recommend that he remove himself from the vicinity of the microphone while measurements are being made. Yet the objective is to measure the sound an observer would hear if he were present. This seems paradoxical, but measurements should be repeatable; i.e., similar equipment should give similar results under similar conditions. The problem with the observer is that no two observers will be acoustically alike; no standard observer exists. Therefore, measurements are made with the observer absent, and the results are equated to what an average observer would hear. This is done automatically with weighting curves and correction factors designed into the indicating equipment.

(f) Overall accuracy. Figs. 7-3 and 7-4 summarize the various factors discussed previously and show the accuracy that can be expected from condenser microphones for frontal free-field and diffuse-field measurements. The figures do not include instrumentation error. They do show that a series of narrow-band measurements provides much greater accuracy than a single broad-band measurement. In addition, narrow-band measurements better enable equating the measured sound to the subjective sensation of hearing. Of course, broad-band measurements may be made for reasons of simplicity, convenience, or economy. In any event, the observer, to evaluate his measurements properly, should be aware of the nature and degree of any errors.

7-2.4 SOUND-LEVEL METERS

When the sound signal is in electrical form, it must be processed in a meaningful way. The sound-level meter was among the first instruments developed to provide correlation between an objective measurement and the subjective sensation of hearing. Frequency response, detection, and measurement for sound-level meters are discussed in the following subparagraphs:

(1) ***Frequency response.*** The sound-level meter is basically an audio rms voltmeter. In measuring the electrical signal from the microphone, then, it provides

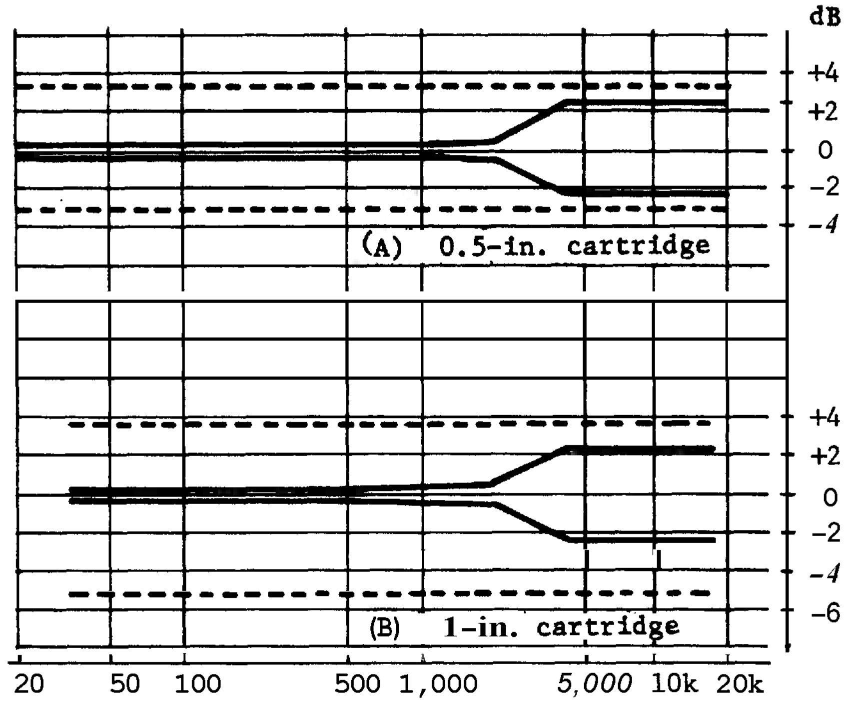


FIGURE 7-3. Accuracy Curves of Condenser Microphone Output for Free-field 0.5-in. and 1-in. Cartridges Mounted on a Tripod (solid lines show narrowband accuracy; dashed lines, broadband accuracy).

a measure of a physical quantity, i.e., sound pressure. This fact is important in evaluating the sound-level meter. The sound-level meter differs from a voltmeter in that the frequency response of a voltmeter is made as flat as possible, while that of the sound-level meter is deliberately altered by weighting networks to account, to a first-order approximation, for the frequency response of the ear. Actually, three frequency-response curves have been standardized because the response of the ear depends upon pressure level as well as frequency. These are the so-called A, B, and C curves, and approximate the inverse of the 40-, 70-, and 100-phon equal loudness curves of Fig. 7-1.

The three most widely used standards describing sound-level meters are IEC Publication 123, *Recommendation for Sound Level Meters* (Ref. 18); IEC Publication 179, *Precision Sound Level Meter* (Ref., 19); and ANSI Standard S1.4, *Specification for General-Purpose Sound Level Meters* (Ref. 20).[6] A consideration of these standards, including the similarities and differences, is relevant.

All three standards specify virtually the same A, B, and *C* curves, and all three state that the tolerances for the curves relate to the entire system; i.e., microphone, attenuator, amplifier, weighting networks, and indicator (meter). All three are also imprecise regarding the effects of extraneous factors such as temperature, humidity, and electromagnetic interference. In general, the standards require the manufacturer to state the range for such factors over which instrument accuracy is not adversely affected.

At this point the standards diverge. The curves and tolerances in IEC 123 specify performance in absolute terms, i.e., with respect to a true sound-pressure level. The curves in IEC 179 and S1.4 are simple frequency-response curves providing only relative data. In addition, the A and B curves in S1.4 are relative to the C curve, so the tolerances specified for the A and B curves must be added to those of the *C* curve. Table 7-5 lists values and tolerances for all three standards. (The tolerances for the A and B curves under S1.4 are the total tolerances.)

The problem is to derive a set of figures from these data for absolute accuracy. Both IEC 179 and S1.4 allow a ± 1 dB tolerance for absolute calibration at a reference frequency. All three standards provide tolerances for making measurements at sound-pressure levels different from the calibration level. Included are range errors in the attenuator and meter (indicator), as well

6. A new ANSI standard (S1.4) became available in late 1971. It is similar to IEC 179 in many respects but is more comprehensive.

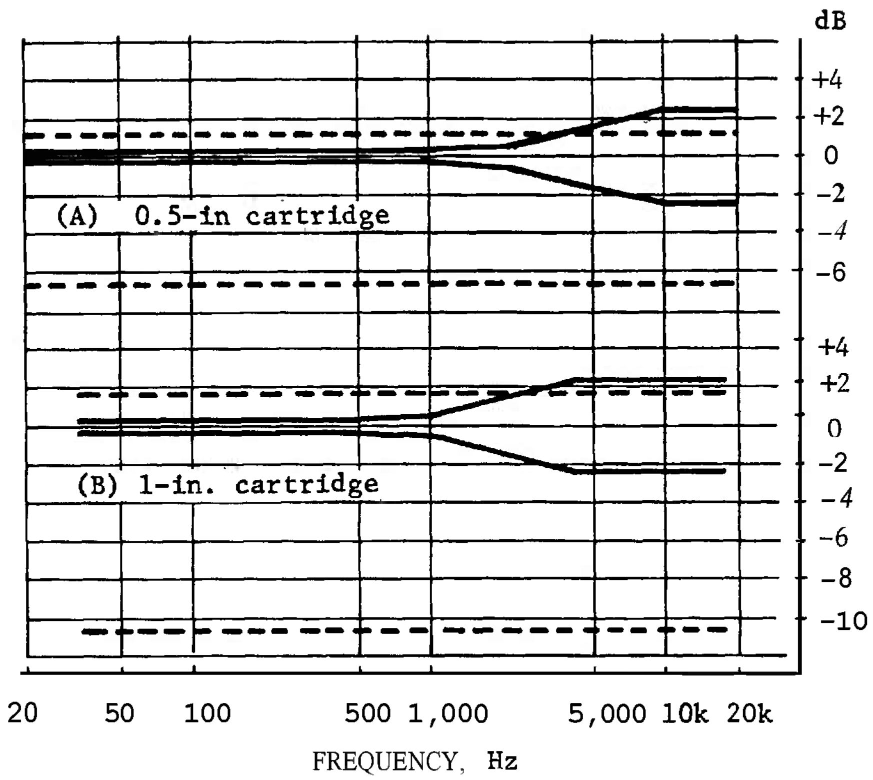


FIGURE 7-4. Accuracy Curves of Condenser Microphone Output for Diffuse-field 0.5-in. and l-in. Cartridges Mounted on a Tripod (solid lines show narrowband accuracy; dashed lines, broadband accuracy).

as calibration and resolution errors. Table 7-6 summarizes these factors. The total addition tolerance shown in Table 7-6 must be added to the tolerances of Table 7-5 to obtain overall performance. Although these curves show the worst possible case, the worst case must be allowed for in evaluating accuracy if a particular sound-level meter is specified only to meet a given standard. In summary, IEC 123 is a loose standard, IEC 179 somewhat tighter, and S1.4 in between.

All three standards recognize that sound-level measurements with the specified instruments are at best first-order approximations of human hearing. Nevertheless, these standards have established limitations within which measurements made at different times, in different places, with different equipment, can be compared. As instrumentation improves, the standards will undoubtedly reduce the tolerances; so accuracy in a sound-level meter is important.

The standards specify performance for the whole system: microphone and preamplifier, attenuator, weighting networks, amplifier, and indicator (meter). However, in practice the microphone is not always an integral part of the sound-level meter but is connected to the rest of the system with a cable. This is desirable, particularly in free-field measurements, in order to remove the indicating unit from the sound field. In such cases, the microphone usually can be detached from the indicating unit, so a variety of microphone-meter combinations can be used.

(2) ***Detection mode and detector dynamics.*** Accurate acoustic measurements involve more than proper frequency response. The detection mode and the dynamic characteristics of the sound-level meter are equally important. The detection mode is dictated by the manner in which sound is heard and measured. Subjective reaction to sound is in proportion to its intensity (analogous to electrical power), while sound pressure or sound-pressure level (analogous to voltage) is measured. To easily equate one with the other, rms values must be measured to avoid errors when the sound signal deviates from a pure, continuous-wave sinusoid.

By definition, the rms value of the signal from the microphone is

$$v_{rms} = \left(\frac{1}{T}\int_0^T V^2 dt\right)^{1/2} \tag{7-6}$$

TABLE 7-5. RESPONSES AND ASSOCIATED TOLERANCES

Frequency, Hz	Curve A, dB	Curve B, dB	Curve C, dB	IEC 123, dB	IEC 179, dB	S1.4 Curve A, dB	S1.4 Curve B, dB	S1.4 Curve C, dB
20	-50.5	-24.2	-6.2	+5, -∞	±5	- -	- -	+3, -∞
25	-44.7	-20.4	-4.4	+5, -∞	±5	+4, -4.5	+3, -3.5	+2, -2.5
31.5	-39.4	-17.1	-3.0	±5	±3	+3.5, -4	+2.5, -3	+1.5, -2
40	-34.6	-14.2	-2.0	±4.5	±3	+3, -3.5	+2, -2.5	+1, -1.5
50	-30.2	-11.6	-1.3	±4	±3	±3	±2	±1
63	-26.2	-9.3	-0.8	±4	±3	±3	±2	±1
80	-22.5	-7.4	-0.5	±3.5	±2	±3	±2	±1
100	-19.1	-5.6	-0.3	±3.5	±1	±2.5	±2	±1
125	-16.1	-4.2	-0.2	±3	±1	±2.5	±2	±1
160	-13.4	-3.0	-0.1	±3	±1	±2.5	±1.5	±1
200	-10.9	-2.0	0	±3	±1	±2.5	±1.5	±1
250	-8.6	-1.3	0	±3	±1	±2.5	±1.5	±1
315	-6.6	-0.8	0	±3	±1	±2	±1.5	±1
400	-4.8	-0.5	0	±3	±1	±2	±1.5	±1
500	-3.2	-0.3	0	±3	±1	±2	±1.5	±1
630	-1.9	-0.1	0	±3	±1	±2	±1.5	±1
800	-0.8	0	0	±2.5	±1	±1.5	±1.5	±1
1000	0	0	0	±2	±1	±2	±2	±1.5
1250	0.6	0	0	±2.5	±1	±2	±2	±1.5
1600	1.0	0	-0.1	±3	±1	±2.5	±2.5	±2
2000	1.2	-0.1	-0.2	±3	±1	±3	±3	±2.5
2500	1.3	-0.2	-0.3	+4, -3	±1	+4, -3.5	+4, -3.5	+3.5, -3
3150	1.2	-0.4	-0.5	+5, -3.5	±1	+5, -4	+5, -4	+4.5, -3.5
4000	1.0	-0.7	-0.8	+5.5, -4	±1	+5.5, -4.5	+5.5, -4.5	+5, -4
5000	0.5	-1.2	-1.3	+5, -4.5	±1.5	+6, -5	+6, -5	+5.5, -4.5
6300	-0.1	-1.9	-2.0	+6, -5	+1.5, -2	+6.5, -5.5	+6.5, -5.5	+6, -5
8000	-1.1	-2.9	-3.0	±6	+1.5, -3	±6.5	±6.5	±6
10000	-2.5	-4.3	-4.4	+6, -∞	+2, -4	- -	- -	+6, -∞
12500	-4.3	-6.1	-6.2	+6, -∞	+3, -6	- -	- -	- -

TABLE 7-6. SUMMARY OF STANDARDS REQUIREMENTS

	IEC 123	IEC 179	S1.4
Frequency range, Hz	31.5 to 8,000	20 to 12,500	20 to 10,000
Frequency response	One network required (A, B, or C)	One network required (A, B, or C)	Three networks required (A, B, and C)
Frequency response calibration	Absolute (free field)	Relative (free field)	Relative (diffuse field)
Tolerance for absolute calibration	- - -	± 1 dB	± 1 dB
Preferred calibrating frequency	- - -	1 kHz	400 Hz
Additional tolerance for range change	± 1 dB	± 0.5 dB	± 1 dB (± 0.5 dB between adjacent ranges)
Additional tolerance for meter accuracy and resolution	± 1 dB	± 0.4 dB	± 0.5 dB
Total additional tolerance for absolute accuracy	± 2 dB	± 1.9 dB	± 2.5 dB

where

V = instantaneous value of the microphone output voltage

T = interval of time over which the integration is carried out

The rms detector must, therefore, include a squaring circuit, an integrator, and a root extraction network. Since many sound signals are nonsinusoidal, the detector must be able to handle a relatively high crest factor (ratio of peak to rms voltage). Many circuits have been developed to approximate the square-law function, but perhaps the most widely used circuit is the quasi-rms detector. In this detector an integrating capacitor biases a rectifier so that no current flows until the absolute value of the input signal exceeds the voltage on the capacitor. Above this point, a linear relationship exists between the input signal and the detector current. By appropriate selection of component values, deviation from the ideal is held within acceptable limits (usually ± 1 dB) up to a crest factor of three. The quasi-rms detector more than satisfies the requirements of IEC and USA standards for sound-level meters. In practice, the detector is a resistance-capacitance (RC) averaging detector wherein the RC time constant is chosen to provide meter response appropriate to that stipulated in the standards for "fast" and "slow" detection characteristics. The standards stipulate overall sound-level meter performance (designated "fast" in the IEC standards) in response to a single 200-ms burst of a 1-kHz sinusoidal signal. IEC 179 requires the meter to read 1 dB $\pm$ 1 dB below the steady-state value, while IEC 123 and S1.4 require a meter reading between 0 and 4 dB below the steady-state value.

The reduction in meter reading (from the steady-state value) for various apparent RC time constants can be calculated from the formula

$$\Delta L = 10 \log \left[1 - \exp\left(-t/c\right)\right] \qquad (7\text{-}7)$$

where

ΔL = meter reading in dB below the steady-state value

t = duration of the tone burst, 200 ms in this case

c = apparent time constant of the detector

(The formula is valid provided that the crest factor capability of the detector is not exceeded, and instrument response is determined by the detector.) Table 7-7 shows some values of apparent time constants and corresponding meter readings.

TABLE 7-7. APPARENT DETECTOR TIME CONSTANT VS METER READING

Time constant c, ms	Deviation ΔL, dB
53	- 0.1
100	- 0.63
127	- 1
200	- 2
390	- 4

In response to a single 0.5-s burst of a 1-kHz tone, the sound-level meter should indicate a nominal 4 dB below the steady state value. IEC 179 puts a ± 1 dB tolerance on the reading; IEC 123 and S1.4, ± 2 dB. The "slow" mode reduces meter jitter in measurements of rapidly varying sound fields by providing a longer averaging time. For "slow", the nominal detector time constant is about 1 s.

(3) ***Measurements with the sound level meter.*** In the final analysis, the sound-level meter measures the frequency- and time-weighted rms value of sound pressure. The frequency weighting is selected as dB(A), dB(B), or dB(C). As noted previously, these response curves make the sound-level meter respond to single tones at various frequencies in approximately the same way as the human ear. As broadband devices, however, sound-level meters cannot indicate the spectral composition of a particular sound; i.e., no correlation exists between our subjective response due to this factor and meter indication. This is the main reason that substantial differences—10 dB and more—can exist between subjectively measured loudness level in phons and sound-pressure level in dB. Furthermore, other factors that contribute include the inability of the sound-level meter to account for masking effects (discussed in par. 7-5) and the impossibility of selecting the right weighting function for all spectral components at once.

Since no reasonable degree of correlation between the loudness levels of widely differing sounds and sound-level meter readings can be achieved, usually no attempt is made to select the most appropriate weighting curve—A, B, or C—for the levels encountered. The quantity that is measured is almost always the A-weighted sound level, even at levels where the high attenuation of low frequency components would not be justified from a physiological point of view.

By itself, then, the sound-level meter can be used only to compare sounds from similar sources. For example, one automobile can be compared with another, "standard" automobile, perhaps as a quality check. However, the automobile cannot be compared with a typewriter because of the different character of the two sounds.

7-2.5 FREQUENCY ANALYSIS

Frequency analysis may be accomplished with either manual systems or spectrum analyzers:

(1) ***Manual systems.*** The simplest frequency-analysis systems are manually operated, octave-band systems. In general, these systems employ a sound-level meter, operating in its linear mode, as the indicating device. The filters themselves are usually supplied as a set with selectable single filters with center frequencies from 63 Hz to 8 kHz. An octave-band analysis enables determination of the part of the spectrum that contributes most heavily to the overall loudness. In noise abatement studies, octave-band analysis can help pinpoint the true offender as well as evaluate corrective action.

The technique of sound analysis using manual systems depends somewhat upon the nature of the sound. Continuous and repetitive sounds can be evaluated on the spot; sufficient time elapses to select each octave band in turn and note the meter reading. To evaluate discontinuous and transient sounds, however, other methods are required. The tape recorder is widely used to preserve a sound in its original form; the sound can then be reproduced as often as necessary to complete the analysis. For convenience, the section of tape containing the particular sound to be evaluated is often cut out of the roll and made into a continuous loop. The tape can be played over and over without stopping to rewind it each time. However, in making the loop, care must be taken not to make it so short that the reproduced sound takes on the nature of a repetitive signal, because the spectrum is then altered. The loop should be long enough to allow time to note the meter reading and change filters before the sound is repeated. Signal level recorders provide a convenient means of obtaining a permanent record of measurement results.

To simplify certain measurements, octave filter sets have provisions for setting the gain through each filter separately. The variable-gain mode permits precalibration of an indicating unit in terms of the measurement criteria. The variable-gain mode can also be used to flatten the frequency response of a measurement system, for example, to compensate for frequency nonlinearities in the sound source.

(2) ***Spectrum analyzers.*** Many applications occur in which the purely physical data provided by a spectrum analyzer are more useful than weighted data. These applications include measurement of acoustical properties of materials; studies of sound propagation in gases, liquids, and solids; and determination of frequency response of transducers. Even in subjective acoustics, different methods of sound evaluation and the procedure for determining noise rating numbers start with physical data.

A variety of real-time audio spectrum analyzers is available for use when detailed acoustical characteristics such as these are needed. Depending upon what is required, 24 or more third-octave channels are provided, and digital computer interfacing may be employed (Ref. 21).

7-3 EFFECTS OF NOISE AND BLAST ON HEARING

This paragraph treats the factors influencing the acquisition and recovery of hearing loss for steady-state and impulse noise, and for a blast (a special case of impulse noise). Specific criteria for minimizing hearing losses from noise exposure are discussed in par. 7-7.

7-3.1 THRESHOLD SHIFTS IN HEARING

The sensitivity of human hearing at a particular test frequency is referred to as the ***threshold*** of audibility. Thresholds stated with reference to standard criteria—such as Ref. 22 or audiometric zero (Ref. 23)—are called ***hearing levels*** with respect to the appropriate reference level. When a loss of sensitivity is temporary, i.e., when hearing returns to the normal baseline after a suitable recovery interval, it is referred to as a ***temporary threshold shift*** (TTS). A loss of sensitivity that does not return to baseline is called a ***permanent threshold shift*** (PTS). TTS is usually measured at 2 min or longer after exposure, and is referred to as TTS, $_{min}$ or, simply, TTS_2.

Some relation is assumed to exist between TTS, experienced on a near-daily basis and the likelihood of eventual accumulation of PTS. CHABA Working Group 46 (Ref. 24) assumed that 10 yr of near-daily exposure would result in PTS,, $_{yr}$ = TTS, $_{min}$. TTS measures are widely used in assessing noise effects on hearing because (1) TTS is a valid measure of the temporary effects of noise exposure, and (2) TTS can affect man's ability to perform tasks requiring maximum hearing sensitivity. In fact, where life-or-death decisions rest on the acuteness of man's hearing, as in reception of speech signals over a communication link or in the perceiving of aural warning signals, prevention of excessive TTS is the most important consideration. Absence of TTS may be responsible for saving human life. TTS is used in this paragraph as the primary indicant of noise effects on hearing threshold sensitivity.

7-3.2 SUSCEPTIBILITY TO TTS

The concept of "susceptibility" here refers jointly to two facts: (1) for a given noise exposure, different ears demonstrate varying amounts of TTS, and (2) for a given sample of ears, different noise conditions may produce varying distributions of TTS. Because of the unpredictable and uncontrollable variability in ear responses to noise—between days and among noise conditions—the possibility of developing criteria for protecting *specific* ears from excessive TTS is at best slim (Refs. 25,26,27). As a result, criteria for determining hazardous and nonhazardous noise exposures are, in reality, a form of actuarial or statistical table in which the responses of certain proportions of noise-exposed populations are predicted. The acquisition of and recovery from TTS are discussed separately:

(1) ***Acquisition of TTS.*** The many factors influencing the acquisition of TTS from steady sound and noise exposure have been reviewed by various authorities (Refs. 28,29,30). Some of the salient aspects are summarized here, including one important concern, the ***interaction*** of variables. The present discussion will be limited primarily to TTS measured 2 min or longer after exposure and is given in terms of the individual factors as follows:

(a) Stimulus amplitude. TTS, increases linearly with average **SPL** over the range of 75 to 120 dB and possibly higher. The difference between TTS produced by 85- and 90-dB noise is about the same as the difference between that produced by 90- and 95-dB **SPL.** This relationship is illustrated in Fig. 7-5.

(b) Exposure frequency. For equal **SPL** in octave bands of noise, low frequencies present less hazard to the ear than higher frequencies up to **4** kHz. This is due to the frequency-response characteristics of the human ear. Fig. 7-6 illustrates the general relation between exposure frequency and TTS for octave bands of noise.

Pure tones produce more TTS than corresponding octave bands of noise of the same amplitude. The overall level of an octave band must be about 5 dB higher than a pure tone at the octave center frequency to produce an equal amount of TTS (Ref. 33). This 5 dB correction has

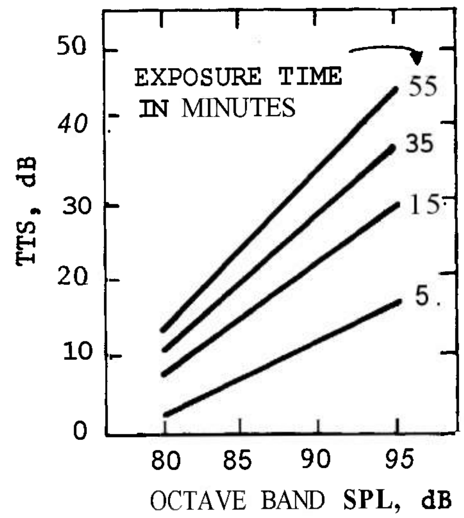


FIGURE 7-5. Temporary Threshold Shift (TTS) as a Function of Sound Pressure Level (SPL) for Exposure to an Octave Band of 2 to 4 kHz (Ref. 31).

been adopted for use in the CHABA steady-state noise damage-risk criterion.

Investigations of TTS from broadband noise show that when pure tones below 2 kHz are present, the combined tone and noise condition produces more TTS than noise alone, even if the overall **SPL** for the two conditions are equated (Ref. 34). Investigations of TTS

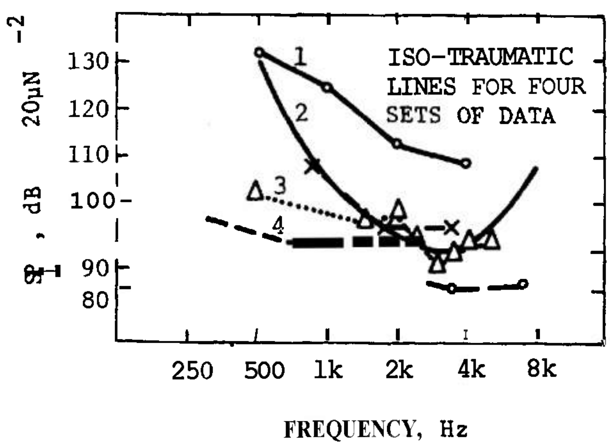


FIGURE 7-6. Relation Between Exposure Frequency and Temporary Threshold Shift (TTS) for Octave Bands of Noise (the iso-traumatic lines are based on TTS and are for four independent sets of data. Within any one set of data, the same exposure time or TTS criterion was used) (Ref. 32).

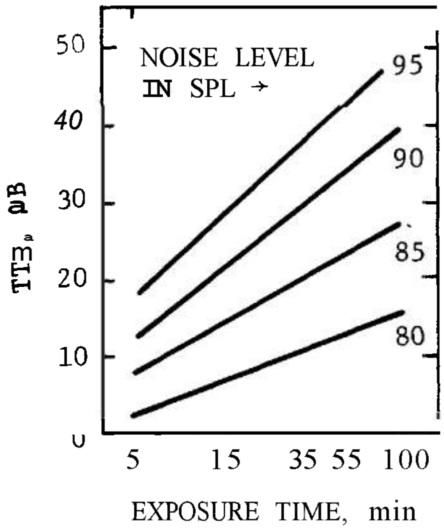


FIGURE 7-7. Temporary Threshold Shift (TTS) at 4 kHz From Exposure to 2 to 4 kHz Octave-band Noise (Ref. 31).

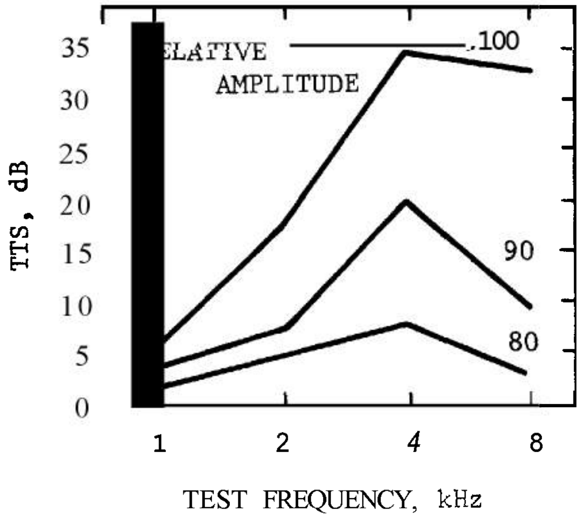


FIGURE 7-8. Distribution of Temporary Threshold Shift (TTS) Resulting From 5-min Exposure to Broadband Noise (Ref. 30).

from infrasonic tones conclude that the most hazardous conditions are at or above 141 dB SPL in the range of 10 to 12 Hz (Refs. 35,36).

Evidence indicates that exposure to ultrasonic tones up to 120 dB SPL is unlikely to produce TTS (Ref. 37). No clear evidence exists upon which to assess the effect of higher SPL.

(c) Duration of exposure. TTS, from steady noise grows linearly with the logarithm of exposure time, as illustrated in Fig. 7-7. Most experiments have involved relatively short exposures (≤ 8 hr), but the rule is possibly valid for exposure times of up to 720 hr (Ref. 38). The effects of intermittent noise exposure have been reviewed, and the conclusion is that, in general, intermittent exposures produce less TTS than continuous exposures (Refs. 28,39,40).

(d) Test frequency. TTS involves areas, not points, on the *basilar* membrane[7] (Ref. 28). Thus, virtually any type of tone or noise exposure affects auditory thresholds over a range of test frequencies. For SPL above 60 dB, maximum TTS occurs at a frequency on the order of 0.5 to 1 octave above the stimulating frequency for pure tones and bands of noise. The relative TTS occurring at various frequencies with a broadband (white) noise exposure is shown in Fig. 7-8.

(e) Preexposure hearing level. This discussion has been based almost entirely on ears with "normal" sensitivity. Impaired ears may demonstrate different results. Ears with *conductive*[8] hearing losses, for example, would be expected to show less TTS because less energy is transmitted to the cochlea. Ears with pure *sensorineural*[8] losses should also show less TTS than normal ears, but this is due to their having less remaining sensitivity to lose.

(f) Sex and age. No systematic differences in TTS as a function of sex and age have been reported (Refs. 41,42). Nor have any systematic trends in TTS growth been reported solely as a function of age.

(g) Monaural vs binaural exposure. In general, monaural exposures are accompanied by about 5 dB more TTS than binaural exposure to the same condition (Ref. 25).

(2) Recovery *of TTS*. When TTS, does not exceed about **40** dB, and is induced by relatively short exposures to continuous blocks of steady-state noise, TTS recovers linearly in log time and occurs within a maximum of 16 to 48 hr (Refs. **28,43**). Under these conditions recovery rate is independent of test frequency. The slope of the recovery rate is also independent of

7. The ***basilar membrane*** is the part of the inner ear that is set in motion by sound at the eardrum. Its movement stimulates the hair cells, which in turn activate auditory nerve fibers.

8. Hearing losses are of two types, ***conductive*** and ***sensorineural***. In *conductive* loss, the conduction of sound to the cochlea is attenuated due to some outer or middle ear problem. In a *sensorineural* loss, either the sensor, i.e., the cochlea, or the auditory nerve is defective.

test frequency. The slope of the recovery function, however, may vary as a function of the amount of TTS_2. Representative recovery functions are shown in Fig. 7-9.

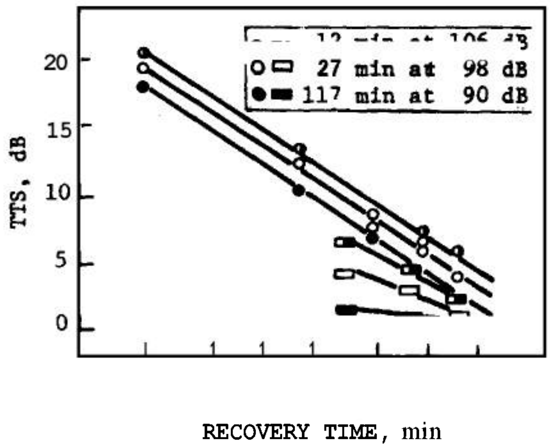


FIGURE 7-9. Recovery From Temporary Threshold Shift (TTS) (Ref. 45).

Since subsequent recovery is usually quite predictable once the value of TTS_2 is known, generalized recovery functions can be developed for TTS < 40 dB. Such functions permit TTS measured at various times after exposure to be converted backward or forward to TTS, for purposes of direct comparison. A graph for converting TTS to TTS, is shown in Fig. 7-10 (Ref. 44).

When TTS is induced by exposures to steady noise longer than 8 hr, or by intermittent noise, these generalized recovery functions are probably invalid. Ward (Ref. 39) states that intermittent noise causes a significant increase in recovery time, for equal TTS; Yuganov et al. (Ref. 38) and Mills et al. (Ref. 46) report similar findings for exposures of 12 to 720 hr.

As TTS_2 exceeds about 40 dB, a change in the recovery function may be noted. Recovery from high values of TTS is linear in time, rather than linear in log time, as illustrated in Fig. 7-11.

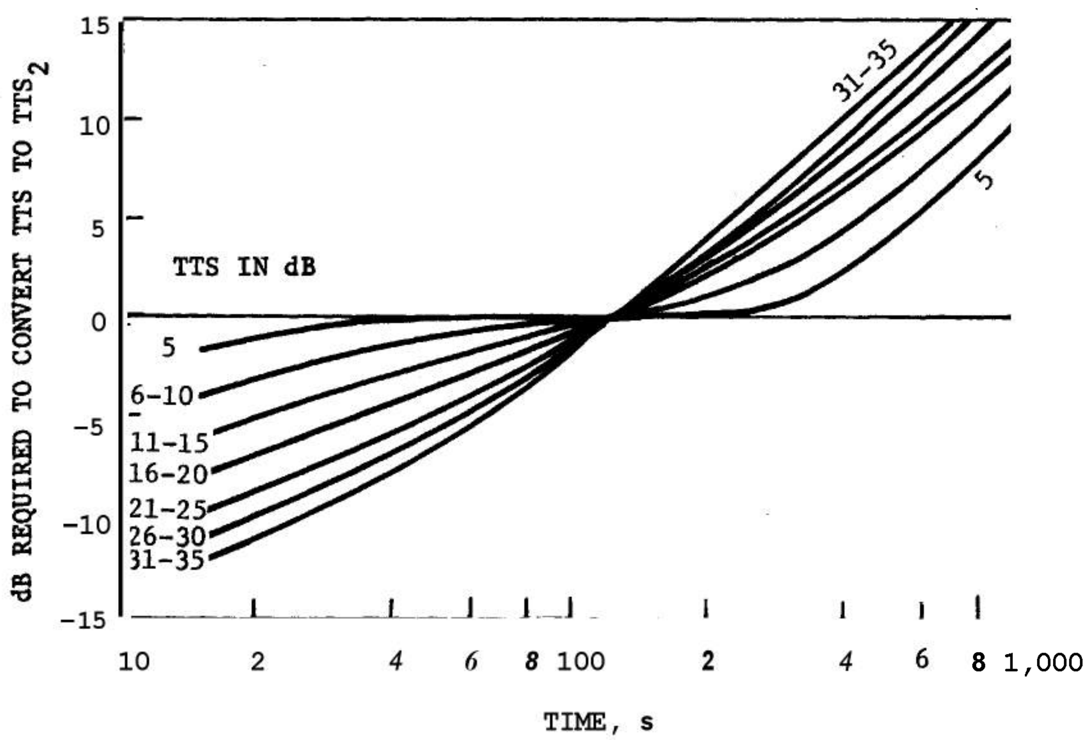
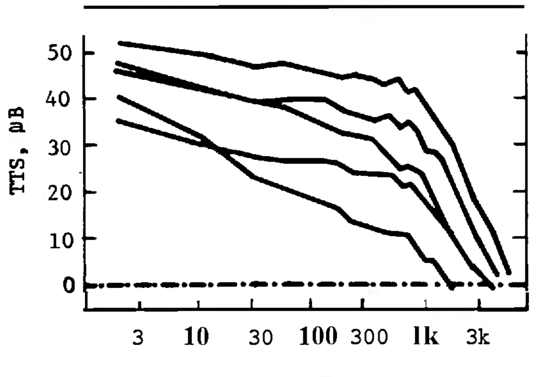
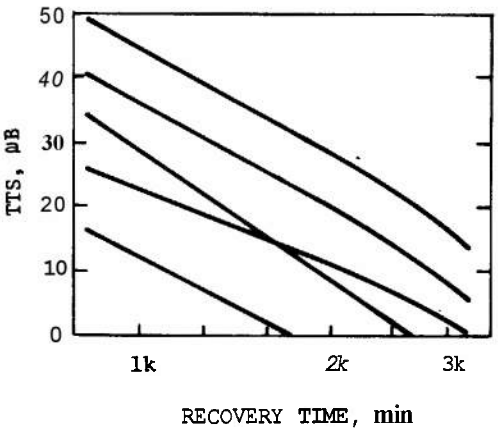


FIGURE 7-10. Conversion of TTS to TTS_2 With TTS as the Parameter (Ref. 44).



(A) Average course of recovery at 3 and 4 kHz following exposure to 105 dB SPL 1.2 to 2.4 kHz noise whose duration was sufficient to produce 50 dB TTS.



(B) Data replotted in terms of time instead of log time.

FIGURE 7-11. Recovery From Temporary Threshold Shift (TTS) (5 subjects) (Ref. 51).

7-3.3 IMPULSE NOISE AND THRESHOLD SHIFT

An impulse is defined as an aperiodic pressure phenomenon of less than 1-s duration, having a fast rise time and a peak-to-rms ratio greater than 10 dB. Such a vague definition fails to define a "gray" area of pressure phenomena that may be considered as either long impulses or short steady sounds. Impulses are, however, characteristic of many working environments, and common examples include the sound of gunfire, impact and power-operated tools, drop forges, and pile drivers.

The impulse-noise-effects literature has been reviewed extensively (Refs. 16,28,47,48). As is the case with steady noise, the interaction of variables is an extremely important consideration. Some of the more important findings are summarized:

(1) *Acquisition of TTS from impulse noise.*

(a) Peak pressure level. The higher the peak pressure level, the greater is the risk of TTS, other parameters being equal. This relation is illustrated in Fig. 7-12 by data from the classic studies of Murray and Reid (Ref. **49**) and in Fig. 7-13 by data from Ward et al. (Ref. **50**). The peak pressure level where TTS is first produced depends in part on other parameters, such as impulse duration or the number of impulses presented, as well as on individual susceptibility.

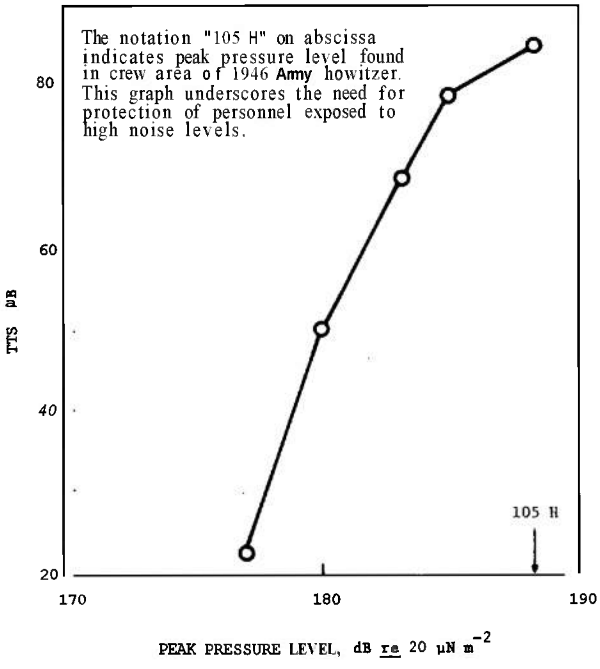


FIGURE 7-12. Temporary Threshold Shift (TTS) as a Function of Peak Pressure Level for Ears Exposed to 10 Impulses Produced by Various Weapons (Ref. 49).

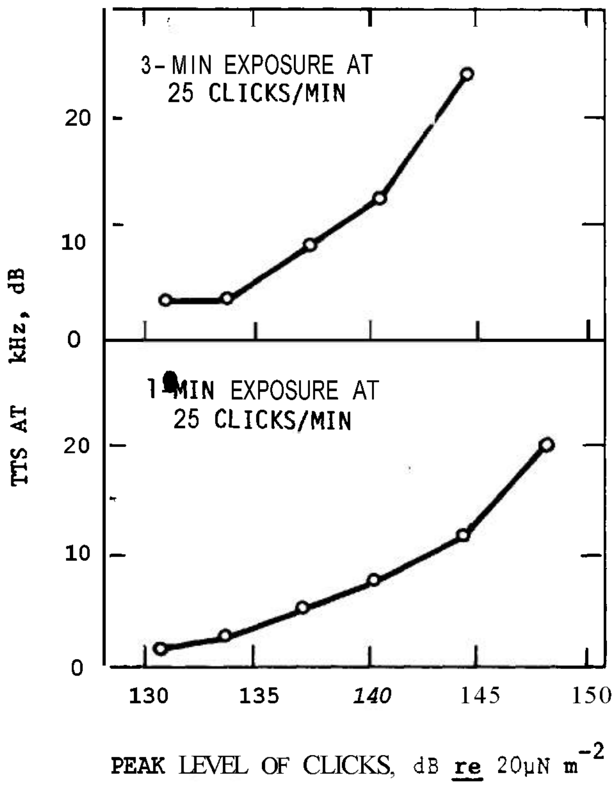


FIGURE 7-13. Temporary Threshold Shift (TTS) at a 4 kHz as a Function of Peak Level of Clicks (Ref. 50).

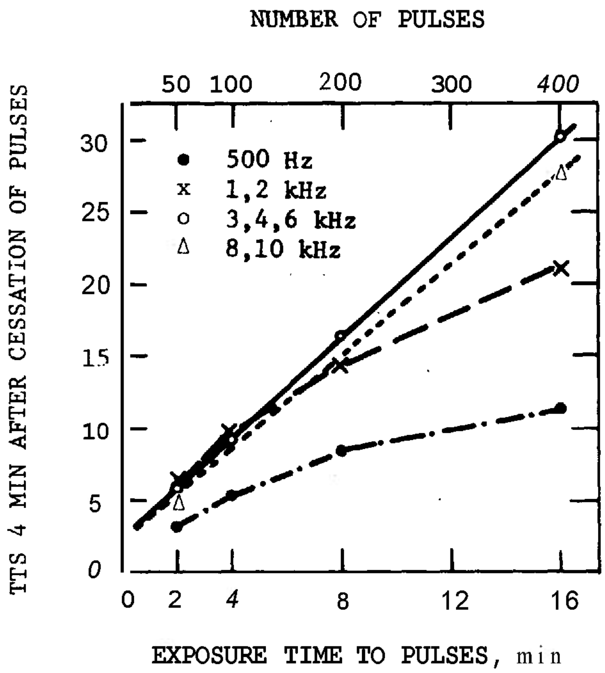


FIGURE 7-14. Average Growth of Temporary Threshold Shift (TTS) From Constant Rate Impulses (Note that in contrast to steady noise, TTS from impulses increases linearly with time or with number of impulses) (Ref. 50).

(b) Impulse duration. It has been shown that, for a peak level of 166 dB, 10 to 25 impulses of 92-μs duration have about the same effect as 75 to 100 impulses of 36-ps duration (Refs. 42,52). Other research shows that cal .22 rifles fired in the open (short duration) do not constitute a hazard to hearing, whereas the same rifles fired in an indoor reverberant range (long duration) do constitute a borderline hazard (Ref. 53). The relation between impulse duration and risk of TTS is best described by reference to the CHABA damage-risk criterion for impulse-noise exposure.

(c) Rise time. Many impulses have rise times less than 1 μs since a shock wave is a major component of the event. To date, however, no serious attempt has been made to relate impulse rise time to the risk of TTS, and this variable is not treated systematically in damage-risk criteria.

(d) Spectrum. Recently, spectral analyses of impulses with a computer have become possible (Ref. 21). Few data exist, however, relating the spectrum of impulses to risk of TTS, and considerably more investigation will be required before such information will be of any real benefit.

(e) Number of impulses. TTS appears to grow linearly with the number of impulses, or linearly in time for a constant rate of presentation, as illustrated in Fig. 7-14.

(f) Rate of impulse presentation. TTS growth rate from impulses does not differ significantly when the interpulse interval is between 1 and 9 s. At less than 1 s between pulses, TTS growth rate is reduced because of the protective action of the aural reflex. Also, when as many as 30 s elapse between successive impulses, TTS grows more slowly because of the recovery that takes place between impulses (Refs. 50,54).

(g) Ear orientation. When the impulse noise includes a shock wave, the orientation of the external ear with respect to the shock front is of considerable importance. Hodge et al. (Ref. 55) show that when the ear is at normal incidence to the shock wave, the TTS produced is approximately equivalent.to that produced by an impulse having 5 dB greater amplitude but arriving at grazing incidence. Golden and Clare (Ref. 56) report a similar difference. Hodge and McCommons (Ref. 27) have shown that when the shock strikes one ear at normal incidence, the other ear is shadowed (protected) by the head and evidences considerably less TTS. This explains why right-handed rifle shooters usually demonstrate more TTS in the left than in the right ear: the right ear is partially protected by the head's shadow.

(h) Test frequency. TTS from impulse-noise exposure occurs over a wide range of frequencies, with the maximum TTS usually occurring in the region of 4 to 6 kHz. This effect is illustrated in Fig. 7-15.

(i) Monaural vs binaural exposure. On the average, TTS growth rates for binaural and monaural exposure do not differ significantly when the interpulse interval is 2 s (Ref. 57). Large individual differences occur among the subjects, but no consistent trend favors either type of exposure.

(2) *Recovery from TTS.* A growing body of data indicates that recovery from TTS induced by various types of intermittent noise differs radically from that caused by steady noise exposure. Research in 1965 found instances of individual subjects with TTS, ≈ 25 dB who showed little or no recovery for periods of up to 1 hr after exposure, but thereafter recovery became

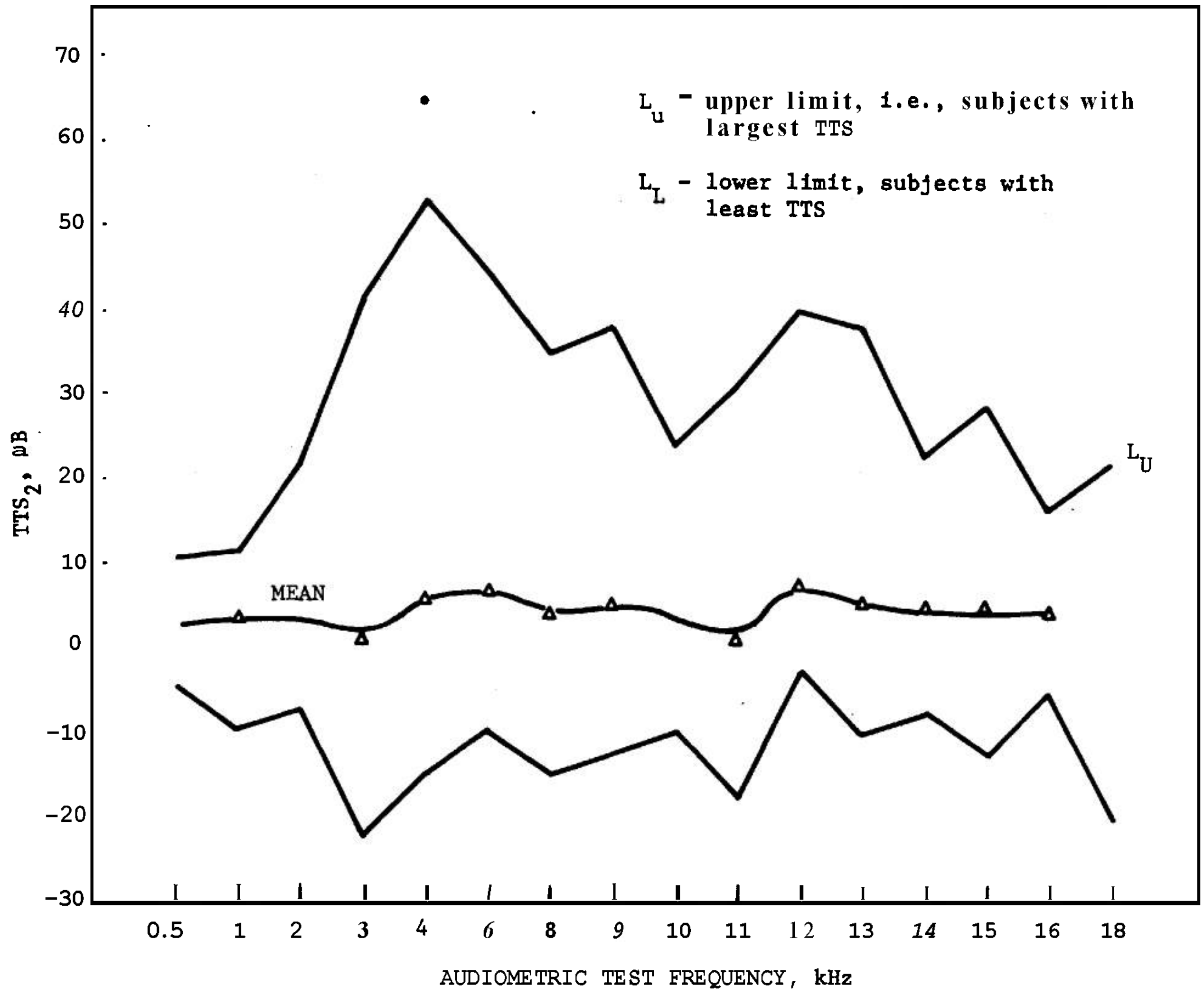


FIGURE 7-15. Distributions of TTS_2 Following Exposure to 25 Gunfire Impulses (16 subjects) (Note that whereas mean and media TTS are between 0 and +10 dB at all frequencies, t a range of effect is from –25 dB (sensitization) at 3 kHz to +55 dB (l... 4 kHz. Also note that this exposure produced TTS at frequencies up to 18 kHz) (Ref. 27).

approximately linear in log time (Ref. 58). Later research has identified four types of recovery curves for impulse-noise-induced TTS in human beings and monkeys: (1) linear recovery in log time; (2) no apparent recovery for periods of up to 1 hr followed by linear in log-time recovery; (3) slight recovery followed by an increase in TTS; and (4) slight recovery followed by a long plateau of no change, and then further recovery (Ref. 59). These diverse functions occur for TTS ≤ 30 dB in human beings, and suggest that considerably more research will be required to derive averaged, generalized recovery functions for impulse-noise-induced TTS.

For TTS, > 40 dB, recovery may be very slow. As long as 6 mo of recovery may be necessary to accurately assess residual PTS from excessive exposure to gunfire noise (Ref. 60).

7-3.4 BLAST AND ITS EFFECTS ON HEARING

Blast differs little from impulse noise insofar as the hearing mechanism is concerned. The term "blast" is typically used to refer to much higher pressures and/or longer durations than are usually associated with common impulse-noise sources. However, insofar as the development of TTS is concerned, the preceding discussion of impulse-noise parameters is equally applicable to the parameters of blast.

Single, large-amplitude blast waves may rupture the eardrum. The threshold for eardrum rupture is about 5 psi; at 15 psi, 50 percent of eardrums will probably be ruptured. When the eardrum is ruptured, loss of hearing is severe in the affected ear. After healing (2 to 6 wk), the ear's sensitivity may return to normal, particularly if the middle ear ossicles are intact (Refs. 61,62). Rupture of the eardrum thus serves as a "safety valve". If the eardrum is not ruptured by the blast, profound PTS may result from a single exposure, particularly at the higher frequencies of hearing (Refs. 63,64).

7-4 EFFECTS OF HEARING LOSS ON PERFORMANCE

Some persons are likely to suffer TTS or PTS from noise exposure in spite of the application of safety criteria or the use of protective equipment. Other persons may have PTS from disease or trauma. Accordingly, the effects of TTS and PTS on performance will be considered briefly.

7-4.1 DETECTION OF LOW-LEVEL SOUNDS

Par. 7-3 notes than an ear's threshold sensitivity (hearing level) is stated with reference to audiometric zero, such as the Ref. 22 or Ref. 23 values. Audiometric zero at various test frequencies represents the lowest SPL that can be detected, on the average, by listeners having "normal" hearing. Table 7-8, Column 2, shows the SPL representing ISO audiometric zero at selected frequencies. Column 3 shows the "allowable TTS" permitted by the CHABA damage-risk criteria for steady and impulse noise (Refs. 24,65). Column 4 shows the minimum detectable SPL, on the average, by a listener whose baseline hearing sensitivity equals ISO audiometric zero and who has the CHABA-limit TTS at the various frequencies. These values also describe the detection limits for a listener who has PTS in the amounts shown in Column 3 of the table.

Given a knowledge of the spectral characteristics of a low-level sound that must be detected, and of the lowest SPL at various test frequencies that a particular listener can detect, predictions can be made of the listener's ability to detect the low-level sound. A convenient example from the military context may be cited. Sounds created by people walking over various types of terrain contain energy primarily in the 3- to 8-kHz range. This knowledge permitted the hypothesis that persons having TTS or PTS in this range of frequencies would be less able to detect such sounds than persons with normal hearing sensitivity; the hypothesis has been confirmed by experimental tests. These results suggest that, for example, military personnel receiving TTS from daytime exposure to weapon noise should not be assigned nighttime duty for perimeter sentry duty where the preservation of human life may depend on maximum hearing sensitivity, unimpaired by slowly recovering TTS. These results further suggest that in any detection situation, the listeners selected should have the most sensitive hearing possible, free of TTS or PTS.

7-4.2 RECEPTION OF SPEECH

The spectral characteristics of speech must be considered in assessing the effects of TTS or PTS on speech reception. Speech sounds range in frequency from 0.1 to 7 kHz; peak energy occurs at about 0.5 kHz. Speech sounds are of two basic types—vowels and consonants. Vowel sounds fall roughly into the frequencies below 1.5 kHz, and consonants, above 1.5 kHz (Ref. 66). Vowels are thus more powerful (i.e., contain more energy)

TABLE 7%. ISO AUDIOMETRIC ZERO VS CHABA*-LIMIT TTS

Frequency, Hz	SPL for ISO zero, dB re 20 μN m^{-2}	CHABA allowable TTS, dB	Minimum detectable SPL, dB re 20 μN m^{-2}†
500	11	10	21
1,000	6.5	10	16.5
2,000	8.5	15	23.5
3,000	7.5	20	27.5
4,000	9	20	29
6,000	8	20	28
8,000	9.5	20	29.5

* CHABA = Committee on Hearing, Bioacoustics, and Biomechanics (of the National Academy of Sciences-National Research Council)

† This interpretation assumes that the listener's preexposure hearing sensitivity was equal to ISO audiometric zero.

than consonants. Vowel sounds indicate that someone is saying something, but consonants aid in discriminating what is being said. Thus, consonants convey more information than vowels.

A person with TTS or PTS only in the range of 0.1 to 1.5 kHz has difficulty hearing speech unless it is quite loud, and he is unable to hear soft voices. If the talker raises his voice level, the listener will be able to understand what is being said.

The person with TTS or PTS only in the range of 1.5 to 7 kHz, on the other hand, hears vowels normally but finds it difficult to discriminate consonants. Increasing the speech level aids little, but careful enunciation by the talker is of benefit. This type of TTS or PTS is a particularly severe problem in occupational deafness since the loss of hearing sensitivity frequently occurs first in the 3- to 6-kHz range. The problem is compounded by the presence of background masking noise, since the low-level consonant sounds are masked to a greater extent by broadband noise than the higher-level vowel sounds. This fact has led some hearing conservation groups to develop criteria for protecting hearing at frequencies up to 4 kHz (Ref. 67). In the United States, however, only frequencies of 0.5 to 2 kHz are considered in assessing occupational hearing impairment (Ref. 68).

Table 7-9 shows classes of hearing handicap defined by the average of PTS at 500, 1,000, and 2,000 Hz. In general, TTS of the same amount will constitute an equivalent degree of impairment although, of course, the impairment disappears when the TTS has recovered.

7-5 SUBJECTIVE AND BEHAVIORAL RESPONSES TO NOISE EXPOSURE

In par. 7-4, the effects of noise that are demonstrated *after* exposure and that are indicative of a *decrease* in the responsiveness or neural activity in the auditory receptors are considered. In this paragraph, by contrast, noise effects that occur *concurrently* with exposure and that result in *increased* neural activity are considered. These responses are discussed in terms of general observations, the masking of auditory signals, and the masking of speech perception. Methods for measuring speech intelligibility and assessing the effect of noise on speech intelligibility are presented. (Other discussion of background noise is presented in par. 7-7.)

7-5.1 GENERAL OBSERVATIONS

Broadbent and Burns (Ref. 70) and Cohen (Ref. 71) have reviewed the effects of noise on behavior and psychological state. In some respects the existing literature does not yet support firm conclusions, but representative subjective and behavioral responses are summarized in Table 7-10.

TABLE 7-9. CHART FOR DETERMINING CLASS OF HEARING IMPAIRMENT (Ref. 69).

Class	Degree of handicap	Average hearing level at 500, 1,000-and 2,001) Hz in the better ear*, dB At least	Less than	Ability to understand ordinary speech
A	Not significant	-	15	No significant difficulty with faint speech
B	Slight	15	30	Difficulty with faint speech only
C	Mild	30	45	Frequent difficulty with normal speech
D	Marked	45	60	Frequent difficulty with loud speech
E	Severe	60	80	Can understand only shouted or amplified speech
F	Extreme	80	-	Usually cannot understand even amplified speech

*If the average of the poorer ear is 25 dB or more greater than that for the better ear, add 5 dB to the average for the better ear.

7-5.2 MASKING OF AUDITORY SIGNALS

The amount of masking is the number of decibels that the quiet threshold of a signal must be raised to be intelligible because of the presence of masking sound. Masking effects are classified as monaural and interaural. Monaural masking occurs when the signal and noise reach the ear(s) at the same time; this type of masking is most critical in working environments where personnel are not wearing earphones. Interaural masking occurs when the signal reaches one ear and noise the other ear. No interaural masking occurs unless the noise exceeds about 40 to 50 dB SPL, since below this level the listener can readily distinguish between the sounds heard separately in his two ears. At higher levels the noise is transmitted to the "signal" ear via bone conduction; thus this situation may be regarded as a special case of monaural masking with the head serving as an attenuator. Interaural masking is a problem generally when the SPL in one ear is much higher than in the other. This is a particular problem when the telephone or radiotelephone is used in a noisy environment.

The monaural masking effect of a pure tone, or of a noise having a strong pure-tone component, is greatest near the frequency of the tone, but also extends to frequencies adjacent to the masking tone. Curves of masking effects as a function of frequency are shown in Fig. 7-16. Audible beats near the frequency of the masking tone increase the audibility of the signal and thus reduce the degree of masking at these frequencies. For tones of low intensity, masking is confined to a region near the masking tone; for higher intensities, the masking is extended, particularly at frequencies above the masking tone.

The masking effect of narrowband noise is quite similar to that for pure tones, except that the dips due to audible beats are absent.

Masking of signals by broadband noise whose level does not exceed about 60 to 70 dB SPL is governed by the "critical band" concept. At low noise levels, a pure tone signal is masked by only a narrow range of frequencies whose width defines the critical band for that signal frequency. The width of the critical band varies from about 40 to 200 Hz, over the range of 0.5 to 8 kHz. Within this range, and for low noise levels, an increase of 10 dB in noise level results in about 10 dB additional masking of tones within the critical band. Above masking levels of about 70 dB SPL, however, the width of

TABLE 7-10. REPRESENTATIVE SUBJECTIVE AND BEHAVIORAL RESPONSES TO NOISE EXPOSURE

Conditions of exposure			Reported disturbances	Reference
SPL, dB	Spectrum	Duration		
150*	1-100 Hz	2 min	Reduced visual acuity; chest wall vibrations; gag sensations; respiratory rhythm changes	72
120	Broadband	-	Reduced ability to balance on a thin rail	73
110	Machinery noise	8 hr	Chronic fatigue	71
105	Aircraft engine noise		Reduced visual acuity, stereoscopic acuity, near-point accommodation	74
90	Broadband	Continuous	Vigilance decrement; altered thought processes; interference with mental work.	70
85	1/3-octave at 16 kHz	Continuous	Fatigue, nausea, headache	75
75	Background noise in spacecraft	10-30 days	Degraded astronauts' performance	38
60	Speech frequencies	80 s/hr	Annoyance reactions in 50% of community residents	76

*In this study subjects wore protective devices to prevent hearing loss.

the critical band increases markedly in both directions. A 10-dB increase in noise level will still cause about 10 dB more masking of frequencies within the noise band, but it may also increase the masking effect at more distant frequencies by as much as 20 dB.

7-5.3 MASKING OF SPEECH BY NOISE

Most of the energy required for near-perfect speech intelligibility is contained in the range of 0.2 to 7 kHz. This range may be narrowed to 0.3 to 4.5 kHz without significant loss in intelligibility. In reducing the frequency range, 1.5 kHz constitutes the "center of importance" of speech, and narrowed pass-bands of a communication system should be centered on about 1.5 kHz. Consonants, such as *S*, contain energy at frequencies above 1.5 kHz; whereas vowels, such as *O*, contain lower-frequency energy. Unfortunately, the consonants, which convey most of the information in English speech, contain relatively little energy. Thus, they are more subject to interference (masking) from noise than are vowels. Speech masking by noise is important in the design of communication systems, in recognizing speech intelligibility factors, and in measurement of speech intelligibility. These are discussed in the following subparagraphs:

(1) Communication system design. Important in communication is the maintenance of a high speech signal-to-noise (S/N) ratio in each frequency band, with particular emphasis on those bands 'that contribute most

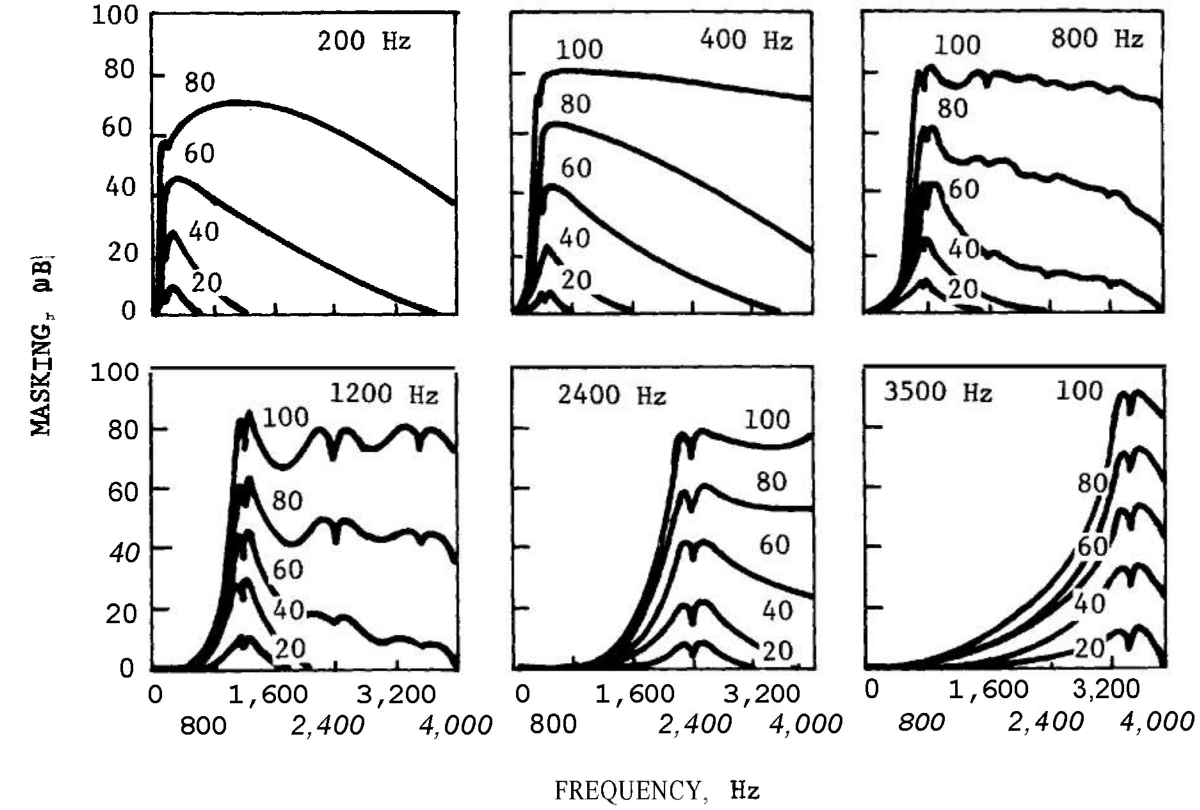


FIGURE 7-16. Masking as a Function of Frequency for Masking by Pure Tones of Various Frequencies and Levels,(Number at top of each graph is the frequency of masking tone. Number of each surve is level above threshold of masking tone) (Ref. 77).

to intelligibility. Another consideration is the point of overload of the hearing mechanism, i.e., the speech SPL level above which intelligence is no longer easily extracted by the ear from the stimulus. The overload effect can be demonstrated quite readily in a noisy environment when a voice comes over a loudspeaker at a very high level. A listener will find the amplified speech more intelligible when his ears are plugged than when he listens without earplugs. This effect occurs because, with the ears plugged, the speech signal no longer overloads the hearing mechanism, and the signal-to-noise ratio is not changed. Overloading of the ear due to speech amplitude begins when the overall rms level of the speech signal is about 100 dB SPL at the normal listener's ear.[9] In addition to not contributing to intelligibility, prolonged listening to high levels of speech signals produces discomfort, TTS, and, with sufficient exposure, even PTS.

9. The average overall rms level of speech may be approximated by subtracting 3 dB from the arithmetic average of the peak level observed on a sound-level meter set for slow meter damping on the C-scale in a quiet environment.

(2) Factors in speech intelligibility. Two types of communication must be considered in discussing speech intelligibility-electrically aided and direct. The effectiveness of both types of voice communication is determined by the following parameters:

(a) Level and spectrum of ambient noise at the ear (includes both acoustical noise and electronically induced noise)

(b) Voice level and spectrum of speech

(c) Distance between the speech source and the listener's ear

(d) Complexity and number of alternative messages available to the listener

(e) Characteristics of the talker's enunciation and of the listener's ears.

Electrically aided speech more specifically depends upon the characteristics of all the components of the transmission and receiving systems.

(3) Recommended approaches to measurement of speech intelligibility. Speech intelligibility is measured

by determining the percentage of words correctly received by listeners. Such measurement may be done through subjective tests with talkers and listeners, or by calculations based on the signal-to-noise ratio in various frequency bands. The choice of approach will be determined by the amount of time, personnel, and/or instrumentation available. Representative tests include the following:

(a) Phonetically Balanced Word Intelligibility *Test*. In the military setting, the intention is usually to discriminate among, or evaluate, highly effective communication systems. This requires a sensitive test of speech intelligibility ——ne that is capable of detecting small differences between systems. Therefore, the use of the Phonetically Balanced (PB) Monosyllabic Word Intelligibility Test (Ref. 78) is recommended for applications requiring maximum evaluation accuracy. Some aspects of the test procedure follow.

The PB test material consists of 20 lists of 50 phonetically balanced words each. Each list is of approximately the same difficulty. The talker reads the words in a "carrier sentence" at **4-s** intervals, and the listener writes down each key word. The hearing level of both talkers and listeners must average no more than 10 dB overall, with no more than 15 dB at any of the frequencies 0.25, 0.5, 1, 2, and **4** kHz (Ref. 22). Talkers must have no obvious speech defects or strong regional or national accents. Listeners must be completely familiar with each of the 1,000 words and with the speech characteristics of the talkers. The test must always be given in its entirety (all 1,000 words must be used), and if the test is to be repeated several times with the same personnel, the order of words within lists should be randomized for each presentation. Normally, 8 to 10 hr of talker and listener training are required to properly use the PB intelligibility test.

PB intelligibility scores may be acceptable in certain instances with values as low as 50 percent; i.e., when half the words spoken are correctly perceived. Only rarely is a PB intelligibility score as high as 90 percent required. For example, single digits may be transmitted with greater than 99-percent reliability with a system providing a PB score of 60 to 70 percent, since the listener has only 10 alternatives. The criterion of acceptability for communication systems should be a mandatory score of 70 percent and a desirable score of 80 percent when the ANSI PB method is followed.

(b) *Modified* Rhyme Test (MRT). If testing time is limited, or time is not available to thoroughly train subjects for the PB method, the second recommended choice is the Modified Rhyme Test (MRT) described by House et al. (Ref. 79). The test material consists of 300 words that are printed on an answer sheet in ***50*** groups of six words each. The talker reads one of the six words in the first group, and each listener selects one word from the closed set of six alternatives. Unlike the PB test, little account is taken of word familiarity or of the relative frequency of occurrence of sounds in the language. This test has the advantage of requiring little or no training and does not require a written response, as is the case with PB tests. A chart for converting MRT scores to PB test scores is shown in Fig. 7-17.

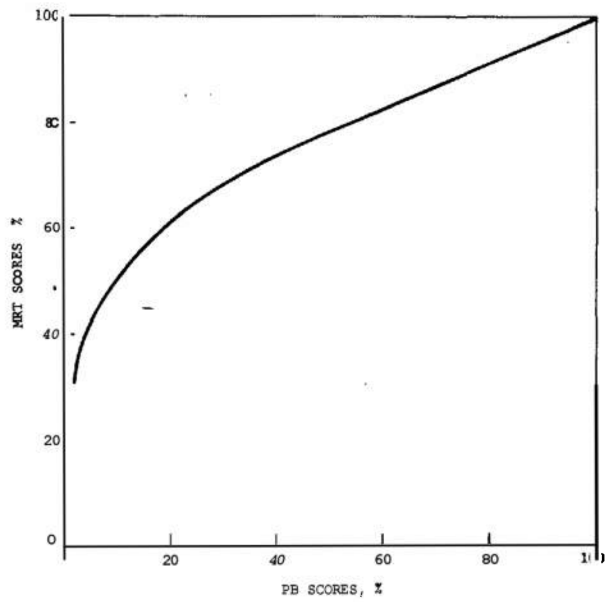


FIGURE 7-17. Relationship Between Modified Rhyme Test (MRT) and Phonetically Balanced (PB) Test Scores (Ref. 81).

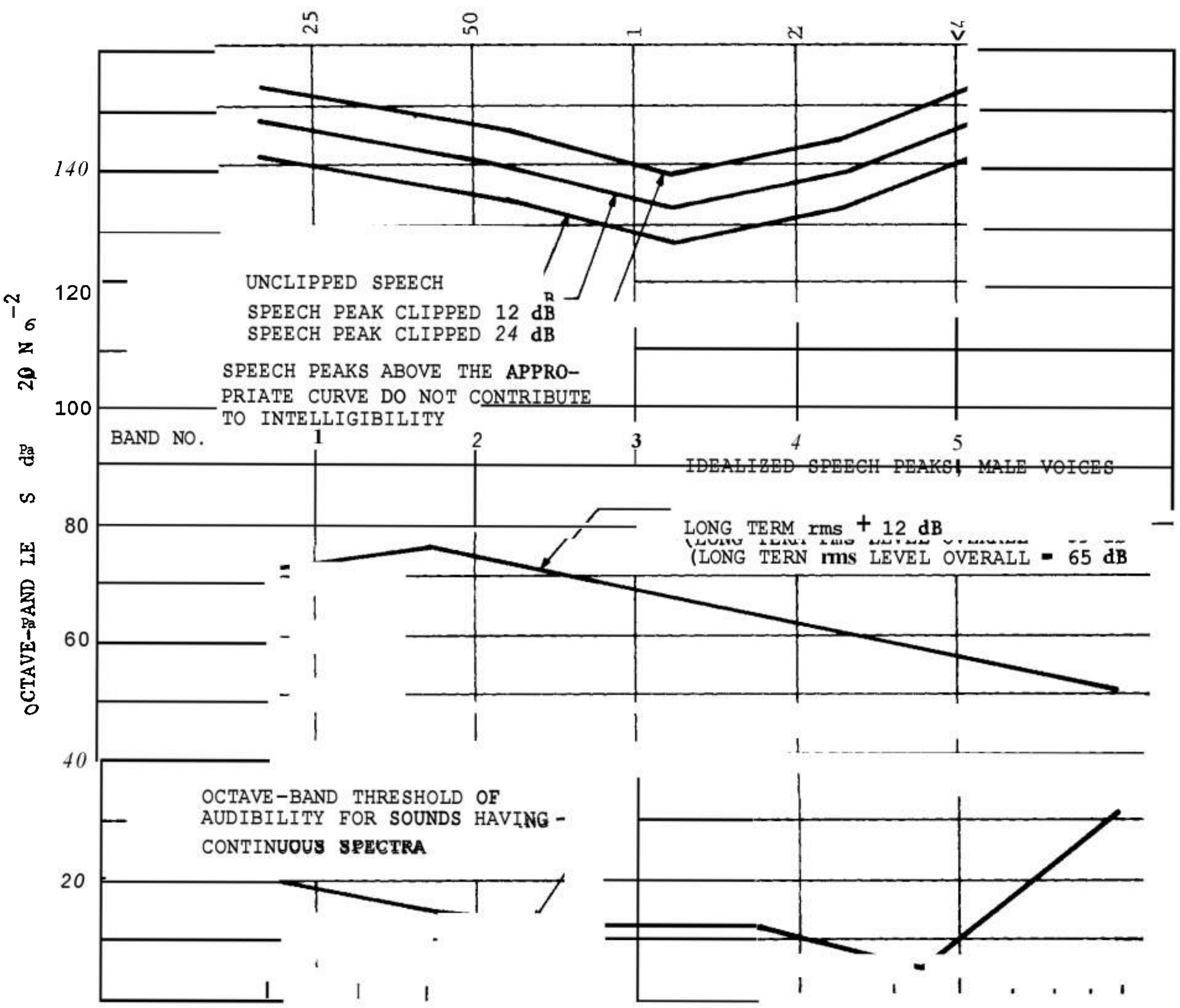
(c) Articulation Index calculation. Intelligibility of speech in noise may also be calculated from measures of the speech and noise levels through use of the Articulation Index (AI) (Ref. 80). AI can be calculated from octave-band measurements using the worksheets shown in Fig. 7-18 and Table 7-11, provided that the noise does not have any severe pure tone components and is steady in character without an extremely sloping spectrum. (Additional worksheets are available for the situation requiring the use of 1/3-octave band measurements (Ref. 80).)

The octave-band method of calculating AI employs the following steps:

1. Plotting of the measured octave-band **SPL** of the noise

2. Adjustment of the idealized speech spectrum shown on the worksheet to reflect its actual level

3. Measurement of the difference between the



speech and noise in each band, and assignment of a value between 0 and 30 dB

4. Multiplication of this assigned value in each band by the appropriate weighting factor (to account for the difference in the importance among the several bands)

5. Addition of the resultant numbers. This number, which is between 0 and 1, is the AI that may then be converted to PB intelligibility score through the use of Fig. 7-19.

The AI method of calculating speech intelligibility may be used for either direct or electrically aided communication, provided only that the speech signal and noise levels at the ear are known.

7-6 PHYSIOLOGICAL (NONAUDITORY) RESPONSES TO NOISE EXPOSURE

7-6.1 LOW-LEVEL STIMULATION

That noise exposure can affect human physiological

TABLE 7-11. WORKSHEET FOR CALCULATUNG ARTICULATION INDEX (AI) (Ref. 80)

Col 1		Col 2	Col 3	Col 4
Octave band, Hz	Frequency, Hz	Speech peak-to-noise difference in dB	Weight	Col 2 x Col 3
1. 180- 335	250	________	0.0018	________
2. 355- 710	500	________	0.0050	________
3. 710-1,400	1,000	________	0.0075	________
4. 1,400-2,800	2,000	________	0.0107	________
5. 2,800-5,600	4,000	________	0.0083	________
			AI =	________

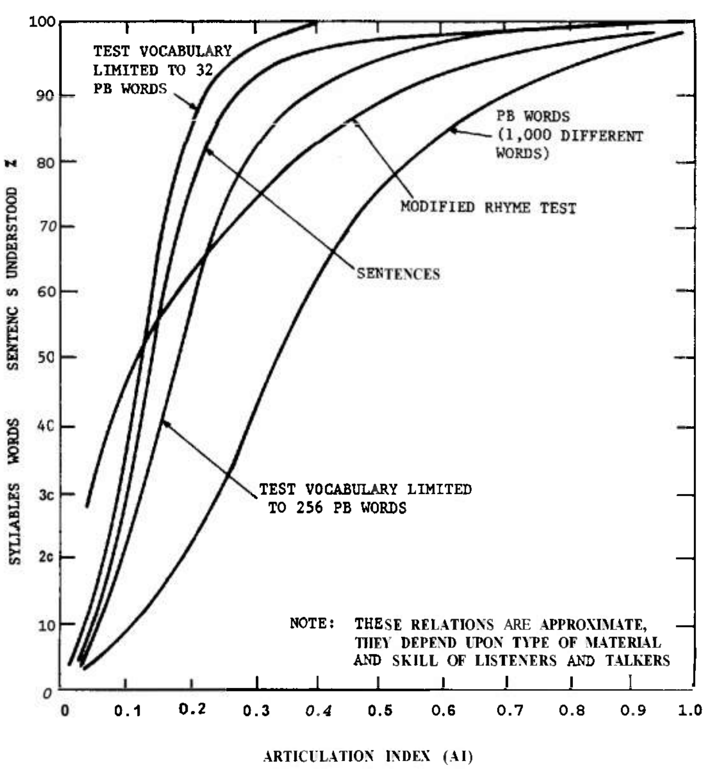


FIGURE 7-19. Relation Between Articulation Index (AI) and Various Measures of Speech Intelligibility (Ref. 80).

processes and that measurable effects are obtained with noise exposure conditions involving little or no risk of TTS are now well established. The main concern of researchers is whether these effects of noise, which in some instances appear to be correlated with pathological effects and/or behavioral alterations, may represent a real hazard to the health and well-being of exposed persons.

Jansen divides physiological responses to noise into (1) stress reactions, and (2) vegetative reactions (Ref. 82). Stress reactions to unfamiliar stimuli, in general, show adaptation with repeated exposure as the stimuli become familiar and gain meaning to man, and, hence, are of little concern in the present context. Vegetative reactions to meaningless noise stimulation are of primary concern here. "Meaningless" noise refers, for example, to the background noise found in work environments and in living environments. Representative observations from various studies are summarized here (Refs. 82,83):

(1) Noise exposure causes increases in the concentration of corticosteroids in the blood and brain and affects the size of the adrenal cortex. Continued exposure is also correlated with changes in the liver and kidneys and with the production of gastrointestinal ulcers.

(2) Electrolytic imbalances (magnesium, potassium, sodium, and calcium) and changes in blood glucose level are associated with noise exposure.

(3) The possibility of effects on sex-hormone secretion and thyroid activity is indicated.

(4) Vasoconstriction, fluctuations in blood pressure, and cardiac muscle changes have been reported. Vasoconstriction in the extremities, with concomitant changes in blood pressure, has been found for noises of 70 dB SPL, and these effects become progressively worse with higher levels of exposure.

(5) Abnormal heart rhythms have been associated with occupational noise exposure. This and other evidence supports the tentative conclusion that noise can cause cardiovascular disorders. Panian (Ref. 74) states that in Russia these cardiovascular symptoms are collectively referred to as "noise sickness".

Yuganov et al. (Ref. 38) state that 10 to 30 days of exposure to noise levels of 75 dB produced electroencephalograph and cardiovascular alterations in astronauts similar to those described previously. Reduction of the noise level to 65 dB resulted in no such observations at all for exposures of up to 60 days.

With respect to impulse-noise exposure, Yuganov et al. (Ref. 84) report that repeated exposure to simulated sonic booms having peak levels up to 9 kg m^{-2} ($\approx$ 133 dB re 20 μN m^{-2}), caused alterations in electrocardiogram and electroencephalogram traces as well as moderate bleeding in tympanic membrane epithelium. Subjectively, exposed individuals reported headache, tinnitus, and "fullness" in their ears.

7-6.2 RISK OF INJURY OR DEATH FROM INTENSE STEADY NOISE

Studies of very intense steady acoustic stimulation have been carried out primarily with animals, and few data are available for human exposures. Three relevant observations follow:

(1) One instance of a ruptured human eardrum has been reported for exposure to 159 dB SPL at 6.5 kHz for 5 min (Ref. 85).

(2) Mohr et al. (Ref. 72) report no risk of bodily injury to astronauts from the intense, low frequency noise simulating a space rocket launch, but a number of questions remain unanswered in this regard. Exposure to tones in the 1 to 100 Hz range should not exceed 2 min or 150 dB SPL, as these values appear to be close to the limits of human tolerance.

(3) Parrack (Ref. 86) calculates that, for a 2-kHz whole-body exposure (probably not attainable in a practical situation), human lethality from overheating would require from 5 min at 167 dB SPL to 40 min at 161 dB. At 6 to 20 kHz, the exposures required for lethality range from 5 min at 187 dB to 40 min at 181 dB SPL. Parrack indicates that ultrasonics pose no special hazard to human life until the SPL exceeds 180 dB.

7-6.3 BLAST AND IMPULSE-NOISE EFFECTS

The effects of high-intensity blast waves on man are classed as primary, secondary, and tertiary. Primary effects are those resulting from the impact of blast waves on tissues; secondary effects are caused by flying debris set in motion by the blast; and tertiary effects result from propulsion of the body by the blast. Only the primary effects of blast on man are summarized here.[10]

The following extrapolations of animal data to human exposure are valid only for exposure to single, fast-rising blast waves involving classical or near-classical waveforms:

(1) Risk of injury or death increases with increased pressure and/or duration, and with the presence of nearby acoustically reflecting surfaces.

10. The effects of blast on materiel are more properly considered shock, rather than an acoustical phenomena. See Chap. 5 for discussion of blast effects on materiel.

(2) Risk of injury is lessened with increased rise time and with higher-than-normal ambient pressures.

(3) Gas-containing organs (ears, lungs, intestines) are very susceptible to blast injury.

(4) The eardrum is most susceptible; its threshold for rupture is about 5 psi overpressure.

(5) The lungs are most critical with regard to possible lethality. The threshold for lung damage (minor hemorrhage) is about 10 psi overpressure.

(6) Animals exposed to blast show evidence of central nervous system (concussive) damage—ataxia, paralysis, convulsions, dazed appearance, and lethargy—and often do not respond to noxious stimuli.

(7) Fig. 7-20 shows 99-percent survival limits and lung damage thresholds for human beings as a function of peak overpressure and blast duration.

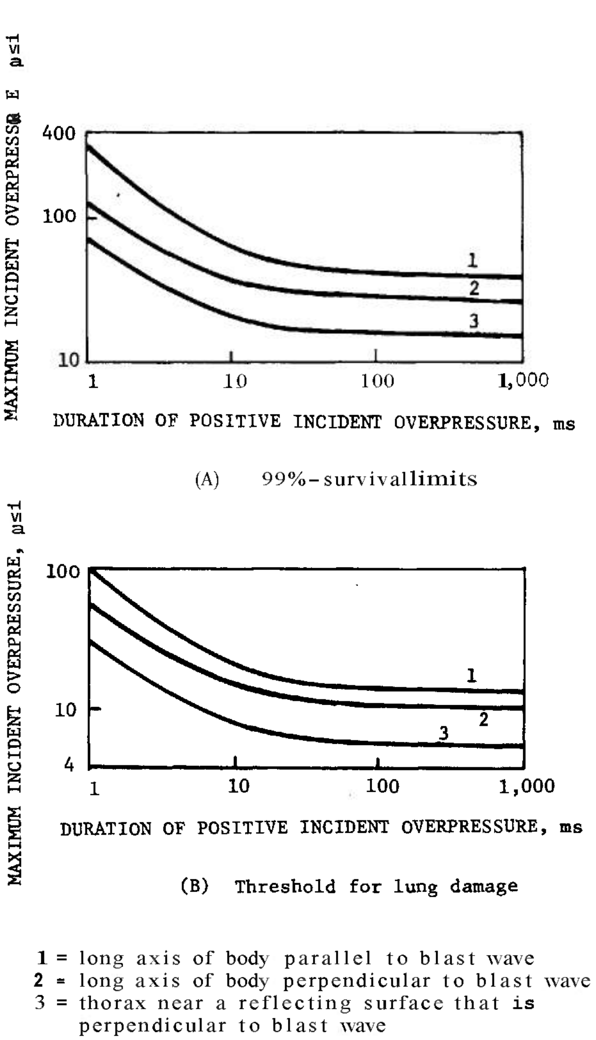


FIGURE 7-20. Blast Exposure Limits as a Function of Peak Overpressure and Duration (All curves relate to subjects facing any direction) (Ref. 90).

Few studies have been made of the effect of repeated, high-amplitude blast waves and impulse-noise waves. De Candole (Ref. 87) states that repeated blast exposure is responsible for the syndrome known as battle fatigue. Anecdotal reports indicate that instructors in the use of large-caliber weapons who are exposed to 50 impulses per day at about 10 psi complain of chest pains, nausea, and sleeplessness. Jacobson et al. (Ref. 88) consider it necessary for subjects exposed to repeated impulses from a howitzer to wear a foam rubber "chest protector" at levels of 6 psi and higher. Tanenholtz (Ref. 89) recommends that artillery crewmen not be exposed to repeated blasts at pressures above 7 psi, even when using protection.

7-7 DESIGN CRITERIA

Noise and blast will never be eliminated from man's environment, much less from the Army environment. Therefore, steps must be taken to insure that the noise that reaches man's receptors is tolerable. The term "tolerable" may be interpreted in several ways. It may refer to the prevention of excessive hearing loss and unpleasant subjective sensations; criteria for this purpose are discussed in par. 7-7.1. Prevention of injury from blast is also considered. Further, tolerable noise exposure refers to limiting background noise levels to the extent required to minimize masking of speech communications, and to providing noise levels in work areas that do not interfere with the performance of duties. Finally, community noise levels must be limited to prevent annoyance, complaints, or threats of legal action.

7-7.1 NOISE EXPOSURE LIMITS

Documents developed to aid in specifying noise exposure limits are variously referred to as damage-risk criteria (DRC), damage-risk contours, and hearing conservation criteria. The first two names point to a consideration which must not be ignored. "Damage risk" implies just that: the risk of some TTS or PTS in a portion of the noise-exposed population always exists. Because of the wide range of susceptibility to hearing loss, DRC that will protect everyone are neither philosophically realistic nor economically feasible to enforce (Ref. 91). A risk always exists that someone will lose a portion of his hearing sensitivity either temporarily or permanently. Thus, the user of any DRC must understand the risks involved.

The noise limits imposed by DRC refer to the noise that *actually* enters the ear canal. If the environmental noise exceeds the allowable limits, several means are available for reducing the levels to or below acceptable limits. These protective measures are discussed in par. 7-7.6.

Noise exposure limits are specified in both the Army and CHABA documents described in the following subparagraphs:

(1) ***HEL*** STD ***S-1-63C and TB MED 251.*** The Army Human Engineering Laboratory (HEL) standard on noise, ***Materiel Design Standard for Noise Levels of Army Materiel Command Equipment*** (Ref. 92), is the basic regulatory document governing maximum noise levels in Army equipment. This standard, however, is not to be considered as a hearing damage-risk criterion; its use is specifically limited to the design of military equipment. The maximum safe level for unprotected exposure for a period of 8 hr day^{-1} is 85 dBA.

TB MED 251, ***Noise and Conservation of Hearing,*** officially defines dangerous noise levels for the Army and specifies methods for controlling noise exposures, and for conserving hearing in high-noise environments (Ref. 12).

(2) ***Steady-state and intermittent noise DRC***

(a) CHABA DRC. The CHABA DRC were developed through the efforts of Working Group 46 of the NAS-NRC Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) (Ref. 24). The DRC acceptable limits for end-ofday TTS_2 are: 10 dB at or below 1 kHz, 15 dB at 2 kHz, and 20 dB at or above 3 kHz, in 50 percent of exposed ears. These TTS limits are considered equal to the maximum acceptable amounts of PTS after about 10 yr of neardaily exposure. The allowance of less TTS in the lower frequencies is designed to provide additional protection for the speech-range frequencies, and the 10-15-20 dB TTS limits are related to the borderline criteria for compensable hearing loss. The attempt to extrapolate the criteria to prevent PTS at intermediate numbers of years or to protect different amounts of hearing is not safe. For such individualized applications, special criteria should be developed.

The CHABA steady noise DRC are presented in the form of 11 graphs relating the trade-offs among (1) spectrum, (2) exposure time up to 8 hr, and (3) SPL. Fig. 7-21 shows the exposure limits for octave (and narrower) bands of noise, and Fig. 7-22 gives the limits for exposure to pure tones.

(b) Walsh-Healey Public Contracts Act. The Department of Labor in 1969 revised the Walsh-Healey Act to include limits on occupational noise exposure. These limits apply to all contractors doing more than $10,000 worth of business annually with the U.S. Government. Noise exposure limits are stated in terms of A-weighted sound levels, and Table 7-12 shows the permissible levels for exposures of 15 min to 8 hr per day. For octaveband SPL data, a graph is provided for determining equivalent A-weighted sound levels, as shown in Fig. 7-23.

(c) Noise limits for extended exposure to noise. To obviate the possibility of TTS during extended missions (up to 60 days), the background noise level should not exceed 65 dB overall (Ref. 38).

(d) Ultrasonic noise limits. To prevent TTS and unpleasant subjective responses to ultrasonic noise, the noise level should not exceed 75 dB SPL in 1/3-octave bands centered at 8 to 16 kHz, or 110 dB SPL at 20 to 31.5 kHz (Ref. 75).

(e) Low frequency and infrasonic noise limits. To prevent physiological injury from low frequency and infrasonic noise (1 to 100 Hz), the noise level should not exceed the limits shown in Table 7-13. Even at these limits, experienced personnel may report transient unpleasant sensations. ABOVE THESE LEVELS WEARING OF HEARING PROTECTIVE DEVICES IS MANDATORY.

(3) ***Impulse-noise limits.*** The most comprehensive DRC for impulse-noise exposure are those published by CHABA (Ref. 93) based on the formulations of Coles et al. (Refs. 16,47). These DRC assume the same TTS limits as do the earlier CHABA steady-noise DRC (Ref. 24). However, the impulse-noise DRC are designed to protect 95 percent of ears exposed. The basic DRC (Fig. 7-24) assume a daily exposure of 100 impulses distributed over a period of from 4 min to several hr, and that the impulses reach the ear at normal incidence.

Two correction factors are included in the DRC. First, if the pulses reach the ear at grazing incidence (rather than normal), the curves can be shifted upward by 5 dB. Second, if the number of impulses in a daily exposure is some value other than 100 (i.e., 1 to 1,000), an adjustment can be made according to the curve shown in Fig. 7-25.

It should also be noted that TB MED 251 (Ref. 12) requires hearing protection for all impulse-noise exposures exceeding 140 dB peak.

7-7.2 BLAST EXPOSURE LIMITS

To minimize temporary or permanent hearing loss from blast, the impulse-noise criteria stated previously are used. To avoid other physiological injury from fast-rising, long-duration blast waves, the following pressures should not be exceeded:

(1) 5 psi (unprotected) to prevent eardrum rupture

(2) 10 psi (ears protected) to prevent lung damage. (See Fig. 7-20.)

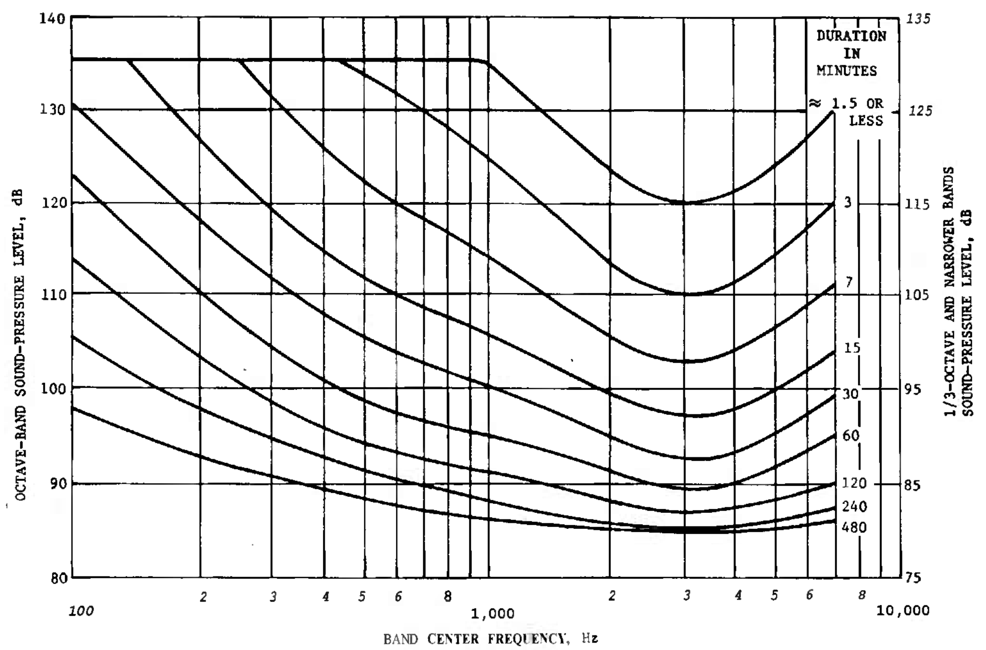


FIGURE 7-21. Damage Risk Contours for One Exposure Per Day to Octave (LH ordinate) and 1/3-Octave or Narrower (RH ordinate) Bands of Noise (Ref. 24).

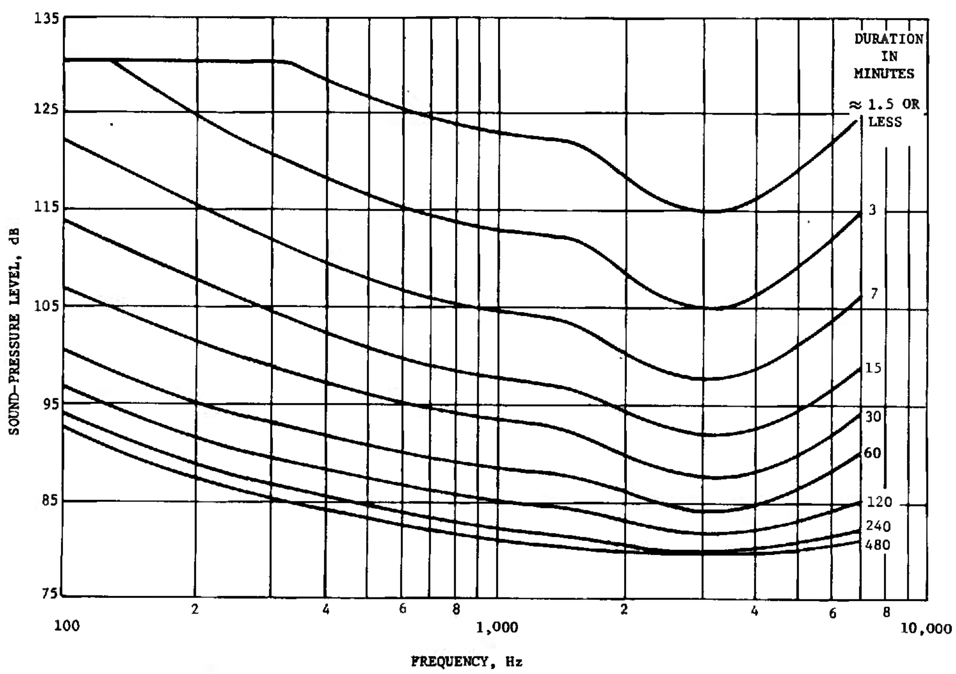


FIGURE 7-22. Damage Risk Contours for One Exposure Per Day to Pure Tones (Ref. 24).

Duration, hr	Sound level, dBA
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
≤ 0.25	115

*When the exposure is intermittent at different levels, the fraction $C_1/T_1 + C_2/T_2 \ldots C_n/T_n$ should not exceed unity to meet the exposure limit.

C_n = total exposure time at the specified noise level.

T_n = total exposure time permitted at the specified level.

7-7.3 SPEECH INTERFERENCE CRITERIA

In par. 7-5.3(c), the calculation of the Articulation Index (AI) is discussed. AI, as a method of estimating the masking effect of noise on speech intelligibility, is quite involved. A relatively simple method devised by Beranek (Ref. 95) is known as "speech interference level" (SIL). SIL is mainly used for determining the effect of noise upon direct person-to-person speech. It is obtained by averaging the noise levels in the three *commercial* octave bands between 600 and 4,800 Hz. (With data from a *preferred* octave-band frequency analyzer, the bands centered at 500, 1,000, and 2,000 Hz should be averaged (Ref. 5).) If the level in the 300- to 600-Hz band exceeds that in the 600- to 1,200-Hz band by 10 dB, Beranek suggests that it also be included in the average.

Once the SIL value has been calculated, reference to Fig. 7-26 may be made to determine the voice level required to provide acceptable intelligibility at a given talker-to-listener distance. "Acceptable intelligibility" here corresponds to a PB intelligibility score of 75 percent without lipreading.

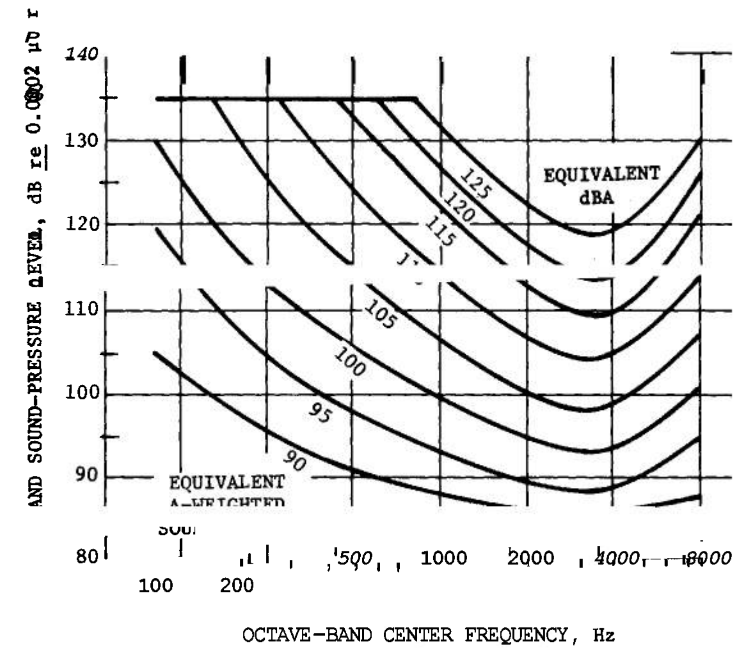


FIGURE 7-23. Contours for Determining Equivalent A-weighted Sound Level.

TABLE 7-13. LOW FREQUENCY AND INFRASONIC NOISE EXPOSURE LIMITS (Ref. 94)

Frequency,* Hz	SPL, dB	Duration,† min/day	Notes
1 - 7	150	4	
8 - 11	145	4	Use of ear plugs will reduce unpleasant sensations
12 - 20	140	4	
21 - 100	135	20	Without protection
21 - 100	150	20	With ear plugs

*Refers to pure tones, or to octave bands with center frequencies as indicated.

†Refers to one exposure per day, with at least 24 hr elapsing between successive exposures.

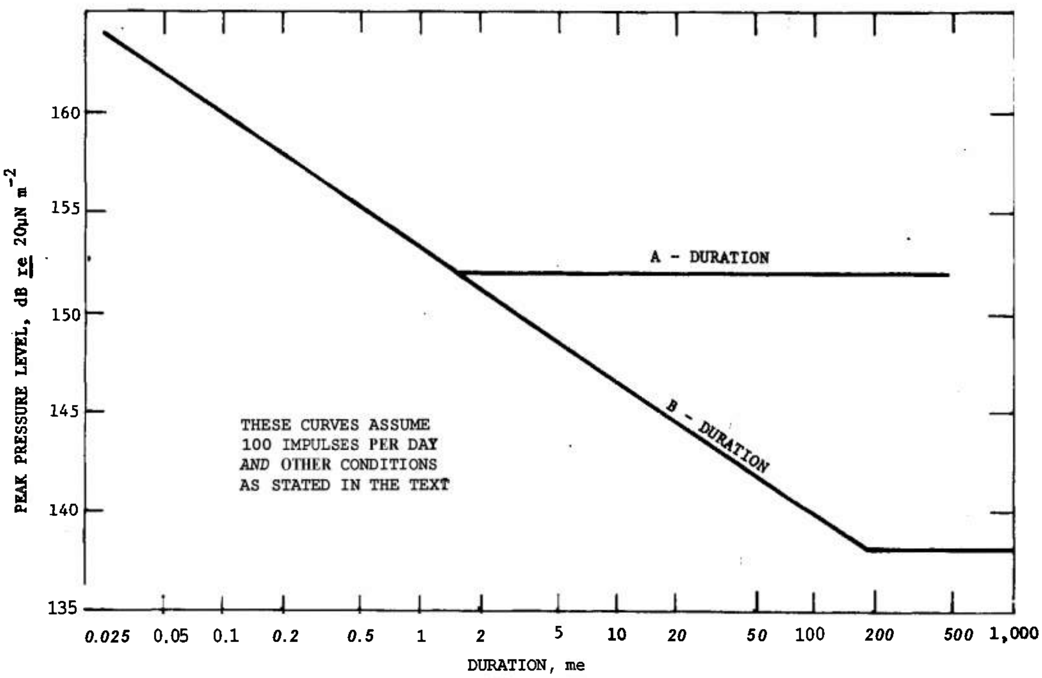


FIGURE 7-24. Basic Limits for Impulse-noise Exposure

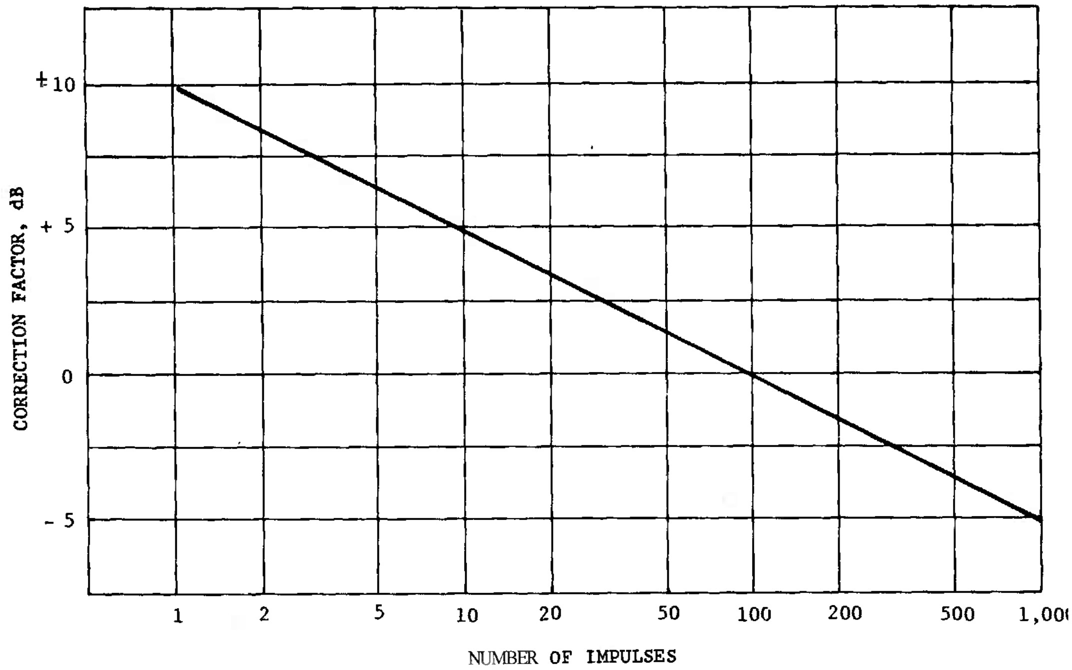


FIGURE 7-25. Correction Factors To Be Added to Ordinate of Fig. 7-22 To Allow for Daily Impulse-noise Exposures Different From 100 Impulses (Ref. 94).

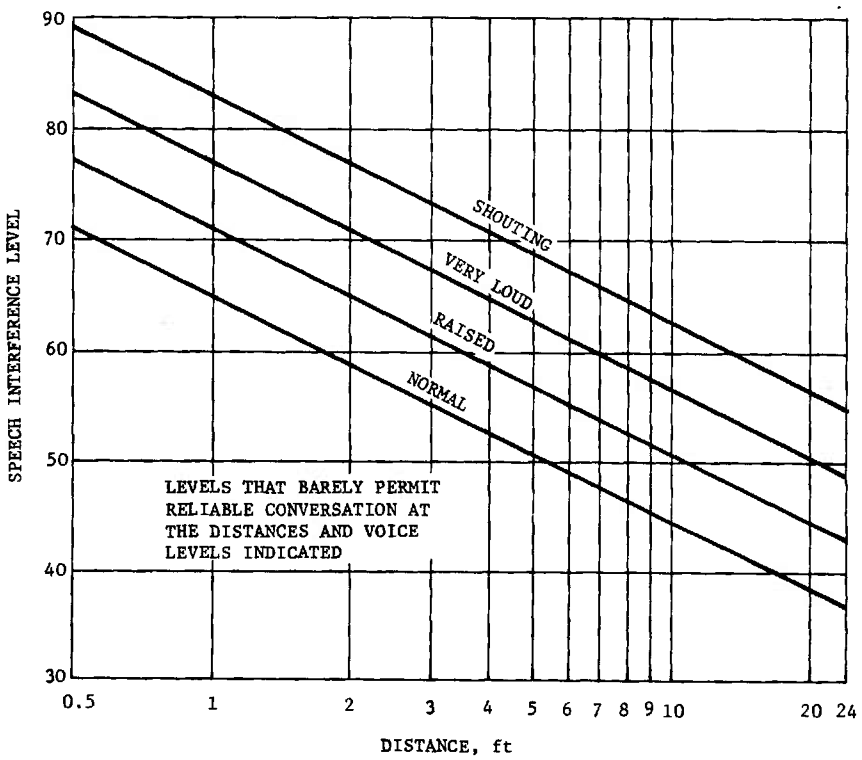


FIGURE 7-26. Speech Interference Levels (in dB re 20μN m^{-2}) (Ref. 95).

7-7.4 WORKSPACE NOISE CRITERIA

Beranek (Ref. 96) presents criteria for limiting background noise in workspaces in which communication interference, loudness, or annoyance of noises is an important design consideration. These noise criterion (NC) curves are widely used as workspace design criteria. Fig. 7-27 shows the allowable octave-band SPL (for both commercial and preferred octave bands), and Table 7-14 identifies typical workspaces with the appropriate NC curves. These curves are derived in such a way that each octave band contributes equally to the loudness of the background noise. To be acceptable, the noise level in each octave band must not exceed the level permitted by the selected NC curve. When *commercial* frequencies are used, the NC number is also the SIL for that particular spectrum.

As a general rule, solving the problem of excessive noise in workspaces is best left to the specialist—the acoustics engineer. Theoretical solutions to sound transmission through structures typically are difficult to obtain. For example, a recent paper describes a theoretical method for computing the sound transmission loss through a *double-leaf wall*[1] (Ref. 98). Even for this problem, various simplifications are necessary to obtain an analytical solution. Fig. 7-28 compares the analytical results with experimental ones for various leaf weights and spacings.

The ranges of sound levels produced by various building equipment are shown in Table 7-15. The ranges of sound level reductions obtained from various building features and sound isolation treatments are shown in Table 7-16.

7-7.5 COMMUNITY NOISE CRITERIA

The final decision on criteria for community noise exposure is an administrative one. Scientific and technical data may aid in answering questions, but legal and administrative officials must make the final decisions concerning community noise (Ref. 100).

As a guideline on community noise, the following references are relevant:

(1) FAA noise limits for new commercial aircraft (Ref. 101)

(2) Department of Defense permitted noise level limits for land-use planning around airports (Ref. 102)

(3) Zoning ordinances for limiting community noise (Ref. 103).

11. A double-leaf wall is one containing two planar members separated (usually) by an air space, such as occurs in dry-wall (sheetrock) construction.

7-7.6 HEARING PROTECTION

Four general approaches may be taken to prevent unwanted sound from reaching the ear. The person may be removed to a distance from the noise source so that spherical divergence and excess attenuation reduce the noise level to an acceptable extent. A physical barrier may be placed between the noise blast source and the person. The natural "aural reflex" action of the human middle-ear muscles may be stimulated as a means of protection. Finally, a mechanical hearing protector may be placed over, or in, the ear canal to attenuate ambient sound energy. Implementation of this mechanical approach is treated here.

(1) Mechanical hearing protection. In situations in which it is neither economical nor practical to remove people to a distance from a noise source or to place a barrier between them and the source, the use of mechanical hearing protection is recommended to reduce the noise to a level that is not hazardous to hearing and/or will permit effective communication.

Hearing protectors will often improve person-to-person and loudspeaker-to-person communication in noise (Ref. 104). The same speech signal-to-noise ratio reaches the ear with and without protection in such cases, but the use of protection may cause the speech signal to reach the ear at a level in the optimal range for speech intelligibility (overall rms level of about 70 dB). This effect may, therefore, influence the selection of hearing protection for use in a given situation. For example, recommending a highly effective hearing protector for use in a relatively low noise level would be undesirable, since this might reduce the speech signal to below the optimum speech level.

Mechanical hearing protectors fall into four general categories-earplugs, semi-inserts, earmuffs, and helmets.

(a) Earplugs. Earplugs are available in two forms: (1) preformed rubber or plastic plugs supplied in up to seven sizes, and (2) disposable plugs, such as wax-impregnated cotton, or "glass down" (a very fine, nonirritating glass wool). Dry cotton is not recommended for use since it provides negligible sound attenuation (2 to 5 dB in the lower frequencies; 6 to 10 dB at the higher frequencies) and may provide a false sense of security.

In order to be maximally effective, earplugs must be properly fitted for size. It is not unusual to find people who require a different size of plug for each ear. Furthermore, the plugs must be properly inserted each time they are used; they must be tight to be effective.

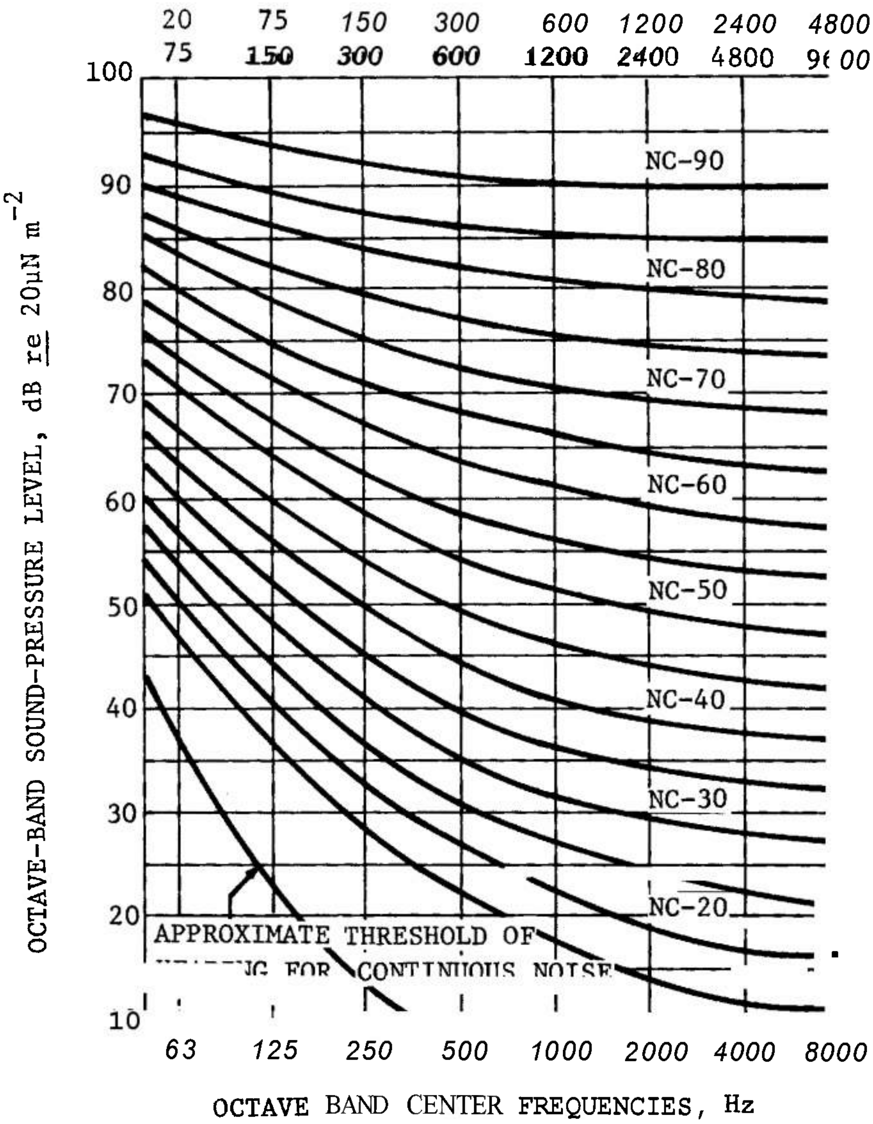
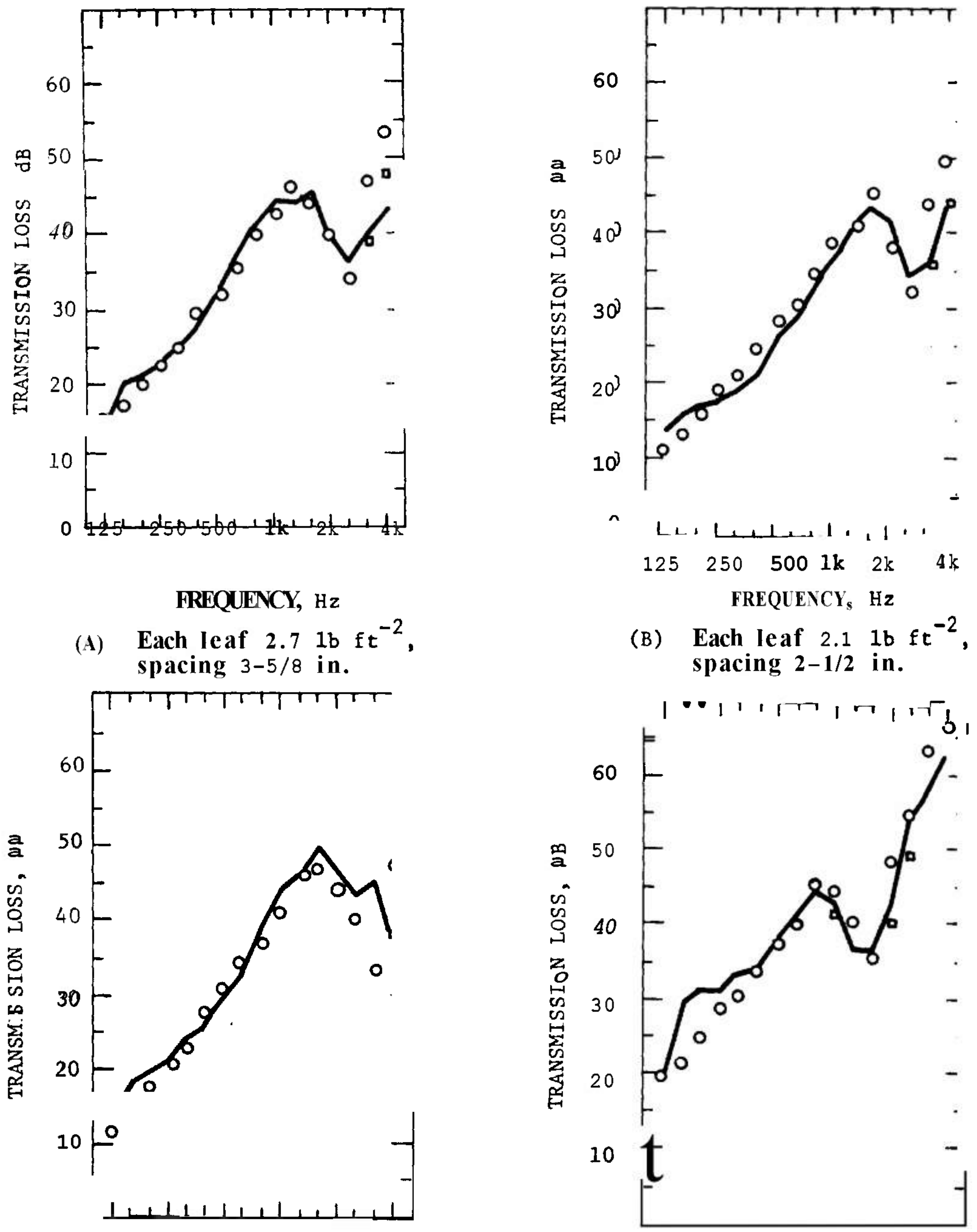


FIGURE 7-27. Noise Criteria (NC Curves) Referred to Preferred Octave Bands (Lower Abscissa) and Commercial Octave Bands (Upper Abscissa) (Ref. 97).

TABLE 7-14. RECOMMENDED NC CURVES FOR VARIOUS WORK SPACES

NC curve	Type of work space	Communication equivalent	Office application
90		Noise-attenuating headset required	Not recomnended
80		Communication very difficult; telephone use unsatisfactory.	Not recomnended
70-80		Raised voice range 1-2 ft; shouting range 3-6 ft; telephone use very difficult.	Not recomnended
60-70		Raised voice range 1-2 ft; telephone use difficult	Not recomnended
55-60		Very noisy; not suited for office; telephone use difficult	Not recommended
55	Spacecraft during non-powered flight		
50-55		Unsatisfactory for conferences of over 3 people; telephone use slightly difficult; normal voice at 2 ft; raised voice at 3 ft.	Areas with typists and accounting machines
40-50	Restaurants, sports coliseums	Conferences at 4-5 ft table; telephone use slightly difficult; normal voice at 3-6-ft; raised voice at 6-12 ft.	Large drafting rooms
35-40		Conferences at 6-8 ft table; telephone use satisfactory; normal voice at 6-12 ft.	Medium-sized offices
30-35	Libraries, hospitals, motion picture theatres, home sleeping areas, assembly halls	Quiet office; conferences at 15-ft table; normal voice at 10-30 ft.	Private or semiprivate offices; reception rooms; conference rooms for up to 20 people
25-30	Court rooms, churches, home sleeping areas, assembly halls, hotels and apartments, TV studios, music rooms, school rooms	Very quiet offices; large conferences.	Executive offices; conference rooms for 50 people
20-25	Legitimate theater, concert halls, broadcasting studios		



(A) Each leaf 2.7 lb ft^{-2}, spacing 3-5/8 in.

(B) Each leaf 2.1 lb ft^{-2}, spacing 2-1/2 in.

(C) Each leaf 2.1 lb ft^{-2}, spacing 3-5/8 in.

FIGURE 7-28. Theoretical and Experimental Transmission Losses for Studless Double-leaf Walls. (—): Experimental Curve; (o): theoretical (Ref. 98).

TABLE 7-15. RANGE OF NOISE IN dBA TYPICAL FOR BUILDING EQUIPMENT AT 3 FT (Ref. 99)

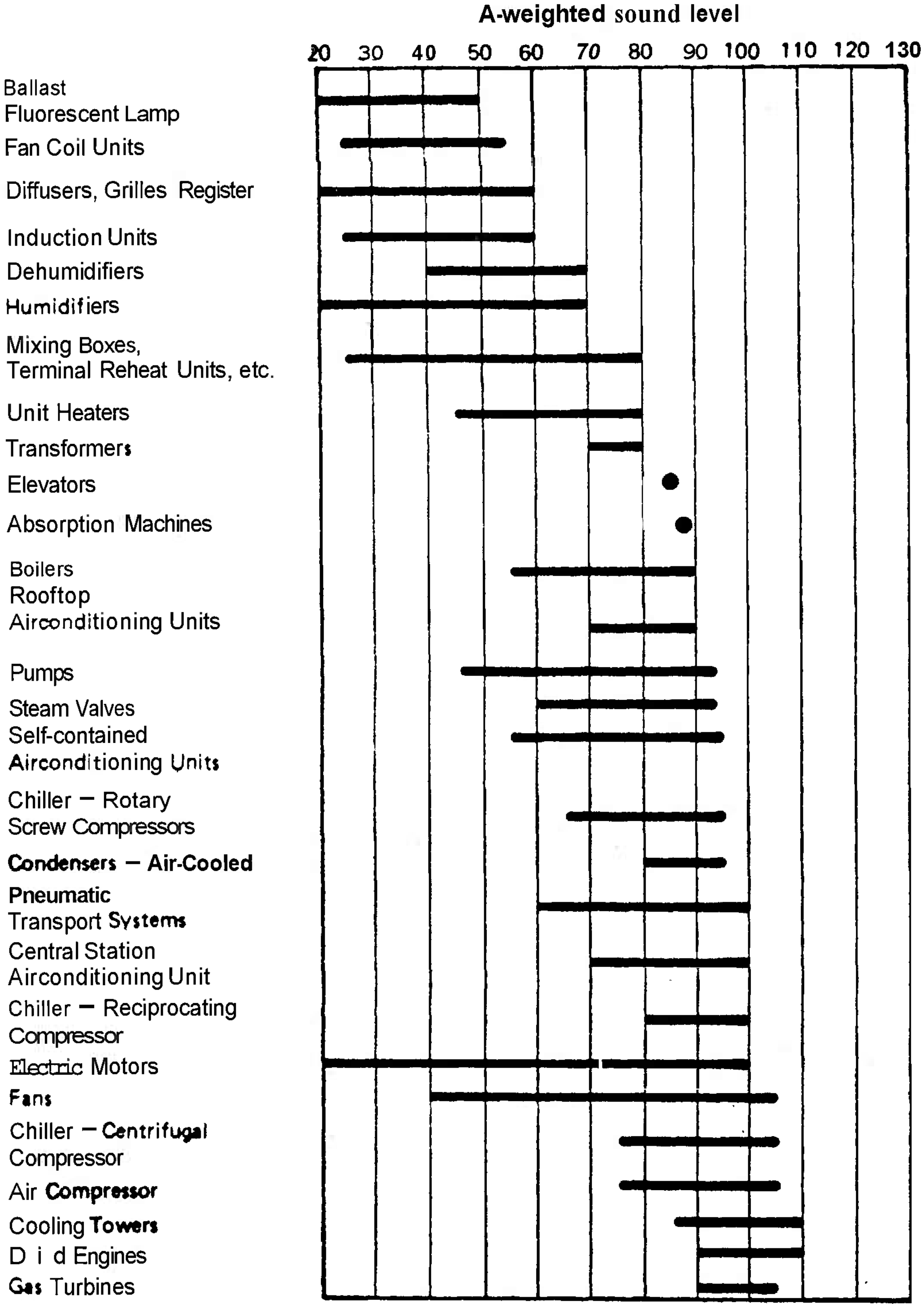
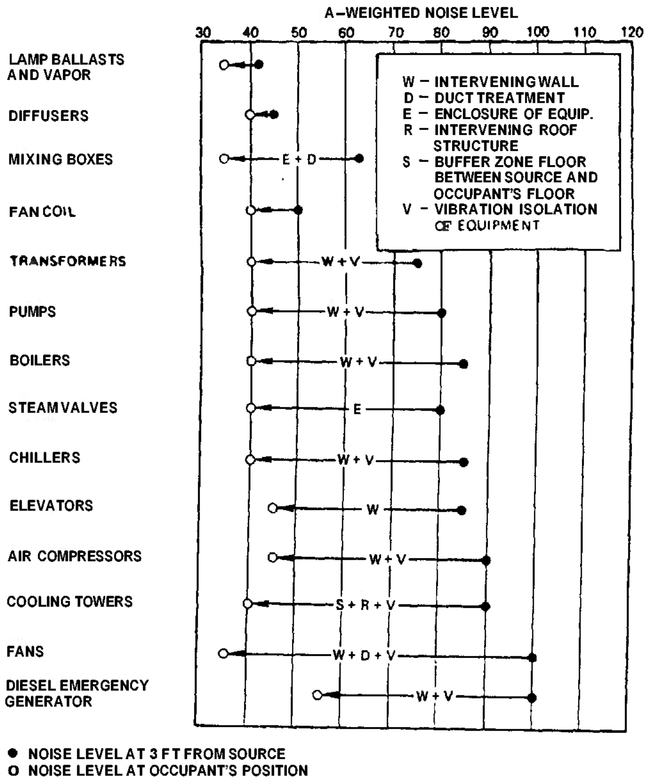


TABLE 7-16. RANGE OF BUILDING EQUIPMENT NOISE LEVELS TO WHICH PEOPLE ARE EXPOSED (Ref. 99)



Finally, the plugs must be kept clean to minimize the possibility of ear infections.

(b) Semi-inserts. These are available in one size only and are pressed against the entrance to the ear canal by a light, spring-loaded headband. If frequent donning and doffing are required, they are very convenient and, unlike bulky earmuffs, may easily be hung around the neck when not in use. On the other hand, semi-inserts may not provide as effective a seal against sound as either earplugs or earmuffs.

(c) Earmuffs. These are made in one size only and almost everyone can be fitted satisfactorily with little difficulty. They attenuate sound as well as, or better than, earplugs at high frequencies, but are slightly poorer than plugs below 1 kHz. The primary disadvantages of earmuffs are their bulk and relative expense. To their credit, however, they do not involve the fitting and insertion problems of earplugs. Another advantage, in some situations, is that a supervisor can readily determine from a distance whether all of his personnel are wearing their hearing protectors. Where very intense noise levels exist, wearing both earplugs and earmuffs may be desired. The total sound attenuation does not, of course, equal the sum of the individual protector attenuations, but this combination will ordinarily provide increased attenuation at most frequencies with particular benefit being derived at the low frequencies (Ref. 105).

(d) Helmets. These can provide more attenuation than the other devices if they cover the greater portion of the head. The acoustical importance of a helmet increases when the SPL reaches the point that bone-conducted sound transmission through the skull becomes a controlling factor. In cases other than this, the use of helmets for hearing-protective purposes alone is not justified. The maximum attenuation that can be provided by a plug, muff, or semi-insert is about 35 dB at 250 Hz and is greater at higher frequencies (Ref. 106). After reductions of this magnitude, the remaining sound is conducted through the bones of the skull directly to the inner ear (Ref. 58), unless a helmet (such as that worn by an astronaut) that seals off the whole head is used, in which case an additional 10 dB of protection is provided. Beyond this point, conduction of sound by the body is the limiting factor.

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CHAPTER 8

ELECTROMAGNETIC RADIATION

8-1 INTRODUCTION AND DESCRIPTION

A century ago, man's electromagnetic environment stemmed entirely from natural phenomena—lightning discharges and solar radiation. Because solar radiation produces many effects on both man and materiel, it is an important environmental factor. Solar radiation is discussed in Chap. 6, Part Two, of the Environmental Handbook Series (AMCP 706-116). Lightning is also a frequently occurring environmental phenomenon—it is discussed in this chapter. The electromagnetic environment of today, however, is much more complex than that of the 19th century. Electromagnetism has become a major tool of modern technology, and the various emissions of energy associated with it constitute an omnipresent environmental factor to which everyone and everything is exposed. Under certain circumstances this environment is capable of affecting and constituting a hazard to people and equipment.

Certain types of electromagnetic energy found in the environment are excluded from the discussion in this chapter. Solar radiation, as previously pointed out, is one such type. The gamma spectrum, associated with nuclear events, is discussed in Chap. 9 of this handbook, although electromagnetic pulse effects that are derived from nuclear events are discussed in this chapter.

While the electromagnetic environment is composed of emanations from a multiplicity of sources, only a few such sources produce radiation of sufficient intensity as to merit consideration. These include:

(1) The near-field radiation from communication and television transmitting antennas

(2) Radiation in the immediate vicinity of diathermy equipment, microwave ovens, and induction heating apparatus

(3) The focused microwave beams associated with all types of radar

(4) Laser-generated coherent light beams

(5) Medical and industrial X-ray apparatus

(6) High intensity and/or high frequency light generated by nuclear events, ultraviolet lamps, and similar sources

(7) The electromagnetic pulse (EMP) effect, associated with nuclear events

(8) The electromagnetic field accompanying lightning.

Except for the radiations originating with the enormous energy releases of nuclear events or the highly focused energy beams of radar and lasers, intensities sufficient to produce observable effects occur only in close proximity to the sources. The multiplicity of sources in the environment, however, causes the probability of such exposure to be relatively high. In military operations, for example, both materiel and personnel are readily exposed to radar beams.

The breadth of considerations related to the electromagnetic environment prohibits comprehensiveness in this chapter. Electromagnetic theory is only briefly discussed, for example. Lasers and X rays are considered only as radiation sources. The interactions between radiation sources, e.g., electromagnetic compatibility and interference, are not considered in any detail. Only those subjects relating to the generation of effects are discussed in detail.

The electromagnetic spectrum covers an enormous frequency range from the very low frequency band, 0 to approximately 10^4 Hz, up through the cosmic ray region, extending from 10^{22} to 10^{25} Hz. This extremely broad spectrum includes low electrical power transmission line frequencies as well as high frequency penetrating radiation such as gamma rays and X rays. Within the limits of this spectrum are contained a number of subdivisions or frequency bands that are used by man for various purposes plus a variety of natural sources of electromagnetic radiation. The best-known bands are those associated with communications such as radio and television transmission, 0.5×10^6 to 10^9 Hz, and the visible region of the spectrum, 3.8×10^{14} to 7.6×10^{14} Hz.

In Fig. 8-1, the various regions of the electromagnetic spectrum are shown. The very low frequency (VLF) band includes the audible and infrasonic ranges. The communications and broadcast bands include low frequency (LF), medium frequency (MF), high frequency (HF), very high frequency (VHF), and ultra high frequencies (UHF). These extend from approximately 2×10^4 Hz to approximately 2×10^9 Hz. The microwave band, which includes most radar systems, overlaps the upper part of the communications band beginning in the region of 2×10^8 Hz and extending to over 10^{11} Hz. These bands are known as the super high frequency

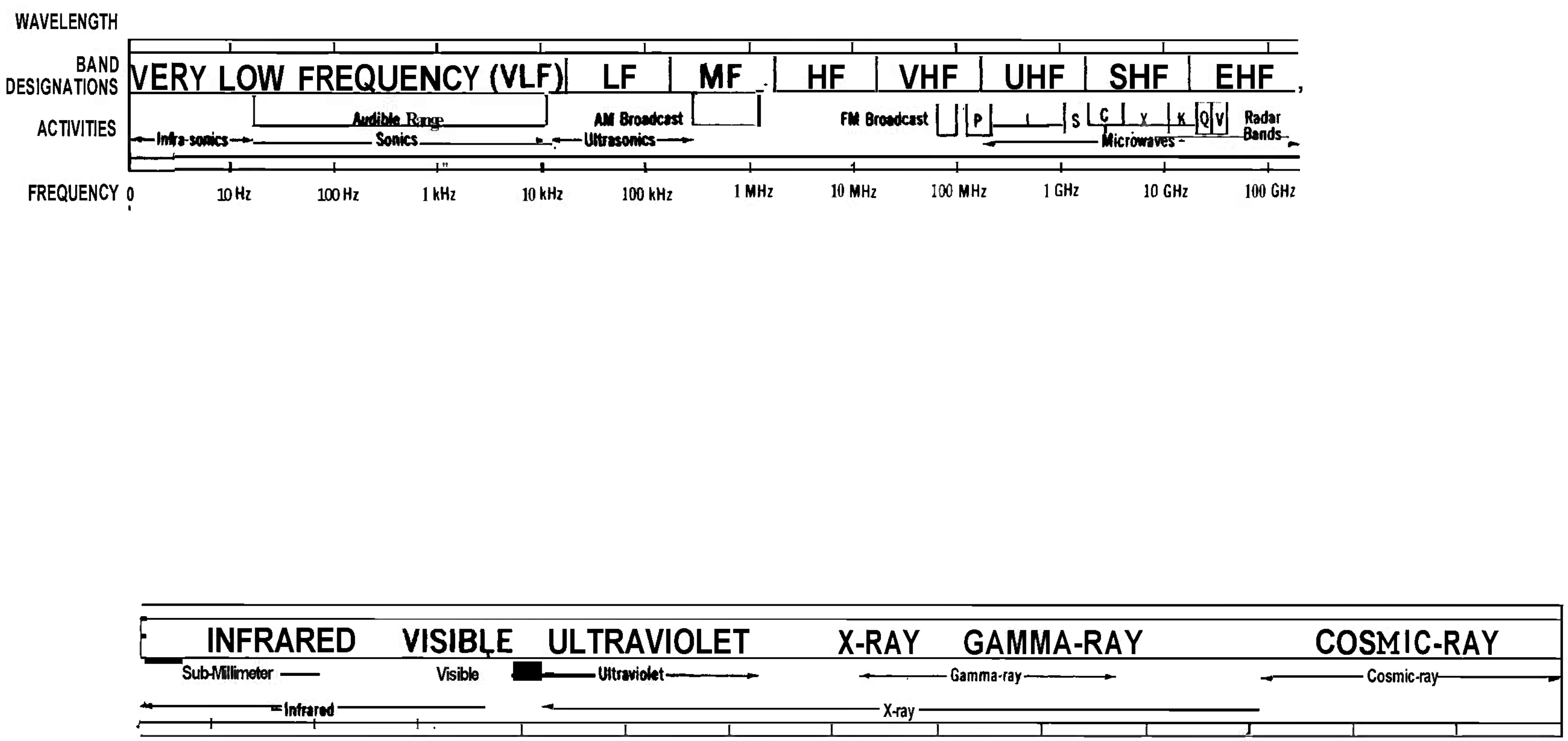


FIGURE 8-1. The Electromagnetic Spectrum (Ref. 1).

(SHF) and the extremely high frequency (EHF) bands. From 10^{11} Hz to slightly above 10^{17} Hz is a region occupied by the optical spectrum. It consists of three parts: the infrared extending from 10^{11} to approximately 5×10^{14} Hz; the visible region, which is a narrow band of frequencies between the infrared band and the ultraviolet band, the latter comprising frequencies between 10^{15} and 10^{17} Hz. At higher frequencies are the more energetic penetrating radiation including X-rays beginning around 10^{18} and extending up to 10^{19} Hz, gamma rays extending from 10^{19} through 10^{21} Hz, and cosmic rays extending from 10^{22} through 10^{25} Hz. In many cases the X-ray region is classified to include both the ultraviolet and the gamma ray regions, as well as that band previously defined.

Basically, the electromagnetic environment consists of two categories of radiation: (1) naturally occurring radiation and (2) radiation generated by man-made equipment. For the purposes of this discussion, the very low frequency waves are not considered to be environmentally important because the radiated power densities are relatively small and because, at their long wavelengths, the energy absorption by materiel is negligible. In the communication bands, the electromagnetic environment consists primarily of radiation from manmade equipment. Of course, frequency components within this spectrum do occur in nature as is evident from the noise sometimes heard on AM radio broadcasts. This noise usually consists of the naturally occurring disturbances called static, which results from lightning discharge.

In the microwave region, environmental radiation also originates from man-made sources. In the optical region, from infrared through ultraviolet to the X-ray region, sources are both man-made and naturally occurring. In the cosmic ray region, the relatively small amount of radiation found in the environment is naturally occurring. However, transient, man-made radiation in these frequency ranges can be generated by nuclear explosions. In the paragraphs that follow, the electromagnetic environment is described by source, frequency, and other special characteristics. Detection and measurement of electromagnetic radiation and the effects of this radiation environment on materiel and on man will be explored in some depth. Basic techniques used to minimize the effects of the electromagnetic environment on man and materiel are reviewed, and the large scale test facilities are described. Finally, standards applicable to electromagnetic radiation in the environment, both as it applies to materiel and to man, are discussed.

8-2 THE ELECTROMAGNETIC ENVIRONMENT

At any point, the electromagnetic radiation environment may be characterized by a power density spectrum. This is a plot of the power level (rate at which energy flows) as a function of frequency. The acquisition of a power density spectrum for the complete electromagnetic spectrum, however, is complex if not impossible. To obtain it empirically, it would be necessary to employ a large array of instrumentation, to calibrate it carefully, and to process a large amount of data. This can be accomplished for certain regions of the spectrum—the RF range up to 100 GHz or the visible spectrum—but not all 24 orders of magnitude of frequency.

Analytically, the power density spectrum at a point in space can be described at times when only a few sources need to be considered. For more than a few emitters or in a complex environment with structures and shielding, analysis is impossible.

Thus, a description of the electromagnetic radiation environment cannot be derived, generally, from either measurement or analysis. Instead it must depend on some detailed knowledge of the source characteristics. In most cases, the power density spectrum is adequately characterized by one or several dominant sources. Consider the dominant radiation sources in various locations:

(1) Broadcast antennas: AM, FM, and TV

(2) Radars: battlefield, air traffic control, search, aircraft and missile defense, marine, and weapon fire control

(3) Microwave heaters: ovens, diathermy, and induction furnaces

(4) Optical sources: lasers, searchlights, nuclear events, and solar X rays

(5) Medical: high voltage power supplies

(6) Industrial: nondestructive testing.

Many of these have short ranges and the presence of the source should be obvious. In other cases general knowledge of the source type is available. Knowledge of the source makes it possible to obtain analytical worst-case estimates or to make measurements in the indicated frequency bands to adequately characterize the environment.

8-2.1 ANALYTICAL TECHNIQUES

The theory of electromagnetic fields is well developed and can be reviewed in a number of texts (see Ref. 2, for example). Analytical approaches are possible for a limited number of electromagnetic sources, the most prominent example being the radio or radar transmitting antenna.

Free-space electromagnetic radiation consists of time-varying electric and magnetic fields that are related to each other by mathematical expressions known as Maxwell's equations. The free-space velocity of wave propagation is approximately equal to the speed of light, which is 3×10^8 ms^{-1}. The wavelength of the propagated electromagnetic wave is related to the frequency and free-space velocity by the formula

$$\lambda = 300/f, \text{ m} \qquad (8\text{-}1)$$

where

λ = wavelength, m
f = frequency, MHz

Radiation from a directive microwave antenna is one of the best examples of a strong electromagnetic field. The maximum radiated power is in the center of the beam and is equal to the product of the transmitter power output and the antenna gain. The power density *PD* of a single radiator is given by the formula

$$PD = P_t G/(4\pi d^2), \text{ W m}^{-2} \qquad (8\text{-}2)$$

where

P_t = transmitter power output, W
G = antenna gain, dimensionless
d = distance from the radiator, m

The power density is related to the electric field strength by the formula

$$PD = E^2/Z, \text{ W m}^{-2} \qquad (8\text{-}3)$$

where

E = field strength, V m^{-1}
Z = impedance of the transmitting media, Ω

For free space where $Z = 120\pi$ Ω, the electric field strength E is given by

$$E = 5.5(P_t G)^{1/2}/d, \text{ V m}^{-1} \qquad (8\text{-}4)$$

Electromagnetic energy radiated into space is described by an electric field E and a magnetic field H where both E and H are vector quantities that are perpendicular to each other and to the direction of propagation. Commonly, the medium surrounding an antenna is divided into two different sections, one called the near-field or Fresnel region, the other the far-field or the Fraunhofer region. Fig. 8-2 illustrates the relationships involved. The distance from the antenna to the boundary between the near- and far-fields can be calculated approximately by the formula

$$d = 2\ell^2/\lambda, \text{ m} \qquad (8\text{-}5)$$

where

d = distance from the antenna to the boundary, m
ℓ = length of the antenna, m
λ = wavelength, m

In this illustration, the antenna is considered to be an isotropic radiator; i.e., it is a point source that radiates in a spherical pattern. Not all antennas radiate in such a pattern. Indeed, most antennas are designed to provide a specific shaped pattern. Fig. 8-3 indicates two other types of antennas and their resultant radiation patterns.

One must note, however, that the electromagnetic radiation from antennas represents one of the easier-to-calculate examples of energy sources. Spurious radiations from equipment or other sources are not so amenable to calculation or prediction.

In describing the electromagnetic environment, a large majority of the energy originates' from known source classes. The principal classes of such sources are considered in the paragraphs that follow. Further information is contained in the ***Handbook on Radio Frequency Interference*** (Ref. *3).*

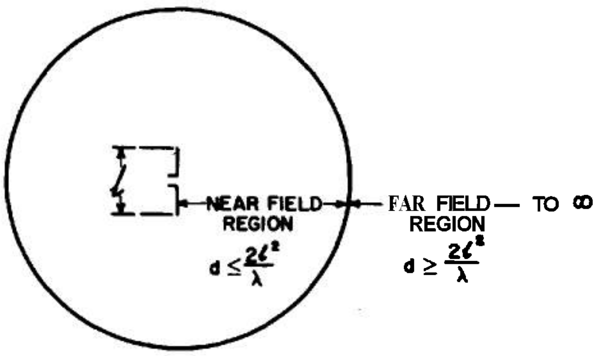


FIGURE 8-2. Near-field and Far-field Relationships.

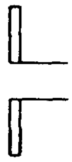
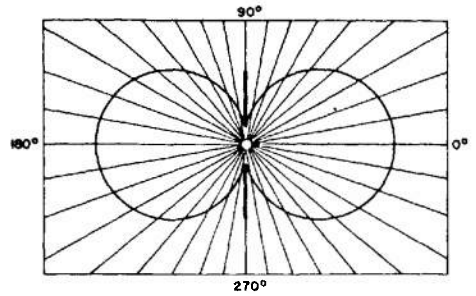
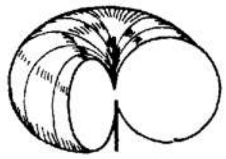
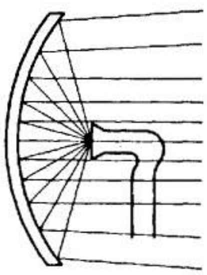
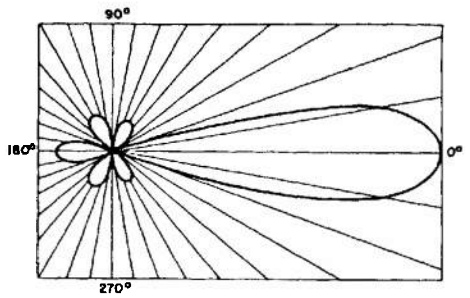
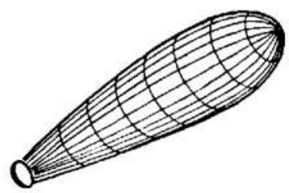
TYPE OF ANTENNA	RADIATION PATTERN Vertical	RADIATION PATTERN Perspective	GAIN
Half-Wave Dipole 			1.64
Parabolic Reflector 			20 dB to 50 dB

FIGURE 8-3. Antenna Radiation Patterns (Ref. 4).

8-2.2 COMMUNICATION AND MICROWAVE SOURCES

The frequency band extending from approximately 10^4 to 10^9 Hz is used primarily for communication purposes. Most of the mass communication media and a significant portion of the personal communication frequencies are in this band. Frequency regions of some interest are those assigned by the Federal Communications Commission for commercial AM (535 to 1605 kHz), FM (88 to 108 MHz), and television (VHF at 54 to 216 MHz and UHF at 470 to 890 MHz) broadcasting services. The two basic signal classifications are communication signals and interference. When two or more communication systems are operating on the same or nearby frequencies and within range of each other, mutual interference may occur. Thus, a signal providing communication to one user may be interference to another. Other sources of natural and man-made interference also are present.

The number, complexity, and power output of electronic systems in use are all expanding rapidly as are the number of other radiation sources. In early 1971 there were 7,868 broadcasting stations on the air, categorized as 596 VHF and 296 UHF television stations, 4,327 AM stations, and 2,649 FM stations. Of the AM radio stations, 131 were 50 kW outlets, that being the maximum allowable radiated power, while there were 209 FM stations, which radiate effective powers of at least 100 kW. The maximum allowable effective radiated power of television stations ranges from 100 kW for VHF channels 2 to 6, 216 kW for VHF channels 7 to 13, to 500 MW for UHF channels 14 to 83 (Ref. 5). The frequency allocation chart in Table 8-1 indicates the wide variety of activities within the communication band. This table lists the frequency, function for which that part of the spectrum is used, and the maximum allowable effective radiated power of the sources. The various uses made of this frequency band are listed in descending order of annual expenditure rate for them in the United States (Ref. 6):

(1) Military; for command, control, and guidance

TABLE 8-1. RF SOURCES (Ref. 4)

Frequency, MHz	Service	Power, W	Frequency, MHz	Service	Power, W
Below 0.010	Mot allocated				
0.010-0.014	Long range navigation	1,200	8.476- 8.815	Marine	140,000
0.014-0.070	Fixed public and marine	50,000	8.815- 9.500	International fixed public	50,000
0.070-0.130	Radiodetermination (Loran C)	300,000	9.500- 9.775	International broadcast	500,000
0.130-0.160	Marine	80,000	9.775-11.700	International fixed public	50,000
0.160-0.200	International fixed	50,000	11.700-11.975	International broadcast	500,000
0.200-0.415	Radiodetermination, aeronautical	1,200	11.975-12.714	Marine	8,000
0.415-0.510	Marine, mobile	40,000	12.714-13.200	Marine	140,000
0.510-0.535	Government	--	13.200-15.100	International fixed public	50,000
0.535-1.605	Commercial AM	50,000	15.100-15.450	International broadcast	500,000
1.605-1.750	International fixed public	50,000	15.450-16.460	International fixed public	50,000
1.750-1.800	Land mobile	10,000	16.460-16.952	Marine	8,000
1.800-2.000	Radiodetermination, amateur	1,200	16.952-17.360	Marine	140,000
2.000-2.107	Marine, mobile	8,000	17.360-17.700	International fixed public	50,000
2.107-2.850	International fixed public	50,000	17.700-17.900	International broadcast	500,000
2.850-3.155	Aeronautical	400	17.900-21.000	International fixed public	50,000
3.155-3.400	International fixed public	50,000	21.000-21.450	Amateur	1,000
3.400-3.500	Aeronautical	400	21.450-21.750	International broadcast	500,000
3.500-4.000	Amateur	1,000	21.750-22.400	International fixed public	50,000
4.000-4.063	International fixed public	50,000	22.400-22.720	Marine	54,000
4.063-4.238	Marine	8,000	22.720-24.990	International fixed public	50,000
4.238-4.438	Marine	140,000	24.990-26.950	Land mobile	500
4.438-5.450	International fixed public	50,000	26.950-26.960	International fixed public	50,000
5.450-5.730	Aeronautical	400	26.960-29.800	Amateur	1,000
5.730-5.950	International fixed public	50,000	29.800-30.000	International fixed public	50,000
5.950-6.200	International broadcast	500,000	30.000-32.00	Land mobile	500
6.200-6.525	Marine	140,000	32.00 -33.00	Government	--
6.525-7.000	Aeronautical	50	33.00 -34.00	Land mobile	500
7.000-7.300	Amateur	1,000	34.00 -35.00	Government	--
7.300-8.195	International fixed public	50,000	35.00 -36.00	Land mobile	--
8.195-8.476	Marine	8,000	36.00 -37.00	Government	--

TABLE 8-1 (continued). RF SOURCES (Ref. 4).

Frequency, MHz	Service	Power, W
37.00 - 38.00	Land mobile	500
38.00 - 39.00	Government	--
39.00 - 40.00	Land mobile	500
40.00 - 42.00	Government	--
42.00 - 50.00	Land mobile	500
50.00 - 54.00	Amateur	1,000
54.00 - 72.00	Commercial television	100,000*
72.00 - 74.60	Fixed	500
74.60 - 76.00	Radiodetermination	2,000
76.00 - 108.00	Commercial, TV, FM	100,000*
108.00 - 117.975	Radiodetermination	2,000
117.975- 144.00	Aeronautical, space	50
144.00 - 148.00	Amateur	1,000
148.00 - 161.575	Land mobile	600
161.575- 161.625	Marine	1,000
161.625- 174.00	Land mobile	600
174- 216	Commercial	316,000
216- 225	Amateur	1,000
225- 250	Radiodetermination	2,000
250- 420	Government	--
420- 450	Amateur	1,000
450- 470	Land mobile	600
470- 890	Commercial television	5,000,000*
890- 960	Fixed	30
960-1,215	Aeronautical	50
1,215-1,300	Amateur	1,000
1,300-1,535	Aeronautical	--
1,535-1,850	Government	--
1,850-2,200	Fixed	18
2,200-2,300	Government	--
2,300- 2,450	Amateur	1,000
2,450- 2,700	Fixed	12
2,700- 3,300	Radiodetermination	--
3,300- 3,500	Amateur	1,000
3,500- 3,700	Government	--
3,700- 4,200	Fixed	100
4,200- 5,650	Government	--
5,650- 5,925	Amateur	1,000
5,925- 6,425	Fixed	10G
6,425- 6,575	Land mobile	100
6,575- 6,875	Fixed	7
6,875- 7,125	Land mobile	100
7,125-10,000	Government	
10,000-10,500	Amateur	1,000
10,500-10,550	Public safety	40
10,550-10,680	Land mobile	6
10,680-12,200	Land mobile and fixed	--
12,200-13,250	Fixed	5
13,250-19,400	Government	--
19,400-19,700	Land mobile and fixed	5
19,700-21,000	Government	--
21,000-22,000	Amateur	1,000
22,000-27,525	Government	--
27,525-31,300	Fixed	5
31,300-38,600	Government	--
38,600-40,000	Land mobile and fixed	5
All above 40,000	Amateur	1,000

*Effective radiated power

of friendly forces and weapons as well as for detection, surveillance, deception of hostile weapon activities and forces

(2) Television broadcasting

(3) Mobile communication to and from aircraft, ships, and land vehicles

(4) Navigation

(5) Long distance radio relay of telephone calls

(6) AM and FM radio broadcasts

(7) Public safety communications by law enforcement agencies, fire services, civil defense, etc.

(8) Space telecommunication

(9) Geodesy

(10) Atmospheric research by remote electromagnetic probing

(11) Voice of America broadcasts

(12) Citizens band radio

(13) Amateur radio

(14) Dissemination of time and frequency standards.

Table 8-2 lists some typical military RF sources and their characteristics while Table 8-3 provides information on the equipment designator system, which identifies the type of source involved. In addition to the wide variety of energy sources indicated by the lists of equipment and uses in the preceding paragraphs, a large number of other sources radiate electrical energy in the communication band, some of which are given in Table 8-4.

The microwave region of the electromagnetic spectrum extends from approximately 0.1 to 10^2 GHz. The upper portion of this frequency band is allocated almost completely to radar systems, and is subdivided into bands as designated in Table 8-5 by letter symbols with the remaining portions being assigned for communications and miscellaneous applications such as medical diathermy, microwave ovens, and microwave dryers. These sources are becoming numerous enough to expose many people and much materiel to fields of significant intensities. Such exposure is limited to the immediate vicinity of the equipment or to the path of a focused beam of energy.

Microwave emitters, being confined largely to line-of-sight applications, are typically in the low-power range. Communication transmitters in this range seldom exceed 100 W in radiated power. An exception is the tropospheric scattering communication systems, which use 10 kW or more power output. Pulse radars, with their low duty cycles, operate at peak power exceeding 10 MW for missile and aircraft defense systems but exceeding 100 kW for normal air and surface surveillance activities. In terms of average power, most radars operate in the 100- to 1,000-W range.

8-2.3 OPTICAL SOURCES

The optical region of the electromagnetic spectrum includes the portion from infrared through visible to ultraviolet: 10^{12} to 10^{18} Hz (10^{-3} to 10^{-9} m). Of course, from an environmental standpoint, the sun is the largest single radiator of light in our environment. In addition, the many man-made sources of light include both those whose primary function is to produce light for illumination as well as those that produce light incidental to their primary purpose. Some light sources are so intense as to constitute an environmental hazard. One such example is the very bright light, rich in ultraviolet energy, produced during welding. Because its effects on the eyes are quite harmful, protection in the form of dark glasses is required. In addition, within both the industrial and military complexes, the use of lasers is increasing at a very rapid rate. Applications that either exist or are being investigated include surveying, weapon guidance, optical radar, communications, computation, image processing, target illumination and designation, machining, and nondestructive structure testing. Because of the coherent nature of laser radiation (i.e., the energy can be confined to a narrow beam similar to microwave energy but with a much narrower, more concentrated beam because of the short wavelength), the direct or reflected energy that can be received by a receptor such as the human eye is large. Lasers are capable of generating extremely high energy densities within a small area. Most lasers generate sufficient energy to cause permanent damage to the retina of the eye. As a result, eye protection must be considered wherever lasers are in use.

Another hazardous man-made source of light is the light emitted by a nuclear explosion. The energy densities are so large in such explosions, even though the person may be protected from blasts, that the light pulse from the explosion can cause destruction of the retina with resultant blindness. The requirement for protection of the eyes from nuclear flashes has been clearly recognized. Eye protection equipment has been developed to permit the observation of deliberate nuclear explosions in the atmosphere of the earth. Of course, nuclear explosions in the atmosphere are now banned by treaty (Ref. 9).

8-2.4 X-RAY SOURCES

X-rays occupy that portion of the electromagnetic spectrum from approximately 10^{15} to 10^{22} Hz. This band overlaps the upper end of the ultraviolet region and

TABLE 8-2. RF SOURCES AND CHARACTERISTICS AT A TYPICAL MILITARY INSTALLATION (Ref. 4)

Emitter	Frequency, MHz	Input power, W	Antenna gain G, dB	ERP*, W
FRT-24	1.8-26	1,000	8	6.3×10^3
FRC-6	1.8-26	1,000	2	1.6×10^3
TCS	1.8-26	40	2	6.3×10
FRT-15	1.8-26	3,000	2	5.8×10^3
TCB	1.8-26	400	2	6.3×10^2
TDO	100-150	25	2	4.0×10^3
GRT-3	225-390	100	10	1.0×10^3
GRC-27	225-390	100	10	1.0×10^3
TED	225-390	50	10	5.0×10^2
AN/GMD-2	225-390	30	10	3.0×10^2
FRW-2	400-500	10,000	15	3.2×10^5
AN/ARSR-1	1,300	4,000	34	1.0×10^7
MPS-19	2,600-3,400	200	33	4.0×10^5
SCR-584	2,700-2,900	300	35	9.5×10^5
AN/FPS-6A	2,700-2,900	4,500	39	3.6×10^4
VERLORT	2,800	150	28	9.5×10^4
AN-APS-20C	2,800	400	34	1.0×10^6
M-33	3,000	1,300	39	1.0×10^7
AN/FPS-68	5,400-5,700	275	40	2.8×10^6
AN/SPS-5	5,400-5,700	285	28	1.8×10^5
AN/MPS-26	5,400-5,700	80	38	4.8×10^5
AN/FPS-16	5,500	1,707	44	4.3×10^8
AN/CPS-9	9,063	1,300	30	1.3×10^6

*ERP = Effective Radiated Power

TABLE 8-3. SOME ARMY/NAVY EQUIPMENT DESIGNATORS* (Ref. 7)

First letter: installation	Second letter: type of equipment
A - Piloted aircraft	C - Carrier
C - Air transportable	D - Radiac
F - Fixed ground	M - Meteorological
G - General ground use	P - Radar
M - Ground mobile	R - Radio
S - Water surface craft	E - Nupac
T - Ground transportable	

Third letter: purpose
B - Bombing
C - Communications
D - Direction finding, reconnaissance, and/or surveillance
Q - Special
R - Receiving
S - Detection and/or range and bearing, search
W - Automatic flight

*The three letter designation system is sometimes but not always preceded by AN/ and is more comprehensive than given here. The ARC-63 is one in a series of aircraft radio communication sets, for example. Complete information can be obtained from MIL-STD-196 (Ref. 7).

the lower part of the gamma ray spectrum. X-rays are generated in the environment both deliberately and accidentally. The deliberate generation comes from the use of X-rays in medicine for visualizing hard body structures as well as industrial and military applications for nondestructive testing. In addition, some X-ray sources, although not primarily designed to produce X-rays, produce them incidentally to accomplishing another desired function. This often occurs, for example, in the extremely high voltage power supplies used in radar, television, research, particle accelerators, power transmission, and similar applications. These high voltage supplies are often shielded in order to prevent spurious X-ray emission.

8-2.5 LIGHTNING

Lightning is a naturally occurring environmental source of electromagnetic energy. Basically, lightning is a secondary effect of electrification within a thunderstorm cloud system. Updrafts of warm, moist air rising in cold air can cause small cumulus clouds to grow into the large cumulonimbus cloud systems associated with thunderstorms. These turbulent cloud systems tower high in the atmosphere and dominate the atmospheric circulation and electrical field over a wide area. The transition of a small cloud into a thunderhead can occur in as little as 30 min.

As a thunderhead develops, interactions of charged particles, external and internal electrical fields, and complex energy exchanges produce a large electrical field within the cloud. The distribution of electricity in a thunderstorm cloud usually consists of a concentrated positive charge in the frozen upper cloud layers and a large negative charge in the lower portions of the cloud. The earth is normally negatively charged with

TABLE 8-4. SOURCES OF ELECTROMAGNETIC INTERFERENCE BY EQUIPMENT

Class	Examples
Rotating machinery	Motors and generators
Mechanical switches	Manual switches, relays, voltage regulators
Transmission lines	Power lines, telephone and and telegraph lines
Lighting	Incandescent, fluorescent, mercury-vapor, and sodium-vapor lamps
Oscillators	Radio and television receivers
Electronic devices	Discharge tubes, diodes, rectifiers, pulsed oscillators, linear oscillators, electronic voltage regulators
Industrial-military equipment	Arc welders, resistance welders, RF heating equipment (including medical) X-ray machines, business machines, electrosuraical apparatus, electrical controller equipment, high-power radars, communication and control equipment

respect to the atmosphere. As the thunderstorm passes over the ground, the negative charge in the base of the cloud induces a positive charge on the earth below and for several miles around the storm. The earth charge follows the storm like an electrical shadow, growing stronger as the negative cloud charge increases. The attraction between positive and negative charges makes the positive earth charge flow upward on buildings, trees, and other elevated objects in an effort to establish a flow of current.

Air, a poor conductor of electricity, prevents the flow of current until large electrical charges are built up. Lightning occurs when the difference between the positive and negative charges becomes great enough to overcome the resistance of the insulating air. The potential required can be as much as 10^9 V.

At any given time, an estimated 1,800 thunderstorms are in progress over the surface of the earth, and lightning strikes the earth about 100 times each second. The number of days per year on which thunderstorms occur worldwide is given in Fig. 8-4. In Chap. 7, "Rain", of Part Two of this handbook series (AMCP 706-116), isopleth maps are included that indicate worldwide average number of days per quarter on which thunderstorms occur. These maps allow an estimate of the probability of lightning. Thus, in central Florida, fewer

TABLE 8-5. MICROWAVE BAND DESIGNATIONS (Ref. 8)

Letter designator	Frequency band, GHz	Wavelength range, cm
P	0.225-0.390	133.3-76.9
L	0.390-1.550	76.9-19.3
S	1.55-5.20	19.3-5.77
X	5.20-10.90	5.77-2.75
K	10.90-36.00	2.75-0.834
Q	36.0-46.0	0.834-0.652
V	46.0-56.0	0.652-0.536
W	56.0-100.0	0.536-0.300

than *5* days with thunderstorms occur in the winter but over 50 occur in the summer. Within the United States, approximately 150 people are killed by lightning each year, and the property loss amounts to more than $10 billion annually (Ref. 10).

Associated with lightning are strong electric fields, massive flows of current, and large electromagnetic energy flow in the atmosphere. Fig. *8-5* demonstrates the time sequence of events involved in the production of lightning bolts. The formation of the stepped leader, the first return streamer, and then dart' leaders and subsequent return streamers are shown. The time values shown are approximate—there is little quantitative information available concerning the actual time duration and velocity of propagation of the stroke (Ref. **4)**.

Cloud-to-earth discharge begins with a pilot streamer that propagates earthward at about 0.15 m μs^{-1} ,followed by a leader consisting of a series of short, stepped strokes. When the stepped leader reaches the earth, the

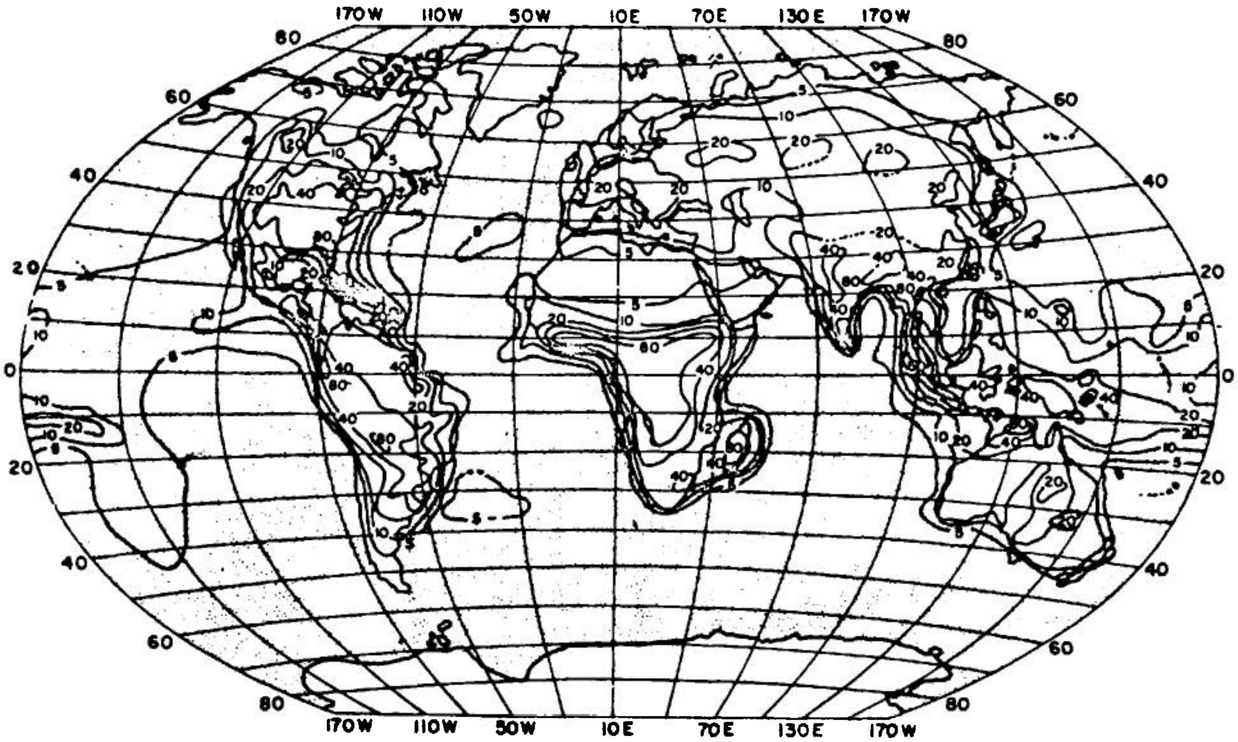
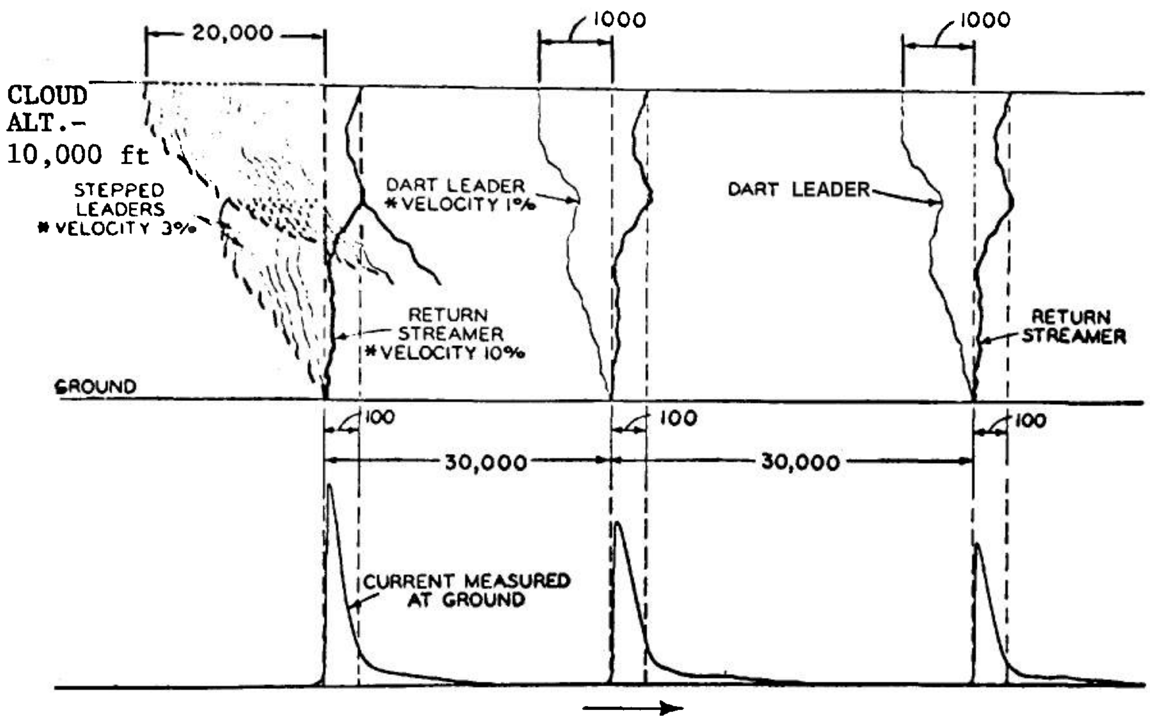


FIGURE 84. Worldwide Thunderstorm Distribution (Number of days per year with thunderstorms) (Ref. 4).



TIME, nonlinear scale, units are μs

*Velocity is given as percent of velocity of light

FIGURE 8-5. Time Sequence of Events in Lightning Discharge (Ref. 4).

negative charge on the cloud is brought closer to the earth with the result that the potential gradient or electric field is increased. Currents involving the stepped leader are normally less than **200** A. At this point, the charge formerly on the cloud is suspended on a column from the cloud to the earth. The head of the positively charged column propagates from the earth upward toward the cloud to neutralize the negative cloud charge. The main stroke of the lightning discharge constitutes this neutralizing process. It has a velocity of about 180 m μs^{-1}, and currents reach a magnitude of 1,000 to 200,000 A. The radiated electromagnetic field from the lightning bolt is proportional to the time rate of change of the electric field. The change of field from the main stroke is approximately three orders of magnitude less in time than that of the leader; consequently, most of the electromagnetic radiation from a lightning discharge is that from the main stroke. The wave shape of the current of a typical lightning stroke is given in Fig. *8-6.*

A lightning discharge, of course, has associated with it both sound and light as well as radiation in the form of electromagnetic, electrostatic, and induction fields. No standard lightning discharge spectrum exists; the electromagnetic spectra of lightning discharges have been observed and found to be different in various parts of the world and, indeed, even in the same thunderstorm. Fig. **8-7** presents a composite source spectrum based on average spectral data from a number of observers. The response at 7,000 Hz is taken as 100, and the response at other frequencies is normalized to this value.

8-2.6 ELECTROMAGNETIC PULSE (EMP) ENERGY

Nuclear explosions generate a multiplicity of phenomena. In addition to blast, shock, light, and radioactivity, a large electrical charge is transported in a short period of time. This produces the large transient pulse of electromagnetic energy known as electromagnetic pulse or **EMP. EMP** is characterized by three transient effects. First, a pulse of ground current flows radially from the point of the explosion. This is followed by a magnetic field that propagates away from

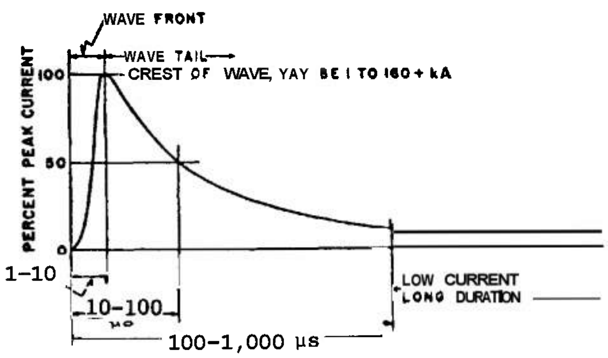


FIGURE 8-6. Wave Shape of Typical Lightning Stroke Current (Ref. 4).

the point of the explosion, followed by a corresponding electric field.

Two mechanisms have been suggested to explain these phenomena (Ref. 11). In the first hypothesis a nuclear explosion causes electrons to be expelled from the center of the explosion in all directions equally and considerably faster than ions because of the mass difference. Were the explosion to occur in homogeneous space, the electron movement would be completely symmetrical and the propagated fields would be neutralized—thus, no **EMP** would be produced. When the explosion is at or near the surface of the earth, however, the electron movement is prevented from being symmetrical so that electric and magnetic fields are propagated.

The second proposed mechanism is hypothesized to operate in connection with the first; **i.e.**, the volume of highly conductive, ionized gases developing around the explosion suddenly excludes the magnetic field of the earth, thus causing a magnetic pulse. The effects of **EMP** can be considered to be very similar to the more common phenomena of a lightning stroke. It should be noted, however, that the magnitude of the fields required to simulate a nuclear **EMP** is far greater than that observed in lightning. Although the magnitude and extent of **EMP** far exceed electromagnetic fields created by any other means, the duration is less than 1ms (Ref. 9). The electromagnetic signal from the **EMP** consists of a continuous spectrum with most of the energy centered about a median frequency of 10 to 15 kHz.

8-3 DETECTION AND MEASUREMENT OF ELECTROMAGNETIC RADIATION

Detection and measurement of electromagnetic radiation is probably as advanced and sophisticated as is that for any physical quantity. For the RF (radio frequency) and optical regions of the spectrum, a large variety of instrumentation is available; for the higher energy gamma and X-ray ranges, the choice is more limited. In this paragraph, the RF range includes all frequencies less than 3 X 10^{11} Hz, the high energy range is above 3 X 10^{17} Hz, and the'optical range is

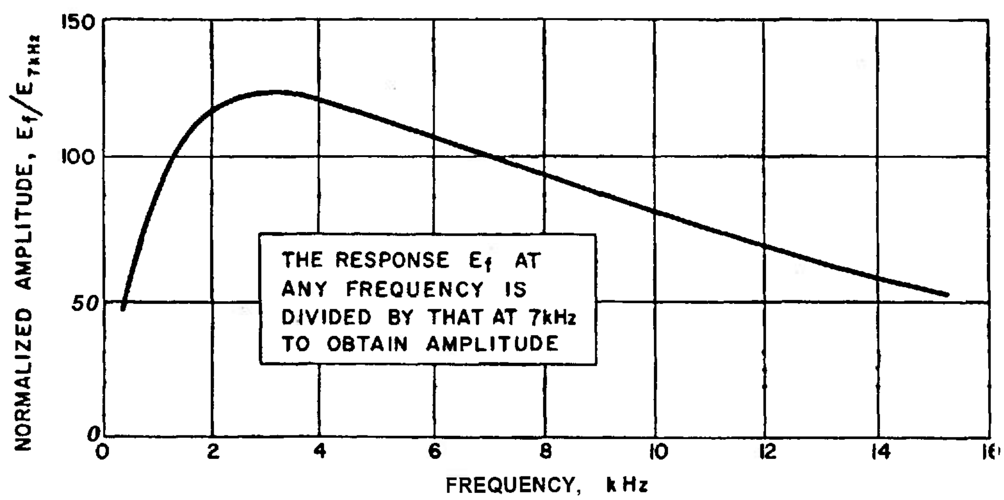


FIGURE 8-7. Normalized Spectrum for Lightning Discharges (Ref. 4).

between these two. Lightning and EMP are included in the discussion of RF instrumentation because the more important portions of their energies lie in the RF frequency range.

The detection and measurement of electromagnetic radiation comprise a complex sphere of scientific and engineering activities employing the talents of many people. A number of excellent texts are available including those of Termon and Petit, ***Electronic Measurements*** (Ref. 12), Norton, ***Handbook of Transducers for Electronic Measuring Systems*** (Ref. 13), and Kraus, ***Antennas*** (Ref. **14**). In this discussion, emphasis is placed on thermal detection in which total power over a broad band of frequencies is obtained as opposed to the detailed power density spectra that are important in electromagnetic compatibility, interference, and warfare measurements.

8-3.1 RADIO FREQUENCY RADIATION

Systems ranging from manually operated to completely automatic measurement systems are available for the RF spectrum. Most such systems consist of specialized, calibrated antennas and sensitive, variable bandpass receivers. Generally speaking, in order to perform tests throughout the entire RF spectrum, several different receivers are required. Using calibrated antennas and such specialized receivers, the user is able, by moving the antenna to various points, to plot RF field intensity as a function of position. Such systems generally are used to survey a region in which interference effects have been experienced or in which sensitive equipment is to be sited.

An example of a highly sophisticated system is the Hewlett-Packard Model 8580A series, an automatic spectrum analyzer system covering the 10 kHz to 18 GHz range. It has a sensitivity down to -130 dBm[1] (10^{-13} mW) and a bandwidth adjustable from 10 Hz to 300 kHz. It provides for automatic frequency scanning and displays the power spectrum on an oscilloscope or records it (Ref. 15).

Instead of determining the electromagnetic fields present around a system, sometimes it is desired to determine the susceptibility of a system to various kinds of electromagnetic interference. In order to do this, specialized test instrumentation is required consisting of calibrated antennas and various RF sources often employed in a shielded "screen" room with nonreflecting walls. Electromagnetic radiation levels are carefully controlled along with the frequency, modulation, and polarization of the field. On some occasions it is necessary to measure induced currents in conductors instead of radiation levels since with some equipment such as computers it is possible for a cable to carry RF energy into the system on the cable. To test for this kind of conducted radio frequency energy, devices such as clamp-on current probes have been developed to measure the RF magnetic field set up by the current. They can be used to detect currents at audio frequencies and radio frequencies.

Electronic and electrical materiel are most susceptible to the effects of electromagnetic radiation. In electronic assemblies, certain components such as the tuner or solid-state digital components are most susceptible to damage. An important example of such a component is the initiator in an electroexplosive device (EED). For test purposes EED's are placed in electromagnetic fields that are more intense than expected in normal operation. To measure such fields, as well as to characterize fields induced in the equipment by other parts, substitutional transducers or sensors are employed. Perhaps one area in which these types of transducers have been most widely used is in the determination of the amount of RF energy induced in bridgewires of EED's. Basically, detectors used in such applications fall into two categories: (1) those that are heat-sensitive, and (2) those that are voltage-sensitive. **As** the name implies, heat-sensing detectors are used primarily to detect the rise in temperature of a component as a result of the dissipation of RF energy (current) in the component. A number of such detectors are available on the commercial market. Several are discussed in the context of sensing the rise in temperature of a bridgewire due to RF energy (Ref. **4**):

(1) The Clairex CL404 detector is a cadmium-sulfide cell with a peak spectral response at 0.68 μm extending beyond 1 μm into the infrared. Radiation impinging on the cell causes the resistance of the cell to decrease. Generally, the cell can detect infrared radiation from a bridgewire that precedes visible glowing of the bridgewire. This type of detector is useful for testing at the firing level of most electroexplosive device initiators or at a point just above the no-fire level and is applicable in other instances where the effect of the RF is to heat a component.

(2) A Kodak Ektron N2 detector is a lead-sulfide cell with a peak spectral response at **2** μm so that it is also employed for thermal detection. Such detectors are usually operated as matched pairs in a bridge circuit with one cell exposed to ambient temperature and the other **to** the radiating source. With such systems, bridgewire power levels significantly below the no-fire level of many **conventional** EED initiators **can** be measured.

(3) A thermocouple can be used to sense the tempera-

1. dBm is a unit for the expression of power levels in decibels with reference to a power of 1 mW.

ture of an RF-heated component. Vacuum-deposited thermocouples have been installed within 0.003 in. of a bridgewire (Ref. 16). The output of the thermocouple is detected with a sensitive recorder or microvoltmeter. It has a threshold sensitivity of 50 μW. In some cases, microminiature thermocouples available commercially have been employed. Such units do not have the fabrication difficulties that are involved in vacuum deposition of thermocouples but they do lack sensitivity when compared with the vacuum-deposited devices.

(4) Thermistors are extremely small devices whose resistance changes rapidly with temperature. One such device exhibits a nominal resistance of 5 kΩ and a resistance change of approximately 70 Ω (deg F)$^{-1}$. When such a thermistor is mounted above the bridgewire of an initiator, it can detect a relatively small temperature rise in the bridgewire. Where extreme precision is required, thermistors are used in matched pairs in a bridge circuit so that the second thermistor can compensate for changes in ambient temperature. Thermistors are notoriously sensitive to drift as a result of ambient temperature fluctuations, however, even when used in matched pairs and, thus, are unsatisfactory for many precise measurements.

(5) The Golay Cell is a heat-sensing device consisting of a gas chamber that is heated by the thermal energy to be detected. Heating of the gas in the chamber causes a change in the pneumatic pressure within the chamber. A mirror-surfaced diaphragm on one wall of the chamber flexes, causing a light beam directed to the mirror to be displaced. By using a remotely located light source and photocell to detect the change in curvature of the diaphragm, Golay Cells can be used to measure small temperature excursions.

Two voltage-sensitive detectors are the crystal-diode detector and the stray voltage detector. The crystal-diode detector is connected across a test device when RF voltage detection is desired. It rectifies the induced RF current, providing an output to an indicating instrument proportional to the level of the induced RF voltage. The stray voltage detector is a one-shot-type detector that can be placed in the circuit being examined. It is similar to a fuse, consisting, in some cases, of a fusible wire element that melts if a predetermined transient power level is exceeded at any time during the test or check-out. Stray voltage detectors can be made to close a switch or trigger an alarm, thus indicating the time at which the predetermined level is exceeded.

These various substitutional detectors are designed to detect temperature rises due to induced RF current heating. While developed for the important case of electroexplosive device testing, the same techniques are readily employed in a variety of equipment. It must be noted, however, that these tests are very frequency-sensitive in that the induced RF energy in any conductor is a strong function of the conductor, nearby conductors, frequency, orientation, and other factors. Thus, such detectors are most useful in testing a specific component in a particular RF field.

In addition to determining the susceptibility of equipment to electromagnetic radiation or the effects of electromagnetic radiation on equipment, the hazard to man as a result of radiated electromagnetic energy must sometimes be evaluated as well. Generally speaking, the measurement of electromagnetic fields hazardous to man is a complex process. Indeed, the wide disagreement within the literature concerning the hazard to man indicates the inadequacy of conventional equipment in determining radiation hazard from electromagnetic sources.

As an example of the difficulty of quantifying hazardous electromagnetic fields, the reader is referred to a review article (Ref. 17). In this paper, the complications and problems of quantifying hazardous electromagnetic fields involving source-subject coupling, reactive near-field components, multipath components, and arbitrary polarization are examined. Dosimetric measurements and hazard survey measurements are discussed in general, and basic considerations for the design of field probes are mentioned as well. Suitable parameters for quantifying complicated electromagnetic fields and essential, desirable characteristics for hazard survey meters are recommended. In addition, several recently designed hazard survey probes capable of measuring those parameters in complex fields are mentioned.

Another discussion of the measurement of electromagnetic wave effects in biologic tissues points out that the only practical way to quantify biological damage accurately in terms of incident power levels is through animal experimentation or by irradiation of biological specimens *in vitro* (Ref. 18). The various parameters and their suitability as an index to absorbed doses are discussed. Generally speaking, proposed parameters are directly proportional either to the magnitude or to the square of the magnitude of the electric field in the tissues. Radiation survey meters are discussed, and their shortcomings for indicating the actual effects occurring in tissue are pointed out. A new thermographic technique for measurement of absorbed power density is discussed in some detail.

The radio frequency and microwave radiation hazards to personnel aboard Navy ships are described (Ref. 19). Typical communication, command and control, surveillance, fire control, and navigation equipment are discussed; and techniques for the prediction and measurement of the microwave fields produced thereby are outlined. A hazard evaluation survey conducted aboard a fictitious ship, closely resembling that performed on actual ships, is described. Methods and techniques used to define and control the potentially hazardous environment that is unique to the Navy are also discussed. This situation is similar, in many respects, to other activities with a concentration of electronic equipment.

Equations for calculating the on-axis power density radiated from large aperture antennas and methods for measuring power density are given in a technical manual, ***Radio Frequency Radiation Hazards,*** published by the Department of the Navy (Ref. 20).

The proper operating characteristics of instruments for measuring voltages and powers at radio frequencies along with a discussion of various instruments and their performance capabilities such as sensitivity, accuracy, antennas, input impedance, selectivity and bandwidth, and rejection of spurious signals for radio noise and field-strength meters in the frequency band 0.015 to 30 MHz are contained in published standards (Ref. 21). These standards include information on radio noise and field-strength meters in the 20- to 1,000-MHz frequency band and the methods of measurement of radio noise voltage and radio noise field strength for low voltage electric equipment and nonelectric equipment in the frequency range 0.015 to 25 MHz.

A recommended practice for accurate measurements of radio frequency generating equipment for the frequency range above 300 MHz is available (Ref. 22). This document gives a brief introduction to two fundamental methods of measuring field intensity using dipole-reflector and horn antennas. General precautions and techniques regarding impedance matching, accuracy, and equipment associated with measurement are also given. Another very useful detailed discussion of electromagnetic interference measurement is given in the ***Handbook*** on ***Radio Frequency Interference*** (Ref. 3).

One of the most widely used methods for detection of lightning depends upon the generation of atmospheric interference as a result of the electromagnetic pulse propagated from a lightning strike. In ordinary radio receivers, for example, a nearby lightning strike is evidenced by static occurring on the output of the radio receiver. These atmospheric bursts of energy, called atmospherics or sferics, can easily be counted by using an ordinary broadcast receiver that is tuned away from any strong station in order to listen to the bursts of static that occur. A small transistor radio operating in the broadcast band, therefore, can be used to detect the approach of a lightning storm, and the number of lightning discharges can be used to give some estimate of the type and intensity of the storm.

Other more sophisticated equipment has also been developed for forecasting lightning danger. MacCready (Ref. 23) has reported on a potential-gradient recorder that can give a 20- to 90-min warning of dangerous lightning conditions. The potential-gradient system utilizes the fact that the potential gradient change varies inversely as the third power of the distance from a discharge. The unit described consists of a highly insulated radioactive probe (which ionizes to couple the probe to the voltage of the air), an electrometer amplifier, and a recorder to record the potential gradient trace. Sharp fluctuations in the trace indicate lightning discharges. The magnitude of the trace is related to the buildup of cloud electrification nearby. In forecasting lightning danger using this equipment, possible lightning danger is indicated when the signal reaches 2 V cm^{-1} or when the signal shows several sharp fluctuations denoting lightning. Immediate lightning danger is indicated when the signal reaches 4 V cm^{-1} or the signal shows lightning fluctuations exceeding 2 V cm^{-1}. It is pointed out that possible lightning danger remains in effect 40 min after the signal has returned to normal. For details on the use of such equipment in forecasting lightning, the reader is referred to the reference.

The nuclear electromagnetic pulse (EMP) is a part of the complex environment produced by nuclear explosions. The detailed frequency spectrum and the magnitude of the EMP are classified information. Nuclear EMP is comparable in its effects to that of lightning, according to some authors. The differences between the protection problems are significant since the magnitude of nuclear EMP may produce more drastic effects than lightning strikes. Because most of the information concerning EMP is classified and because the ban on atmospheric nuclear weapon testing limits the occurrence of EMP to simulation, this chapter does not deal with the measurement of EMP phenomena (Ref. 24).

8-3.2 SHORT WAVELENGTHS

The hazards associated with electromagnetic energy in the optical region of the spectrum (infrared, visible, and ultraviolet) generally apply to man rather than to equipment. Since infrared energy can be sensed by thermal receptors in the skin, other warning is not usually required except for extremely high energy pulses. On the other hand, ultraviolet light poses a problem since the skin receptors are not sensitive to ultraviolet, and dangerous skin dosages can be received without a person's knowledge, For example, conjunctivitis and erythema can occur from prolonged or intense ultraviolet radiation. An exposure to 36 $\mu W\ cm^{-2}$ of radiation at a wavelength of 253.7 nm produces an erythema in about 15 min. The basic measurement technique used for sensing incident ultraviolet energy is photoelectric dosage intensity meters. Such units are commercially available from a variety of sources.

Within the optical band, lasers are a distinct hazard to man. Because of the extremely high energy that can be concentrated in laser beams, the hazard is perhaps more acute because damage can occur very rapidly as a result of an extremely short exposure. Generally speaking, the output power from lasers can be measured using power meters that are commercially available such as photometers and light meters.

A variety of methods can detect and measure X-ray dosage. One classical technique involves the use of an ionization chamber and an electrometer combination to detect incident X-ray energy. This technique is outlined in a publication of the Electronic Industries Association (Ref. 25).

Another method for measuring radiation dosage from X rays involves the use of dosimeters (film badge), which employ photographic film. These dosimeters are either worn by the person whose environment it is desired to monitor or placed in a particular position at which it is desired to measure the total X-ray dosage. The exposed photographic film is then developed. The darkness of the film is an index of the total X-ray exposure. Dosimeters are limited, of course, to measuring the total dosage received during the exposure period and are energy dependent. A variety of more sophisticated X-ray detectors employing scintillation crystals, thermoluminescent devices, and solid-state radiation detectors have also been employed to measure X-ray radiation as well as dose rate. Specialized reports on the operation and use of such equipment to measure X-ray radiation are available in the literature. One example of these more sophisticated systems is the pulse height spectrometer, which is employed to measure gamma energy (Ref. 26).

8-4 EFFECTS OF ELECTROMAGNETIC RADIATION

In considering the effects of electromagnetic radiation, it is useful to consider the several mechanisms whereby these fields produce undesirable effects. Some of these effects are specific to various wavelengths of electromagnetic radiation. For example, the effects of electromagnetic radiation within the frequency spectrum allotted to the communications band are generally not believed to cause significant effects on man. On the other hand, it is documented and well known that the effects of X rays, lightning strikes, high intensity light pulses, and even microwaves—under the right combination of conditions—can produce hazardous effects on biologic systems, including man.

For electronic equipment operating within the communications and microwave bands, environmental electromagnetic fields can be harmful in three basic ways: (1) interference, (2) overheating, and (3) electric breakdown. First, the presence of extraneous electromagnetic fields can produce interference, particularly in communication channels, but also in other electronic equipment such as navigation, radar, and command and control units. This interference to a system can be caused by (1) other systems operating in frequency ranges that interfere with the operation of the desired equipment, and (2) undesired signals generated by the system itself. Good design practice and proper siting of equipment are usually sufficient to eliminate problems encountered in the second category.

Electromagnetic interference is classified in a number of ways but, for measurement purposes, it is usually classified according to its spectral characteristics. The two general classifications are broadband interference, in which a wide range of frequencies are involved, and narrowband interference, which is centered about a discrete frequency. In addition, the interference is classified with respect to its duration. That which is constant without interruption is called continuous wave or CW interference. Interference that is periodic and occurs in bursts with a regular period is called pulse interference. Pulse interference can be either narrowband or broadband depending upon the pulse duration. In addition, nonrepetitive short duration bursts of broadband noise are called transient interference. Lightning, for example, is a typical example of transient interference. Electromagnetic interference can be coupled into equipment either by direct radiation or by conduction on power lines or structures.

Through proper frequency management, many interference problems can be reduced. Unfortunately, the problem is complicated because the electromagnetic environment contains not only the desired electromagnetic radiation, but also spurious and undesired interference from both natural and man-made sources. As the number, complexity, and output power of electronic systems in use grow, the problem of the electromagnetic environment and equipment compatibility becomes more serious. For example, within the military, the density of electronic equipment in the field has grown to the point that hundreds of equipments now occupy the same operational environment as did a few equipments in World War II. It is noted that, in discussing electromagnetic interference, the fields usually spoken of are not high enough to cause permanent damage to the system or equipment under consideration.

When electromagnetic fields become very large, permanent damage can occur to operating equipment. For example, if the electrical field becomes sufficiently high, electric breakdown can occur, destroying the equipment. On the other hand, at some intermediate values of field strength, overheating can occur in which the RF field induces currents that contribute to the heat load already present as a consequence of operation of the equipment. This overheating can lead to failure of components and malfunction of the system.

In addition to the effects of electromagnetic radiation on equipment, another consideration involves the effects of the electromagnetic environment on man and the extent that this must be considered in the design of electronic materiel. Basically, the effects produced by electromagnetic fields on man are classified into thermal and nonthermal. Some portions of a man's physiology are particularly susceptible to certain frequencies of electromagnetic energy. One of the prime areas of environmental concern involves the effect of microwaves on human beings. The effects of microwaves, as well as other frequency bands, on human beings are discussed in detail in par. **8-4.2** and are considered because of (1) the requirements that may be placed on materiel to provide protection from such effects, and (2) the design and operating limitations that may be placed on materiel to limit personnel exposure to such radiation.

As an example, it is well documented that microwaves produce cataracts in the eyes of persons who are subjected to strong microwave fields for long periods of time. Other effects also occur in man, but cataracts seem to appear first. The importance of nonthermal effects is a source of scientific discussion; sufficient evidence is not yet present to specify the nonthermal effects that are both important and originate with the electromagnetic environment.

In the paragraphs that follow, three effects of electromagnetic fields on hardware are discussed: (1) electromagnetic interference, (2) overheating, and (3) electric breakdown. This is followed by a more detailed discussion of the effects of electromagnetic radiation on biologic systems in general and on man in particular.

8-4.1 EFFECTS ON MATERIEL

8-4.1.1 Interference

Generally, electromagnetic interference refers to the situation in which electromagnetic energy produces a temporary undesirable effect on the functioning of equipment without producing permanent damage. The term electromagnetic interference finds its widest usage in those areas in which communication and control signals are transmitted via electromagnetic waves. In these cases, electromagnetic interference usually involves the coupling of undesirable signals into equipment so that the desired signals are degraded or completely obscured. For example, most communication equipment is unable to reject undesired signals that are present in the frequency band to which the communication equipment is tuned. National and international agreements on the allocation of frequencies for particular users and particular uses are an attempt to help eliminate as far as possible the effects of electromagnetic interference caused by multiple users operating at the same frequency.

In addition to the electromagnetic interference produced by multiple users of the same frequency band, some interference effects are produced by equipment whose primary function is not to produce electromagnetic energy. Such interference can be produced from a variety of sources, including rotating machinery, mechanical switches, telephone and telegraph equipment, and power and lighting circuits (see Table **8-4**).

8-4.1.1.1 Source Interactions

The extent to which electromagnetic interference is a problem is a function of the density of equipments producing electromagnetic radiation. If large numbers of equipments produce electromagnetic energy within a given frequency spectrum, the probability of electromagnetic interference is high. By the same token, if a large number of equipments producing electromagnetic energy are present either deliberately or accidentally within a small geographic area, the probability of electromagnetic interference is also increased. Since electromagnetic energy flux decreases as the reciprocal of the square of the distance from the source, a high density of electronic equipments or electrically operated machinery in a given area is more likely to produce electromagnetic interference than the same number of equipments spread out over a large geographic area. For example, military installations have a large number and variety of electronic equipments; most weapon systems include communication and surveillance equipments employing electromagnetic radiation. As a consequence, the probability of electromagnetic interference around military installations is higher than in the overall general environment.

When interference is the result of propagation in space beyond the near field, a number of mechanisms can be propagating the interfering electromagnetic energy to the site where interference takes place. When line-of-sight conditions prevail between the interfering source and the source being interfered with, then direct free-space propagation of the interfering source signal is most important. Transmission can also occur well beyond the line of sight under certain circumstances. For example, when a sharp rise in atmospheric temperature or a drop in water vapor content of the air occurs with an increase in altitude above the surface of the earth, then the refractive index of the atmosphere can be changed sufficiently to cause a radio wave to be bent back downward to the earth. It can be reflected upward again and refracted downward again by the atmosphere, producing an effect known as tropospheric ducting.

Another mechanism whereby interfering energy can reach an equipment beyond direct line of sight is the diffraction of radio frequency energy by obstructions. If a sharp terrain feature such as a ridge or mountain peak occurs between a transmitter and a receiver, then the received signals can be much larger than if the obstacle were not present. Another mechanism of beyond-the-horizon propagation is called tropospheric scatter. In this mechanism it is hypothesized that energy beamed into the atmosphere at a low elevation angle with respect to the horizon is scattered due to the variations in the refractive index of the atmosphere. Tropospheric scatter occurs in the range of 40 to 10,000 MHz.

Another electromagnetic transmission mechanism is surface wave propagation in which radio waves tend to travel along the interface between the surface of the earth and the upper atmosphere. For frequencies less than approximately 30 MHz, the ionosphere acts as a metallic reflector causing waves to be reflected back to earth, and long distance transmissions over several thousand miles can be obtained. For frequencies of 30 to 60 MHz, a small fraction of the energy that is beamed into the ionosphere is scattered downward to earth. This scattering is thought to be caused by irregularities in electron density in the ionosphere causing variations in the refractive index. This propagation mechanism is called ionospheric scatter. Finally, large particles (meteors) falling into the atmosphere of the earth produce ionized trails as a result of the ionization of the evaporated meteoric materiel. These ionized trails provide a mode of communication by scattering or reflecting a portion of incident RF energy back to the earth. These propagation mechanisms provide propagation paths for both desirable signals and unwanted electromagnetic interference (Ref. 27).

8-4.1.1.2 Electroexplosive Devices (EED's)

Many types of electromagnetic interference are troublesome—in some cases very hazardous situations can be produced. For example, an experience common to virtually all automobile users is to encounter signs, near construction sites where blasting is occurring, that instruct the automobile user to turn off two-way radios. These signs are necessary to prevent transmission of electromagnetic energy by two-way radio transmitters that could initiate the firing of explosives in the area. This rather simple civilian example is illustrative of a considerably greater hazard in military installations where weapon systems employing **EED's** exist in relatively high density. In this environment, it is extremely important that systems be designed to eliminate as far as possible any hazardous effects caused by stray electromagnetic fields.

EED's are widely used in the Army because of their light weight, small size, high reliability, low energy requirements, and their variety of input and output characteristics. The following discussion of **EED's** has been adapted from ***Hardening Weapon Systems Against RF Energy,*** AMCP *706-235* (Ref. **4).** The basic parts of an electroexplosive device are the lead wires, header, bridgewire, case, and charge as shown in Fig. 8-8. Table 8-6 lists a few types of electroexplosive devices with typical input characteristics and Table 8-7 lists some aerospace ordnance devices.

The transducer, which receives the electrical firing impulse and initiates the explosion, is the most sensitive component with respect to electromagnetic radiation. This component is carefully protected from stray electromagnetic fields in order to prevent undesired detonation of the explosive. Basically, the transducer in an **EED** converts the electrical energy supplied to the transducer into another form of energy that is used to activate the explosive. Generally speaking, the application governs the choice of **EED** transducer. For example, an antitank projectile making use of a shaped charge frequently requires functioning times on the order of several microseconds. Such a projectile has very little space for control circuitry and power sources so that a transducer requiring very small amounts of energy to initiate the bridge is required. For such applications, a carbon-bridge detonator may be used. Such a device is extremely sensitive and requires a very small power source to initiate firing. Its extreme sensitivity, however, makes it susceptible to detonation by spurious electromagnetic fields. Other devices, such as explosive bolts used to hold missiles on their launching platforms, can employ virtually any desired power supply

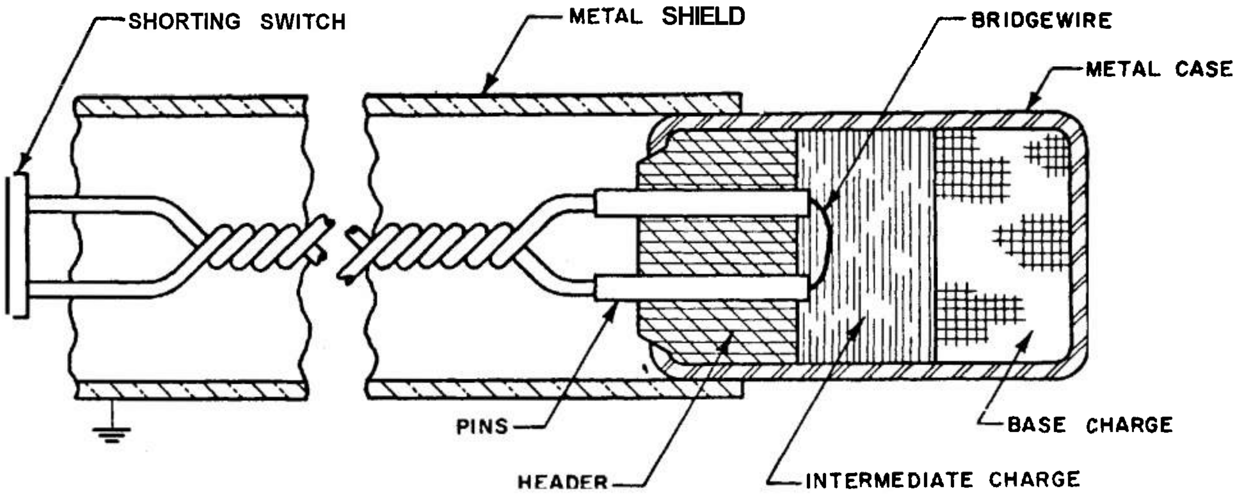


FIGURE 8%. Electroexplosive Device (EED) Components (Ref. 4).

TABLE 8-6. SOME ELECTROEXPLOSIVE DEVICE (EED) TYPES (Ref. 4)

Transducer	DC resistance, ohms	Sensitivity	
		No-fire	All-fire
Hot wire bridge, standard	0.1-10	0.1 A	1.0 A
Exploding bridgewire			
Gapped	∞	1 μF 800 V	1 μF at 2,000 V
Ungapped	0.01-0.1	1 μF 800 V	1 μF at 2,000 V
Conductive mix	$0.01\text{-}10^6$	0.1 A	10 A
Carbon bridge	800-12,000	10 V	1,000 V

TABLE 8-7. BASIC AEROSPACE ORDNANCE DEVICES (Ref. 4).

Name	Description	Application
Igniter	A complete ignition system consisting of an initiator and a deflpgrating material of a pyrotechnic or propellant type. Produces sustained generation of hot particles, flames, and gas.	For ignition of solid- and liquid-propellant rocket motors and gas generators.
Initiator	Can be divided into 3 groups: squibs; primers, detonators. Squibs produce a hot flash and little brisance; primers produce a brisant hot flash; detonators produce high-velocity shock waves.	Primers and squibs initiate the burning of igniters in pressure cartridges, gas generators, rocket motors, flares, and spotting charges. Detonators provide high-order detonation in high explosives, explosive bolts, Primacord, and other high-explosive systems.
Squib	A flame producer with no brisance, i.e., produces no high-explosive effect and is used to ignite deflaqrating mixtures.	(See "Initiator" above). For actuation of explosive valves, drogue guns, thrust-reversal and termination systems, shear-pin systems, and pressurization of small volumes.
Primer	Produces higher brisance than a squib and is lower in energy production than a detonator.	(See "Initiator" above)
Detonator	Produces high brisance and high-velocity shock waves almost instantaneously.	(See "Initiator" above)
Pressure cartridges	Consist of an initiator (squib or primer) and a main charge which contains a pressure-producing propellant.	For pressurization of systems with high-energy hot gas for operation of linear and rotary actuators, explosive valves, disconnects, staqe-separation devices, thrust-reversal and termination systems, detent and unlatch mechanisms, thrusters, pin pullers, and reefing-line cutters.
Boosters	Produce high-order shock waves to detonate high explosives	Initiate Primacord, line charges, destructors, MDF, FLSC, and other high explosives.
Explosive bolts	Fragmenting and nonfragmenting special or standard bolts with an integral or separately installed high-explosive charge.	Missile-stage separation, nosecone separation, booster-motor release, rocket-sled release, thrust termination and reversal; jettisoning of special devices, solar panels, and antenna deployment, missile-launcher separation, destruct.
Gas generators	Hot or cool gas. Essentially small rocket engines consisting of a propellant, an initiator, igniter, and a pressure-regulating nozzle. Produces hot or cool gas at controlled pressure.	Operation of APU, APS, CAD, hydraulic pumps, gyroscopes, turbo blowers; for pressurization of liquid-propellant systems, hydraulic accumulators-, and fire extinguishers; inflation of flotation units; and ignition of solid and liquid propellants.

since the firing current can be obtained from equipment that can generate a large current.

The normal firing stimulus for an EED is usually specified by the manufacturer. In operation, this electrical stimulus is applied to the transducer with a magnitude and shape so as to initiate the explosion with high reliability. Unfortunately, electromagnetic fields from other equipment operating in the area, from lightning, from static electricity, from electrical transients, or from other sources can be picked up by the external circuit and coupled into the electroexplosive device in such a manner as to produce a stimulus that initiates action of the EED.

These extraneous excitations can also produce effects other than an instantaneous initiation. For example, if the magnitude of the stimulus is very low but is applied for a sufficiently long time, initiation of the explosive may eventually be produced by cook-off or thermal stacking. Thermal stacking refers to the process by which an area of a component or circuit receives energy, then dissipates it in the form of heat. The continuous input of heat causes a gradual rise in temperature of the component or circuit. After sufficient time this additional heat may be adequate to initiate the EED.

The passage of current less than the no-fire current through a transducer can produce dudding as well. When electromagnetic radiation induces current in the transducer or other component of the EED, the temperature of the device may slowly rise. If the temperature remains below that of autoignition for a significant period of time, the explosive mix adjacent to the transducer may decompose. When the normal firing stimulus is applied, the decomposed mixture can prevent ignition of the EED.

Cook-off is a related term involving basically the same kinds of thermal problems. Each explosive mix has some particular autoignition temperature. For example, the autoignition temperature for lead styphnate is 350°C.If additional heat provided by electromagnetic pickup slowly raises the temperature of,the explosive mix to the point of autoignition, this process is called cook-off. Normally, this condition is minimized by providing a large heat sink. If the EED is surrounded by poor thermal conducting material, the possibility of cook-off should not be ignored. A special case of cook-off occurs when pulsed RF energy is encountered. Fig. 8-9 indicates the manner by which a pulsed electromagnetic field (for example, a high-powered, pulse radar system) can lead to ignition of an EED. The transducer temperature will increase when a pulse is being received and will decrease when there is no pulse present. If the transducer temperature does not fall to its previous value in the time between the pulses, then successive pulses will gradually increase the temperature of the transducer as indicated by the dotted line in Fig. 8-9. If pulses continue to be received, it is possible for the transducer temperature to exceed the threshhold temperature required for ignition. It can be seen from this discussion that the exact result of electromagnetic pickup by an EED is difficult to predict.

To illustrate the variable effects that can be produced by an electromagnetic signal, a typical case that can occur for many electroexplosive devices is outlined. When electromagnetic energy at a frequency of approximately 1.5 MHz is coupled into the transducer of the EED, localized heating of the transducer occurs. In this case, the voltage would be low, the RF current large, and the RF power required to initiate the EED would be comparable to the DC power required 'for initiation. If the energy is absorbed at other points within the device, for example, between the pins and the case of the EED, a different situation occurs. The pin-to-case impedances of a typical EED at this frequency consists of a small resistive part and a large reactive part. Because of the large reactive part, a small quantity of RF power can produce a large RF voltage. This can result in electrical breakdown between the pins and the case.

Determining the actual electromagnetic energy levels that will produce damage in a system is difficult. Measurement of RF current or voltage is often of little value unless the impedance at the point is known. Determination of the impedance at the exact point of interest is difficult at high frequencies. As a result, it is frequently necessary to use an empirical approach to establish the sensitivity of a component to electromagnetic energy.

Sources of information on electroexplosive devices and problems associated therewith include the Harry Diamond Laboratories, Washington, D.C.; Frankford Arsenal, Philadelphia, Pa.; Picatinny Arsenal, Dover, N.J.; and the Army Missile Command, Redstone Arsenal, Ala.

8-4.1.2 Overheating and Dielectric Breakdown

In addition to interference effects, electromagnetic radiation can produce localized heating, within equipment other than EED's, that can in turn lead 'to thermal breakdown. Further, when RF fields are very high, dielectric materials break down as a result of the high voltages sustained. In par. 8-4.1.1.2, overheating effects on electroexplosive devices are discussed. Most modem electronic equipment, both commercial and military, employ a variety of electrical circuits subject to overheating or electrical breakdown in the presence of electromagnetic fields.

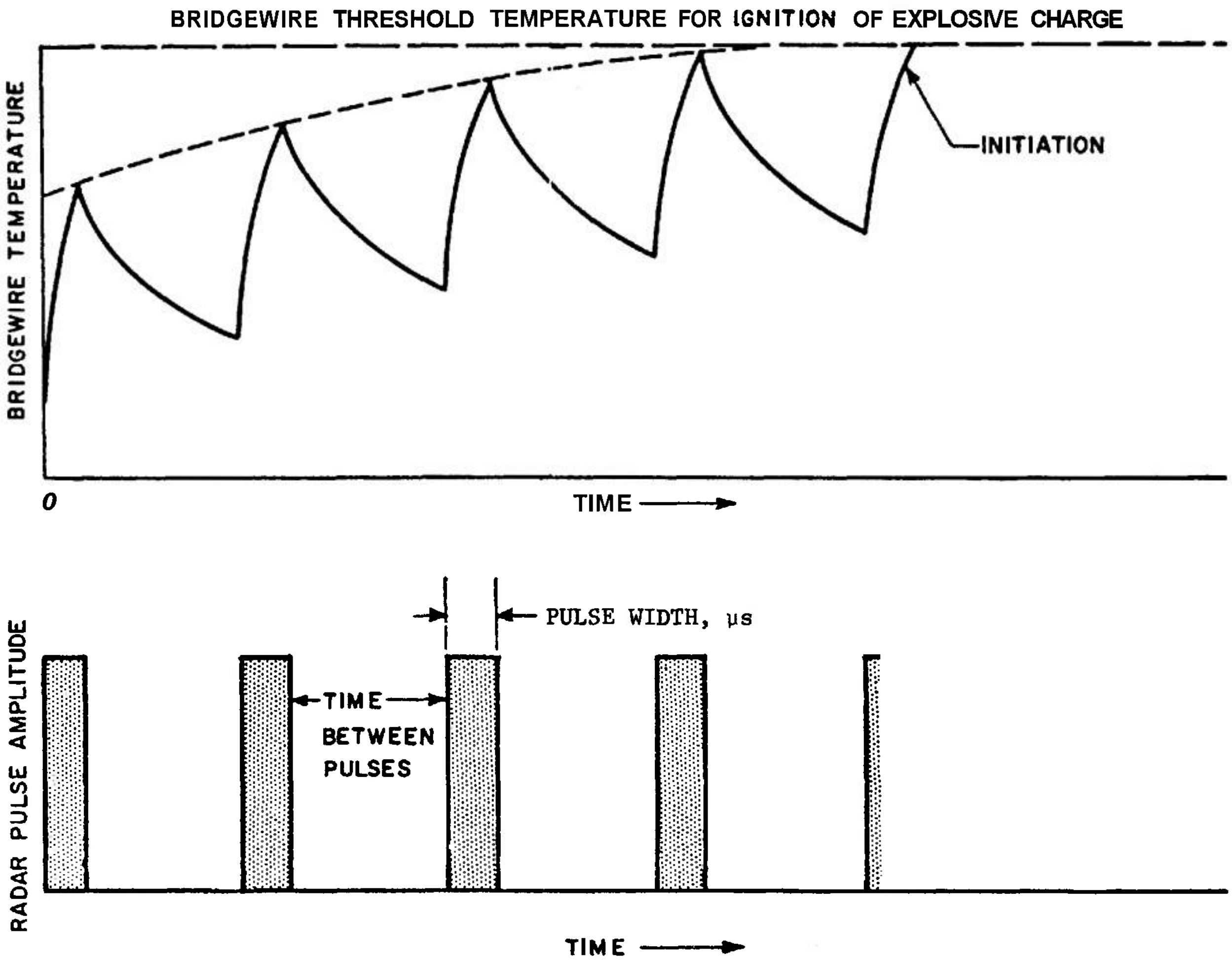


FIGURE 8-9. Ignition of Explosive Charge by Thermal Stacking of RF Pulse Energy (Ref. 4).

The trend in electronic equipment has been to use more semiconductors and integrated circuits, and fewer vacuum tubes and discrete components. Even discrete component circuitry employing transistors is disappearing with the advent of integrated circuits. The discrete component circuit uses a number of individual components such as transistors, resistors, capacitors, and inductors to implement the circuit, whereas in integrated circuits all of the components are fabricated within a small silicon substrate. The amount of extraneous electromagnetic energy that the small integrated circuit can intercept is small compared to vacuum tube or discrete component circuits employing semiconductors. Unfortunately, the interconnecting wiring and structures surrounding the integrated circuit increase the amount of RF energy that is intercepted. The very small size of integrated circuits prevents them from dissipating as much heat as conventional circuits, and reduces the magnitude of voltage gradients they can withstand without failure. Thus, integrated circuits are particularly susceptible to damage by absorbed electromagnetic energy, and the induced currents may inhibit normal operation or cause temporary failure of the devices (Ref. 4).

Another special case is that of electronic memories in which are stored instructions and data pertinent to successful performance of the equipment. Induced voltage transients can readily modify the stored information, thereby providing erroneous instructions or false data. This is a particularly serious problem with various types of guided missiles and fuzing systems.

Discrete component circuits are also susceptible to component failure as a result of electromagnetic radiation. The stress that causes failure in a component depends on the nature of the component. For example, an electrolytic capacitor is sensitive to overvoltage and to excessive reverse voltage. In addition, at high frequencies the dielectric of the capacitor may absorb electromagnetic energy and dissipate it in the form of heat. The voltage breakdown rating of a capacitor decreases with an increase in temperature. Therefore, the increase in temperature renders the component more susceptible to failure.

Abrupt failure of devices and components occurs in two fashions: the device can develop either an open or a short circuit. For example, a resistor in the presence of a high magnitude field can fail by arcing or by burnout. Table 8-8 is a summary of the failure mode (open circuit or short circuit) by which various electronic components normally fail.

The sensitive parameters that indicate damage to various components as a result of abrupt failures are very easy to detect. Slow deterioration over a period of time is more subtle, however, and much more difficult to recognize. A component is said to fail by deterioration when some given parameter has exceeded a specified limit. The parameter and the limit depend on the type of component and its application. Variation of the parameters of some components over a fairly wide range can be tolerated without significant deterioration of the performance of the system, whereas in other applications, slight changes in certain parameters might cause unacceptable performance.

TABLE 8-8. FAILURE MODES (Ref. 28)

Part type	Abrupt failure mode, % occurrence	
	Short	Open
Capacitors		
Ceramic (general purpose)	95	5
Ceramic (temp. comp.)	80	20
Glass	90	10
Mica (dipped)	90	10
Mica (molded)	90	10
Paper	80	20
Metallized (paper Mylar)	80	20
Polystyrene	90	10
Teflon	80	20
Mylar	90	10
Tantalum		
Solid	90	10
Wet slug	80	20
Wet foil	75	25
Resistors		
Carbon composition	90	10
Carbon film	5	95
Metal film	5	95
Power (wire-wound)	5	95
Precision (wire-wound)	5	95
Variable (composition)	10	90
Variable (wire-wound)	10	90
Variable (metal film)	10	90
Variable (carbon film)	10	90
Transistors	90	10
Diodes	90	10
Transformers	60	40
Chokes and coils		
Single layer	5	95
Multilayer	50	50

Lightning is a specialized case of the very high magnitude electromagnetic radiation field. A direct strike by a lightning bolt can render virtually any electronic system completely useless. Fortunately, direct strikes are relatively rare. Near strikes, however, are frequent. A lightning strike generates an electromagnetic field that can damage components in much the same manner as other forms of electromagnetic radiation. The hazards to electronic components from near lightning strikes are the result of five basic phenomena:

(1) The electrostatic field that exists prior to a lightning stroke

(2) The dynamic electric field that occurs during the leader and main strokes

(3) The dynamic magnetic field that emanates from the main stroke

(4) The electric field set up in the earth as a result of the main stroke

(5) The direct conduction of current from the main stroke.

For example, enormous charge displacements can occur in clouds or objects on the ground during the lightning stroke process. These charge displacements occur rapidly, causing sizable charge movements in the electrical ground. This in turn can cause large DC currents to be induced in the electrical circuits of equipment with significant damage. The very strong magnetic field associated with a lightning stroke can penetrate the usual electromagnetic shielding of electronic equipment, thereby coupling energy into the system and causing heavy current flow and damage or failure to system components.

As another example, missiles in flight are exposed to hazards from both direct and induced effects of lightning. Jet aircraft seem to encounter fewer lightning strikes than propeller-driven aircraft, probably because of the higher altitude at which jet aircraft normally operate. In an experimental study it was demonstrated that abrupt changes in the electric field occur inside an aircraft when lightning strokes pass within 500 yd (Ref. 29).

When in flight, most lightning hazards are cloud-to-earth discharges. Cloud-to-cloud discharges do not contain the return stroke component characteristic of cloud-to-earth discharges, and the maximum current for cloud-to-cloud discharge is approximately three orders of magnitude less than that for cloud-to-earth discharge. In addition, the time rate of change in both the magnetic and electric fields is considerably less so that the induced effects are greatly reduced. On the average, every aircraft in the world is hit by lightning once a year or once every 2,700 flying hr. In Europe, the average is three times greater. Approximately one-fourth of the lightning strokes burn holes in the aircraft, but the rest cause little or no damage. Lightning tends to strike all-metal aircraft in two places, at the nose and toward the wing tips. Burns through the structure seem to occur when the aircraft is caught in the path of a positive discharge from the top of the clouds (Ref. 30).

In many cases damage from lightning occurs to outside equipment such as power and telephone equipment. For power equipment, power lines, and telephone equipment, the most common damage from lightning is the result of a direct strike. It can cause short circuits in electrical cables by damaging the insulation and can melt conductor wires, thus causing open circuits. In Fig. 8-10 the failures produced by lightning current surges in telephone cables are given. In the time notation used, the first figure is the time to peak current and the second figure is the time to reduction of the current to one-half of the peak value. For example, a $10 \times 150\ \mu s$ surge is one with a $10\ \mu s$ time to peak current and a $150\ \mu s$ time required to fall to one-half of the peak value.

Sheathed or shielded aerial cables may puncture when subjected to a direct lightning strike. In such cases, the shielding is punctured at the point of strike, and additional punctures from the shield or sheath to the internal conductors can occur.

Although aerial cables are most susceptible to lightning strikes, even buried cables are not immune. The resistivity of the soil in which the cable is buried has an influence on the hazard to the cable. Ground currents to and from the cable are affected by the resistivity of the soil. High resistivity soils are the worst for buried cables because of the higher potential gradients produced. Consequently, lightning strokes will arc a greater distance to cables that are buried in high resistivity soils as compared to low resistivity soil. Cable puncture cannot be prevented by providing heavy insulation around the cable because the magnitude of the currents involved makes this approach impractical; the amount of insulation required would cost too much.

The induced voltages on telephone aerial equipment resulting from lightning have been measured (Ref. 31). In this study, it is concluded that:

(1) Voltages may be generated in cables as a result of the inactivity of lightning protectors until a peak voltage of 600 V is reached at the terminals of the line.

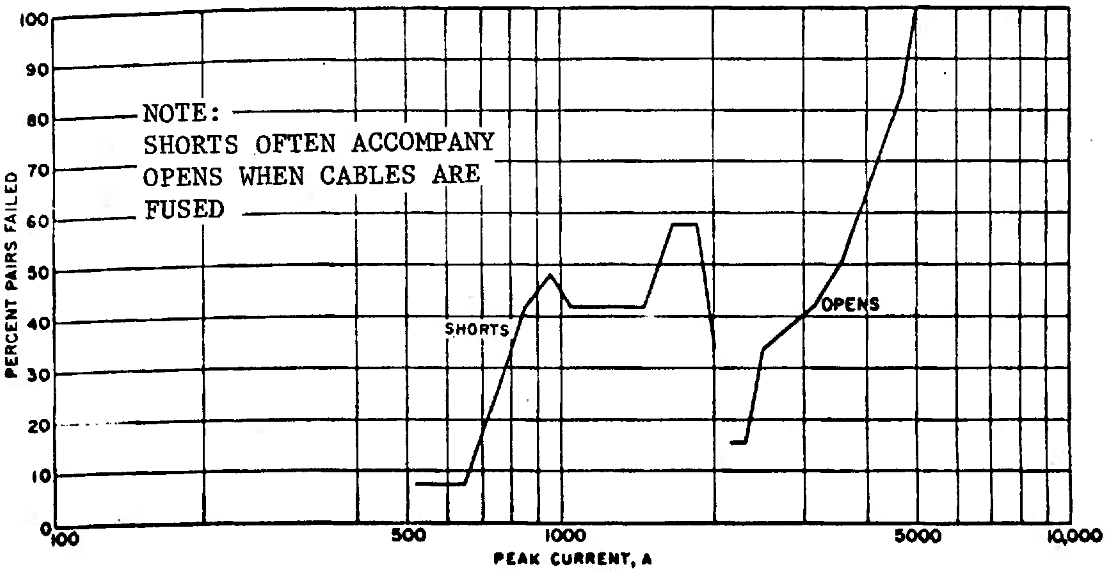
(2) The incidence of voltages exceeding 40 V peak may, on the average, exceed 15 on a day during which thunderstorms occur.

(3) The most extreme condition met in telephone service, insofar as wave shape is concerned, is a $10 \times 600\ \mu s$ pulse.

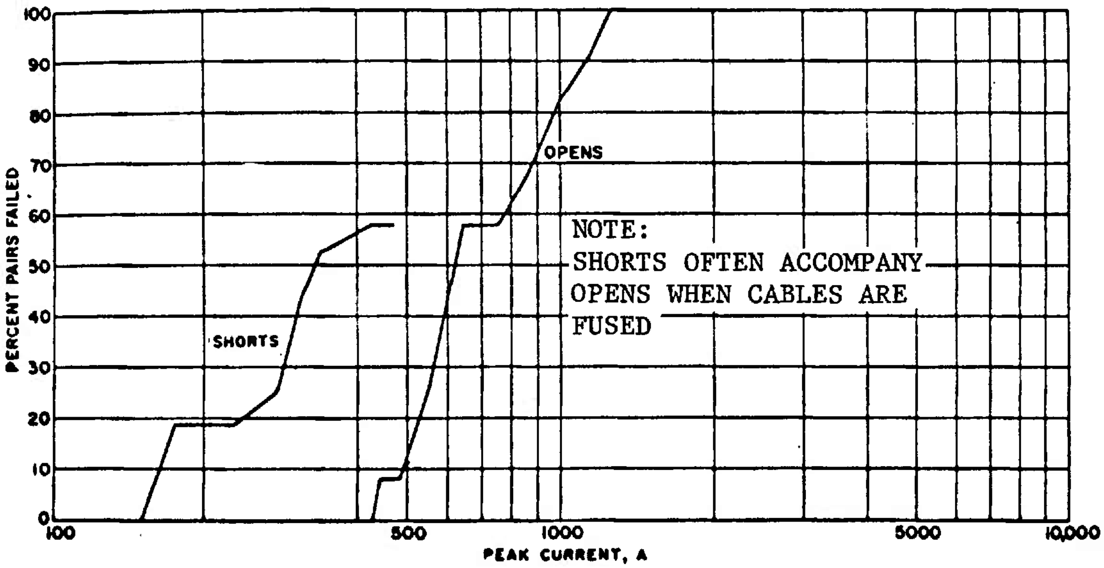
These conditions apply to telephone lines that were provided with gap protectors.

Pierce (Ref. 32) discusses unusual lightning incidents involving triggered lightning and its effects. Triggered lightning is defined as that caused by some human modification of the natural atmospheric environment with the emphasis, of course, on the human modification of the natural atmospheric environment with the emphasis, of course, on the human modification. Virtually all instances of lightning being triggered by man involve the introduction of a long electrical conductor into a thunderstorm in which the electric field is on the order of $10\ kV\ m^{-1}$. If the potential discontinuity between the tip of the conductor and the ambient atmosphere becomes approximately 1 MV, then a leader streamer is initiated and triggered lightning can occur. The two main categories of triggered lightning are those in which the conductor is connected to the earth and those in which it is in free flight. In the first category are tall structures including buildings, rocket launch towers, and antennas, as well as tethered balloons, wire-controlled rockets, and even water columns initiated by depth charges. Even kites are included in this category and, indeed, some fatalities to kite fliers have been reported as a result of triggered lightning. In the second category, in which the conductor is in free flight, the two prime examples are rockets and aircraft. For examples of category one, see Fig. 8-11. Examples of triggered lightning involving free flight conductors are illustrated in Fig. 8-12.

One of the well-publicized incidents involving triggered lightning is that which occurred during launch of the Apollo 12 space vehicle on November 14, 1969. Lightning flashes occurred when the vehicle was within clouds at altitudes of approximately 2,000 and 4,400 m. Lightning had not been reported in the immediate vicinity of the launch pad, but a few isolated flashes had no doubt occurred within 30 km of the area during the 30 min prior to launch. The clouds above the launch pad were not classified as active thunderheads at the time, but they were considered to be strongly electrified. Estimates have been given that the surface field was approximately 3 to 4 $kV\ m^{-1}$. Using a number of assumptions regarding typical values, Pierce calculated



(A) 10 x 150 μs Surge



(B) 20 x 450 μs Surge

FIGURE 8-10. Peak Currents That Cause Permanent Faults in Telephone Cable (Ref. 4).

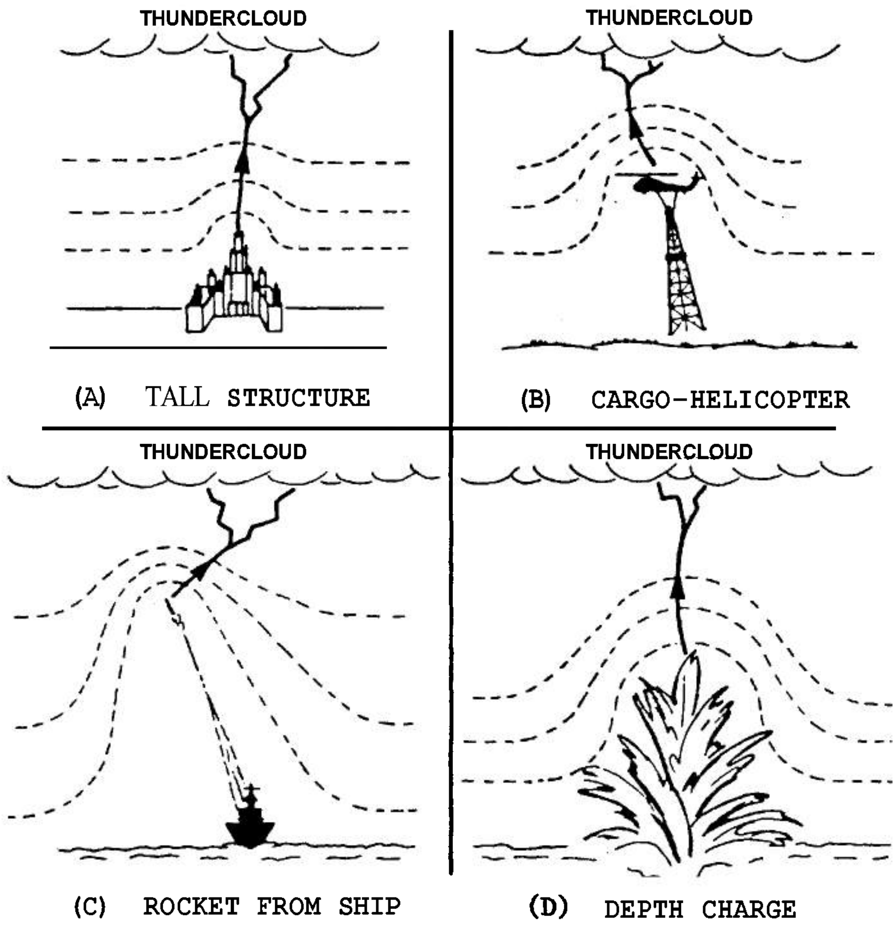


FIGURE 8-11. Examples of Triggered Lightning Involving Conductors Connected to the Earth (Ref. 32).

that the voltage discontinuity at the tip of the missile could have reached approximately 2 MV (Ref. 32).

Vulnerability of solid-state circuitry involving semiconductors and low signal microcircuits has already been discussed. On the other hand, an interesting point involves the fact that computer operations are especially vulnerable to lightning. The effects of power surges associated with lightning can range from mere lost time to very serious damage to magnetic disks, recording arms, and other components. Magnetic and electromagnetic fields radiated by a lightning flash can seriously modify the core memory cells of any computer that is insufficiently shielded. Consequences of such an accident in areas such as military logistics, for example, could be disastrous, and damage to computer-controlled weapon systems could be worse.

With peak voltages of up to 600 V induced in electrical circuits and with a waveform described by a 10 X 600 μs pulse, some components will be unaffected while others will be destroyed unless protective steps are taken (beyond high-tension arrestors and low voltage gaps). As noted before, semiconductor devices are particularly vulnerable. Because of the wide variety of semiconductor devices available, it is not possible to specify a general limiting value of waveshape that will protect all such components. Components being considered for application in electronic systems should be evaluated for ability to survive lightning-created surges.

Field-effect transistors of the metal-oxide-semiconductor type are even more prone to damage than are junction transistors. The mere act of inserting and removing such transistors in styrofoam blocks for storage and shipping purposes has resulted in their destruction by the static charge generated. Since the sensitivity of such devices to static electricity has been recognized by the electronics industry, special storage and shipping precautions are taken. Precautions include the use

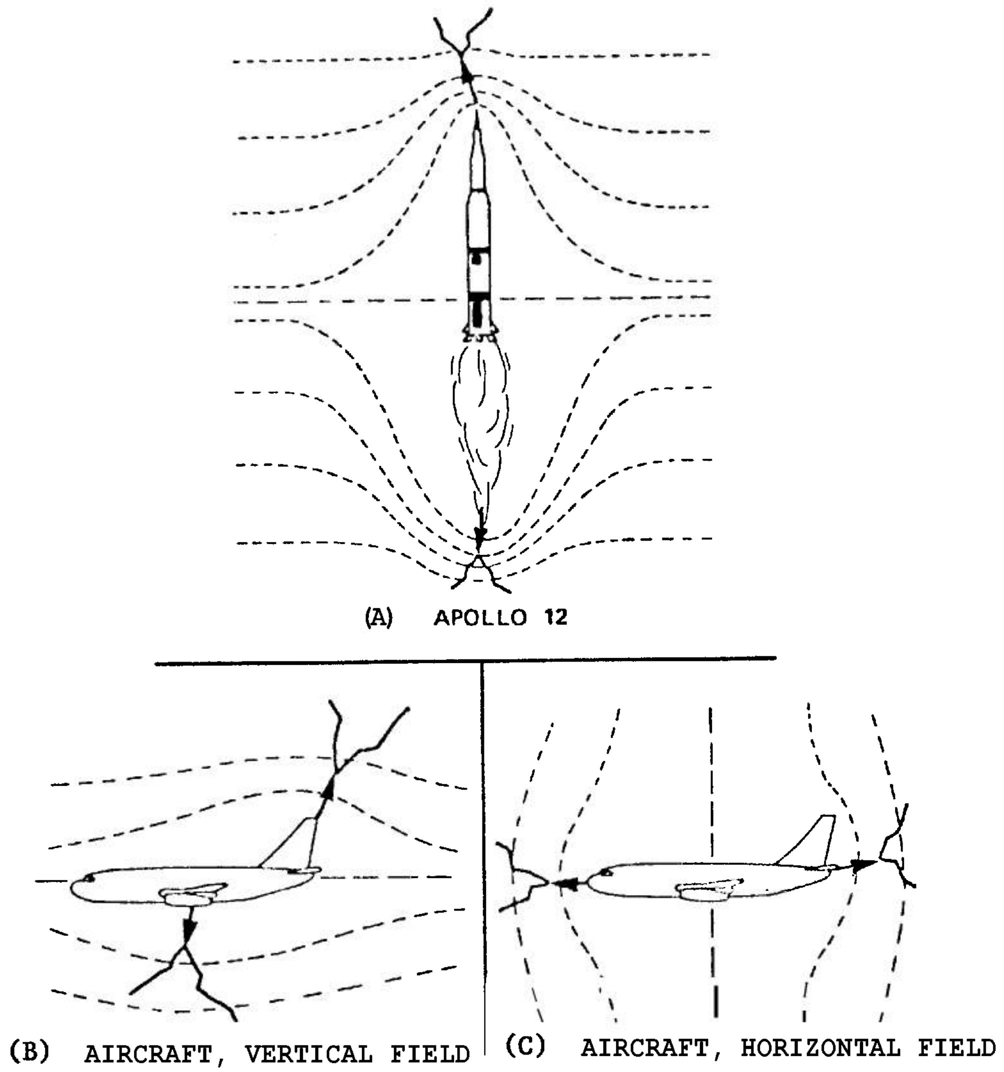


FIGURE 8-12. Examples of Triggered Lightning Involving Conductors in Free Flight (Ref. 32).

of conductive foam for packaging and the bundling of leads and shorting them together. During wiring, the installer is grounded and a wire clip is employed to shunt sensitive portions of the device. The clip is removed only after installation is complete. Such extreme sensitivity underscores the difficulties of protecting such circuits from lightning surges.

8-4.1.3 Static Electricity[2]

In the discussion on lightning, the buildup of static electric fields associated with thunderstorms and its effect on components has been discussed. This is not the only case in which static electricity can be a hazard. Basically, the electrostatic hazard can be characterized as primarily a high voltage, low current, breakdown phenomenon. The electrostatic discharge pulse is very closely related to the capacitor discharge pulse. However, the electrostatic discharge damages components in the same modes as RF energy and is very similar to high frequency radar pulses with respect to the damage it causes. The parameter of importance in this case, however, is the DC resistance rather than the complex impedance that is the significant parameter when dealing with RF energy.

Electric charges are transferred when two masses come in contact, particularly when the masses are non-

2. A general reference for this paragraph is Ref. 4.

conductors. Multiple contact, such as created by rubbing or by multiple particles impacting on a surface, can greatly increase this charge transfer. In addition, a charged body does not actually have to come in contact with a second body to induce a redistribution of the charge in the second body. Examples of electrostatic charge mechanisms are relatively common in modern Army materiel. For example, a projectile, passing through rain or dust, a plastic cover removed suddenly from a weapon, or the presence of a highly charged thunderhead can all provide methods of producing a charge buildup. Any contact or rupture of insulation between a charged body and a circuit component can result in an electric discharge through the component. EED's are particularly sensitive to static electricity that is stored on some object or on the human body and is applied to the EED leads during handling, causing a current to flow through the explosive material to the case and igniting the explosive material.

One of the sources of static electricity is the electric field from a lightning storm. This electric field exists either in the form of a static field around the cloud or in dynamic form being discharged from a cloud. EED's have been fired with voltages on the order of 2,000 V applied pins-to-case from a 500 pF capacitor. Some have been fired with potentials applied from current-limited DC sources of 500 V. A serious hazard exists in that they could be explosively coupled to extremely large amounts of explosive or propellant. Unless adequate precautions are taken to prevent their inadvertent ignition, the results could approach major disaster proportions.

8-4.2 EFFECTS ON MAN

In the study of the effects of electromagnetic radiation on man, certain areas of the electromagnetic spectrum have received significantly more attention than others. Within the communication band little attention has been given to any human hazard involved at these frequencies because little evidence of hazard exists. For example, in the telecommunications range radiated powers are limited by Federal statute. For AM broadcast transmitters the maximum power output is 50 kW over the frequency range 535 to 1605 kHz. This can result in signal strengths of some tens of volts per meter at 0.1 mi from the antenna. For FM broadcast transmitters in the frequency range 88 to 108 MHz, the maximum allowed radiated power is 100 kW. A dipole antenna 2,000 ft above the surrounding terrain emitting 100 kW would yield a field strength of about 1 Vm^{-1} approximately 1 mi from the antenna; at 10 mi the field strength would be approximately 0.1 $V\ m^{-1}$ (see Eq. 8-4). Commercial television stations can emit 5 MW in the 470 to 890 MHz range. The field strength under the same conditions for FM transmission at 1 mi is about 20 $V\ m^{-1}$ and at 10 mi is about 2 $V\ m^{-1}$. These specifications by the Federal Communications Commission are made by-and-large to reduce the possibilities of interference between stations rather than because of any hazard to man.

The microwave frequency spectrum has received most of the interest and emphasis on electromagnetic radiation hazard to man. Much literature exists on the various effects caused by microwaves, including debate concerning the levels of signals that constitute a hazard to man.

In the optical region of the electromagnetic spectrum, several hazards are worthy of note. Retinal burns and blindness can be caused as a result of exposure to the flash from nuclear explosions. During the period of atmospheric testing of nuclear devices, it was necessary to provide protection to observers to prevent impairment of vision as a result of exposure to nuclear flashes. Indeed, specialized goggles have been devised for this purpose. Although the possibility of exposure to flash from nuclear explosion is still a consideration with the military, it seems to be, at least under the present circumstances, a relatively low probability event. Another hazard occurring in the visible spectrum involves the use of lasers. A great number of lasers are in use, particularly within the industrial and military environments. In recent times many new laser applications have also appeared on the commercial market. The trend indicates that lasers will continue to be used at an expanding rate and will pose a hazard in the environment for man. The major hazard of lasers is the possibility of retinal burn with the resulting visual effects.

The X-ray portion of the electromagnetic spectrum clearly constitutes a hazard to mankind. The diagnostic and therapeutic uses of X rays in medicine and use of X rays in nondestructive testing have increased significantly in recent years. The use of high voltages in color television receivers has added an additional environmental X-ray hazard. Regulation of the amount of X rays emitted by color television receivers has been necessary; standards have been set by the Federal Government to insure that X-ray radiation from color television receivers is kept within specified limits. Within the industrial and military environments are additional X-ray hazards. Many equipments that require extremely high-voltage power supplies are capable of generating X rays of sufficient intensity to be harmful. Generally speaking, these equipments include effective shielding techniques and interlocks to prevent operation of the equipment when the shielding is removed. These unintentional producers of X-ray energy can be overlooked in considering the X-ray dosage received by personnel. Particularly in the industrial and military environment where such high-voltage supplies are encountered by personnel, the potential hazard of inadvertent X-ray exposure should be recognized.

In the previous discussion of equipment hazards, lightning has been included as a hazard, both for its direct effects resulting from a direct stroke and the indirect effects resulting from the magnetic and electric fields generated by the stroke. Of course, a direct lightning strike is not only hazardous but usually fatal to man. Direct strikes certainly constitute the greatest hazard to man from lightning. Because of the extremely low probability of a direct strike, lightning effects on man will not be considered in detail. For discussion of safety rules to reduce the possibility of receiving a direct lightning strike, the reader is referred to a pamphlet entitled *Lightning* (Ref. 10) or other such compilations.

8-4.2.1 Optical Radiation

That many lasers operate at power levels sufficient to cause retinal damage is an undisputed fact. In a report by the Bureau of Radiological Health, the available specifications and regulations concerning the use of lasers and the hazards involved in laser use are enumerated (Ref. 33). For example, in Air Force Regulation 161-24 the "retinal hazard exposure level" for a ruby laser, Q-switched with a pulse duration of 10 to 100 ns, is given as an energy density of 0.125 J cm^{-2} incident on the retina. An iris diameter of 7 mm under night conditions and 3 mm under daylight conditions is used for calculating the exposure of the retina. In a British standard the maximum permitted exposure to laser energy is given as defined in Table 8-9 (Ref. 34).

The American Conference of Governmental Industrial Hygienists gives as the maximum permissible exposure levels for direct illumination or specular reflection at a wavelength of 694.3 nm the levels as listed in Table 8-10 (Ref. 35). The levels given in the table can be adjusted for other wavelengths by use of a graph given in the original document. The U.S. Atomic Energy Commission lists the overall permitted energy values given in Table 8-11 for the infrared, visible, and ultraviolet portions of the spectrum (Ref. 33). In this document the exposure of the skin, not including the eye, in the ultraviolet, visible, near-infrared, and infrared portions of the spectrum is limited to a maximum incident intensity of 0.1 J cm^{-2} per pulse or 1.0 W cm^{-2} for continuous-wave operation.

In addition to lasers, one other potential hazard to man occurs in the ultraviolet spectrum. Because of its ultraviolet components, sunlight exposure on the skin causes tanning and, if exposure is too long, painful sunburning. Except for personnel with extreme sensitivity, sunlight exposures do not produce hazardous effects unless unusually long exposure durations are involved. Most people have learned to deal with the ultraviolet problem as far as naturally occurring sunlight is concerned. In addition to this naturally occurring source of ultraviolet radiation, however, some commercial and medical applications use ultraviolet light. One example is the use of an ultraviolet lamp as a substitute for sunlight in order to obtain a tan. Prolonged exposure under ultraviolet tanning lamps can produce very painful burns.

A number of ultraviolet lamps of various kinds are produced for use in hospitals, nurseries, and operating rooms, all designed to produce ultraviolet energy sufficient for disinfection purposes. In order to control the amount of exposure given to patients, staff, and bystanders in hospitals, nurseries, and operating rooms, the American Medical Association has produced a report recommending acceptable exposures (Ref. 36). In this report the maximum intensity of ultraviolet radiation emanating directly from disinfectant lamps and diffusely reflected from the walls and fixtures incident on the occupant for 7 hr or less is specified as 0.5 $\mu W\ cm^{-2}$. For continuous exposure of 24 hr a day, the energy should not exceed 0.10 $\mu W\ cm^{-2}$. These figures are given based upon a wavelength of 253.7 nm. As an indication of the harmful effects of more intense ultraviolet radiation, exposure of human skin to an intensity of 36 $\mu W\ cm^{-2}$ of radiation of wavelength 253.7 nm produces an erythema in about 15 min.

8-4.2.2 Microwave Radiation

The widespread use of microwave generators for navigation, tracking, communications, food ovens, and other industrial and medical purposes poses a potential hazard to the health of personnel concerned with their operation and to those who might be exposed in some other manner. Microwave generators can produce not only microwaves but also X rays and small amounts of ultraviolet radiation, which may constitute a local hazard. Modem, high-powered radars are capable of producing high-power densities at appreciable distances from the source. The potential hazards of these devices were recognized early in their development, the concern for health hazards dating back to the early days of World War II.

That microwaves constitute a hazard to human be-

TABLE 8-9. MAXIMUM PERMITTED EXPOSURE TO LASER ENERGY (Ref. 34)

Condition	Type of pulse	Time or pulse duration	Permitted energy density falling on retina
1.	Single pulse	0.001 to 1 μs	0.001 J cm^{-2}
2.	Single or train of pulses	1 to 1,000 μs	0.01 J cm^{-2}
3.	Pulses or train of pulses	0.1 s	0.1 J cm^{-2}
4.	Continuous-wave laser power incident upon the retina shall not exceed that value which makes $ab^2 = 1.0$; where a = power at the retina W cm^{-2} and b = greatest dimension of the image on the retina, mm.		
5.	Any part of body except eye: total incident laser energy during any 1-s period shall not exceed 0.1 J cm^{-2}.		

Acceptable alternatives to the above conditions:

Condition 1.

Where the eye cannot resolve the image, the energy density at the pupil of the eye must not exceed 0.02 erg cm^{-2} indoors or 0.2 erg cm^{-2} in bright sunlight out-of-doors. Where the eye can resolve the image from a diffuse reflector, viewing is permissible if the energy density at the diffuse reflector does not exceed 0.03 J cm^{-2} indoors or 0.3 J cm^{-2} in bright sunlight out-of-doors. These levels must be reduced threefold if optical glint occurs.

Condition 2.

Same as alternatives to Condition 1, except permissible energy density is increased by a factor of 10.

Condition 3.

A continuous-wave laser of power output less than 50 μW may be viewed under any conditions.

TABLE 8-10. MAXIMUM PERMISSIBLE EXPOSURE LEVELS FOR LASER RADIATION AT THE CORNEA FOR DIRECT ILLUMINATION OR SPECULAR REFLECTION AT WAVELENGTH = 694.3 mm (Ref. 35)

Condition	Q-switched 1 ns to 1 μs pulse (PRF* > 10), erg cm^{-2}	Non-Q-switched 1 μs to 0.1 s pulse (PRF* > 10), erg cm^{-2}	Continuous-wave exposures, μW cm^{-2}
Daylight (3-mm pupil)	0.5	5.0	50
Laboratory (5-mm pupil)	0.2	2.0	20
NIght (7-mm pupil)	0.1	1.0	10

*PRF is "pulsed reoccurrence frequency".

TABLE 8-11. PERMITTED ENERGY FALLING DIRECTLY ON CORNEA (Ref. 33)

Type of laser	Type of pulse	Duration of single pulse	Permitted energy or power density directly falling on cornea
Infrared (> 14,000 Å)	Single,	Not specified	0.1 J cm^{-2} pulse
	continuous	--	1.0 W cm^{-2}
Visible and near infrared (4,900 to 14,000 Å)	Pulses with an off time between pulses of ≥ 100 ms	≤ 100 ns	0.1 W cm^{-2} peak power
		≥ 100 ns	0.1 erg cm^{-2} per pulse
	Continuous	--	3 μW cm^{-2}
Ultraviolet (< 4,000 Å)	Not specified	Not specified	0.5 μW cm^{-2} average power

ings under certain conditions is an uncontested fact. The degree of the hazard, however, is a highly contested issue. Many people (Ref. 37) feel that little or no hazard to man is involved in exposure to low-power microwaves, while others feel that a potential hazard may exist (Ref. 38). Nearly everyone is in agreement that when microwave energy is sufficiently high to cause thermal effects in tissue, then microwaves constitute a hazard to man. The question being debated pertains to nonthermal effects of microwaves. Effects of microwaves in which no evidence of microwave heating has occurred are widely reported in the literature, particularly the foreign literature and especially the Russian literature. The debate centers around two points: (1) whether or not nonthermal effects do, indeed, occur, and (2) if they do occur, whether they constitute a hazard to man.

Because of the increasing uses to which microwaves are being put and the resultant increase in the possibility of exposure to low-power microwaves by the general public, the question of the relative hazard to man is of much interest. In addition to such microwave sources as radar sets and communications gear, new applications continue to be made of microwaves. For example, the cooking of food by microwaves is becoming fairly widespread, as is the use of microwaves in industrial drying and heating processes. The use of microwaves in medicine is increasing.

In medicine microwaves are used for two purposes: heating of tissue and diagnostic uses (Ref. 18). Diathermy, the heating of tissues, is certainly the oldest application in medicine. Diathermy is used to produce heating of tissues beneath the skin to the point that therapeutic benefits are achieved through localized increases in metabolic activity and through increased blood flow due to dilation of the blood vessels. Other heating applications include rewarming of refrigerated whole blood, thawing of frozen human organs, production of differential hypothermia in connection with cancer treatment, and certain localized heating treatments in connection with open-heart surgery. In the diagnostic area, microwaves are used to measure the dielectric constant in order to determine the properties and conditions of certain biological tissues, while reflectance and transmission measurements are used to assess significant parameters such as blood or respiratory volume changes.

Johnson and Guy (Ref. 18) point out that electromagnetic fields in the spectrum between 1 MHz and 100 GHz have special biological significance because they can be readily transmitted through, absorbed by, and reflected at biological tissue boundaries in varying degrees. The effects of this electromagnetic energy can be either medically beneficial or biologically damaging, depending upon the conditions. The recommended maximum safe power density for long-term human exposure in the United States is 10 mW cm^{-2} while that in the U.S.S.R. is 0.01 mW cm^{-2}. This represents a difference of over 1,000 in the allowed exposure. Medical uses of microwaves involve irradiation during diathermy treatments of many areas of the human body with power densities of up to 590 mW cm^{-2}. The maximum permissible dosage for human beings is not yet known because of the conflicting results of research and the inadequate data that exist on the biological effects of microwaves.

In order to highlight this problem, it is perhaps appropriate to discuss the recommended maximum permissible intensities of exposure to RF energy that have been assigned by various countries. In the discussion of the biological response to microwaves, a number of problems are involved because of the complexity of the interactions. For example, the frequency spectrum is extremely wide, a large number of physical and biological variables exist, and the microwave signals themselves can be characterized by a number of different characteristics, including frequency, power level, waveform (for example, continuous wave, pulsed, modulated), and the orientation of the radiation source. Other factors include exposure time versus intensity factors; environmental conditions such as temperature, humidity, and air circulation rate; and shielding. The wide number of variables and the possible interrelationships among these variables, therefore, contribute to a very difficult situation with respect to analyzing the maximum exposure that can be tolerated without harm to man. Another factor contributing to the general lack of agreement in this field is the fact that a difference exists between the responses of the biologic organism: one that represents some sort of physiologic adjustment and another that represents a pathophysiologic decrement. The point is that it may be possible to have biological short-term effects that produce no long-term decrement in the functioning of the organism. Much of the controversy in this area has arisen as a result of trying to separate the temporary effect from the positive hazard.

Basically, the United States has set up microwave exposure criteria on the basis of the premise that the thermal factors are the important ones in evaluating microwave radiation hazards. With respect to the additional heat load (thermal effects) imposed by microwave radiation, some comments about the ability of the body

to dissipate heat are in order. The following comments on body thermal load are excerpted from Michaelson (Ref. 39). Under normal conditions the body is able to dissipate an average of about 5 mW cm^{-2}. This figure has been derived on the basis of an energy supply[3] from food of 3,000 kcal days-', an efficiency of slightly below 30 percent, and a body surface area of approximately 2 m^2. The body has a capacity to dissipate 10 mW cm^{-2} and can, under very favorable conditions, dissipate perhaps as much as 50 mW cm^{-2}. Based on this reasoning, Michaelson concludes that if only half the body is exposed at one time, an absorbed energy of 10 mW cm^{-2} can easily be considered to be a safe thermal load and, therefore, tolerated by the body.

When this U.S. standard was established, wavelength, duration of exposure, environmental conditions, portion of the body exposed, or physiologic status of the individual were not considered. Table 8-12 lists the recommended maximum permissible intensities for radio frequency radiation in various countries. It can be seen that the United States of America Standards Institute and Canada have both adopted a maximum permissible intensity of 10 mW cm^{-2} over the frequency range 10 to 100,000 MHz as averaged over any possible 0.1-hr period. Further recommendations by USASI include cautions against other environmental factors that might increase the heat load on the body, such as physical labor, high ambient temperature, clothing, humidity, etc.

In the U.S.S.R., the maximum permissible levels of microwave radiation for frequencies greater than 300 MHz are 0.01 mW cm^{-2} over an entire workday (6 hr); 0.1 mW cm^{-2} for no more than 3 hr during a work day (protective goggles required); 1.0 mW cm^{-2} for not more than 15 to 20 min during a work day (protective goggles required). In Czechoslovakia, the standards recommended by the U.S.S.R. are followed more or less for pulsed fields. For CW operation a level of 0.025 mW cm^{-2} is accepted since CW radiation is deemed to be less biologically effective than pulsed radiation. As can be seen, the various other standards fall somewhere between these two extremes.

Russian scientists have conducted a large number of scientific research and clinical studies on the effects of UHF electromagnetic fields on biological organisms. They have concluded that the central nervous system is most vulnerable, followed by the cardiovascular system. EEG studies on rabbits have indicated biopotential changes in brain activity from the direct effect of UHF fields on the brain tissue. Soviet researchers also feel that pulsed microwaves have a greater biological effect than do CW microwaves. They appear convinced that microwave field intensities not sufficient to produce a thermodynamic effect do, indeed, affect neural structures. As a consequence of the consideration of these nonthermal effects that occur at much lower values of microwave field intensity, the accepted maximum field intensities of the U.S.S.R. reflect this caution with the 0.01-mW cm^{-2} day^{-1} standard. Generally, U.S.S.R. authorities have agreed that a microwave field intensity exceeding 10 mW cm^{-2} constitutes a definite occupational hazard and adversely affects the central nervous system. In the U.S.S.R., workers exposed to centimeter wave intensities have a 6-hr work day while certain other workers are granted an additional 14-day vacation (Ref. 40).

3. The physiologist uses as a measure of energy the large calorie or kilogram-calorie as opposed to the more common gram-calorie. Thus, the 3,000 kcal/day used here is the small calorie more familiar to engineers and is equivalent to 3,000 calories/day in the units employed by physiologists (or dieticians).

8-4.2.2.1 Thermal Effects

Thermal effects in the body occur when electromagnetic radiation is absorbed by the tissue to the extent that a heat load is imposed on a part of the body beyond its heat dissipation capability. It is accepted that certain organs of the body are more susceptible than others to microwave radiation. The increased susceptibility of these organs appears to be due to the difference in the magnitude of blood flow, which in turn affects the rate of heat removal from these tissues during exposure. Organs that have limited blood flow cannot sustain as much absorption of microwave energy without a concurrent rise in temperature.

With respect to the eye, it is noted that a high incidence of cataracts existed among technicians at distant early warning radar installations in Canada. Most evidence linking microwaves and cataracts has been inconclusive. In a news release (Ref. 41), Dr. Russell L. Carpenter, Chief of the Biological Effects Branch at the Public Health Services, Bureau of Radiological Health, Northeastern Radiological Health Laboratory, reports the case history of a 38-yr-old man who was treated with a 2,440 MHz diathermy unit to cure a painful neck sprain. Twelve 15-min treatments were given over a 6-mo period. A month after the last treatment, blurring of vision occurred; 6 mo later, an examination revealed cataracts in both eyes. Reconstructing the treatment, it was determined that the eyes of the patient were exposed to radiation intensity of 22 mW cm^{-2}. Since other causes for cataracts were not found, it was concluded that the cataracts were caused as the result of microwave radiation of the eyes.

The potential hazard to the eye is one of the most

TABLE 8-12. RECOMMENDED MAXIMUM PERMISSIBLE INTENSITIES FOR RADIO FREQUENCY RADIATION (Ref. 39)

Maximum permissible intensity	Frequency, MHz	Country or source	Specifications
$10\ mW\ cm^{-2}$	10-100,000	USASI 1966; Canada 1966	$1\ mWhr\ cm^{-2}$ for each 6 min
	30-30,000	Great Britain 1960	Daily exposure
	All	U.S. Army and Air Force 1965	$10\ mW\ cm^{-2}$ cont. exp. $10\text{-}100\ mW\ cm^{-2}$, Lim. Occupancy [exposure (min hr^{-1})] X [power density ($mW\ cm^{-2}$)]^2 ≤ 6,000
		Sweden 1961	Occas. exp.
$1\ mW\ cm^{-2}$	700-30,000	U.S. Electronics and Communicat. Ind. 1956	Whole body
	All	Sweden 1961	General public prolonged occupat. exp.
	> 300	U.S.S.R. 1965; Poland 1961	15-20 min/day
$0.5\ mW\ cm^{-2}$	All	NATO 1956	---
$0.1\ mW\ cm^{-2}$	> 300	U.S.S.R. 1965; Poland 1961	2-3 hr/day
$0.025\ mW\ cm^{-2}$	> 300	Czechoslvakia 1965	CW, 8 hr/day
$0.01\ mW\ cm^{-2}$	> 300	U.S.S.R. 1965 Poland 1961 Czechoslovakia 1965	6 hr/day Entire day Pulsed, 8 hr/day
$20\ V\ m^{-1}$	0.1-30	U.S.S.R. 1969	
$10\ V\ m^{-1}$	0.01-300	Czechoslovakia 1965	Pulsed, 8 hr/day
$5\ V\ m^{-1}$	30-300	U.S.S.R. 1965	---

*Original references for these data are in Ref. 39.

serious aspects of microwave exposure (Ref. **42).** The eye has a relatively poor blood supply and cannot tolerate large heat loads without sustaining a rise in temperature. In addition, the cavities near the eye, the high electrical conductivity of the intraocular fluids, and the consequent short penetration of electromagnetic radiation into the eyeball all affect the ability of the eye to conduct excessive heat to other parts of the body. The lens is at a disadvantage since it does not have a cooling system, i.e., a vascular system, as other tissues do. The lens cannot repair itself since it does not have available either microphages to remove dead cells or replacement cells. **As** a result, when damage to the lens occurs, it is generally irreversible. Cells damaged by microwave radiation slowly lose their transparency, with opacity possibly not occurring until sometime after exposure. In addition, microwave radiation can produce damage to other ocular structures such as the conjunctiva, cornea, and iris.

The testes are extremely sensitive to elevation of temperature; indeed, spermatogenesis can take place only at temperatures below that of the body core. Normal human testicular temperature averages **2** deg C below body temperature.

The testes seem to be the most sensitive organs in terms of the minimum exposure required to produce a detectable change. The changes that occur in the testes include some degeneration of tissue as well as a reduction in the number of maturing spermatocytes. Reduction of testicular function due to heating appears to be temporary and is probably reversible except in severe cases. The genetic effects of microwave radiation have not been determined (Ref. **42).**

One of the questions still to be answered with respect to the effects of microwave radiation on human beings is the matter of the possibility of cumulative damage resulting from repeated exposures. This entire area has been little explored, although a number of researchers have examined various aspects of the problem. **A** summary of some observed biological effects of microwaves is given in Table 8-13.

In summary, indirect effects caused by the reaction of the body to the heat load induced by microwave exposure include such changes as cataracts, cardiovascular changes, neuroendocrine alteration, and effects on skin receptors. Secondary effects of uncompensated thermal regulation include fluid loss, hemoconcentration leading to shock, local loss of circulation with the resulting burns, local vascular degeneration, specific regional cooking, or coagulation (Ref. **43).**

8-4.2.2.2 Nonthermal Effects

A variety of effects are attributed to microwaves in the literature that do not appear to be associated with

TABLE 8-13. SUMMARY OF BIOLOGICAL EFFECTS OF MICROWAVES (Ref. 42)

Frequency, MHz	Wavelength, cm	Site of major tissue effects	Major biological effects
Less than 150	Above 200	-	Body is transparent to waves above 200 cm
150-1,200	200-30	Internal body organs	Damage to internal organs from overheating
1,000-3,300	30-10	Lens of the eye	Damage to lens resulting from tissue heating
3,300-10,000	10-3	Top layers of the skin, lens of the eye	Skin heating with the sensation of warmth
Above 10,000	Less than 3	Skin	Skin surface acts as reflector or absorber with heating effects

any generalized heating of the animal. Of course, some researchers deny that nonthermal effects exist. Among these, opinion is divided into (1) those who deny the existence of any low level effects whatsoever that constitute a hazard to man, and (2) those who admit the possibility of low level effects of microwaves but who consider these effects merely to be due to microthermal effects. Indeed, the Russian literature contains a controversy as to whether the low level effects observed by various Russian researchers can be attributed to microthermal effects or to nonthermal effects. A. S. Presman, one of the leading researchers in the field of the effects of microwaves on living organisms in the U.S.S.R., appears to attribute the stress stimuli from microwaves, regardless of the frequency or power level, not only to the stimulation of thermal receptors in the skin but also to other sensory skin receptors. He discusses the impulses that flow from the skin receptors to the cortical areas of the brain and then to specific target organs or systems (Ref. 44).

Observations of behavioral disturbances associated with exposure to microwave radiation of low or moderate intensities have been reported. In some of these investigations, a threshold irritant as low as 0.01 to 0.025 mW cm^{-2} can induce behavioral changes. The olfactory sensitivities of 358 workers exposed to microwaves are reported to be less than among members of a controlled group (Ref. 45). In a survey of the literature on the influence of low intensity microwaves on nervous function, several experiments in which microwaves were employed to induce hallucinatory sounds in subjects were discussed (Ref. 46).

Buzzing, ticking, hissing, or knocking sounds are sensed by human beings exposed to mean power densities as low as 0.1 mW cm^{-2}. It appears that the peak power density is a more critical measure than mean power density in these measurements. The peak power threshold for the hallucinatory sounds do not appear to be associated with the eyes, ears, or teeth, but they can be blocked by shielding a small area of the cerebral cortex just above the temporal lobe.

A recent report details the effects of low intensity microwaves on performance (Ref. 47). In this investigation rhesus monkeys were exposed to microwave radiation for 10 to 95 min, during which time the monkeys were performing an operant-conditioned task in order to establish the effects of microwaves on activity level. The intensity levels of microwave exposure were 10 and 13 mW cm^{-2} at 750 MHz, and 3 and 8 mW cm^{-2} at 1,000 MHz. The results of the tests indicated that exposure to microwaves decreased performance rate directly proportional to the field intensity and the exposure time. In the experiments, no difference was observed in the overall effects of the two frequencies of 750 and 1000 MHz. In addition, no difference was observed between continuous radiation and pulsed radiation (2 to 12 Hz). Microwave radiation at the low intensity of 3 mW cm^{-2} seemed to produce two effects on performance: (1) a stimulation during short exposure, and (2) an inhibition during longer exposure. The author concludes that further deterioration of performance can be expected under the following circumstances: (1) if the psychological tasks are made more complex, or (2) if the intensity of radiation is increased. The rate of performance decrease was found to be proportional to the power level and to the duration of exposure.

A number of experiments have involved experimental animals in which microwaves have been observed to produce various neuroelectric responses. Microwave intensities as low as 30 mW cm^{-2} average and 60 mW cm^{-2} peak have produced evoked responses in the brain stem of cats. Microwave stimulation has produced alteration in the electroencephalogram. Microwave stimulation is often followed by increased amplitude and decreased frequency of EEG components or by decreased amplitude and increased frequency. In addition, exposure to radiation produces increased conduction speed, decrease in refractoriness, and changes in action current amplitude in frog nerve fiber with exposures of 1 to 11 mW cm^{-2} (Ref. 46).

Additional discussions of biological experiments and biophysical mechanisms are contained in a special issue on the biological effects of microwaves in the *IEEE Transactions on Microwave Theory and Techniques* (Ref. 47). Effects of low intensity microwave radiation (Ref. 48) and pulse modulated UHF energy (Ref. 49), effects on the central nervous system (Ref. 50), and Russian research (Ref. 40) are discussed in the literature as cited.

8-5 DESIGN

Methods for the suppression of the effects of electromagnetic radiation are diverse, encompassing a complex technology for electronic materiel, a cautious design approach for other materiel, and an awareness of safety measures with respect to personnel hazards. In this paragraph, these various design considerations are outlined and specific references are cited to provide a starting point for more detailed analysis of specific design problem areas. The electronic design engineer is normally aware of the interference and compatibility problems associated with the equipment that he is designing. He may be less aware of the damage it may cause to other materiel or to personnel. The optical design engineer is alert to the personnel hazards of laser radiation but is less aware of possible effects on materiel. Although lightning protection is a routine provision for some materiel, in other types it is not considered. Protection against the effects of EMP is receiving considerable attention with respect to survival of strategic and retaliatory missile defense systems but less attention with respect to other materiel. With the proliferation of electromagnetic energy sources and the growth in their radiated power levels, more attention must be given to the electromagnetic environment and its many interactions with materiel and personnel.

The design techniques that are used to alleviate the effects of electromagnetic interference on equipment are wide in scope and extremely detailed in their methodologies for implementation. With respect to the communications and microwave bands, the most widely used techniques of electromagnetic interference suppression include physical siting of equipment to avoid near-field effects, specialized antennas, shielding, bonding, grounding, filters, special suppression networks, and special attention during the design process to eliminate sources of interference originating within the equipment itself. Detailed discussions of these techniques are found in Refs. 3, 51, 52, 53.

For biological hazards of microwaves, the basic approach has been to limit exposure. This has been accomplished in two ways: (1) by limiting the microwave radiation around personnel, and (2) in those cases where it is not feasible to limit microwave radiation to a safe level, by employing warning devices such as signs, lights, etc., indicating the presence of hazardous electromagnetic fields and the necessity for the use of protective clothing and goggles (Refs. 19,54).

Within the optical spectrum, including ultraviolet and infrared, primary emphasis has been on the biological effects of lasers as an environmental hazard. Generally speaking, areas in which high-power lasers are being used are posted with warning signs. Protective goggles are required for eye protection. Discussions of the recommended precautions with respect to the use of lasers are found in the pertinent specifications on laser hazards listed in par. 8-4.2.1. Some specialized weapon systems and equipments employ electromagnetic energy within this portion of the frequency spectrum for guidance, control, detection, and measurement purposes. Of course, both man-made and natural sources of interference can interfere with the proper operation of these equipments. Discussion of the electromagnetic interference problem with respect to these highly specialized equipments is beyond the scope of this handbook.

X-radiation and other nuclear radiation present a definite problem to the designer. Basically, if equipment or personnel must operate in a high radiation environment, shielding is the only feasible design choice that will achieve protection. A number of articles in the open literature discuss the fundamentals of shielding design for nuclear radiation. An example of the overall approach to the design of shielding for nuclear radiation can be found in a report issued by the Oak Ridge National Laboratory (Ref. 55).

The problems of lightning protection and protection from the EMP effects are very similar except for the differing magnitudes of the signals. Lightning protection involves the use of lightning rods, lightning arrestors, overvoltage protectors, fuses, and grounding techniques (Ref. 4). Although many of the techniques used in lightning protection are also useful in EMP protection, additional shielding of sensitive components is required. Discussions of the particular requirements associated with EMP phenomena are given in the following handbooks: ***Design Engineers' Nuclear Effects Manual*** (a comprehensive series of documents on nuclear weapon effects) (Refs. 56-59), ***DASA*** EMP ***Handbook*** (Ref. 24), and the ***TREE (Transient Radiation Effects on Electronics) Handbook*** (Ref. 60).

8-6 TEST FACILITIES

In spite of the efforts to eliminate electromagnetic interference problems from equipment and systems, the necessary tests that simulate the expected electromagnetic radiation environment must be made. Many Government and military laboratories maintain a variety of test equipment and facilities used for testing and simulation. Among the large-scale facilities are the following (Ref. 4):

(1) The U S Army Electronics Command, Ft. Monmouth, N.J., maintains a portable 1.5×10^6 volt, 1.25×10^4 ampere Artificial Atmospheric Generator, which is used for evaluating weapon system vulnerability to lightning.

(2) The Lightning Transient Research Institute of Minneapolis, Minn., has facilities for conducting tests on components and subsystems, and the Picatinny Arsenal, Dover, N.J., also has some provisions for making lightning tests on components and subsystems.

(3) The U S Army has two large RF facilities that are used to expose complete weapon systems to electromagnetic radiation. The White Sands Missile Range

facility in New Mexico has the frequency spectrum and field intensity capabilities shown in Fig. 8-13. The RF hazard facility at the Picatinny Arsenai can generate the radiation environment illustrated in Fig. **8-14.** The capability of this simulation chamber includes a field intensity of 100 V m^{-1} from 300 kHz to 3 MHz at a field impedance of either 377 or 4,000 Ω and a 266 mV m^{-1} field at a field impedance of 40 Ω. The Picatinny Arsenal facility is designed to accommodate weapon systems with major dimensions of 15 ft, although items as large as 60 ft can be accommodated with certain limitations.

(4) The Naval Weapons Laboratory at Dahlgren, Va., maintains a facility for irradiating weapon systems with RF energy. This facility has a large metal groundplane (240 by 100 ft) located in the center of the radiation pattern.

These facilities are constantly modernized so that the exact capabilities at any given time must be obtained by inquiry to the particular facility of interest.

The National Bureau of Standards also offers to industry and to Government agencies a number of Calibration services that are of interest in the field of electromagnetic interference. For example, for a number of years the calibration of antennas has been carried out at the Boulder Laboratories of the National Bureau of Standards. Loop antennas are calibrated at frequencies from 30 Hz to 30 MHz, and dipole antennas are calibrated at frequencies from 30 to 1,000 MHz (Ref. 61).

With respect to EMP testing, several facilities have been designated to perform EMP effects research and to provide EMP information for special problems. These include:

(1) The Air Force Weapons Laboratory, Kirtland Air Force Base, N. Mex., is designated as the official source of EMP information, specification, and requirements and testing for all Air Force systems. It has full capability in terms of manpower, data processing equipment, and technical competence to provide specific EMP information for a wide range of problems.

(2) Los Alamos Scientific Laboratory, Los Alamos, N. Mex., is a source of EMP information not only from a vulnerability point of view, but also from that of detection, diagnostics, and general weapon effects phenomena.

(3) Army Mobility Equipment Research and Development Center, Ft. Belvoir, Va., is designated as the Army Materiel Command lead laboratory for EMP nuclear weapon effects. It is responsible for performing applied research on EMP phenomenology and effects to meet Army requirements and to participate in EMP vulnerability evaluation and hardening programs on Army systems.

8-7 GOVERNMENT STANDARDS

The equipment and electronics used in military sys-

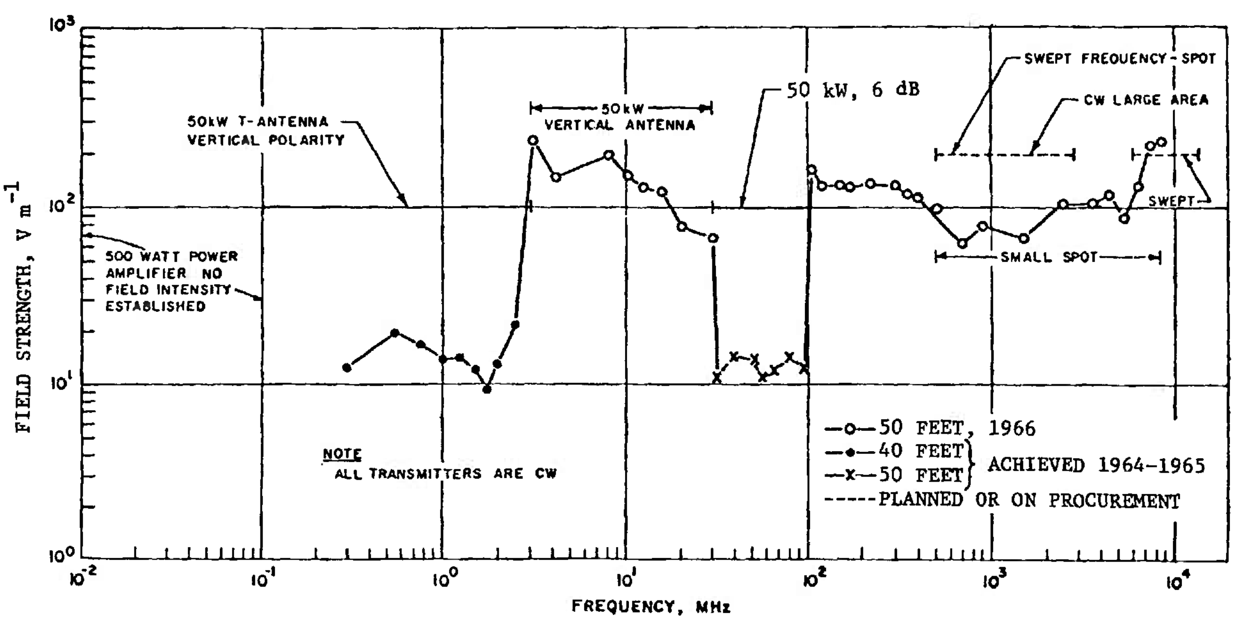


FIGURE 8-13. Radiation Environment Testing Capabilities at White Sands Missile Range (Ref. 4).

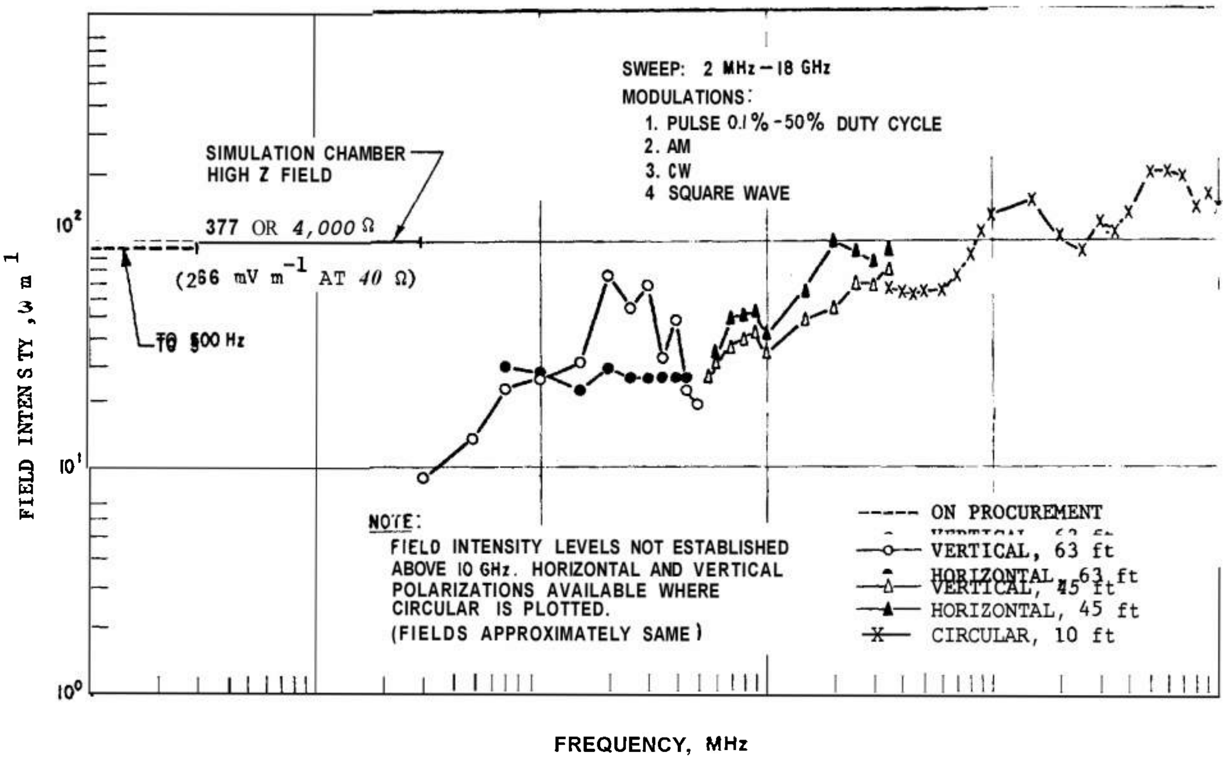


FIGURE 8-14. Radiation Environment Testing Capabilities at Picatinny Arsenal (Ref. 4).

tems must meet specific radio frequency interference and electromagnetic interference requirements to be acceptable. These specifications have as their objective the prevention of interference and resulting degradation of performance in actual use of the equipment. In order to indicate the nature of the variety of these specifications, Table 8-14 is included. In this table the document number, its title, the using agency, the scope of the specification, and some comments on the specification are given (Ref. 3). These specifications are revised at intervals, and users should be certain to have the latest issue. In general, the primary specifications in the field of RFI/EMI are MIL-STD-461, MIL-STD-462, and MIL-STD-463.

In addition to these Military Standards, the U.S. Government sets certain standards that apply to manufacturers for the civilian markets as well. These standards primarily concern electromagnetic interference and the hazard to personnel from radiation. Information on these specifications is published by the Bureau of Radiological Health (Ref. 33). Another nonmilitary Government agency concerned with electromagnetic interference is the National Aeronautics and Space Administration, which also issues electromagnetic compatibility specifications (Refs. 62,63). Bonding and grounding, filtering, transient protection, and lightning protection are specified and specific tests and limits are defined.

TABLE 8-14. APPLICABLE MILITARY DOCUMENTS

No.	Title	Mandatory use by	Scope	Comments
MIL-STD-449	Measurement of Radio Frequency Spectrum Characteristics	Army, Navy, Air Force	This technical standard establishes uniform measurement techniques that are applicable to the determination of the spectral characteristics of radio-frequency transmitters and receivers. The ultimate goal is to insure the compatibility of present and future systems.	Successful operation of most weapon systems depends upon the transfer of information to and from the system, usually in the form of radio waves. Operation is degraded if other energy sources interfere with this flow of information; therefore, it is desirable to know the spectral characteristics of both the on-board and support receivers and transmitters. This standard establishes uniform measurement techniques of the spectral characteristics of the receivers and transmitters and gives forms for recording these data. This information is available to the designer and can be used to determine the characteristics of the receivers and transmitters that will be associated with the weapon system.
MIL-STD-461	Requirements for Electromagnetic Interference Characteristics	Army, Navy, Air Force	This standard establishes the requirements for the measurement and determination of electromagnetic	The purposes of the standard are as follows: (a) To insure that interference control design is

TABLE 8-14 (cont.). APPLICABLE MILITARY DOCUMENTS,

No.	Title	Mandatory use by	Scope	Comments
MIL-STD-461 (cont.)			interference characteristics (emission and susceptibility) of equipment, systems, and subsystems.	incorporated into equipment, subsystems, and systems, and that applicable requirements are met. (b) To specify levels of electromagnetic interference emanation and interference susceptibility for equipment and subsystems that will enable compatible operation in a complex electromagnetic environment. The limits and referenced tests are established to increase the probability that operational systems or equipment will be compatible. This standard contains the requirements that are to be met when performing the tests specified for the electronic, electrical, or electromechanical equipment being purchased. The required tests referenced in this standard are found in MIL-STD-462.
MIL-STD-462	Measurement of Electromagnetic Interference Characteristics	Army, Navy, Air Force	This standard establishes the accepted techniques used for the measurement and determination of	This standard takes the requirements set forth in MIL-STD-461 and presents a detailed discussion on how the

TABLE 8-14 (cont.). APPLICABLE MILITARY DOCUMENTS

No.	Title	Mandatory use by	Scope	Comments
MIL-STD-462 (cont.)			electromagnetic interference characteristics (emission and susceptibility) of electrical, electronic and electromechanical equipment, subsystems, and systems in the frequency range of 20 Hz to 20 GHz (optional 40 GHz).	tests are to be conducted.
MIL-STD-463	Electromagnetic Interference Characteristics, Definitions, and System-of-Units	Army, Navy, Air Force	This standard establishes the system of units to be used.	The International System of Units, as adopted by the United States Bureau of Standards, is used in MIL-STD-461 and MIL-STD-462. MIL-STD-463 contains a complete description of these units.
MIL-STD-825	Electromagnetic Interference Test Requirements and Test Methods	Air Force	This standard establishes uniform test methods for testing equipment, systems, and subsystems to determine their electromagnetic interference and susceptibility characteristics.	Superseded by MIL-STD-461 and MIL-STD-462.

TABLE 8-14 (cont.). APPLICABLE MILITARY DOCUMENTS

No.	Title	Mandatory use by	Scope	Coments
MIL-STD-833	Minimization of Hazards of Electromagnetic Radiation to Electroexplosive Devices	Air Force	This standard delineates criteria to be applied to the design of electro-explosive devices (EED's) and their application in systems. The purpose of this standard is to minimize the hazards of electromagnetic radiation to electro-explosive devices. The standard will apply to the design selection and application of electro-explosive devices and their firing circuits for all new development programs of systems that use electro-explosive devices.	This standard is used by the Air Force. It differs from the other MIL-STD's in that it deals with the hazard of electromagnetic energy to electroexplosive devices (EED's). EED's are required to meet one of the following standards: (1) EED's will not fire as a result of the application of 1 W of DC power for 5 min and also will not fire as a result of the application of 1 A of DC for 5 min. This requirement must be met without the use of external shunts. (2) EED's with electroexplosive elements that do not meet the above 1-W/1-A/5-min standard will be designed so that the integral unit will survive in an electromagnetic field intensity of 100 W m^{-2} (3) Recommended circuit configuration and shielding practices are included.

TABLE 8-14 (cont.). APPLICABLE MILITARY DOCUMENTS

No.	Title	Mandatory use by	Scope	Comments
MIL-A-3933	Attenuators, Fixed	Navy, Air Force, Army	This specification covers attenuators for use as attenuating elements in coaxial lines and wave-guides. These attenuators are used for Armed Services application in the trans-mission lines of radar, radio, and associated equipment.	This specification documents the various methods of mea-suring the worst-case loss of an attenuator using match-ing systems,
MIL-9-5087	Bonding, Electri-cal, and Lightning Protection for Aerospace Systems	Navy, Air Force	This specification covers the characteristics, ap-plication, and testing of electrical bonding for aerospace systems, as well as bonding for the installation and inter-connection of electrical and electronic equipment therein, and lightning protection.	This specification is used by the Air Force and the Navy and deals with the bonding of metal-to-metal surfaces to provide pro-tection against RF, light-ning, and static electri-city. Recommended proce-dures for preparing of the surface of the two metals to be joined is given. Methods of bonding are illustrated,
MIL-E-6051	Electrical-Electronic System Compatibility and Interference Control Require-ments for Aero-nautical Weapons	Army, Navy, Air Force	This specification outlines design requirements and tests necessary to control the electronic interference environment of weapon systems, associated electronic and electrical	This specification can be considered as a guide for the contractor who is submitting equipment for approval. It tells what tests must be run but does not tell how to conduct the

TABLE 8-14 (cont.). APPLICABLE MILITARY DOCUMENTS

No.	Title	Mandatory use by	Scope	Comments
MIL-E-6051 (cont.)			subsystems, and aircraft.	test. Test procedures are referred to MIL-1-6181. Superseded by MIL-STD-461 and MIL-STD-462.
MIL-E-55301	Electromagnetic Compatibility	Army	This specification covers the electromagnetic interference reduction design requirements, emission and susceptibility limits, and test procedures for assuring the electromagnetic compatibility of all equipments and systems intended for use by the Department of the Army. It includes all types of items that are capable of generating or being adversely affected by electromagnetic interference.	Superseded by MIL-STD-461 and MIL-STD-462.
MIL-1-6181	Interference Control Requirements, Aircraft Equipment	Army, Navy, Air Force	This specification covers design requirements, interference test procedures, and limits for electrical and electronic aeronautical equipment to be installed in or closely associated with aircraft.	Superseded by MIL-STD-461 and MIL-STD-462.

TABLE 8-14 (cont.). APPLICABLE MILITARY DOCUMENTS

No.	Title	Mandatory use by	Scope	Comments
ML-P-24014	Preclusion of Hazards from Electromagnetic Radiation to Ordnance, General Requirements for	Navy	This specification establishes general requirements for weapon systems to preclude hazards from environmental electromagnetic fields in the frequency range, of 10 Hz to 40 GHz. These requirements apply to all Navy weapon systems, including safety and emergency devices and other ancillary equipment that contain electrically initiated, explosive or pyrotechnic components.	This specification is used by the Navy and deals with the hazards of electromagnetic energy to electro-explosive devices.
MIL-E-4957	Enclosure, Electromagnetic-Shielding, Demountable, Prefabricated for Electronic Test Purposes	Navy, Air Force	This specification covers shielding enclosures (screen rooms) that provide specified frequency ranges for the purpose of test and alignment of electronic equipment and other related purposes.	
MIL-E-8881	Enclosure, Electromagnetic-Shielding, Demountable, Prefabricated, General Specification for	Army, Navy, Air Force	This specification covers shielding enclosures that provide specified degrees of attenuation of electromagnetic fields for the purpose of test and alignment of electronic equipment,	

TABLE 8-14 (cont.). APPLICABLE MILITARY DOCUMENTS

No.	Title	Mandatory use by	Scope
MIL-E-18639	Enclosures, Electromagnetic-Shielding, Knockdown Design	Navy	This specification covers shielding enclosures that shall provide stated minimum degrees of attenuation to electromagnetic fields for the purpose of test alignment of electronic equipment and for other related purposes.
MIL-E-15733	Filters, Radio Interference, General Specification for	Army Navy, Air Force	This specification covers the general requirements for current-carrying filters (AC and DC), for use primarily in the reduction of broadband radio interference.
MIL-I-11683	Interference Suppression, Radio, Requirements for Engine Generators and Miscellaneous Engines	Army	Superseded by MIL-STD-461 and MIL-STD-462.
MIL-I-25171	Interference Limits and Tests for Modified or Reconditioned Aircraft	Air Force	This specification covers interference limits applicable to aircraft being modified or reconditioned.

TABLE 8-14 (cont.). APPLICABLE MILITARY DOCUMENTS

No.	Title	Mandatory use by	Scope
ML-I-26600	Interference Control Requirements, Aeronautical Equipment	Air Force	Superseded by MIL-STD-461 and MIL-STD-462,
ML-S-5786	Suppressor, Electrical Noise, Radio Frequency	Air Force	This specification covers one type of radio frequency noise suppressor.
MIL-S-10379	Suppression, Radio Interference General Requirements for Vehicles (and Vehicular Subassemblies)	Army, Navy, Air Force	Superseded by MIL-STD-461 and MIL-STD-462.
MIL-S-12348	Suppression, Radio Interference General Requirements for Railway Rolling Stock, and Maintenance of Way Equipment	Army, Navy, Air Force	Superseded by MIL-STD-461 and MIL-STD-462.
MIL-S-13237	Suppression, Radio Interference Requirements for Watercraft	Army	Superseded by MIL-STD-461 and MIL-STD-462.

TABLE 8-14 (cont.). APPLICABLE MILITARY DOCUMENTS

No.	Title	Mandatory use by	Scope
MIL-STD-220	Method of Insertion-Loss Measurement for Radio Frequency Filters	Army, Navy, Air Force	This standard covers a method of measuring, in a 50-Ω system, the insertion loss of single and multiple-circuit radio frequency filters at frequencies up to 1 GHz.
MIL-I-11748	Interference Reduction for Electrical and Electronic Equipment	Army	Superseded by MIL-STD-461 and MIL-STD-462.
MIL-I-16165	Interference Shielding, Engine Electrical Systems	Navy	This specification covers requirements for interference shielding items and shielded harnesses for engine electrical systems aboard Naval ships, at advance bases, and in the vicinity of electronic installations. It includes the allowable interference limits for such items and the permissible limits for auxiliary devices normally installed on electrical wiring systems associated with these engines.
MIL-I-16910	Interference Measurement, Electromagnetic, Methods and Limits	Navy	Superseded by MIL-STD-461 and MIL-STD-462.

TABLE 8-14 (cont.). APPLICABLE MILITARY DOCUMENTS

No.	Title	Mandatory use by	Scope
MIL-1-17623	Interference Measurement, Electromagnetic, Methods and Limits, for Electric Office Machines, Printing and Lithographic Equipment	Navy	Superseded by MIL-STD-461 and MIL-STD-462.
MIL-STD-285	Attenuation Measurements for Enclosures, Electromagnetic Shielding, for Electronic Test Purposes, Method of	Army, Navy, Air Force	This standard covers a method of measuring the attenuation characteristics of electromagnetic shielding enclosures used for electronic test purposes.

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CHAPTER 9

NUCLEAR RADIATION

Nuclear radiation is an induced environmental factor of increasing importance to military activities because of the increasing capacity for employment of nuclear weapons and because of the variety of applications of nuclear reactions for other purposes. The importance of the nuclear radiation environment has led to the compilation of an Engineering Design Handbook, ***Design Engineers' Nuclear Effects Manual*** (DENEM), which is published in four volumes as follows:

Vol. I, ***Munitions and Weapon Systems*** (Ref. 1)

Vol. II, ***Electronic Systems and Logistical Systems*** (Ref. 2)

Vol. III, ***Nuclear Environment*** (Ref. 3)

Vol. IV, ***Nuclear Effects*** (Ref. 4)

The ***Design Engineers' Nuclear Effects Manual*** includes voluminous information on the interactions between the nuclear weapons environment and materiel. Because of this, it includes much information that is not pertinent to nuclear radiation as an induced environmental factor. Such effects include airblast and shock, thermal radiation, and the electromagnetic pulse. It does, however, consider the nuclear radiation environment in detail and discusses effects of this environment on a variety of materiel. This discussion of effects is separated into three categories: weapons, electronics, and survival and logistical support systems. The manual has, in addition, seven appendixes:

I. Blast

II. Thermal Radiation

III. X-radiation

IV. Nuclear Radiation

V. Electromagnetic Pulses (EMP)

VI. Transient Radiation Effects on Electronics (TREE)

VII. Degradation of Electromagnetic Waves

Appendix IV, "Nuclear Radiation", and Appendix VI, "Transient Radiation Effects on Electronics", contain the information on the nuclear radiation environment that is of interest in this chapter.

The components of the nuclear radiation environment are gamma rays, X rays, and neutrons. Many other types of nuclear particles are produced in nuclear reactions, but these are normally of very short range and are unimportant in the environment. X rays are electromagnetic radiation similar to those of visible and ultraviolet light but of much shorter wavelength. X rays, such as those employed in medical diagnostics, are generated by the impact of electrons on metallic targets. Higher energy, shorter wavelength X rays are produced in high voltage nuclear accelerators and by nuclear reactions. It is important to note that X rays are the electromagnetic radiations that accompany electronic transitions; therefore, they include all energetic photons originating outside an atomic nucleus, including those due to the energy transition of other elementary particles. In contrast, gamma rays are electromagnetic radiations that originate in transitions within the atomic nucleus. The energy spectrum of these two forms of nuclear radiation overlap, although the center of the X-ray spectrum is at about 100 pm (picometer) while that of the gamma ray spectrum is at about 1 pm.

Neutrons are small particles produced in nuclear reactions. They exist as an element in the nuclear radiation environment because of their long range, which in turn results from their lack of electrical charge. Since other nuclear particles possess charge, they interact strongly with matter of all types. Thus, their range is very limited.

To one unfamiliar with nuclear radiation, the units by which such radiation is measured may be confusing. Gamma-ray exposure is generally given in terms of roentgens (r) or in terms of incident energy per unit area (MeV cm^{-2}). The roentgen is defined as the quantity of gamma radiation that produces ions carrying one electrostatic unit quantity of charge of either sign per 0.001293 g of dry air which corresponds to 1 cm^3 of air at standard temperature and pressure (0°C and 760 mm Hg). The most common unit of absorbed dose of gamma radiation is the rad, defined as the absorption of 100 erg g^{-1} of material. For practical purposes a roentgen is about 2×10^9 MeV cm^{-2} or 3×10^3 erg cm^{-2}. For many materials, gamma radiation is absorbed relatively uniformly throughout the volume and a relationship exists between the incident gamma-ray intensity and the absorbed dose. For example, at an exposure of 1 r, air will absorb 0.877 rad, while silicon, the semiconductor material employed in most devices, will absorb 0.90 rad.

X-ray exposure is normally expressed in cal cm^{-2} where 1 cal cm^{-2} is equal to 4.18 X 10^7 erg cm^{-2} or 2.6 X 10^{13} MeV cm^{-2}. Thus, 1 cal cm^{-2} is approximately equal to 1.3 X 10^4 r, although the intensity of X-radiation generally is not expressed in roentgens when discussing nuclear weapon effects. Since X rays are absorbed exponentially in a material, the absorbed dose at the surface of entry of a thick target will be considerably greater than the absorbed dose at the rear. The absorbed dose for X-radiation is generally measured in terms of cal g^{-1} where 1 cal g^{-1} equals 4.18 X 10^5 rad.

Neutron exposure is normally given as the total fluence (neutrons cm^{-2}). For many applications, expressions of the absorbed dose in rad provides a measure of damage but, in others, damage is a strong function of the incident neutron energy. For this reason, exposure is often given in terms of the 1-MeV-equivalent neutron fluence. This unit is a direct measure of the damage potential of the neutrons in a specified material, expressed in terms of the damage produced by 1-MeV neutrons within the same material.

The effects of nuclear radiation are derived from the amount of energy deposited within a material by the radiation and the form that the energy deposition assumes. Thus, if a material absorbs little radiation, it may be unaffected in many applications. If the energy deposition is large, however, a material may lose its structural integrity. Most effects fall between these extremes. Solid-state electronic devices, for example, are extremely sensitive to nuclear radiation effects because their operation is very sensitive to the structure of the material. Absorbed radiation that ionizes an atom or displaces an atom in a semiconductor will affect the operation of a device that utilizes that material. In order to obtain a comprehensive understanding of the effects of nuclear radiation on materials, it is necessary to utilize the classified literature such as the ***Design Engineers' Nuclear Effects Manual.***

Damage to materials is classified into two categories: transient radiation damage and permanent radiation damage. This categorization is derived from the fact that many incidents of nuclear radiation in the environment are transient and produce transient effects in material. The magnitude of such effects decays with time and the performance of material exposed to a transient radiation event will often return to its initial state. Transient damage is usually associated with low doses. Relatively larger amounts of deposited energy, however, produce permanent and cumulative damage.

The design of materiel that will be exposed to a nuclear radiation environment can be extremely complex. Of prime consideration is the radiation level for which the item is being designed. For a given radiation level, the materials that are employed in a given item must be carefully considered. Materials that have a low absorption coefficient for the radiation are often chosen for the active parts. For example, in the design of semiconductor devices for nuclear radiation environments, the use of gold, which has a large absorption cross section, is sometimes avoided. For items that are sensitive to nuclear radiation, the use of shielding is often considered. In this case, a material that has a large absorption coefficient, such as lead, is chosen. Employing shielding as an enclosure for a sensitive item lessens the dosage and serves to protect it. Other design methods are applicable. In electronic circuits, for example, knowledge of the radiation sensitivity of particular circuit elements is employed in the design so as to provide for continued operation of the circuit even when the properties of the sensitive elements vary within wide limits.

A variety of methods are used for simulating the nuclear radiation environment that is derived from weapons. Nuclear reactors, nuclear accelerators, pulsed nuclear reactors, and similar facilities are employed. The large interest in building systems that will survive a nuclear radiation environment has led to the development of a large number of such simulation facilities. The use of these facilities and the interpretation of results obtained are the province of experts in nuclear radiation effects. Complex procedures and computer simulation techniques have been developed for evaluating nuclear radiation effects and for deriving radiation-hardened designs.

Most specifications and regulations relative to the nuclear radiation environment are classified since they depend upon the nature of weapons.

This chapter is not intended to give more than a brief introduction to the nuclear radiation environment. Its inclusion in this handbook is in recognition of the fact that nuclear radiation is an important induced environmental factor. Its limited treatment is in recognition of the complexity of the subject and the necessity for classification of any document that provides a comprehensive treatment of the subject. The excellent handbooks (Refs. 1-4) to which reference has already been made provide such information in cdmprehensive and complete terms.

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