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Special Report ETL-SR-72-2

PARTICULATE MATTER CONSIDERATIONS IN THE DESIGN OF V/STOL AIRCRAFT

(Report No. 2 of "Studies of the Army Aviation V/STOL Environment")

by
John Viletto, Jr. and Howard L. Ohman

August 1972

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U.S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES
FORT BELVOIR, VIRGINIA

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The Commanding Officer
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Prepared by

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Earth Sciences Division
Geographic Sciences Laboratory

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SUMMARY

Certain airborne particles cause serious damage to V/STOL aircraft. Particularly serious is the erosion on internal engine parts and rotor blades, but damage is not limited to these parts. In addition to erosion caused by the abrasiveness of the airborne particles, the particles also cause electric failures, clog or partially block small openings, and restrict pilot visibility. Certain particles also promote chemical corrosion.

Erosiveness of particles is a function of their hardness, angularity, velocity, mass, and angle of impact. The hardness of particles is related more to the mineral than to what chemical elements make up the particles. Erosiveness increases as angularity increases.

Silica (SiO_2), alumina (Al_2O_3), and hematite (Fe_2O_3) are the three most common and troublesome airborne particles, on a world basis, that cause serious erosion to V/STOL aircraft systems, subsystems, and components. All three minerals are hard; however, alumina is considerably harder than either silica or hematite. With respect to the amount of erosion damage, the softer nature of silica, compared to alumina, is more than compensated for by the fact that silica, except in relatively limited areas of the world, constitutes a considerably greater percentage of the surface soil than does either alumina or hematite.

Engine erosion damage due to ingested particles varies considerably for different parts of the world. This is primarily due to the differences in particle size and the percentage composition of SiO_2, Al_2O_3, or Fe_2O_3 in the soil. These differences are quite marked. For example, in Innisfail, Queensland, Australia, the three minerals constitute nearly 84% of the soil sample; whereas, on Wake Island, they constitute slightly over 1%.

Areas having at least 9% of its soil particle diameters 74 μm or less are potential airborne particulate matter problem areas.* Conditions that hinder or prevent soil particles from becoming airborne are paving, vegetative cover, wetting, and freezing.

Over a freshly plowed field, the concentrations (mg/ft^3) of airborne particles measured near a hovering H-21 helicopter for different levels are as follows: takeoff, 40.0; 1 foot, 15.5; 10 feet, 18.1; 75 feet, 7.3. Concentrations increase considerably when two or more helicopters are operating near one another.

*The symbol for micrometer is "μm." One μm is 1/1,000,000 of a meter or 1/25,400 of an inch.

Airborne oceanic and soil salts when combined with moisture promote chemical corrosion. Sulfates, chlorides, and carbonates are the most common airborne salt particulate matter.

At the lower levels (ground to 5.0 feet) in the interaction plane, calculated updraft velocities range from 50 to 94 ft/sec when the helicopter skid height ranges from ground level to 36 feet. Vertical updraft velocities of 50 to 94 ft/sec, respectively, will keep rounded SiO_2 particles of 4,060 and 13,000 μm airborne.

FOREWORD

This report is the second of a planned series, "Studies of Army Aviation (V/STOL) Environment," requested by the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, and funded under Reimbursable Service Directive RO 72-10.

Existing criteria reflected in military specifications and standards and design guides are inadequate for V/STOL aircraft. The present criteria for helicopter design and testing are those which evolved and have been used over several years for U. S. Air Force fixed-wing aircraft. The helicopter takeoff and landing environment, particularly airborne particle concentration, is markedly more severe than that for fixed-wing aircraft. This report presents data and conclusions which can be used to establish design and testing criteria for future V/STOL aircraft.

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13. ABSTRACT

Erosion and corrosion by selected airborne particles cause serious damage to V/STOL aircraft. The design and testing criteria for the fixed-wing aircraft, which has also been used for V/STOL aircraft, is inadequate for V/STOL aircraft because the takeoff and landing environment of the V/STOL aircraft is much more severe than that of the fixed-wing aircraft.

Inconsistencies and confusion in the use of the terms "sand" and "dust" in official Army design and testing criteria documents can be corrected by using the term "particle" and specifying the mineral and diameter size range.

The amount of erosion and chemical corrosion varies considerably for different places in the world because the concentrations of the damaging particles vary. Silica (SiO_2), alumina (Al_2O_3), and hematite (Fe_2O_3) are the three most common and troublesome airborne particles that cause erosion damage. Airborne oceanic and soil salts cause corrosion damage.

Over a freshly plowed field, the concentrations (mg/ft^3) of airborne particles measured near a hovering H-21 helicopter for different levels are: takeoff, 40.0; 1 foot, 15.5; 10 feet, 18.1; 75 feet, 7.3. Measured velocities in the interaction plane near the ground range from 50 to 94 ft/sec; these are capable of maintaining airborne rounded SiO_2 particles of 4,060 to 13,000 μm.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Particulate matter						
Sand and dust						
Particle size						
Particle angularity						
Particle velocity						
Particle concentration						
Chemical corrosion						
Silica (SiO_2)						
Alumina (Al_2O_3)						
Hematite (Fe_2O_3)						

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PARTICULATE MATTER CONSIDERATIONS IN THE DESIGN OF V/STOL AIRCRAFT

I. INTRODUCTION

Airborne particles must be considered when designing V/STOL aircraft systems, subsystems, and components. Damage is particularly serious to the engine. Ingested particles excessively erode the internal parts of the engine, thereby drastically reducing the engine life. In addition to internal-engine damage, considerable erosion to exposed components such as rotor blades is not uncommon.

Tests using an Army helicopter hovering over sand test sites were conducted at the Yuma Proving Ground, Arizona, and Fort Benning, Georgia, to investigate potential helicopter airborne particle problems.[1] Within a 3-month period at Yuma, the helicopter was used 50 times for 4-minute tests. During the 3-month period, the rotor blades were replaced three times, and the engine was replaced once. In the first few test runs, after a total hovering time of about 20 minutes in the airborne particles, three layers of wood on the leading edges of the rotor blades were worn away. For subsequent tests at Yuma, the leading edges were taped for protection. The tape was effective as long as it was replaced after 12- to 16-minute periods of hovering. Before the tests at Fort Benning, metal rotor blades were installed, and the leading edges of the blades were covered with a special polyurethane film for protection. The film provided excellent protection for the leading edges, but after 25 tests the unprotected rotor tip caps were completely eroded through.

In addition to causing erosion problems, the airborne particles are significant because they promote chemical corrosion, cause electrical failures, clog or partially block critical small intake openings, cause pilot visibility problems, and are present in varying concentrations over all land and water surfaces.

The major constitutents of airborne particulate matter over the land and water surfaces are, respectively, soil and oceanic salt particles.

1. **Particulate Matter.** For this report, "particulate matter" includes particles kept airborne by currents and eddies of the atmosphere and by the updrafts from V/STOL aircraft. (Vegetative litter and organic soil particles are not considered in this

[1] S. J. Rodgers, "Evaluation of the Dust Cloud Generated by Helicopter Rotor Blade Downwash," USA AVLABS Technical Report 67-81, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Va., March 1968.

report because they are scheduled for discussion in a separate report dealing exclusively with vegetation.)

2. **Definition of Sand and Dust.** Practically all Army testing literature discusses "sand" and "dust" rather than the more inclusive term "particulate matter." It is, therefore, appropriate to summarize or review the definitions of sand and dust as used in the testing literature.

"Sand" and "dust" are terms normally used for all small particles of matter found on the surface of the earth or suspended in its atmosphere. Sand and dust have usually been differentiated on the basis of particle diameter; but the terms often overlap, and they are often used loosely and sometimes interchangeably. The terms "sand" and "dust" cover a range of particle diameters from a fraction of a micrometer (μm) to 2000 μm. The 2000-μm size is the lower limit for very fine pebbles; 2000 μm equals 2 mm or nearly 0.08 inch.

(Webster's New World Dictionary defines "particle" as: "(1) an extremely small piece; (2) tiny fragment; (3) slightest trace; and (4) speck.")

Results of Bagnold's research indicate that airborne particle behavior changes markedly within the 70 to 150 μm diameter range.[2] Settling velocities for particles of different sizes and densities differ markedly. Particles less than about 70 μm can remain suspended in the atmosphere for very long periods of time (days, weeks, months, and even years). The small particles are maintained airborne by the natural turbulence of the air. Particles greater than 150 μm are made airborne by strong, natural winds and by the high-velocity winds and turbulence caused by the downwash from V/STOL aircraft. Gravel as large as 1/4 to 1/2 inch in diameter can be made airborne by winds induced by some present V/STOL aircraft.

In many Army documents, there has been a lack of consisteney in the particle diameter used to distinguish between sand and dust. Table I shows these inconsistencies in several official DOD and open-literature sources.[3] For the documents listed in Table I, the higher values for dust vary from 10 to 150 μm and the upper limits for sand vary from 50 to 2000 μm.

Because of these inconsistencies and confusion in the meaning of sand and dust in official Army documents concerning testing and design criteria, this report,

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[2] R. A. Bagnold, *The Physics of Blown Sand and Desert Dunes*, Methuen and Co., Ltd., London, 1941.

[3] P. Blackford and H. S. McPhilimy, "Sand and Dust Considerations in the Design of Military Equipment," USAETL Technical Report ETL-TR-72-7, Fort Belvoir, Va., 1972.

Table I. Particle Sizes Listed by Various Sources to Distinguish Between Dust and Sand
(Size ranges given in micrometers (μm))

Source	Dust	Sand	Remarks
Bagnold, R. A., *The Physics of Blown Sand and Desert Dunes* (see footnote 2).	1 to 80	80 to 1,000	Oversimplified—Bagnold states that predominant diameters of sand are never less than 80.
Glossary of Geology (after Wentworth).		62 to 2,000	Dust size not given; presumably less than 62.
Pauly, James, "The Dust Environment and its Effect on Dust Penetration," WADC Report No. 56-556.	1 to 150	100 to 300	Particles between 100 and 150 are in both classes.
MIL-STD 210, "Climatic Extremes for Military Equipment," 1 June 1953.	1 to 10	180 to 300	Particles between 10 and 180 are unclassified. Size for sand is that given by OQMG, EPB Report No. 146 as the predominant diameters for windborne sand.
MIL-STD 210A, "Climatic Extremes for Military Equipment," 2 Aug 1957.	0.1 to 10	10 to 1,000	Source unknown: Specifies predominant diameters for sand as 150 to 300, which corresponds to Bagnold's statements, taken in turn, from Udden.
MIL-STD 810B, "Environmental Test Methods," 15 June 1967.	Up to 150	Not defined	Dust is defined as fine sand in the document.
MIL-STD-1165 "Glossary of Environmental Terms (Terrestrial)," 25 Mar 1968.	Less than 75	More than 74	Dust size recommended by ECOM.
AR 70-38, "Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions," 5 May 1969.	0.1 to 10	10 to 1,000	Same as MIL-STD 210A.
Naval Weapons Center, China Lake, Calif.	2 to 50	50 to 2,000	Proposed in unpublished report which also includes a range for dust particles from 2 down to colloidal size.
AF Systems Command Design Handbook 1-5, "Environmental Engineering."	0.1 to 50 (Ave. size: 0.5 to 1.5)	Larger than 50 (Ave. size: 150 to 300)	–
NASA Technical Memorandum, Report No. 53872	0.1 to 80 (90% between 0.1 and 2)	80 to 1,000 (90% between 80 and 306)	–
UK, Particle sizes recommended on a draft environmental handbook.	1 to 150	100 to 1,000	Specifies rounded quartz grains for sand; otherwise, same as Pauly.

Source: P. Blackford and H. S. McPhilimy, *Sand and Dust Considerations in the Design of Military Equipment*, USAETL Technical Report ETL-TR-72-7, Fort Belvoir, Va., 1972.

henceforth, uses "particle" rather than "sand." It is also suggested that all future Army documents on testing and design criteria use "particle" rather than "sand."

Precise but brief testing criteria are possible by merely stating shape, size, and kind of mineral. For example, a test criterion could specify the following: Use rounded, 100- to 200-μm diameter, quartz (SiO_2) particles. This could very easily eliminate further inconsistencies and confusion of particle size in future design and testing criteria documents.

There is one additional advantage of using "particle" rather than "sand." "Particle" merely connotes small grains. "Sand," however, for the majority of people, connotes silica (SiO_2) in addition to small grains. The small-grain idea is useful, but the SiO_2 connotation is undesirable especially when testing criteria are involved.

The term "dust," however, can still be used to designate those particles of any material that are maintained aloft indefinitely by normal winds and their associated turbulence and eddy currents. The term "dust" should be used only qualitatively; it should never have any quantitative connotations.

3. **Measurement of Particle Size.** For particles down to 74 μm, which are those that will be retained by a No. 200 U. S. Standard Sieve, it is customary to use a series of sieves to differentiate particle size. Below 74 μm, the use of mechanical sieves is considered impractical by many investigators because of large variations in the sieves and a consequent large number of errors. Therefore, particles smaller than 74 μm are often referred to as sub-sieve size. Table II summarizes several methods of particle size analysis and lists the lower limit of particle size for each method.

There are various ways to measure sub-sieve particles, but tests have shown that measurements made by different methods seldom are in close agreement. Therefore, data comparisons for small sizes are not likely to be representative unless it is known that the same measurement methods were used.

Table II. Methods for Particle Size Analysis

Method	Approximate Lower Limit of Particle Size (μm)
Sieving	
Normal screens	40
Micromesh	10
Membrane filters	0.01
Elutriation	10
(For heavy minerals)	5
Sedimentation	
Gravitational	2
Centrifugal	0.1
Coulter Counter	0.5
Microscopic	
Visible light	0.2
Ultraviolet in air	0.1
Ultraviolet in vacuum	0.03
Electron microscope	0.001

II. MAJOR FACTORS AFFECTING PARTICLE EROSIVENESS

Erosiveness of particles is a function of their hardness, angularity, mass, velocity, and angle of impact. The two most important characteristics are abrasiveness and velocity.

4. Abrasiveness. Abrasiveness of particles is related to hardness, angularity, size, and chemical compounds present.

a. Hardness. Particles vary considerably in hardness. Hardness is related, primarily, to what mineral is present. Another aspect influencing the hardness of some substances is whether they are wet or dry. Hardness of a substance is determined by its ability to abrade or indent other substances. Several test methods have been devised to measure hardness. The best known are: (1) scratch, (2) grinding, (3) boring, (4) indentation, and (5) height of rebound of a drop hammer. Several hardness scales have resulted from these methods. Those most often referred to include: (1) Mohs, by far the best known, (2) Knoop, (3) Pfaff, (4) Rosiwal, (5) Jaggar, and (6) Holmquist and Auerbach.

The Mohs scale is a relative hardness scale (Table III), and it is possible that some individuals will misinterpret the hardness of soil mineral particles when using the Mohs scale. One might logically assume that calcite is about three times harder than talc and diamond is ten times harder than talc. Actually, the Mohs scale increases exponentially. Diamond hardness is many magnitudes of a thousand greater than "1" which is listed for talc.

Table III. Mohs Mineral Hardness Scale

Mineral	Formula	Hardness
Talc	$3M_2 0.4SiO_2 .H_2 0$	1
Gypsum	$CaSO_4 .2H_2 0$	2
Calcite	$CaCO_3$	3
Fluorite	CaF_2	4
		Carbon Steel
Apatite	$CaF_2 .3Ca_3 (PO_4)_2$	5
Orthoclase	$K_2 0.Al_2 0_3 .6SiO_2$	6
Quartz	SiO_2	7
Topaz	$(AlF)_2 SiO_4$	8
Sapphire	$Al_2 0_3$	9
Diamond	C	10

The Knoop hardness scale is not nearly as well known as the Mohs scale but is much more comprehensive and meaningful. The Knoop values are absolute values computed by dividing the force applied on a diamond point by the surface area of the indentation in the substance being tested. Table IV is a comparison of hardness values from the Mohs and Knoop scales for several selected substances.[4] On the Mohs scale, the values for gypsum and quartz are, respectively, 2 and 7. The Knoop values, however, are 32 for gypsum and 820 for quartz. Because the Knoop scale is a ratio scale rather than a relative and much more comprehensive than the Mohs scale, the Knoop scale is recommended for criteria and testing purposes.

[4] *Handbook of Chemistry and Physics*, 48th Edition, 1967-68, Chemical Rubber Publishing Co., Cleveland, Ohio.

Table IV. Comparison of Hardness Values of Various Materials on Mohs and Knoop Scales*

Compiled by Laurence S. Foster

Substance	Formula	Mohs value	Knoop value
Talc	$3MgO{\cdot}4SiO_2{\cdot}H_2O$	1	
Gypsum	$CaSO_4{\cdot}2H_2O$	2	32
Cadmium	Cd	...	37
Silver	Ag	...	60
Zinc	Zn	...	119
Calcite	$CaCO_3$	3	135
Fluorite	CaF_2	4	163
Copper	Cu	...	163
Magnesia	MgO	...	370
Apatite	$CaF_2{\cdot}3Ca_3(PO_4)_2$	5	430
Nickel	Ni	...	557
Glass (soda lime)	.....	..	530
Feldspar (orthoclase)	$K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$	6	560
Quartz	SiO_2	7	820
Chromium	Cr	...	935
Zirconia	ZrO_2	...	1160
Beryllia	BeO	...	1250
Topaz	$(AlF)_2SiO_4$	8	1340
Garnet	$Al_2O_3{\cdot}3FeO{\cdot}3SiO_2$	...	1360
Tungsten carbide alloy	WC, Co	...	1400–1800
Zirconium boride	ZrB_2	...	1550
Titanium nitride	TiN	9	1800
Tungsten carbide	WC	...	1880
Tantalum carbide	TaC	...	2000
Zirconium carbide	ZrC	...	2100
Alumina	Al_2O_3	...	2100
Beryllium carbide	Be_2C	...	2410
Titanium carbide	TiC	...	2470
Silicon carbide	SiC	...	2480
Aluminum boride	AlB	...	2500
Boron carbide	B_3C	...	2750
Diamond	C	10	7000

* Source: *Handbook of Chemistry and Physics*, College Edition, 48th Edition, 1967-68, p. F-17, Chemical Rubber Publishing Co.

It is readily seen from Table IV that mineral hardness varies considerably. In fact, some minerals with the identical formula differ in hardness. This shows the importance of the mineral rather than the chemical elements or chemical compounds. For example, quartz (SiO_2) and flint (SiO_2), two different minerals, are listed in Table V as mineral constituents of sand. The Knoop hardness values for quartz and flint are 820 and 560, respectively.[5]

The erosiveness of selected materials is well established. Kleis tested the erosiveness of glass powder on various metals and found it about 100 times less erosive than corundum.[6] The glass powder is essentially SiO_2; whereas, the corundum is an aluminum oxide (Al_2O_3).

Table V. Mineral Constituents of Sand

Mineral		Formula	Hardness	
			Mohs Value	Knoop Value
Quartz		SiO_2	7	820
Feldspars	(Orthoclase	$K_2O.Al_2O_3.6SiO_2$	6	560
	(Albite	$Na_2O.Al_2O_3.6SiO_2$	6 to 6.5	560-650
	(Anorthite	$CaO.Al_2O_3.2SiO_2$	6 to 6.5	560-650
Limonite		$2Fe_2O_3.3H_2O$	5 to 5.5	430-490
Olivine		$(M_2,Fe)_2SiO_4$ [Mg in excess of Fe]	6 to 7	560-820
Mica		$KAl_2(AlSi_3)O_{10}(OH,F)_2$	2 to 2.5	32-80
Magnetite		Fe_3O_4	5.5 to 6.5	490-650
Kaolinite		$Al_2O_3.2SiO_2.2H_2O$	2 to 2.5	32-80
Serpentine		$2M_2O.2SiO_2.2H_2O$	3 to 4	135-160
Flint		SiO_2	6	560

Source: Modified from Wendy Sage, "The Erosive Characteristics of Natural Sands and Abrasive Dusts," N.G.T.E., Note No. NT 699, U.S. Ministry of Technology, National Gas Turbine Establishment, Byestock Hants, May 1963.

b. Angularity. The interrelationships of the many physical and chemical characteristics responsible for material erosion by airborne soil mineral particles are complex and not fully understood nor documented. For example, are angular quartz or angular flint particles more erosive? Noted under the hardness section of this report.

[5]Wendy Sage, "The Erosive Characteristics of Natural Sands and Abrasive Dusts," N.G.T.E., Note No. NT 699, U.K. Ministry of Technology, National Gas Turbine Establishment, Byestock Hants, May 1963.

[6]I. Kleis, "A Study of Metallo-Ceramic Solid Alloys of Different Hardness," Trudy Tallin Polytech Inst. Series A (219), 1965 (as quoted by Sage, Wendy, May 1963).

both quartz and flint have the same chemical formulas (SiO_2). The Knoop hardness values are 820 for quartz and 560 for flint. Flint is softer than quartz, but flint forms sharper edges, i.e., more angular than quartz when broken. Experiments show that erosion is negligible for spheres but increases as angularity increases. Therefore, from the currently available information, it cannot be stated definitely which of the two, angular quartz or angular flint particles, are more erosive. These unanswered questions show the need for additional research on the problem.

The higher than expected erosion of engine compressor blades for turboprop aircraft in Iceland has been attributed to the highly angular nature of the glassy particles which are weathered from extensive lava formations. Similar material erosion problems will exist in other acidic, volcanic areas. All other things being equal, the soils derived from acidic basalt will be more abrasive than those derived from the basic basalts. The acidic basalts contain a higher percentage of SiO_2 than do the basic basalts.

Some generalizations can be made relative to angularity of soil particles and their distribution. Particles transported by wind or water generally have their sharp corners and edges removed by abrasion. This means that most of the mineral particles from deserts, beaches, terraces, and river flood plains are sub-rounded to rounded. On the other hand, residual-soil mineral particles on the uplands and interfluves would generally be angular to sub-rounded.

c. **Size.** Sage's experiments using quartz particles show that erosion increases with increasing particle size (Table VI and Fig. 1).[7]

Considering only the particles impacted at 420 ft/s at 90^0, the erosion increased about fourfold (0.4 to 1.3 mg/g) as the average particle size increased from 25 to 193 μm. The relationship between erosion and particle size is neither direct nor at a constant rate of change. There is no noticeable erosion when the particles are about 6 μm, but erosion increases rapidly with increasing particle sizes greater than about 6 μm. Between around 50 to around 100 μm, depending on the particle velocity, the erosion rate decreases abruptly and, for practical purposes, remains constant (Fig. 1).

[7] Wendy Sage, "The Erosive Characteristics of Natural Sands and Abrasive Dusts," N.G.T.E., Note No. NT 699, U.K. Ministry of Technology, National Gas Turbine Establishment, Byestock Hants, May 1963.

Table VI. Influence of Particle Size on Amount of Erosion

Particle Range (μm)	Mean Particle Size (μm)	Erosion Loss (μm/g impacted) A 420 ft/s at 90°*	B 800 ft/s at 90°*	C 1000 ft/s at 90°*
0-5.5	2.8			0
0-11	6			0.7
18-29	25	0.4	0.7, 1.0	1.0, 1.2
31-45	38	0.5	1.5	2.2, 2.7
45-53	49	1.3		5.2, 5.4
53-63	58		2.7	5.6, 5.8
63-76	70	1.2	2.8	5.6
76-90	83	1.3	4.9	6.2
90-105	98			6.7, 8.1
105-125	115		4.2	9.2, 8.0
125-150	137	1.3	4.6	8.6, 8.1, 8.2
150-180	165			8.2, 7.7
180-210	195	1.3	4.7	8.2

*Particles impacted at 90° to sample being eroded.

(Adapted from Wendy Sage, *The Erosive Characteristics of Natural Sands and Abrasive Dusts.*)

5. **Velocity.** For quartz particles from about 6 to about 100 μm, the velocity of the impacting particle influences the amount of erosion as much as the particle size does (Fig. 1). For all three velocities checked (420, 800, and 1000 ft/s), the amount of erosion was negligible below 6 μm but increased to 8.2 mg/g for particles averaging 195 μm in size and having a velocity of 1000 ft/s. The rate of erosion increases rapidly as the particle size increases for each of the velocities tested. For each velocity, however, the erosion reaches a leveling-off point where the erosion is negligible with increasing particle size.

Velocities imparted to particles by the helicopter rotor are comparable to velocities created by compressed air sand blasting. Moreover, the effectiveness of the particle velocity is greatly increased on the rotor blades, especially the leading edge at the outer end of the rotor blades. With respect to the rotor blades, the effective velocity of the abrasive particles is the resultant velocity of the particles and the rotor blade. The erosion on the blade increases with distance from the hub because the velocity of the blade increases with distance from the rotor hub.

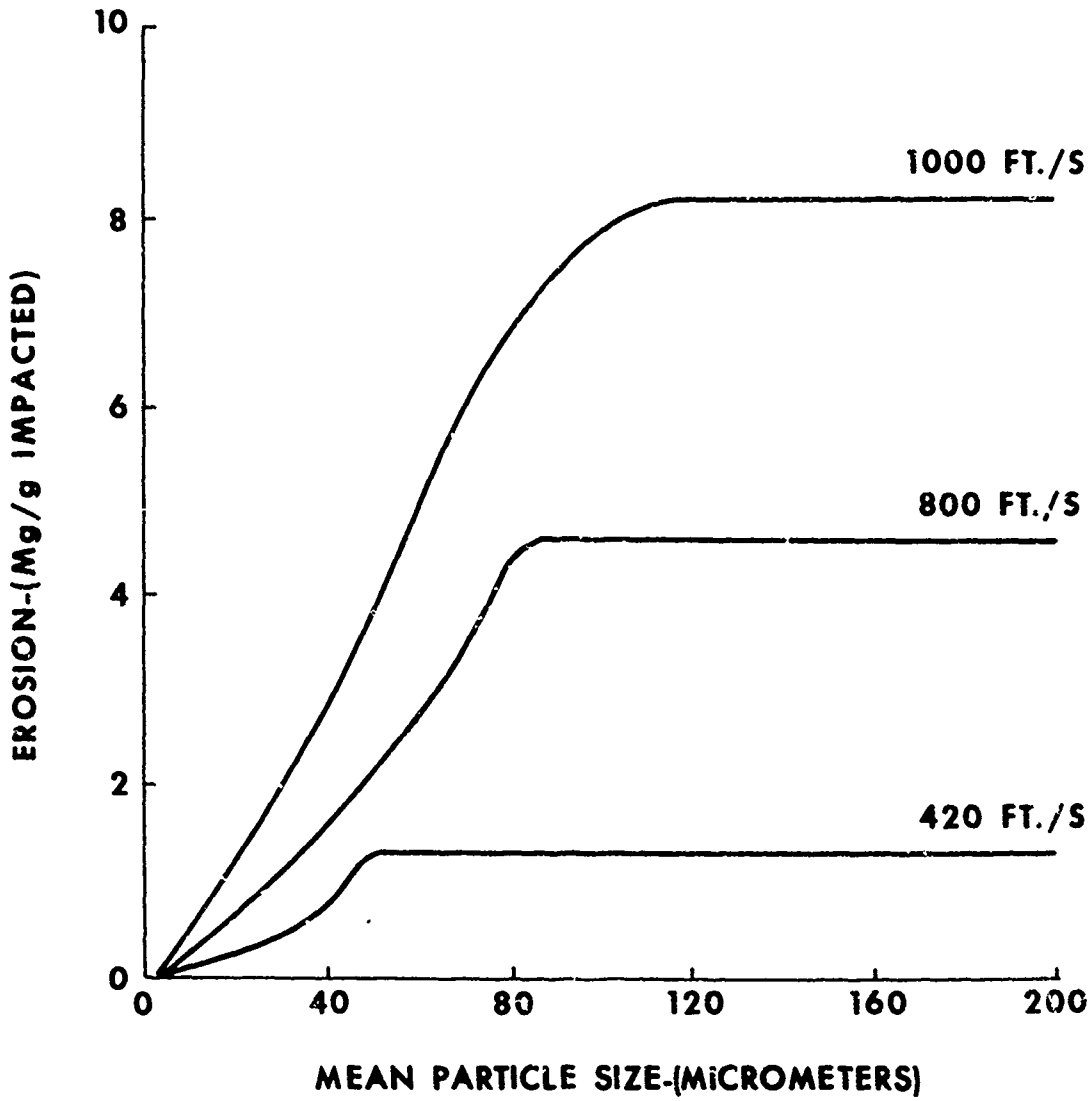

Fig. 1. The influence of particle size on the erosion of steel. (Adapted from Wendy Sage, *The Erosive Characteristics of Natural Sands and Abrasive Dusts.*)

III. CHEMICAL CORROSION BY AIRBORNE PARTICLES

6. Corrosiveness of Natural Chemical Compounds. Many chemical compounds, chlorides and sulfates being the most troublesome on a worldwide basis, when combined with moisture form highly corrosive agents which attack both organic and inorganic material. The oceans, seas, and some lakes and land surfaces in arid and semiarid areas are sources for corrosive, airborne particles.

Coastal areas, especially those having predominantly on-shore winds, will have high concentrations of atmospheric oceanic source salts. Woodcock reports that ordinary sea winds carry from 10 to 100 pounds of sea salt per cubic mile of air, and storm winds may bear as much as 1,000 pounds or more per cubic mile.[8] High concentrations of atmospheric salts are also present in areas surrounding large lakes in arid and semiarid areas. Great Salt Lake, Utah, the Dead Sea, and the Caspian Sea are only a few of the many examples of inland lakes and seas where the atmospheric salt concentrations are high enough to cause severe local corrosion problems.

From available data, the consensus is that for littoral areas the sea-salt content of the air increases from the poles toward the equator. Much more data is needed on a world basis to be able to map atmospheric sea-salt content for a desirable level of reliability or completeness. Maps showing the concentration of oceanic salts in the atmosphere are not available. However, two maps closely related to the problem have been produced (Figs. 2 and 3).[9] Figure 2 gives an indication of the chloride that is washed out of the atmosphere in 1 year. Figure 3 shows relative amounts of atmospheric sea salt over the land surfaces of the world.

Areas of internal drainage in hot deserts are soil problem areas with respect to high concentrations of soil mineral salts, of which the most common are sulfates, chlorides, and carbonates. In some deserts, there are sections where these salts make up the major part of the surface material. In these areas, strong surface winds stir up and keep in suspension high concentrations of these corrosive salts.

Large land areas have been drained for agriculture and/or insect control in selected parts of the world. Some of these drained areas develop sulfatic soils (high-sulfate soils). These sulfatic soils do not cover vast continuous areas; rather, they appear as discontinuous patches, the total area of which is estimated in terms of hundreds of thousands of acres. The major sulfatic-soil areas of the world are:

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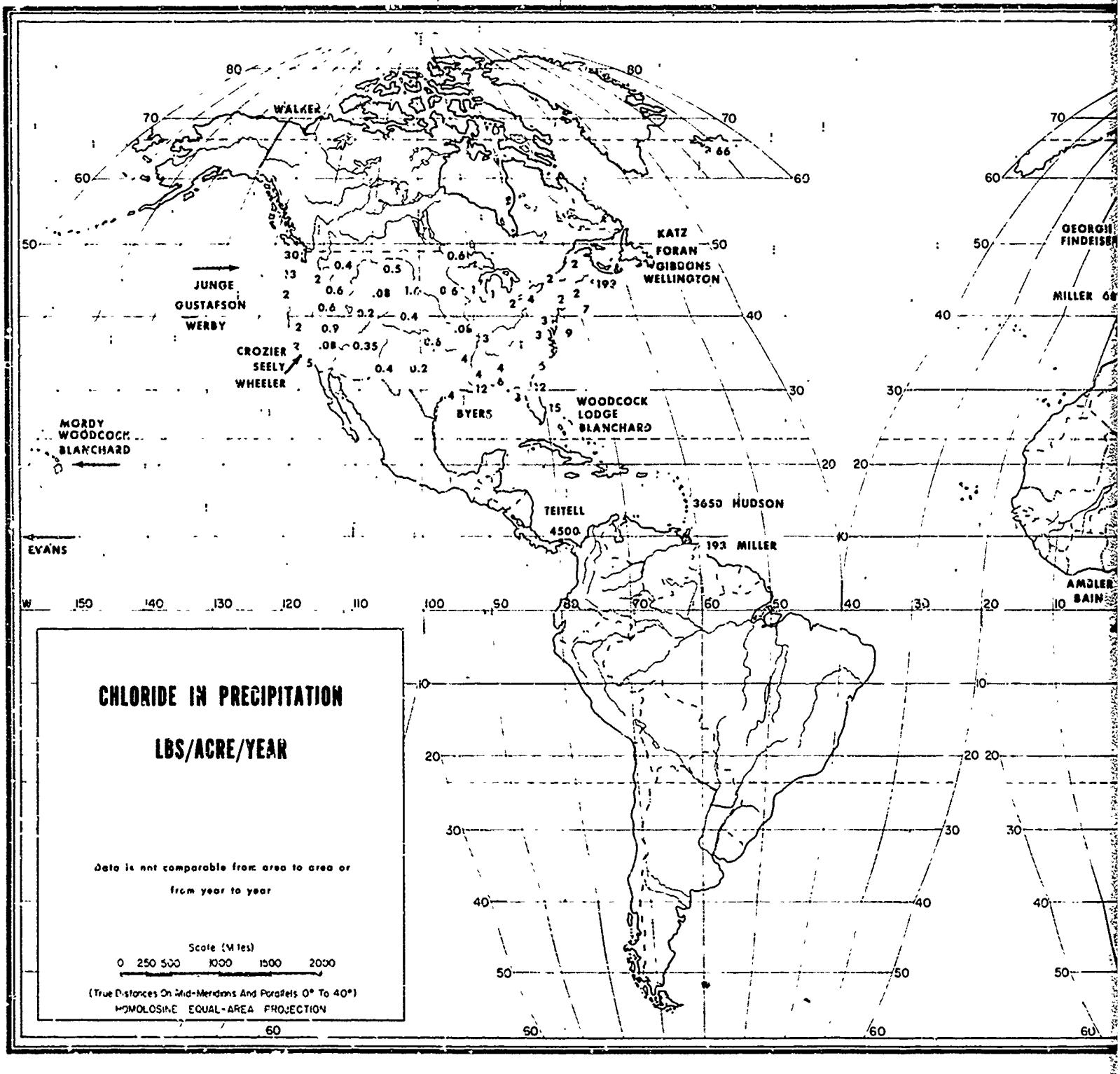
[8] A. H. Woodcock, "Salt and Rain," *Scientific American*, Vol. 197, No. 4, Oct. 1957.

[9] W. B. Brierly, "Atmosphere Sea-Salts Design Criteria Areas," *Journal of Environmental Sciences*, Vol. 8, No. 5, Oct. 1965.


WALKER
KATZ
FORAN
GIBBONS
WELLINGTON
JUNGE
GUSTAFSON
WERBY
CROZIER
SEELY
WHEELER
BYERS
WOODCOCK
LODGE
BLANCHARD
MORDY
WOODCOCK
BLANCHARD
EVANS
TEITELL
4500
3650 HUDSON
193 MILLER
MILLER 68
AMBLER
BAIN
GEORGII
FINDEISEN
CHLORIDE IN PRECIPITATION
LBS/ACRE/YEAR
Data is not comparable from area to area or
from year to year
Scale (Miles)
0 250 500 1000 1500 2000
(True Distances On Mid-Meridians And Parallels 0° To 40°)
HOMOLOSINE EQUAL-AREA PROJECTION

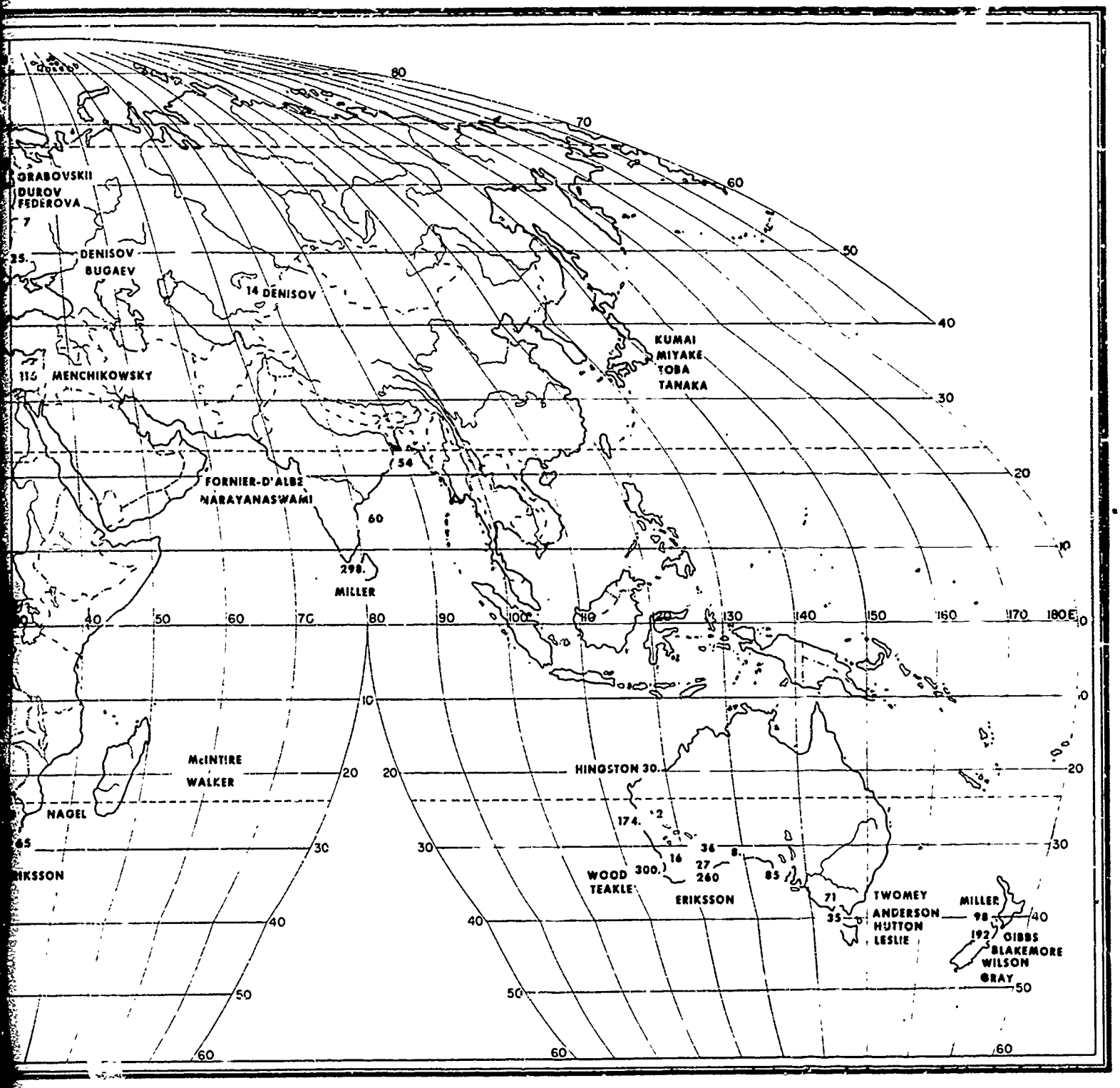
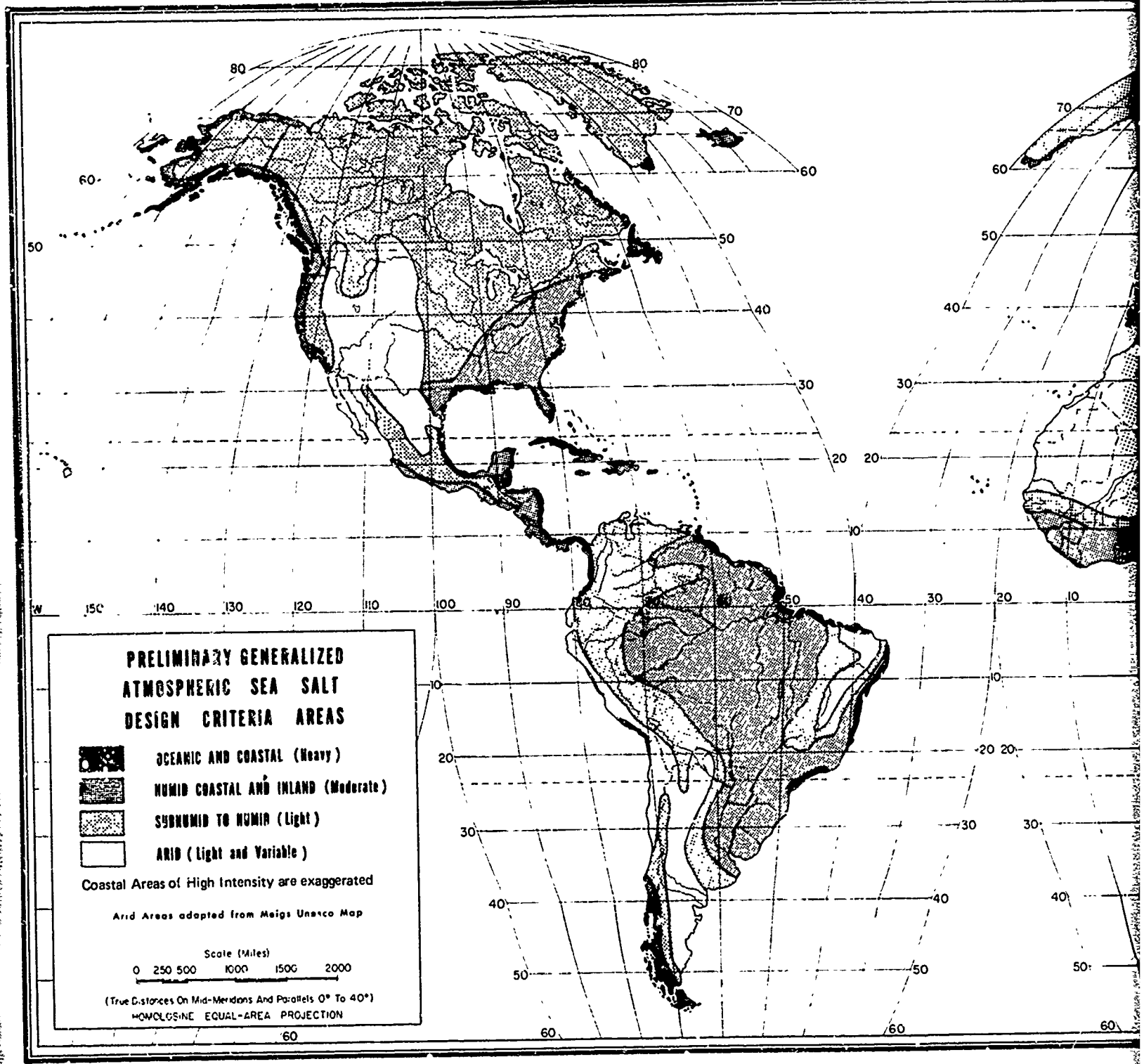


Fig. 2. Chloride in precipitation. Names indicate source of data used in preparing the text and maps. (Source: W. B. Brierly, "Atmosphere Sea-Salts Design Criteria Areas," *Journal of Environmental Sciences*, 8, No. 5, October 1965, pp. 18, 19.)

3


PRELIMINARY GENERALIZED
ATMOSPHERIC SEA SALT
DESIGN CRITERIA AREAS
OCEANIC AND COASTAL (Heavy)
HUMID COASTAL AND INLAND (Moderate)
SUBHUMID TO HUMID (Light)
ARID (Light and Variable)
Coastal Areas of High Intensity are exaggerated
Arid Areas adopted from Meigs Unesco Map
Scale (Miles)
0 250 500 1000 1500 2000
(True Distances On Mid-Meridians And Parallels 0° To 40°)
HOMOLOSINE EQUAL-AREA PROJECTION

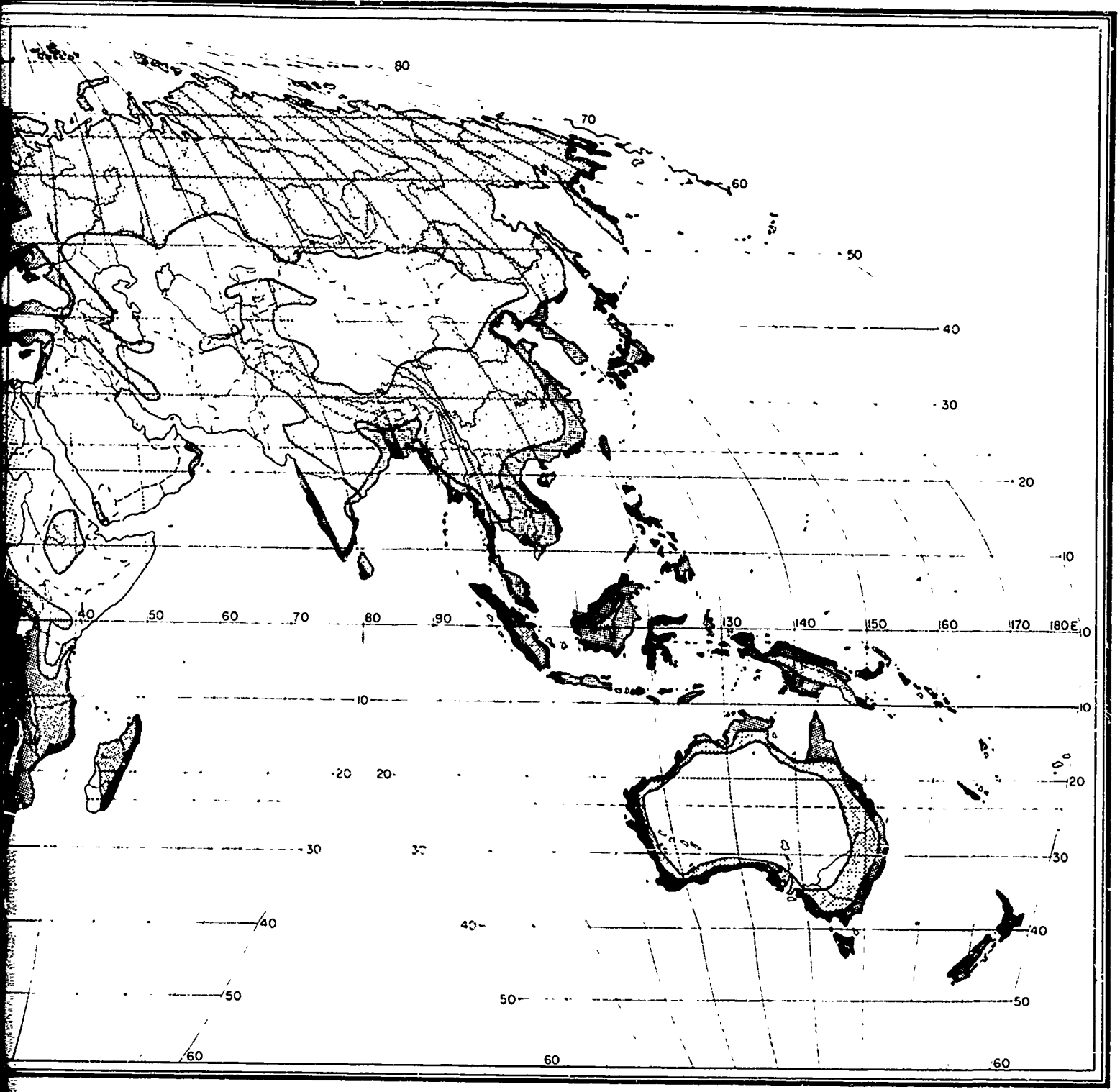


Fig. 3. Preliminary generalized atmospheric sea salt design criteria areas. (Source: W. B. Brierly, "Atmosphere Sea-Salts Design Criteria Areas," *Journal of Environmental Sciences*, 8, No. 5, October 1965.)

a. coastal U.S.A., Virginia to northern Florida

b. gulf coast of the U.S.A., west of the Mississippi River delta

c. northeastern coastal area of South America

d. coastal west central Africa

e. coastal Holland

f. scattered coastal areas of Southeast Asia including Burma, Thailand, Vietnam, Java, and New Guinea.

7. **Corrosiveness of Industrial Chemical Compounds.** In addition to the natural sources, including volcano fumes, of corrosive chemical compounds in the lower levels of the atmosphere, there are chemical compounds introduced by the various industrial processes and by industrial, commercial, and domestic burning of fossil fuels. Sulfur compounds are the most common corrosive chemical compounds in the atmosphere, but by no means the only ones, on a world basis. A few of the worst offending industries in regard to releasing sulfur compounds to the atmosphere are metal refining, petrochemical processing, and paper manufacturing.

IV. OTHER PROBLEMS CAUSED BY AIRBORNE PARTICLES

Other problems caused by airborne particles include: (1) electrical failures, (2) clogging and partial blocking, (3) additional weight, and (4) restricted visibility.

8. **Electrical Failures.** Electrical components utilizing high voltages or moving parts such as breaker points often fail when subjected even to low concentrations of fine, airborne soil particles. Arcing between high-tension electrodes is promoted by accumulations of fine particles. Bearings and armatures of motors, dynamotors, and generators are damaged by the abrasion action of fine particles. These fine particles, a fraction of a micrometer to around 80 μm, enter all containerized components except those that are truly airtight.

In addition to fine airborne soil particles, sea salt in the air, fog, dew, and precipitation foul electrical equipment by coating surfaces of insulators with a conductive coating. This conductive coating is undesirable because it promotes sparking, causes energy losses, and accelerates corrosion of the insulating material and metal parts of the electrical equipment.

The generalization of higher sea-salt content in the air in the equatorial littoral areas is supported by the following observations. Corrosion in the tropical littoral corrosion testing station in Abidjan, Ivory Coast (5^{o}N), was approximately twice as rapid as in coastal regions of France.[10]

9. Clogging and Partial Blocking. The effects of fine particles in the category of clogging and blocking include a wide variety of problems. Small openings, such as in pitot tubes and grease fittings, become blocked and inoperative by fine-particle accumulations. Fine particles of montmorillonitic clay are especially undesirable. Montmorillonitic clays swell with absorption of moisture. Such swelling clays can cause serious compaction problems in critical small openings, and they can also cause compaction and abrasion in ball and socket joints.

Ball and socket joints and other types of joints between moving parts which require lubrication will accumulate airborne particles. The lubricant and particles together act as a polishing or grinding compound. The lubrication holds abrasive particles which cause erosion not only during the period that the equipment is operating in an abrasive airborne particle environment but also in a clean environment thereafter. For example, a helicopter may hover for 5 minutes in an environment with a high concentration of airborne $Si0_2$ particles over a sandy beach. During the 5-minute period, the oiled and greased joints will accumulate some of the airborne particles. The helicopter then flies for 2 hours well above any airborne beach particles. The oiled and greased joints have been subjected to particle abrasion for 2 hours and 5 minutes rather than the 5-minute hovering time.

10. Additional Weight. After several hours of operating an aircraft in extremely dusty conditions, the accumulated particles in dead airspaces could seriously affect performance by changing the center of gravity and total aircraft gross weight. The additional weight from the accumulated particles could conceivably lower the ceiling level of operations--especially when the air temperatures are very high.

11. Restricted Visibility. High concentrations of airborne particles are a serious safety hazard--especially during V/STOL aircraft takeoffs and landings. The high concentration of fine particles may obscure the horizon and, on many occasions, may even reduce pilot visibility to zero. The seriousness is increased many times when this condition prevails during takeoffs and landings of several V/STOL aircraft in close formation. Unless the pilots can make a very rapid change from contact to instrument flying, mass crack-ups of the aircraft with each other and with the ground is highly possible.

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[10] Rychter and Bartakova, *Tropicproofing Electrical Equipment*, Leonard Hill (Books), Ltd., London, 1963.

On two test occasions at the Yuma Vehicle Dust Course, visibility was so reduced that the pilot lost all ground reference during attempts to clear the hover area. It was also found that dust concentrations were much higher (by a factor of about 3) when the helicopter landed and took off again after the dust cloud was allowed to clear.

V. MAJOR DETRIMENTAL AIRBORNE SOIL PARTICLES AND THEIR GEOGRAPHIC DISTRIBUTION

12. Distribution. Fine particles exist in the atmosphere to varying degrees all over the world. The land areas are the major source for airborne particles, but oceans and large lakes in arid and semiarid areas also contribute microscopic particles of various salts which, as mentioned earlier, can be highly corrosive when combined with moisture.

The greater part of the sparsely vegetated areas of the world present an immediate airborne particle problem for V/STOL aircraft. The exceptions to this generalization include the following: (1) wet or frozen soil areas, (2) coarse gravel desert areas with no fine particles at the surface, and (3) extensive surface bedrock areas.

In contrast, the vegetated areas (grasses, low shrubs, brush, and trees) present much less of a problem, but these areas become real problem areas as the vegetation is destroyed by man's activities—military as well as civilian. (Dangers resulting from organic debris will be discussed in a later report on vegetation.)

Experience has shown that engine erosion damage due to ingested particles varies with location of operations. It is well documented that erosion due to fine particles ingested by helicopters in Vietnam and Aden is greater than expected. The rapid erosion in these areas is attributable to the relatively high concentrations of aluminum and iron oxides.[11]

Mineral analyses for several soil samples collected at various places around the world are listed in Table VII. It must be noted, however, that there is no assurance that these samples are representative of the surface soil for broad areas around the sample sites. These samples are useful and valuable, but there is a valid question as to just what they represent. Is it surface or sub-surface material? Is it fill material brought in from some other location? For these soil samples, the Naval Weapons Center, China Lake, California, stated the following: "Find plot of dirt that is out of the direct stream of

[11] Report No. 1 of this series, *Potential Sand and Dust Source Areas*, delineates on world maps several of the particle characteristics and soil conditions that are important when considering airborne particles that are detrimental to V/STOL aircraft.

Table VII. Characterization of Soil Samples

Location	Composition (percent by weight)[a]									Ignition[b] loss, %	Density, g/cm³	Average particle size, μm
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	CaO	MgO	K_2O	Na_2O			
Da Nang, Vietnam	80.21	7.61	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, Philippine 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	6.29	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	16.39	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	6.48	0.85		7.75	3.65			7.91	2.744	8
White 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, [illegible]	68.41	13.22	5.35	1.10		1.10	1.63			7.46	2.711	10
Fairfax, Va.	65.18	14.16	7.28	1.37		2.28	1.35			6.39	2.735	19
Eglin AFB, 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	25.86	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
Keplavik, Iceland	31.34	23.66	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	2.86	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] Al, metals reported as oxides.

[b] Ignition loss: 1 hour 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.

Source: E. Kuletz and H. C. Schafer, *Survey and Study on Sand and Dust*, NWC TP 5170, Propulsion Development Department, Naval Weapons Center, China Lake, California, Aug. 1971.

foot and vehicle traffic."[12] These samples have value, but they would be much more valuable if they were chosen more discriminately. Nevertheless, they show that at spot locations there are considerable differences in mineral constituency of soils around the world.

13. Silica (SiO_2). Considering soils on a world basis, quartz (SiO_2) is the most common soil constituent.[13] For practical purposes, one can say that SiO_2 particles are ubiquitous, but the percentage of SiO_2 to the total soil composition varies considerably from place to place. For example, in the soil samples listed in Table VII, the SiO_2 content ranges from 0.13 percent for Wake Island to 95.18 percent for Eglin Air Force Base, Florida.

The most extensive areas with the highest percentage of SiO_2 in the surface soils are the deserts.[14] The major sand silica deserts of the world and their estimated area in square miles are listed in Table VIII. The deserts are widely scattered—Africa, Asia, Australia, South America, and North America. On an areal basis, however, the deserts of North Africa and the Middle East constitute the major portion of the desert world.

In addition to the major deserts, there are millions of square miles of minor deserts and semiarid areas which also have a high percentage of SiO_2 in the surface soil.

The majority of coastal soils have a high percentage of SiO_2. In some places, however, particularly coral islands, the SiO_2 content is relatively low and the CaO and/or $CaCO_3$ is relatively high. The samples from Tahiti, Pago Pago, Wake Island, Bermuda, and Puerto Rico are examples where the CaO and/or $CaCO_3$ percentages are much higher than average and the SiO_2 percentage is lower than average. All islands and continental shelf areas where there is an abundance of seashell fragments or extensive coral development have higher than average percentages of CaO and/or $CaCO_3$ and lower than average percentages of SiO_2.

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[12] E. Kuletz and D. D. Schafer, "Survey and Study on Sand and Dust," NWC TP 5170, Propulsion Development Department, Naval Weapons Center, China Lake, Calif., Aug. 1971.

[13] Quartz is hard, chemically inert, and insoluble so it is not easily reduced in size as are most other minerals.

[14] The term "desert" used here includes: (1) the middle latitude deserts in the basinlike interiors of the continents, such as the Gobi, characterized by scant rainfall and high summer temperatures, (2) the trade wind deserts, notably the Sahara, the distinguishing features of which are negligible precipitation and large daily temperature range, and (3) coastal deserts where there is a cold current on the western coast of a large land mass such as occurs in Peru. Excluded are the polar ice and snow deserts marked by perpetual snow and intense cold.

Table VIII. Major Sand (SiO_2) Deserts of the World

Name	Location	Estimated Area in Square Miles
Sahara	North Africa	3,000,000
Libyan	Libya	650,000
Gobi	Mongolia	400,000
Rubi al Khali	Southeast Saudi Arabia	250,000
Kalahari	South Africa	200,000
Great Sandy	Northwest Australia	160,000
Great Victoria	Southwest Australia	125,000
Taklamakan	China	125,000
Syrian	Northwest Arabian Peninsula	125,000
Arunta	Central Australia	120,000
Kara-Kum	U.S.S.R.	105,000
Nubian	Northeast Sudan	100,000
Thar or Indian	Northwest India	100,000
Kyzl-Kum	U.S.S.R.	90,000
Gibson	Western Australia	85,000
Atacama	Northern Chile	70,000
Nefud	Saudi Arabia	50,000
Dasht-i-Lut	Eastern Iran	20,000
Dasht-i-Kavir	North Central Iran	18,000
Peski-Muyan-Kum	U.S.S.R.	17,000
Mojave	Southern California	13,500
Sechura	Northwestern Peru	10,000

14. Alumina (Al_2O_3 and Hematite (Fe_2O_3). As a general rule, soils high in Al_2O_3 are in tropical and semitropical areas (Table VII). Adak No. 1, Alaska, however, is a noticeable exception. A second generalization is that soils high in Al_2O_3 are also high in Fe_2O_3. Both Al_2O_3 and Fe_2O_3 are hard minerals; the former, however, is much harder than the latter. On the Knoop scale, Al_2O_3 is rated 2100 and Fe_2O_3 varies from 430 to 560. Much of the fine, reddish dust that becomes airborne and coats everything in much of the tropics and semitropics is some form of iron oxide.

VI. FACTORS INFLUENCING SOIL PARTICLES BECOMING AIRBORNE

15. Dust Potential of an Area Based on Amount and Size of Particles. Some effort has been made to evaluate the potential dustiness of areas by examining the proportion of particles smaller than 74 μm in the surface soil.[15] It was concluded that any area whose soil contains more than 9 percent by weight of such particles may become at least moderately dusty at times. Soils with 14 percent or more of dust-size particles are potentially very dusty. It was also concluded, however, that soils with more than 9 percent of dust particles are very common on a world basis; so one must look for other factors on which to base estimates of the likelihood of dust problems.

16. Other Factors Influencing Dust Potential. Other factors influencing dust potential, however, are so closely interrelated that it is impossible to identify their individual effects except under carefully controlled, long-term studies. For example, the state of agglomeration of the surface particles, caused either by chemical association or the binding action of moisture, is an extremely important consideration in the prediction of dust problems. Agglomeration of surface particles occurs anywhere there is a wetting and drying process of fine, unconsolidated soil particles. Bare soil with an agglomeration of surface particles may not give rise to dust problems until the soil is disturbed or agitated by mechanical means. Such agitation, commonly associated with many activities, facilitates the drying process and breaks the surface crust into its constituent particles. It also happens in many cases that surface dust particles become conglutinated soon after disturbing forces cease. (The Vehicle Dust Course, Yuma Proving Ground, for example, is disked prior to use for testing.)

Another important factor in assessing the dust potential of a given area is the presence or absence of protective cover – either natural or artificial. Dense vegetation of any kind, for example, provides excellent mechanical protection from wind movement, and plant roots tend to bind the soil particles together. Artificial protection is provided by means of paving areas subject to hard usage or by means of various soil stabilization techniques. Even a sprinkling with water will provide temporary relief from dust problems.

Climatic factors, particularly precipitation, are of considerable importance in determining the state of agglomeration of particles. Since moisture is a primary agglomerating factor, any climatic condition that fav ; evaporation tends to increase the dust potential. Excluding Antarctica, over 40 percent of the world's land surface is classified as moisture deficient. Another 40 percent of the earth is seasonally dry, which means potentially severe dust conditions for parts of the year. Less obvious is the fact

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[15] S. J. Rodgers, "Evaluation of the Dust Cloud Generated by Helicopter Rotor Blade Downwash," USA AVLABS Technical Report 67-81, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Va., March 1968.

that even in high-moisture regions during the seasons of high rainfall, dust continues to create problems where protective cover has been removed. Many moist areas are so well drained that mud becomes dust in a surprisingly short time after heavy rains. A good example is the situation in Vietnam where many Americans have been surprised at the airborne soil particle problems between rains during the wet seasons.

Climatic factors other than precipitation also have an effect on the potential for fine-particle production. Since dust may be hygroscopic, it is dependent in part on relative humidity. Many dust tests, for example, specify a relative humidity of less than 30 percent in order to achieve maximum particle separation. There is also some evidence that dust problems are more severe at higher temperatures. And, finally, natural wind, both because of its drying action and because of its ability to circulate dust, has a considerable effect on dust potential.

VII. AIRBORNE PARTICLE CONCENTRATIONS UNDER VARIOUS FIELD CONDITIONS

17. Variability of Fine Particle Concentrations. There is a wide variability in the concentration of fine particles suspended in the air. This variability within a seemingly uniform micro-environment is illustrated by a series of nine samples collected next to a bulldozer backfilling a trench with dry soil. All samples were collected within a time span of 1 hour, and care was taken to get as nearly identical conditions as possible. Yet, the concentrations varied from 0.26 to 5.19 mg/cu ft (9 to 183 mg/cu m). Most of the pertinent data available regarding measured fine particle concentrations are incorporated in Table IX.

18. Correlating Concentrations with Visibility. In addition to actual measurements of fine-particle concentrations, some attempts have been made to correlate concentrations with visibility. In fact, the most common method of reporting airborne particles is based on restriction to visibility. Apart from the inherent differences among observers in their perception of what constitutes poor visibility, consistent correlation between visibility and dust concentration is difficult to achieve because properties other than concentration are important in determining light transmission. For example, at a given concentration (weight per volume of air), clouds composed of smaller particles pass much less light than those composed of larger particles. Particle shape and composition may also have significant effects on the transmission of light. As an example of the kinds of variations that may result from these differences, concentrations of small particles as low as 0.3 mg/cu ft (10.6 mg/cu m) have been known to restrict visibility to less than 50 feet; yet, under other circumstances, concentrations as high as 8 mg/cu ft (282 mg/cu m) of larger particles have resulted in visibility of 500 feet or more.

Table IX. Airborne Particle Concentrations under Various Field Conditions

Activity or Event	Type of Surface	Concentration	
		mg/ft^3	mg/in^3
Dust Storm in Australia			
500 feet above ground	Dry surface: little protective	0.06	2.1
1,000 feet above ground	cover.	0.5	17.6
2,000 feet above ground	Wind: 24 to 30 mph	0.2	7.1
3,000 feet above ground	Ground visibility: 1,000 feet	0.05	1.8
4,000 feet above ground		0.02	0.7
Wind: 12 to 14 mph	Scrub covered field: no activity	0.4	14.1
Fresh breeze: 19 to 24 mph	Unpaved, sandy area: no disturbing activity	1.7	60.0
Severe storm: not defined	Dry surface: no cover	5.0	176.5
Troops drilling	Dry parade ground	0.9	31.8
Troops marching	Dry, unpaved road	2.0	70.6
One staff car	Unpaved maneuver road	2.9	102.4
Convoy of trucks and towed guns	Unpaved maneuver road	5.1	180.0
Column of tanks	Bare, dry, sand and dust surface: measured beside column	7.3	257.7
Muzzle blast from gun on M-60 Tank	Bare, dry surface: measured approx. 65 feet away	1.3	45.9
MQN61-A Drones: one JATO Bottle	Hard packed sand and gravel:	0.9	31.8
	two separate measurements	2.4	84.7
Half-track in operation	Loose sand: measured 30 feet away	29.2	1030.8
One Tank -- 10 mph	Heavy dust surface	27.2	960.2
Column of 6 Light Tanks	Moving into wind over heavy dust surface	53.5	1888.6
Engine compartment in Tank		170.0	6001.0
Aircraft taking off	Clean, paved runway	0.8	28.2
H-21 Helicopter	Over freshly plowed fields		
During take-off		40.0	1412.0
Hovering at 1 foot		15.5	547.2
Hovering at 10 feet		18.1	638.9
Hovering at 75 feet		7.3	257.7
Hovering with second Helicopter maneuvering nearby		64.0	2259.2

(Source: P. Blackford and H. S. McPhilimy, *Sand and Dust Considerations in the Design of Military Equipment*, USAETL Technical Report ETL-TR-72-7, Fort Belvoir, Va., 1972.)

VIII. MEASURED AIRBORNE PARTICLE SIZES AND CONCENTRATIONS NEAR A HOVERING HELICOPTER

19. Tests at Yuma Proving Ground and Fort Benning. Concentration measurements and some particle size determinations were made in dust clouds generated by a tandem-rotor H-21 helicopter at Yuma Proving Ground and at Fort Benning.[16] These measurements are partially summarized in Table X. To obtain the data, 25 samplers were mounted on a framework attached to the helicopter fuselage and others, on a boom under the rotor. For uniformity, all three of the test sites (two separate sites at Yuma) were plowed to a depth of 6 inches and then disked prior to the test runs. This process was repeated after each of six tests. One of the significant things shown by the data in Table X is that at all three sites and at all three test elevations, substantial proportions of the particles were in the 74 to 250 μm range.

IX. COMPUTED VELOCITIES AND MAXIMUM PARTICLE DIAMETER SIZES IN THE INTERACTION PLANE PRODUCED BY TWO OPPOSING WALL JETS

20. Tests of the Downwash Eddies of V/STOL Aircraft. The downwash eddies and turbulence produced by V/STOL aircraft are very complicated and not yet fully understood. Complexity is further increased by the pulsating nature of the downwash.

USA AVLABS Technical Report 68-52 presents the best (but not completely satisfactory) analytical downwash prediction techniques available.[17] Comparisons of predicted downwash velocities and test measurements of downwash from a helicopter with a gross weight of 9500 pounds indicated an average error of 40 percent (difference/predicted). To compensate for the inaccuracy of the downwash predicted values, 40 percent has been added to the predicted horizontal velocities in the wall jet. These results would then be more realistic for the maximum, horizontal velocities which could be encountered around a 15,000-pound helicopter.

Wall jet velocities produced by this single helicopter of 15,000 pounds gross weight and a disk loading of 8.0 pounds per square foot were calculated by AVLABS of the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory (Table XI). The velocities listed are those calculated and corrected by AVLABS using the method mentioned in the previous paragraph.

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[16] S. J. Rodgers, "Evaluation of the Dust Cloud Generated by Helicopter Rotor Blade Downwash," USA AVLABS Technical Report 67-81, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Va., March 1968.

[17] M. George, *et al.*, "Investigation of the Downwash Environment Generated by V/STOL Aircraft Operating in Ground Effect," USA AVLABS Technical Report 68-52, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Va., July 1968.

Table X. Mean and Maximum Airborne Particle Concentrations Near a Hovering Helicopter[a]

Location	Hover Height[b]											
	1 Foot				10 Feet				75 Feet			
	(μm)	(μm)	(μm)	(μm)	(μm)	(μm)	(μm)	(μm)	(μm)	(μm)	(μm)	(μm)
	<74[c]	74[c] to 250	250[c] to 500	Max. (All sizes)	74[c]	74[c] to 250	250[c] to 500	Max. (All sizes)	74[c]	74[c] to 250	250[c] to 500	Max. (All sizes)
Phillips Drop Zone, YPG	2.1 (74)	9.7 (341)	0.6 (22)	27.9 (985)	4.6 (163)	12.9 (457)	0.9 (33)	27.6 (974)	3.4 (120)	1.9 (65)	0.1 (2)	7.8 (275)
Vehicle Dust Course, YPG	8.1 (285)	7.4 (263)	0	28.6 (1010)	9.6 (339)	8.5 (300)	0	33.6 (1186)				
Lee Drop Zone, Ft. Benning, Ga.	3.3 (117)	13.8 (487)	1.3 (45)	28.5 (1006)	2.3 (81)	14.1 (497)	1.2 (43)	40.6 (1433)	1.7 (59)	0.9 (33)	0.1 (3)	3.5 (124)

[a]Concentrations are given in mg/ft^3; nos. in parens. are conversions to mg/m^3.

[b]Hover height refers to wheel clearance.

[c]Particle sizes.

(Source: P. Blackford and H. S. McPhilimy, *Sand and Dust Considerations in the Design of Military Equipment*, USAETL Technical Report ETL-TR-72-7, Fort Belvoir, Va., 1972.)

Table XI. Calculated Interaction Plane Updraft Velocities and Theoretical Maximum Particle Size in the Interaction Plane Produced by Two Opposing Wall Jets

Skid Height Above Ground (feet)	Height in Interaction Plane (ft)																			
	0.0		2.5		5.0		7.5		10.0		12.5		15.0		17.5		20.0		22.5	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
	ft/sec	dia.[c] (μm)	ft/sec	dia.[c] (μm)	ft/sec	dia.[c] (μm)	ft/sec	dia.[c] (μm)	ft/sec	dia.[c] (μm)	ft/sec	dia.[c] (μm)	ft/sec	dia.[c] (μm)	ft/sec	dia.[c] (μm)	ft/sec	dia.[c] (μm)	ft/sec	dia.[c] (μm)
0.0	71	7,900	77	8,100	62	6,000	40	2,800	30	1,700	22	1,000	15	600	10	150	5	250	0	0
5.0	82	10,300	85	10,700	65	7,000	43	3,050	27	1,350	15	600	7	330	3	165	0	0	0	0
12.5	90	12,000	86	10,800	62	6,000	39	2,600	26	1,300	16	675	10	450	4	200	0	0	0	0
18.0	91	13,100	86	10,800	65	7,000	39	2,600	23	1,200	11	575	7	330	2	120	0	0	0	0
23.0	92	12,600	85	10,700	61	5,850	37	2,160	23	1,200	12	530	4	200	0	0	0	0	0	0
30.0	92	12,600	82	10,300	60	6,000	37	2,160	19	945	7	330	2	120	0	0	0	0	0	0
36.0	87	10,900	77	8,100	50	4,060	31	1,780	17	760	7	330	2	120	0	0	0	0	0	0

[a]Updraft velocity.

[b]Maximum particle size.

[c]Estimated from terminal velocity curve (Fig. 1) for spherical SiO_2 particles. One inch equals 25,400 micrometers (μm).

Note: Velocities listed are calculated for the assumed interaction plane produced by two helicopters operating together at a 100-foot distance from rotor center to rotor center. These velocities were generated by a helicopter of 15,000 pounds gross weight and a disk loading of 8 pounds per square foot.

The following conditions and assumptions were prescribed by AVLABS for determining the velocities and the maximum particle sizes at selected levels in the interaction plane:

a. Two aircraft (24-foot rotor radius) of 15,000 pounds gross weight and disk loading of 8.0 pounds per square foot operating side by side.

b. Separation distance of 52 feet from tip to tip of the two rotors.

c. There is no energy dissipation as the two opposing horizontal wall jets combine to form a vertical updraft interaction plane.

d. Only aircraft skid heights of 0, 5, 12.5, 18, 23, 30, and 36 feet are to be considered in determining the vertical velocities in the interaction plane to identify those particles which are capable of being supported by the air velocities.

e. Assume SiO_2 as the particle chemical composition.

f. Assume rounded to sub-rounded particles.

Assuming no losses due to energy dissipation (c above) means assuming no energy loss by the two opposing horizontal wall jets due to their head-on convergence which produces an upward resultant force (referred to as the interaction plane). This, in turn, means to assume that at the same level the vertical velocities in the interaction plane are the same as those in the horizontal wall jet.

The calculated interaction plane velocities are listed for a helicopter operating at different skid heights (Table XI). The left column lists the skid heights. The rows list at selected heights above the ground in the interaction plane the calculated vertical air velocities and the theoretical maximum spherical SiO_2 particle diameter that can be supported by that velocity.

The maximum particle size that a vertical column of air will support is determined by terminal velocities. Kuhn states that the freefall terminal velocity of a particle is equated to the upflow velocity required to support this particle.[18] Figure 4, adapted from Kuhn's report, was used to determine the maximum particle size for the computed velocities listed in Table XI. For example, when the helicopter is operating at a skid height of 36.0 feet above the ground, the vertical air velocity and maximum particle size in the interaction plane at the 2.5-foot level are, respectively, 77 ft/sec and

[18] R. E. Kuhn, "An Investigation to Determine Conditions Under Which Downwash from V/STOL Aircraft will Start Surface Erosion from Various Types of Terrains," NASA TND-56, Sept. 1959.

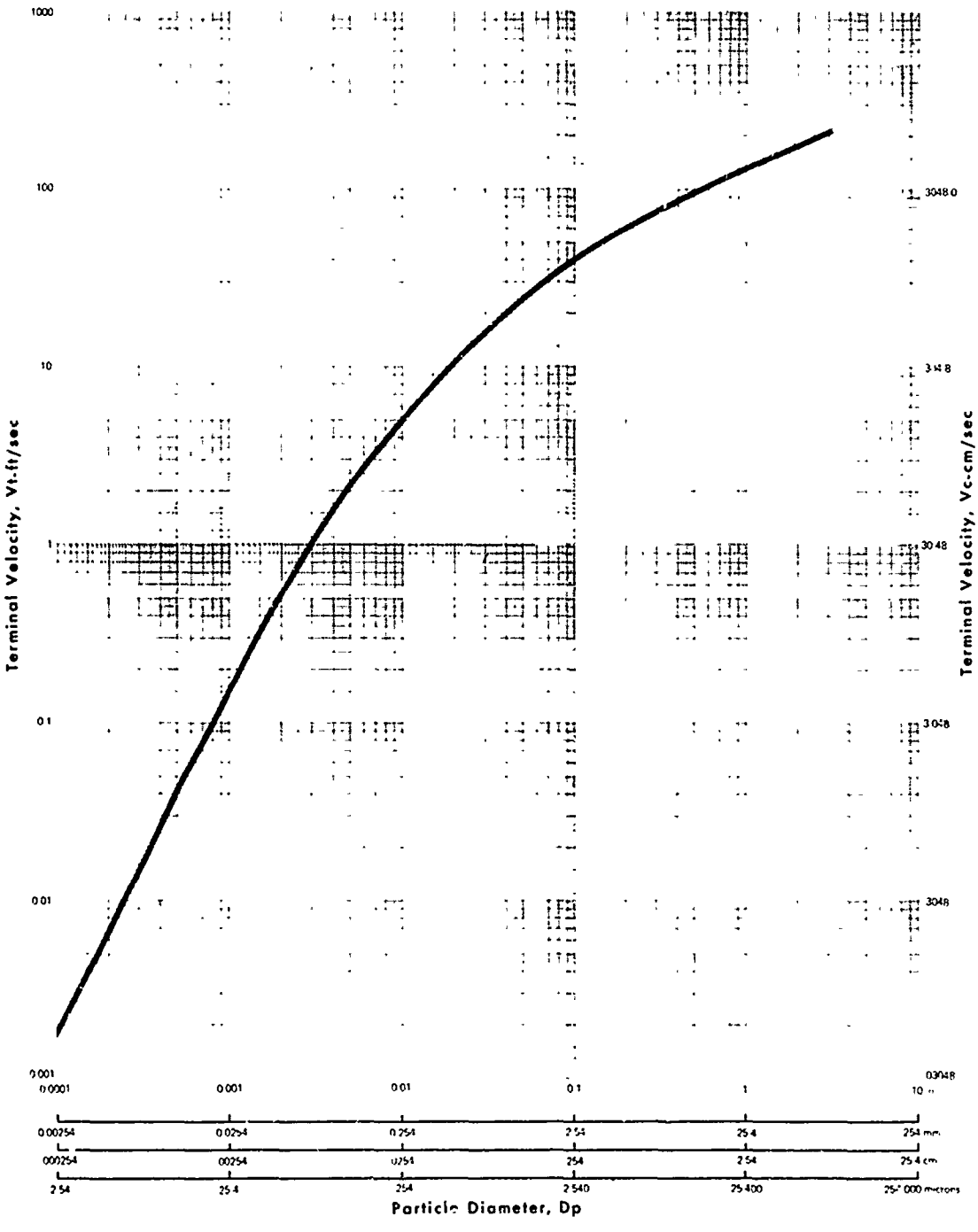

Fig. 4. Relationship of terminal velocity to spherical SiO_2 particle diameter. (Source: Adapted from Richard E. Kuhn, "An Investigation to Determine Conditions Under Which Downwash from VTOL Aircraft will Start Surface Erosion from Various Types of Terrain," Langley Research Center, Langley Field, Virginia, 1959.)

8,100 μm. A second example shows that at a 5.0-foot skid height the velocity and particle size at the 5.0-foot level in the interaction plane are, respectively, 65 ft/sec and 7,000 μm.

Note that for both the 0.0- and 5.0-foot skid heights the velocities are higher at the 2.5-foot interaction plane level than at the 0.0-foot level. When the skid height is ground level (0.0-foot), the velocities at the 0.0- and 2.5-foot interaction plane levels are, respectively, 74 and 77 ft/sec. With a skid height of 5.0 feet, the velocities at the 0.0- and 2.5-foot interaction plane levels are, respectively, 82 and 85 ft/sec. These lower velocities at and very close to the ground are probably due to the friction and turbulence produced as the air moves over the paved surface.

The higher velocity at the 2.5-foot interaction plane level than at the 0.0 level means that, theoretically, larger particles can be supported at the 2.5 level than at the 0.0 level. The first thought is that this will not happen because the particles must get off the ground before they can be supported at the 2.5-foot level. Until reliable and accurate particle sampling and air-velocity measurements are made in the interaction plane and particularly at and near the ground, there will be some question as to what the particle distribution and maximum particle size are at the different levels.

X. CONCLUSIONS

21. Conclusions. It is concluded that:

a. More reliable mathematical models than those currently available are needed to better define and describe the following:

(1) Downwash and updraft patterns and velocities induced by single- and dual-rotor aircrafts.

(2) Particle size distributions and maximum particle concentrations at all lower levels around the helicopters and in the interaction planes between the helicopters.

b. A V/STOL testing area should be established, and programs should be initiated to empirically check the mathematical models for downwash, updrafts, particle sizes, and concentrations. All types of surface conditions including surface materials, particle sizes, soil moisture content, and vegetation should be available naturally or man-tailored in the test area.

The testing could utilize aircraft with crews for low or no-risk situations and aircraft mounted and/or suspended from cranes with booms for high-risk tests. Several cranes and booms would be used for tests involving more than one helicopter. By using cranes and booms, test pilots would not be subjected to unnecessary risks, and the tests could be continued to completion (failure) if so desired.

c. Accurate, reliable, and instantaneous measuring and sampling instruments should be developed that can be easily mounted on the aircraft and at selected distances and heights within the space influenced by the downwash of the rotor or rotors. The most desirable instruments would be those that are automatic and will transmit the measurements to a recording and/or storage bank.

d. A soil sampling program should be initiated, patterned, with one exception, after the one conducted by the Environmental Determination Section of the Naval Weapons Center, China Lake, California. The exception is that the samples should be chosen more discriminately, in other words, not just "out of the direct stream of foot and vehicle traffic." The sample should be surface soil taken from a representative natural (not excavated or filled) surface. This sample, within limits, could then be considered representative of the surface soil mapped for that area and for other areas mapped with the same designators. In the event that the soils are not mapped or are mapped at a gross level, the sample can at least be considered representative of the natural surface in the immediate area.

e. The term "particle" should be used rather than "sand" in all future Army testing and design criteria documents to eliminate the confusion and inconsistencies that are so common in the published testing and design documents..

f. The Knoop hardness values rather than the Mohs hardness values should be used in all design and testing criteria documents.