ENGINEERING DESIGN HANDBOOK

ENVIRONMENTAL SERIES PART ONE

BASIC ENVIRONMENTAL CONCEPTS

HEADQUARTERS, U S ARMY MATERIEL COMMAND JULY 1974

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ENGINEERING DESIGN HANDBOOK

ENVIRONMENTAL SERIES, PART ONE
BASIC ENVIRONMENTAL CONCEPTS

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PREFACE

This handbook, *Basic Environmental Concepts*, is the first in a series on the nature and effects of the environmental phenomena.

Part One introduces the importance of the environment; i.e., its effects, the factors of the environment, the complex combinations of the environment that occur, quantitative environmental concepts, and the testing of materiel and simulation of the environment. The categorization of materiel as it exists and relates to environmental effects also is discussed.

Part One introduces in a general and qualitative manner those factors that are to be treated quantitatively in the succeeding volumes. The revision augments the treatment of those factors and climates, which are a combination of the factors that were discussed only briefly in the original handbook. The chapter on materiel categorization also is added by the revision.

The majority of the handbook content was obtained from various individual contributors, reports, and other publications. Accordingly, it is impractical to acknowledge the assistance of each individual or even each organization which has contributed materially to the preparation of this volume. Appreciation is extended, however, in a general way to the following US Army Materiel Command organizations and through them to the individuals concerned: Frankford Arsenal, Waterways Experiment Station, Army Tank-Automotive Command, Cold Regions Research and Engineering Laboratories, Electronics Command, Harry Diamond Laboratories, Natick Laboratories, Picatinny Arsenal, and Test and Evaluation Command.

The original Part One was prepared by the Southwest Research Institute; the revision was prepared by the Research Triangle Institute, Research Triangle Park, NC–for the Engineering Handbook Office of Duke University, prime contractor to the US Army Materiel Command–under the general direction of Dr. Robert M. Burger. Technical guidance and coordination were provided by a committee under the direction of Mr. Richard C. Navarin, Hq, US Army Materiel Command.

The Engineering Design Handbooks fall into two basic categories, those approved for release and sale, and those classified for security reasons. The US Army Materiel Command policy is to release these Engineering Design Handbooks to other DOD activities and their contractors and other Government agencies in accordance with current Army Regulation 70-31, dated 9 September 1966. It will be noted that the majority of these Handbooks can be obtained from the National Technical Information Service (NTIS). Procedures for acquiring these Handbooks follow:

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CHAPTER 1

THE ENVIRONMENT FACED BY THE MILITARY

1-1 INTRODUCTION

This handbook—the first of the Environmental Series of Engineering Design Handbooks—is an introduction to the environment faced by the military. Emphasis is on information that relates to environmental effects on materiel or materiel requirements. The objectives are to describe the characteristics of the environment, to set forth the situations in which such environmental conditions are encountered, and to identify the adverse effects of the environment on materiel.

In this introductory part of the Environmental Series of Engineering Design Handbooks, the importance of the environment is discussed and the 21 natural and induced environmental factors that produce significant effects on military materiel are identified and individually described. In addition, the nature of the real environment in which various combinations of factors act in concert is discussed. Quantitative concepts relative to the environment, simulation of the environment and materiel testing, and materiel categorization are also included in this introductory part.

1-2 THE ENVIRONMENT DEFINED

Environment is defined in MIL-STD-1165 (Ref. 1) as "the totality of natural and induced conditions occurring or encountered at any one time and place." An alternative definition states that environment is the complex of climatic, edaphic, biotic, and topographic factors that describes a given place.

The description of the environment is tailored for particular considerations. Thus, one may view the environment as having $(n + 4)$ parameters where the three spatial coordinates and time comprise four of these parameters, plus n ($n = 21$ in this handbook series) factors that comprise the climatic, edaphic, biotic, and topographic description. If, however, one is interested in a particular materiel type, many of the environmental factors are of little importance and a more limited set will comprise a sufficient description.

One environment at one location has different factor values than that at another location and, for a given location, the description of the environment at a given time is different from that at another time. In different environments, the environmental factors vary in importance. For example, solid precipitants comprise an important factor in Alaska, but this factor is absent in the Panama Canal Zone. In similar fashion, rain is an important factor in the outdoor environment in the temperate zone but is unimportant inside a warehouse. The interior of the warehouse, however, is an important region of the environment for military materiel. An attempt is made in Chap. 2 to identify those environmental factors that are important for specific regions of the environment.

In addition to obtaining an accurate definition of environment, it is important to understand the meaning of terminology that includes the word "environmental" as an adjective. Thus, environmental control implies modifying the effects of certain environmental factors to reduce stresses on materiel or personnel. Environmental design criteria are environmental factors representing a given degree of stress severity with regard to equipment, and environmental engineering is that branch of engineering concerned with the control of environmental factors and the design of materiel to function adequately under various environmental conditions. Environmental protection is provided to people or equipment and evaluated performance will be obtained under various environmental operating conditions.

1-3 ENVIRONMENTAL FACTORS

The components or descriptors of the environment are termed "environmental factors". Table 1-1 lists the 21 environmental factors that are discussed in the Environmental Series of Engineering Design Handbooks. These factors are believed to provide a complete description of the environment for the use of design engineers. Additional factors could have been included, or some of the factors that are included could have been either subdivided into several factors or combined with other factors to provide a more comprehensive factor. For example, terrain is included as a factor but could have been readily divided into hydrography, topography, and soils. Sand and dust could have been combined with atmospheric pollutants; vibration, shock, and acceleration could have been made a single factor; and other modifications are equally possible. Consideration of environmental effects on materiel and military operations resulted in the list given in Table 1-1 as being deemed most appropriate.

Most environmental factors are neither static nor universal. The occurrence or absence of environmental factors, or ranges of factor characteristics normally are used as a basis for defining terrestrial regions such as arctic, tropic, or temperate. The wet tropics, for example, are characterized by heavy rainfall, high atmospheric humidity levels, moderately high ambient temperatures, abundant vegetation, and a large population of both micro- and macrobiological organisms. The wet tropics, however, are void of sand or dust, solid precipitants, and fog. In particular, all of the environmental factors characterized as induced factors are produced primarily by man's activities. In all cases, caution must be employed in the assignment of specific environmental factors to a given area, since these may change radically with seasons of the year or with climatic conditions. It is well known that some regions of the earth previously covered with vegetation are now almost desert in character, that rainfall patterns are continuing to change, and that man's activities sometimes have large effects on local environmental factors.

1-4 CLASSIFICATION SYSTEMS

Classification of the different types of environment is useful since unique sets of factors are associated with various places, conditions, or functions. For example, the "operational environment" and the "logistics environment" are important functional classifications that are employed to categorize those environmental conditions associated with military operations or with the logistic system. In similar fashion, one may use "warehouse environment" to categorize environmental conditions found within warehouses; other examples are "laboratory environment", "aircraft environment", "open-storage environment", or "battlefield environment".

Important classification systems are associated with terrain and are employed in topographic mapping. Descriptors such as mountains, plains, marshlands, and rivers have definite and important meanings. A system for more precise classification of topographic features is described in Chap. 2, Part Two, as are various classification systems for soils.

Probably the most important classification systems are those associated with climate. While a variety of climatic classification systems exist, the one defined in AR 70-38 is applicable to Army materiel considerations (Ref. 2). Eight climatic categories are grouped into four types of climate as given in Table 1-2. The ranges of environmental factors associated with each of these climatic categories is given in Table 1-3; their geographic extent is given in the map of Fig. 1-1 and

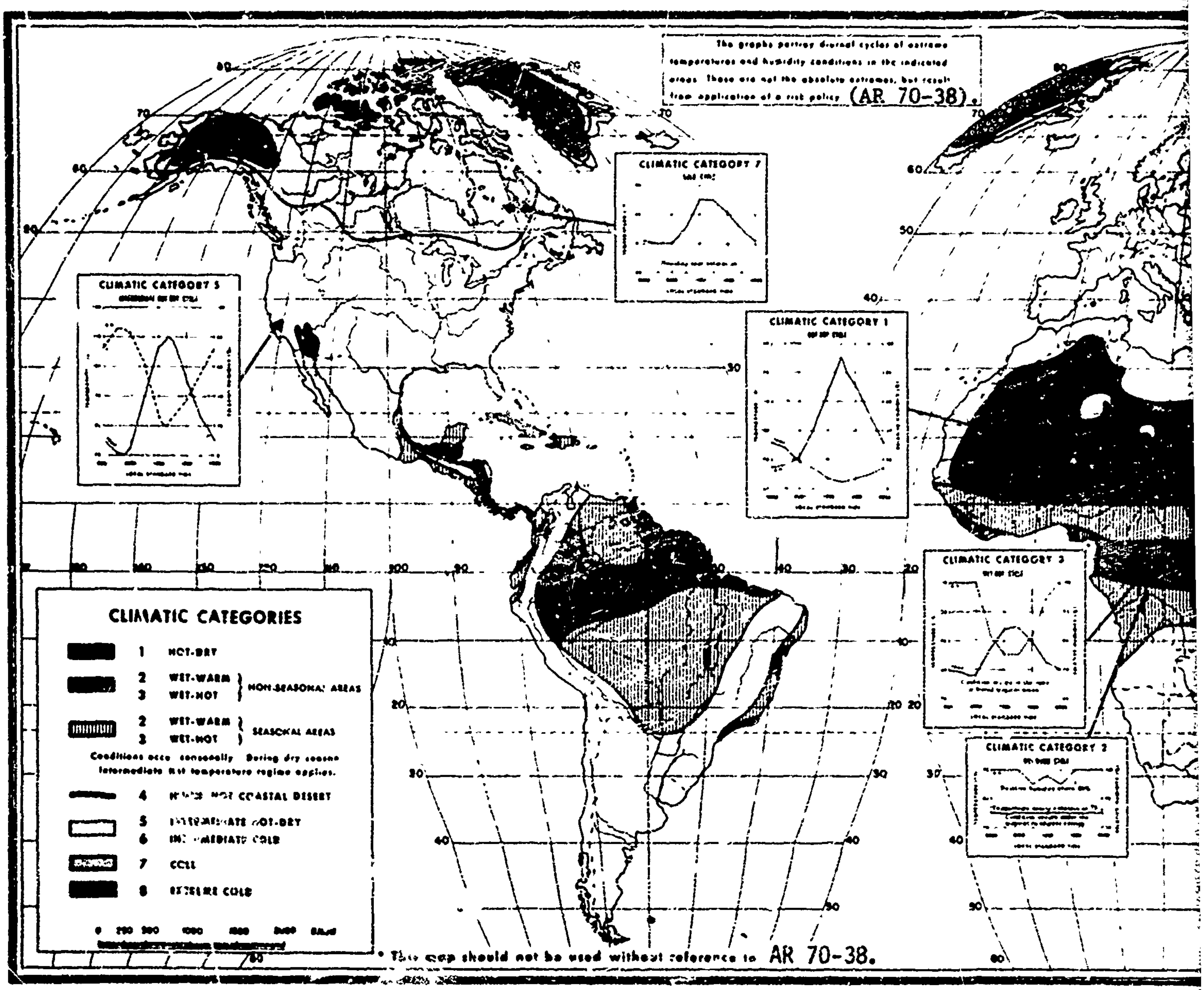
TABLE 1-1
MAJOR ENVIRONMENTAL FACTORS

Type	Class	Factor
Natural	Terrain*	Topography Hydrology Soils Vegetation
	Climatic	Temperature Humidity Pressure Solar radiation Rain Solid precipitants Fog Wind Salt Ozone
	Biological	Macrobiological organisms Microbiological organisms
Induced	Airborne	Sand and dust Pollutants
	Mechanical	Vibration Shock Acceleration
	Energy	Acoustics Electromagnetic radiation Nuclear radiation

*In this handbook series, terrain is considered to be one factor.

TABLE 1-2
CLIMATIC CLASSIFICATION SYSTEM

Climatic type	Climatic category
A. Hot-wet	1. Wet-warm 2. Wet-hot 3. Humid-hot coastal desert
B. Hot-dry	4. Hot-dry
C. Intermediate	5. Intermediate hot-dry 6. Intermediate cold
D. Cold	7. Cold 8. Extreme cold


The graphs portray diurnal cycles of extreme temperatures and humidity conditions in the indicated areas. These are not the absolute extremes, but result from application of a risk policy (AR 70-38).
CLIMATIC CATEGORY 7
CLIMATIC CATEGORY 5
CLIMATIC CATEGORY 1
CLIMATIC CATEGORY 3
CLIMATIC CATEGORY 2
CLIMATIC CATEGORIES
1 HOT-DRY
2 WET-WARM
3 WET-HOT
NON-SEASONAL AREAS
2 WET-WARM
3 WET-HOT
SEASONAL AREAS
Conditions occur seasonally. During dry season intermediate hot temperature regime applies.
4 HOT COASTAL DESERT
7 COLD
8 EXTREME COLD
This map should not be used without reference to AR 70-38.

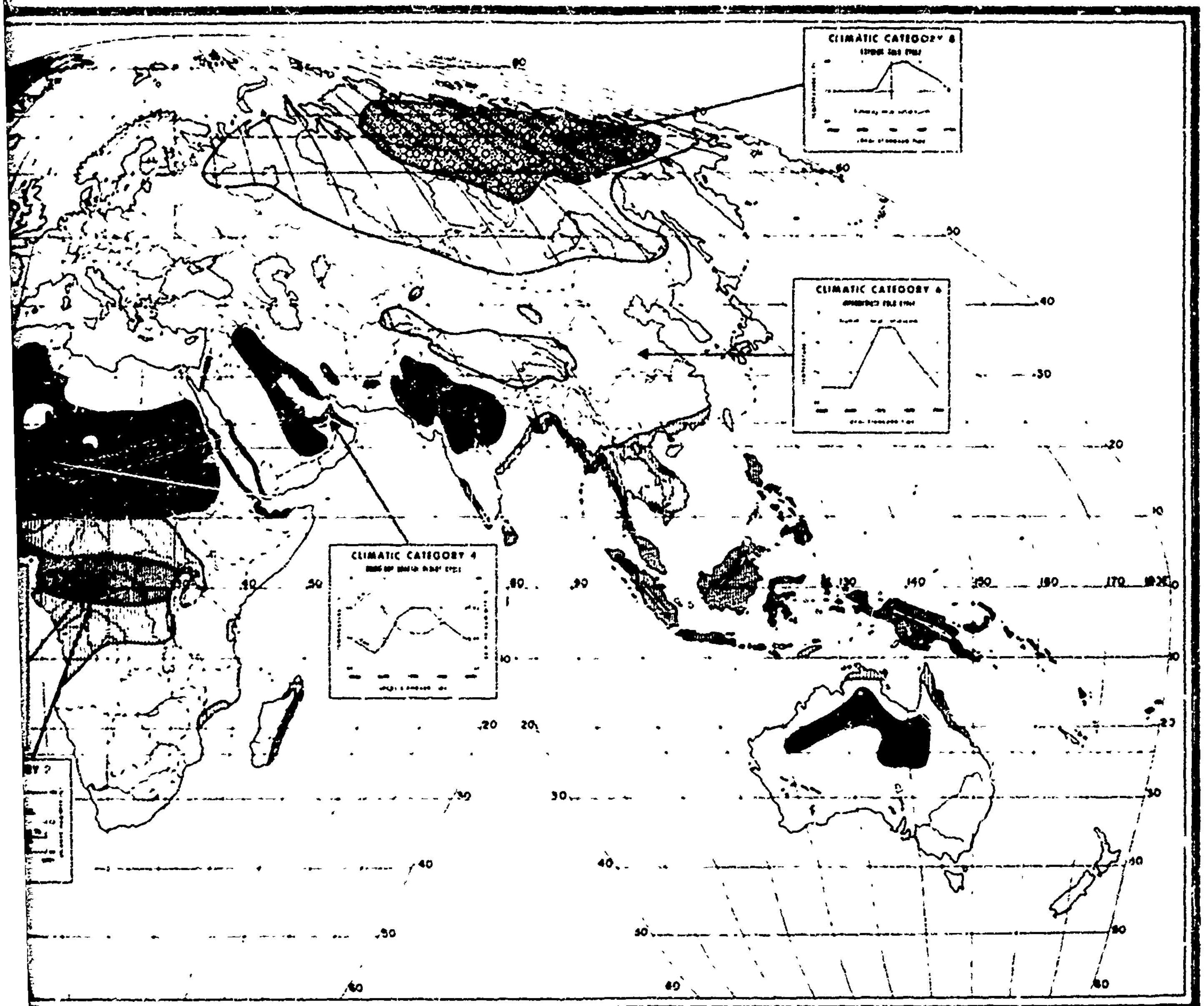


Figure 1-1. Areas of Occurrence of Indicated Climatic Categories

TABLE 1-3
SUMMARY OF TEMPERATURE, SOLAR RADIATION, AND RELATIVE HUMIDITY DIURNAL EXTREMES (Ref. 2)

Climatic category	Operational conditions			Storage and transit conditions	
	Ambient air temperature, °F	Solar radiation, Btu/ft²/hr	Ambient relative humidity, percent	Induced air temperature, °F	Induced relative humidity, percent
1 Wet-warm	Nearly constant 75	Negligible	95 to 100	Nearly constant 80	95 to 100
2 Wet-hot	78 to 95	0 to 360	74 to 100	90 to 160	10 to 85
3 Humid-hot coastal desert	85 to 100	0 to 360	63 to 90	90 to 160	10 to 85
4 Hot-dry	90 to 125	0 to 360	5 to 20	90 to 160	2 to 50
5 Intermediate hot-dry	70 to 110	0 to 360	20 to 85	70 to 145	5 to 50
6 Intermediate cold	-5 to -25	Negligible	Tending toward saturation	-10 to -30	Tending toward saturation
7 Cold	-35 to -50	Negligible	Tending toward saturation	-35 to -50	Tending toward saturation
8 Extreme cold	-60 to -70	Negligible	Tending toward saturation	-60 to -70	Tending toward saturation

additional details concerning each climatic category are given in AR 70-38.

Terminology such as shock and vibration environment, temperature environment, or nuclear radiation environment often is used in the literature. This usage is misleading--shock and vibration are important in some environments and unimportant in others; the temperature range of a given environment always can be given special consideration; and a significant level of radiation can be used to distinguish certain environments from others. To avoid ambiguity, however, it is best not to classify environments on the basis of single environmental factors.

REFERENCES

1. MIL-STD-1165, *Glossary of Environmental Terms.*
2. AR 70-38, *Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions.*

CHAPTER 2

IMPORTANCE OF ENVIRONMENT

2-1 INTRODUCTION

The importance of environment to materiel may be categorized as follows:

(1) Environmental effects result in performance deterioration, thereby creating a maintenance burden.

(2) Environmental effects shorten the useful life of many materiel items, thereby affecting the procurement and logistic functions.

(3) Environmental effects create a requirement for many specialized materiel items in order to insure operational capabilities.

(4) Environmental effects place demands on materiel performance that greatly increase the costs of development and production of all materiel subject to Military Specifications.

(5) Environmental effects on materiel sometimes have major impact on the success or failure of military operations.

The importance of environment is established by the large magnitude of these maintenance, procurement and logistic, operational, and performance burdens. This chapter provides information on these environmentally imposed burdens in order to substantiate the pervasive importance of environment in all materiel considerations. It also seeks to identify those factors of most concern in the more important regions of the environment.

In discussing the importance of environment to materiel, it is essential to recognize that both effects of environment on materiel and requirements for materiel resulting from environment are important; e.g., it is equally as important for the design engineer to know that airborne sand can rapidly destroy a truck engine as it is to know that operations in regions where blowing sand is common require the placement of additional filters on engine-air intakes. Solutions to problems associated with vehicular mobility on snow cover may be better solved by use of special vehicles than by design changes in conventional transport. Examples such as these are found throughout the discussion of environmental factors in subsequent parts of this Environmental Series.

Material deterioration assumes a variety of forms, depending on the particular item of materiel being considered. That such deterioration occurs is neither surprising nor without benefits. In fact, manmade materials that are not biodegradable have generated considerable concern since, after their useful purpose has been realized, they become problems in the waste stream. Deterioration is just a form of natural change that is more obvious in those material forms that man has created. Given sufficient time, nature would restore all manmade materials to their natural forms.

Maintenance is the effort to counteract the effects of materiel deterioration, whether the deterioration is induced by environmental factors or results from normal wear during use. It takes the form of cleaning, parts replacement, repainting, lubrication, performance testing, and similar functions. Maintenance required by environmental effects is costly and every effort is made to design materiel that is impervious to environmental effects.

In this discussion we are concerned with those forces associated with environmental factors that tend to degrade the useful function that man has built into materials and structures.

2-2 PERFORMANCE DETERIORATION AND REQUIRED MAINTENANCE

In order to gain perspective on the importance of environment, it is useful to examine the spectrum of environmental effects that result in materiel deterioration. In the paragraphs that follow, this is accomplished by giving examples of deteriorative effects. The list of examples is not exhaustive; additional examples are given in subsequent parts of this Environmental Series of Engineering Design Handbooks. The examples given, however, are sufficient to indicate the importance of such effects.

2-2.1 EFFECTS ON SURFACE FINISHES

A majority of the materials used in structures, mechanisms, and devices are chosen for useful functions, not necessarily for their stability in the natural environment. For this reason a majority of these materials are furnished with a surface protective coating of some type. It may be a plating on metal, paint, or a chemical treatment of the surface. In the complete spectrum of environmental factors, these surface finishes deteriorate with time. Sometimes the deterioration process is more rapid than at other times. Experience of the Army with the deterioration of surface finishes covers many areas. It has been noted, for example, that trucks received in specific operational areas during World War II often required painting upon arrival before being put into service. This resulted from the severe stress of the tropical environment on the then available surface finishes.

Surface finishes may be deteriorated by temperature, humidity, solar radiation, rain, solid precipitants, fog, wind, salt, ozone, macrobiological organisms, microbiological organisms (microbes), pollutants, and sand. Often, these factors act in synergism, or one of them is supportive of the action of another. Microbes, for example, are inactive without sufficient humidity and a sufficiently high temperature. Sand requires wind to damage a surface. It has been noted that a sandstorm can strip the paint from a vehicle and thus expose the bare metal to corrosion. Humidity, rain, solid precipitants, and fog are very similar in their effects. Often the specific deteriorative factor cannot be identified, but a combined effect of several factors with unknown relative impacts is assumed. Too often, surface deterioration results from damage that compromises the protective coating and allows corrosion, rot, or abrasion to start.

2-2.2 EROSION

Erosion is employed here to describe gross removal of materiel from a structure. This occurs, for example, when windblown sand actually cuts away wood from telephone poles, often reducing their diameter by 50 percent in less than 1 yr. Erosion is produced by natural forces such as windblown sand, water, or the action of wind by itself. Its primary effects in military operations are the erosion of roadways and other topological features by water, erosion of exposed surfaces by blowing sand and dust, and the induced erosion of sand. Another commonly observed example of erosion is that of pilings in saltwater that are so weakened by molluscan borers that the wood is carried away by the wave action.

2-2.3 ROT AND DECAY

Rot and decay are products of deteriorative processes associated primarily with microbes. Common evidences of such processes include the spoiling of foodstuffs, loss of strength in wood and other cellulosic materials, and the weakening and disintegration of textile products. A large proportion of the consumables used by society eventually are subjected to conditions wherein rot and decay are encouraged. The final result is the eventual mineralization and disposal of the product.

Rot and decay are useful processes contributing much to the economy as well as to the esthetics of modern life. The problem with respect to military materiel is to recognize these materials that are subject to this environmental factor and to provide techniques for avoiding deterioration during the useful life of the materiel item. This is accomplished with protective barriers, chemical treatment, dehumidification, and cold storage.

2-2.4 CORROSION

Corrosion is a form of deterioration that is associated primarily with metals. It is an extremely important form of deterioration and is influenced by a variety of environmental factors. For example, a type of corrosion closely associated with vibration and shock is known as stress-corrosion, which is very important in vehicles as well as other metal structures. It results from the combined effect of strain on the metal and subsequent corrosion induced at the strain point through microscopic cracks. The rusty nail, however, is the most common evidence of the corrosion processes that are most evident in areas where atmospheric salt or pollutants support the corrosion processes. Although the corrosion of metals is one of the most costly and prevalent material deterioration processes, it can be avoided by adequate surface protection and good practices.

2-2.5 ELECTRICAL PROPERTIES

Environmental effects on electrical and electronic components are related primarily to temperature and humidity, although other factors produce less important effects. Classifications of electrical failures include insulation breakdown, nonconducting switch contacts, changing resistance values, physically broken components, and the change in parameters of active devices such as tubes and transistors. Dirt and other atmospheric contaminants contribute to problems with switch contacts and the deterioration of insulation. Heat, however, is the most important deteriorative factor for electrical properties, causing reduced tube or transistor life, breakdown of insulation, and other similar processes. Shock and vibration, acting in synergism with temperature, result in most physical breakage. Examples of this include broken wires, cracked insulators, and malfunctioning electromechanical mechanisms.

Much effort is expended in the design of electrical and electronic apparatus to provide protection from environmental effects. This includes provision for cooling and dehumidification, shock mounts, derating of components, filtering of cooling air, and extensive use of protective coatings.

2-3 REDUCTION IN USEFUL LIFE

A large quantity of military materiel is lost through the effect of environmental factors without ever being used because of the conditions under which it is transported and stored. An even larger quantity of materiel has a reduced useful life because of environmental effects. This is most obvious in operational situations where materiel is more exposed to environmental stresses. Rust, mildew, and rot are common effects that cause various items to be discarded. Rubber hoses attacked by ozone, wood damaged by termites, pilings eroded by marine borers, textiles damaged by moths, aircraft antennas corroded by salt, and vehicle brake linings prematurely worn by sand are other examples.

Many forms of attack by environmental factors can be alleviated or obviated by proper design and procurement. Much progress has been made in preventing the common forms of deterioration. The effects of shock and vibration during off-the-road operation of vehicles, the peculiar problems of oversnow transport, the severe corrosion and microbiological attack of the wet-tropics, and the erosion of blowing sand and dust, however, are examples of environmental stresses for which complete protection is too costly. The military accepts, then, the resultant deterioration and pays the cost in reduced useful life of materiel until more cost-effective protective measures are found.

Much environmental damage is triggered by misuse and other types of damage. Corrosion may start with a scratch in a painted surface; rot may follow damaged packaging; erosion of roads follows inadequate maintenance; and termite damage may result from poor construction practices. If the designer uses the best materials and provides the known protective measures, and if the materiel is used properly and carefully, then much of the concern with environmental damage would be unnecessary and the useful life of Army materiel would be little affected by the environment.

2-4 SPECIAL MATERIEL REQUIREMENTS

The identification of special materiel requirements with environmental effects is not necessarily clear. For example, the effect of terrain on mobility may call for tracked vehicles, but tracked vehicles are also required to provide operational capabilities not otherwise available. Is this a requirement imposed by the environment or by operations? The same ambiguity applies to such materiel requirements as oversnow transport vehicles, fog dissipation systems, warehouse dehumidifiers, nuclear-radiation-hardened equipment, and amphibious vehicles. In each case, an operational requirement exists for operating in an environment that has adverse effects on materiel. Without the operational requirement, special equipment would not be required; because of the requirement, special equipment must be provided because of the various environmental factors to be faced.

It is thus clear that, while the environment imposes a need for much special equipment, the provision of such equipment directly determines the operational capability of the Army. The analysis of the costs and benefits of such requirements is beyond the scope of this handbook. The provision of such equipment, however, does constitute a major element of cost in materiel procurement.

Examples of special materiel requirements, in addition to those cited previously, include raincoats, snowshoes, foghorns, pontoon bridges, air conditioners, and cushioning materials for packing. This list could have included a very large number of supply items.

2-5 MILITARY SPECIFICATIONS

Aside from the costs asso[illegible]h special materiel items but closely [illegible] maintenance costs and the limitations on useful life of Army materiel are the costs associated with procurement of materiel to Military Specifications, including stringent environmental requirements. The requirement that an item not only survive undamaged but also operate normally in a full range of environmental factors is sometimes very difficult to meet. The testing to prove that the requirements are met is an additional cost factor. That these requirements are placed on large quantities of materiel items, the majority of which are never exposed to environmental extremes, is adequate testimony to the importance placed on such requirements. The sometimes large cost escalation associated with meeting the environmental requirements in Military Specifications is deemed fully justified by the assurance of performance obtained for those few items that are exposed to severe environmental stresses. The added reliability achieved under normal conditions of such materiel is a bonus.

2-6 SUCCESS OF OPERATIONS

Environmental effects on materiel have a large impact on military operations—at times determining the success or failure of a mission. It is well known, for example, that the inoperability of German vehicles in the severe Russian winter was a factor in the defeat of the German Army in Russia during World War II. Even aircraft engines could not be started in the extreme cold. Another example of environment affecting large military operations is the delay of the Normandy landings by adverse environmental conditions—the storm in the English Channel. However, a majority of environmental effects on operations are found in the smaller day to day operations, e.g., (Ref. 1):

> "... meanwhile the tanks had charged down the road to perform the second part of the mission, but just short of this goal, they ran into a stretch of boggy land that proved to be a veritable tank trap. This area of wet ground limited the area of maneuverability to the road and a stretch immediately south of the road. In this unfavorable position, the tanks were hit by 88's with such deadly fire that after losing nine vehicles the attack was forced to withdraw."

This example was obtained from the operational report of an infantry regiment in Tunisia in 1943. The success or failure of military operations is compounded from a multitude of such small events. Such events as mud inhibiting mobility, inclement weather preventing aircraft operations, personnel performance being restricted by extreme cold, and artillery fire being inhibited by poor visibility can be vitally important tactical effects. In some cases, the effects result from a lack of capability of available materiel, while in others they result from deterioration of materiel performance or from unavailability of suitable materiel.

There is insufficient information available to document the direct effects of materiel deterioration on mission failure or success. The failure of a piece of electronic equipment, gun, tank, or other materiel item due to cumulative deterioration resulting from environmental stresses is not documented as an environment effect. Often such data only appear as a statistic describing the useful lifetime of a particular item. The total of such effects, however, is one of the more important environmental effects and, through its cumulative impact on logistics, maintenance, and operations, contributes importantly to the probability of mission success.

2-7 FACTOR IMPORTANCE

The relative importance of the various environmental factors varies with circumstances. If one considers that the materiel life cycle consists of storage, transportation, and operational use, then this variation may be examined. In the storage environment, materiel is protected by both the warehouse and its packaging from factors such as rain and solar radiation. On the other hand, because of the possible long duration of such storage, slow-acting factors such as ozone and salt are more important than would otherwise be true. In transportation, the mechanical factors are important but the slow-acting factors have little or no effects. In operations, the packaging that protects materiel is discarded, and full exposure to the natural and induced factors occurs. Not only are more factors active, but their severity is greater. Materiel with an expected lengthy operational life receives more exposure to the environmental factors and thus is susceptible to greater effects.

The importance of environmental factors is tabulated in Table 2-1 for the various regions of the environment.

REFERENCES

1. C. E. Hesaltine, *Military Operations As Characterized by the Effects of Environment*, George Washington University, Washington, D.C., September 1957.

TABLE 2-1
ASSOCIATION OF FACTOR IMPORTANCE WITH REGION OF ENVIRONMENT

Region of the environment	Terrain	Temperature	Humidity	Pressure	Solar radiation	Rain	Solid precipitation	Fog	Wind	Salt	Ozone	Macrobiological organisms	Microbiological organisms	Atmospheric pollutants	Sand and dust	Vibration	Shock	Acceleration	Acoustics	Electromagnetic radiation	Nuclear radiation
Storage	0	A	A	C	0	0	0	0	0	C	C	B	B	C	C	C	B	0	0	0	0
Transportation																					
Highway	A	B	B	0	C	B	B	B	C	0	0	0	0	0	C	A	A	C	0	0	0
Rail	A	B	B	0	C	C	B	C	C	0	0	0	0	0	C	A	A	C	0	0	0
Ship	0	C	B	0	C	C	0	B	C	B	0	C	0	0	0	B	C	C	0	0	0
Air	0	B	C	C	0	C	C	A	B	0	0	0	0	0	C	B	B	B	0	0	0
Operational use																					
Cold regions	A	A	A	0	B	A	A	B	B	C	0	C	0	C	C	B	B	0	C	B	C
Hot-wet	A	A	A	C	B	A	0	0	B	B	0	C	A	0	0	B	B	0	C	B	C
Hot-dry	A	A	0	0	A	0	0	0	B	B	0	0	0	0	A	B	B	0	C	B	C
Temperate	A	A	A	C	B	A	B	B	B	B	C	C	B	C	B	B	B	0	C	B	C
Indoor use	0	B	B	0	0	0	0	0	0	0	0	C	C	C	B	C	0	0	0	B	C
Operational storage	0	A	A	0	B	B	B	0	C	B	C	B	B	C	C	0	C	0	0	C	C

A - Major importance
B - Important
C - Minor
0 - Absent

CHAPTER 3

NATURAL ENVIRONMENTAL FACTORS

3-1 INTRODUCTION

Thirteen natural environmental factors are discussed at length in this series of handbooks and also are described briefly in the following paragraphs. These factors and the induced environmental factors discussed in Chap. 4 are associated with climatic categories in Chap. 5. When the effects of factors are considered individually as in this chapter and in Parts Two and Three of the Environmental Series of handbooks, the process is referred to as single-factor analysis and offers the most direct means for assessing environmental effects. Such analysis is limited, however, in its applicability since it does not describe the actual circumstances encountered in the environment. Multifactor combinations are discussed in Chap. 5 and, at length, in Part Four, *Life Cycle Environments*, of the Environmental Series of handbooks. Detailed data on natural environmental factors are presented in Part Two of this handbook series which serves as the prime reference for all of this chapter. The information in this chapter is intended only to identify and introduce each factor.

3-2 TERRAIN

By definition, terrain comprises the physical features of land and thus includes topography—the geometric contours of the landscape; hydrography—the lakes, streams, and other water bodies on the land; vegetation—forest, grasslands, or thickets; and soils—the composition and strength properties of the underlying earth. In describing terrain, therefore, it is necessary to discuss each of these major parts of the terrain separately since each is a major field of knowledge and activity.

The topography of land normally is indicated on maps by contour lines of equal elevation above a reference level, i.e., sea level. The spacings between contour lines thus provide information on slope. Additional information is provided by indicating the land areas that consist of mountains, plateau regions, hilly areas, or plains. More quantitative descriptions of topography are obtained by classifications based on slope angles or obstacle dimensions (Ref. 1).

Qualitatively, the vegetation portion of terrain is described as dense forrests, wooded areas, thickets, underbrush, grasslands, marshlands, or cultivated agricultural areas. For military purposes, where mobility is of major concern, quantitative vegetation descriptors include parameters such as stem diameter, stem spacing, and recognition distance. Such descriptions are not concerned directly with the type of vegetation present nor with the coexistence of different types (Ref. 1).

Hydrologic descriptions of terrain are concerned primarily with rivers because of their varying nature although the presence of lakes and marshlands is important. The presence and course of rivers are indicated on maps. Additional quantitative information that is employed for military purposes includes parameters such as differential bank height, gap side slopes, water depth, water width, and water velocity, which would indicate the fordability of a stream. Quantitative information is usually unavailable on seasonal variability in water flow parameters which are sometimes the most important element of hydrography for military considerations. An example of a hydrologically complex terrain is shown in Fig. 3-1.

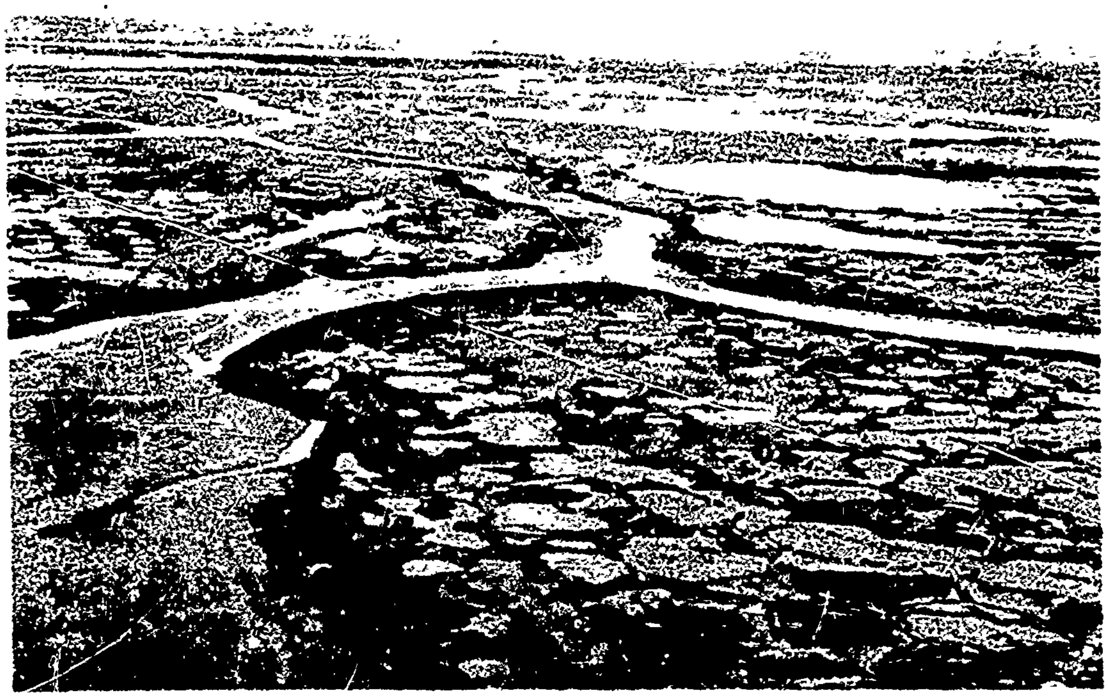


Figure 3-1. Coastal Plain in Arctic Showing Summer Surface Conditions With Numerous Thaw Lakes and Stream Channels (Ref. 4)

The composition and physical properties of soils are very important to mobility and construction considerations. This has led to the evolution of a number of classification systems based on soil type (e.g., clay, loam, or sand), on the physical nature of the soils (e.g., rock content, plasticity, or grain size), or on macroscopic mechanical properties (e.g., tractive and bearing capabilities). One of the more important of these classification systems is known as the Unified Soil Classification System which is widely employed by engineers for construction purposes (Ref. 2).

Information on terrain is available in a variety of forms including tabulated engineering data and maps which display a variety of terrain information in a wide range of detail and of accuracy. Efforts are underway to obtain a greater amount of usable information in terrain descriptions. An example of this is the generation of areal terrain-factor complex maps which include classifications based upon 21 terrain parameters (Ref. 1). Another attempt to enhance the data base for terrain uses power spectrum density curves to describe the roughness of terrain on a local level. Terrain information is being expanded rapidly by the increased use of a variety of remote sensing techniques, both aircraft and satellite borne, which provide a very large amount of terrain data (Ref. 3).

The effects of terrain vary in their nature and importance. Mobility is often the prime element of success in military operations and terrain determines land mobility. It is not surprising, therefore, to find much emphasis on trafficability, off-road mobility, and river crossing problems. In any theater of operations in which ground forces play a major role, mobility will continue to be of major importance, and this importance has many effects both on materiel and on materiel requirements. Materiel is exposed to all modes of transport across terrain; materiel requirements are determined by the nature of the terrain; and much special materiel is required for achieving an effective ground mobility (Ref. 5).

Terrain has other effects of lesser importance on materiel. For example, all types of construction are affected by the terrain, particularly soil strength properties. The approach to the consideration of such effects, however, is similar to that employed in nonmilitary construction and, as a result, a large body of information and techniques as well as materiel is available and is used. Another important effect of terrain relates to concealment and visibility. For example, mountains affect artillery effectiveness, provide concealment, and degrade detectability. The same is true of many types of terrain features and, because of these effects, new materiel requirements are created to lessen their impact.

3-3 TEMPERATURE

No environmental factor is more pervasive than temperature. The temperature of the earth as determined by its thermal energy balance is the prime determinant of human existence. It also controls and determines the nature of other environmental processes. All natural environmental factors are affected by temperature, and most induced environmental factors are influenced greatly by temperature. The measurement and study of temperature processes have received more attention than almost any other subject, and the consideration of environmental effects on materiel has, at times, consisted exclusively of temperature studies.

The average temperature of the earth, of course, is determined primarily by the amount of solar radiation that impinges on the earth. Variations in temperature in various regions of the earth thus depend to a large extent on the variability of insolation levels, although other factors play important roles. Regional and local temperatures are subject to various thermal energy controls and circulation patterns involving ocean and air currents, terrain features, and even the gross effects of civilization. Thus, the descriptions of the temperature of the environment involve details of these thermal energy controls.

Temperature patterns in forests, soils, urbanized areas, mountains, and other regions of the environment must be specified so that the effects of temperature in such circumstances can be defined. Much data have been assembled on temperature phenomena, and both gross and detailed patterns are known. The extremes of temperature, both high and low, for these different regions and for the different components of the environment are documented. An example of data is shown in Fig. 3-2 where the diurnal temperature cycles of six locations are shown for a 1-yr span. These studies extend into those portions of the environment in which the temperature is controlled or affected by man's activities (Ref.6).

The internal temperatures of structures and vehicles are equally important. These are subject to control but are often uncontrolled, being determined by combinations of natural and induced processes.

The effects of temperature on materials is a complex subject. All deteriorative processes are affected by temperature. Usually, the extremes of temperature are most important. Most material changes are accelerated by increases in temperature and are slowed by decreases in temperature. Any extreme of temperature or rapid change in temperature has adverse effects on some materials.

3-4 HUMIDITY

Humidity closely follows temperature in importance as an environmental factor. Atmospheric water vapor is essential to life and is a determinant of the importance of the effects of a number of other environmental factors.

The exchange processes between the various physical states of water are well known so that the water vapor content of the atmosphere can be correlated closely with other environmental conditions. Terminology such as vapor pressure, relative humidity, mixing ratio, absolute humidity, mole fraction, saturation, dewpoint, and latent heat is employed to describe various properties or processes involving atmospheric water vapor (Ref. 8). With such descriptions, reasonably valid descriptions can be obtained of the geographic distribution of atmospheric water vapor without actual measurement data. Proximity to bodies of water, rainfall, snow cover, atmospheric circulation patterns, and, above all, temperature determine the wetness of the air. The importance of temperature is indicated by the observation that a larger quantity of water is found in the desert air of the Southwestern United States than in the winter air over Alaskan snow cover.

The variation in the concentration of atmospheric water vapor closely follows that of temperature. With increasing altitude, for example, both the temperature and the water vapor content of the air decrease. Diurnal variations in water vapor content follow the daily march of temperature. When the temperature decreases to the extent that air becomes saturated with water vapor, precipitation is likely to occur. Because of their important effects on materiel, the conjunction of high temperatures and high dewpoints has received particular attention. Places where high temperature air is almost saturated with water vapor are limited to seacoasts bordering on warm bodies of water (Ref. 9). An example of a high, fluctuating dewpoint cycle and its associated very hot temperature cycle is given in Fig. 3-3.

Porous materials and the surfaces of materials maintain a moisture level that is in equilibrium with the water vapor in the surrounding air. This moisture level is determined, of course, by the temperatures of both the air and materials. In normal diurnal variations of temperature, it is common for material temperatures to be sufficiently below air temperatures to induce frequent condensation of water onto surfaces.

It is important to note that, while the presence of humidity–particularly when in excess–is a deteriorating factor with respect

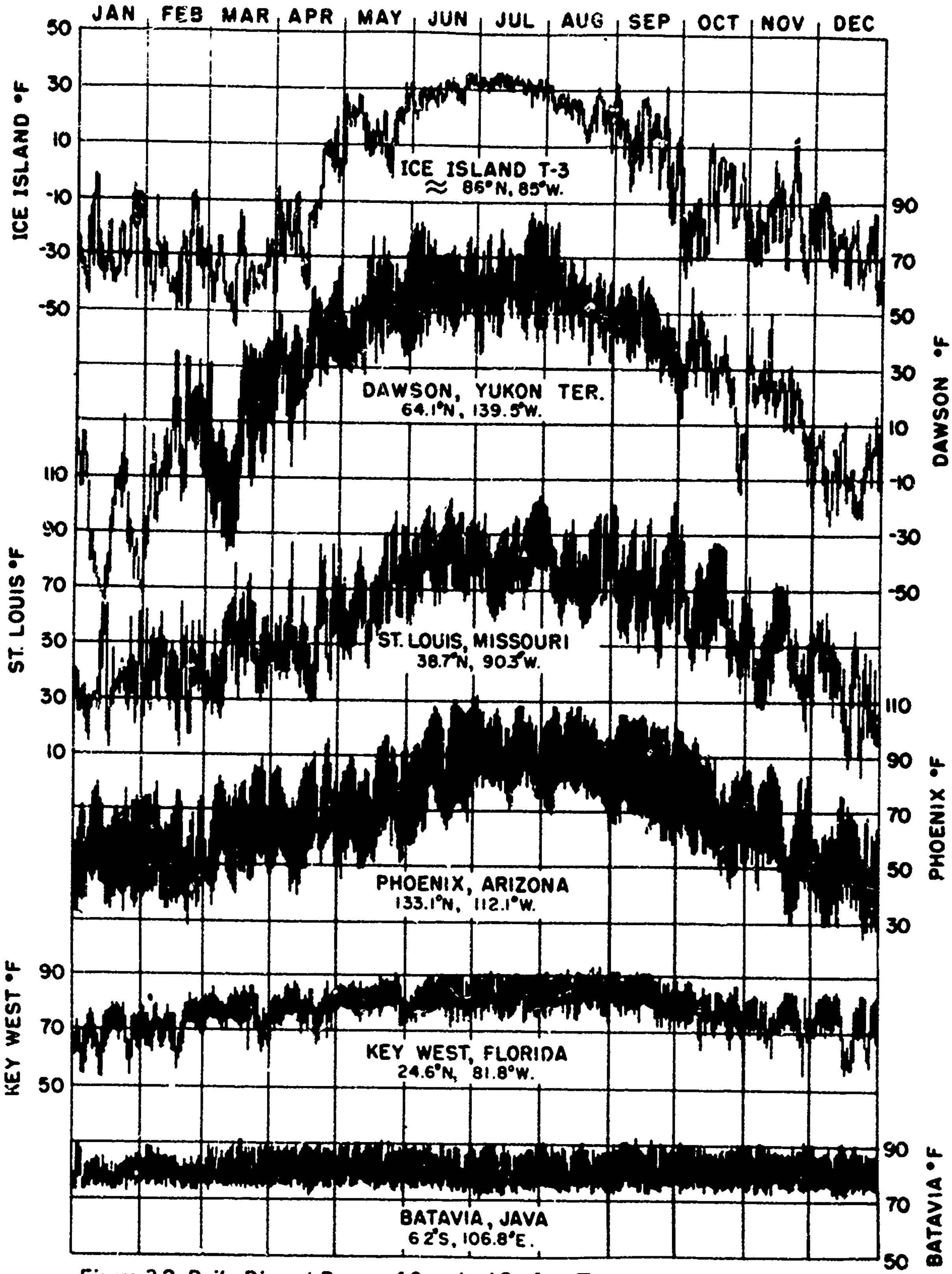


Figure 3-2. Daily Diurnal Range of Standard Surface Temperature at Various Stations for 1943 (Batavia); 1953 (Key West, Phoenix, St. Louis, Ice Island T-3); and November-December 1952, January-October 1953 (Dawson, Canada) (Ref. 7)

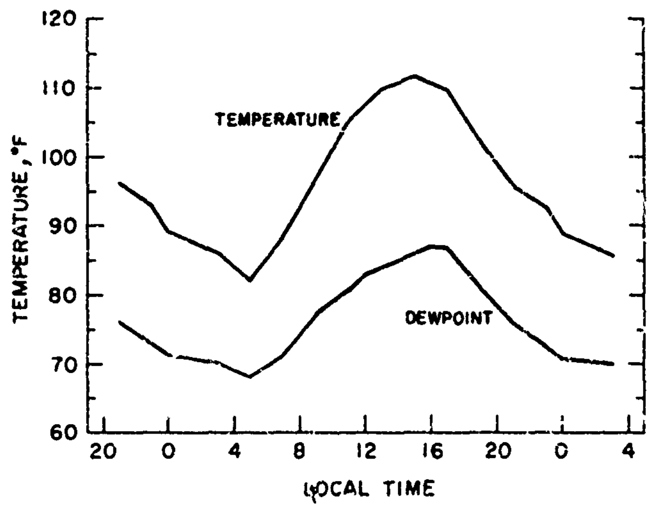


Figure 3-3. Composite of Five Daily Cycles of High Temperatures and Dewpoint for Abadan, Iran (Ref. 11)

to many materials, in some cases low water vapor content of the atmosphere constitutes an equally deteriorating factor. Rations, cellulosic products, and textiles are affected directly by low water vapor content and the static electricity that results from extreme dryness can produce undesirable effects.

The primary effects of high humidity are to promote corrosion and microbiological attack on material. The most common form of corrosion is the rust that appears on ferrous metals, but other forms of chemical and electrochemical corrosion are common. Humidity affects in subtle ways the performance of electrical and electronic equipment by deterioration of the properties of components. Microbiological deterioration as evidenced by fungal attack, mildew, and rot requires certain minimum levels of humidity to be active. This is observed most commonly in textiles stored in damp environments where mildew growth rapidly ensues but is found also with corrugated packing materials, many types of rations, wood products, and certain types of corrosion. In almost all of these instances, humidity is working in combination with another environmental factor to create the undesirable effect (Ref. 10).

3-5 PRESSURE

The effects of pressure are not sufficiently common to make it one of the more important environmental factors. Pressure variations due to meteorological processes range from lows of about 880 mb to an upper extreme of 1,083 mb. The low pressures are associated with the eyes of tropical storms while the high pressures are associated with wintertime continental high pressure systems (Ref. 12).

Pressure variations also are associated with changes in altitude. As altitude increases, the mass of the air above a given point decreases and, consequently, the pressure decreases. At about 18,000 ft altitude, the atmospheric pressure is reduced to about one-half of its sea level value while at 53,000 ft the pressure is about one-tenth of the sea level value (Ref. 13).

The effects of pressure result primarily from the rapid changes that occur with moving storm systems or with the transport or flight of material to high altitudes. Such variations in pressure can cause the rupture of seals, distort containers, or move objects. In moving storm systems, pressure differentials may actually cause the explosion of buildings or the breakage of windows. Pressure changes cause leakage of fluids from containers and control systems, the condensation of trapped water vapor, and equivalent effects. Other effects of pressure include those phenomena associated with the availability of a certain amount of air. Combustion processes are less efficient at lower pressures, the lubrication capability of oils and greases decreases, electrical breakdown occurs more frequently, heat transfer is less efficient, and liquids vaporize more readily. The heat-absorbing capacity of air, for example, varies as shown in Table 3-1. Design engineers should be alert to these effects of pressure on materiel that will or may be exposed to reduced pressures of high altitude, either in shipment or in use, as well as to the effects of rapid pressure changes associated with storm systems.

3-6 SOLAR RADIATION

Although the radiation that impinges on the earth from the sun is essential to life on earth, it would be lethal to life without the filtering effect of the atmosphere. The quantity and specular distribution of solar radiation that is absorbed at the surface of the earth is dependent upon the motion and orientation of the earth with respect to the sun, atmospheric absorption processes, and the nature of the surface on which solar radiation impinges (Ref. 15). The effect of atmospheric absorption is seen in the solar irradiance curves of Fig. 3-4.

Diurnal and seasonal changes in insolation are dependent on the rotation of the earth about its axis and its orbit about the sun. These predictable changes vary only slightly over longer time periods (Ref. 6).

TABLE 3-1

HEAT-ABSORBING CAPACITY OF AIR (Ref. 14)

Altitude, ft	Percent heat-absorbing capacity of given volume of air to that at sea level
0	100
20,000	50
40,000	25
60,000	10
80,000	3
100,000	1

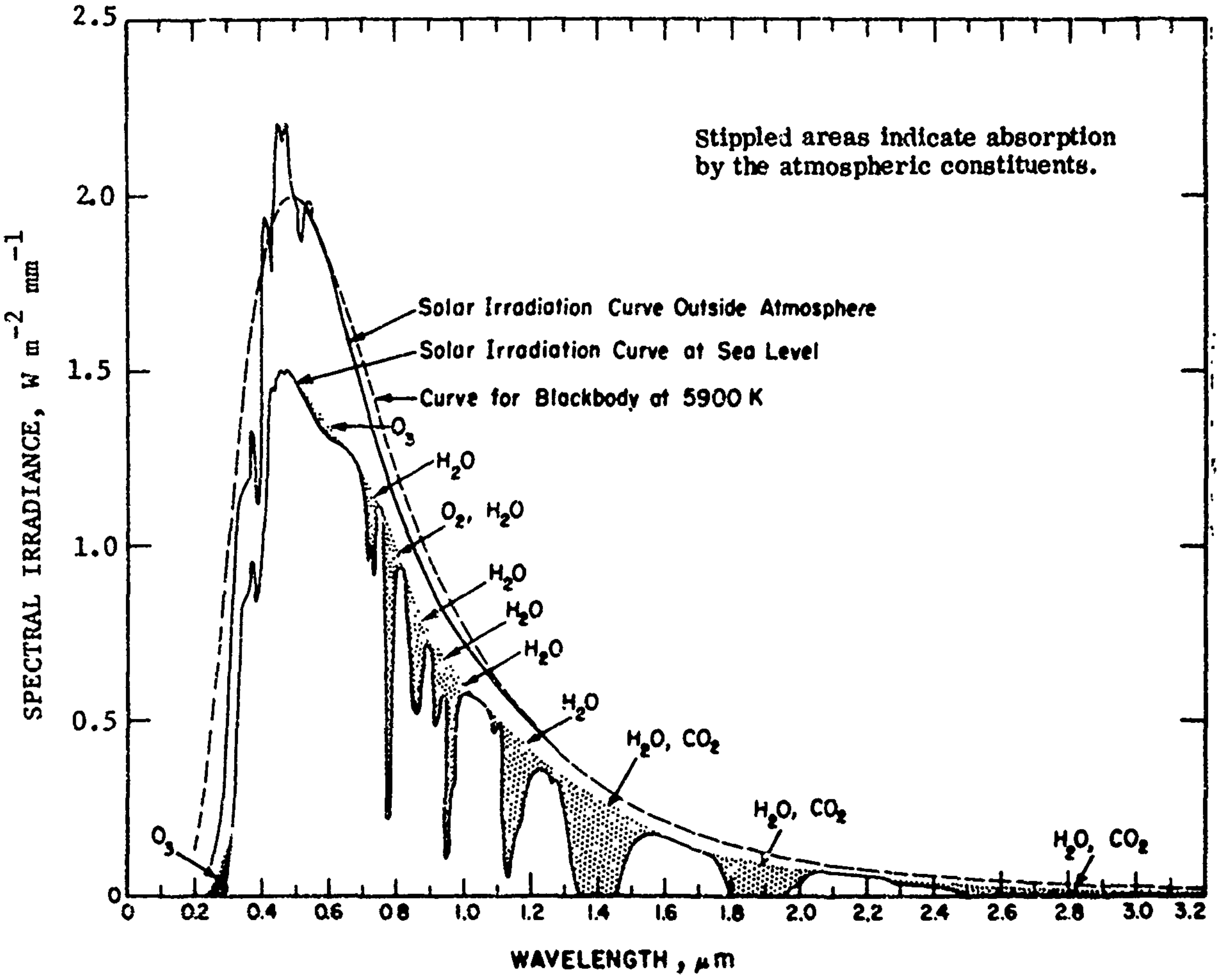


Figure 3-4. Spectral Distribution of Solar Radiation (Ref. 14)

Atmospheric processes contribute a large amount of variability to the solar radiation at the surface of the earth due to the changes in atmospheric absorption and reflection processes as evidenced, for example, by cloud cover. These changes are less predictable on any but a short-term basis but do occur in certain regular patterns.

At the surface of the earth, as little as 5 percent (fresh snow) to as much as 95 percent (coniferous forest) of the incident energy is absorbed. The remainder is reflected. In most cases the energy is absorbed in a thin layer on the surface, but in the case of clear water, it may penetrate for large distances below the surface. The most significant part of this absorbed energy is reradiated at a different wavelength into the atmosphere and provides the bulk of the atmospheric thermal energy. The remainder of the absorbed energy serves to heat the oceans or soil and participates in various forms of energy circulation or storage before it ultimately is reradiated into the atmosphere (Ref. 6). Estimates of mean global energy-flow patterns are given in Fig. 3-5.

Since solar radiation incident on the surface of the earth is highly dependent on atmospheric conditions (primarily cloud cover), intuitive concepts with regard to those geographic regions receiving the maximum solar radiation are sometimes erroneous. Data on solar radiation also are affected by the period of time for which average solar radiation is being reported. For example, the maximum and the minimum average monthly solar radiation levels are found in the Arctic and Antarctic where, during the long winter nights, the average monthly solar radiation is zero and, during the summer with 24 hr of solar radiation each day, the monthly averages are the largest observed on earth. On an annual basis, however, the subtropics with their long periods of clear skies receive more solar radiation than elsewhere on earth. Nevertheless, when considering the effects of solar radiation, one must be aware that 1 mo of exposure in an arctic summer can exceed exposure levels anywhere else on earth (Refs. 17,18).

The effects of solar radiation on materiel are often similar to those of high temperature since solar radiation elevates the temperature of many materials quite rapidly. Nonthermal effects, however, are important. The high-energy short-wavelength components of solar radiation induce reactions in materials that often deteriorate their functional properties. Textiles, paper, plastics, rubber, and various surface coatings are susceptible to solar radiation induced changes. A commonly observed effect is that of bleaching of colors from textiles through the action of sunlight. This is brought about through chemical changes in the dyes induced by the ultraviolet portion of the solar radiation.

Solar radiation is an environmental factor for which special material requirements are established that may be as costly as the deteriorating effects that solar radiation has on materials. Requirements for air conditioning, shade, special clothing, sunglasses, and other protection from the direct effects of solar radiation are important to the materiel design engineer. But for all of these adverse effects of solar radiation, its beneficial effects, although not discussed here, are much greater.

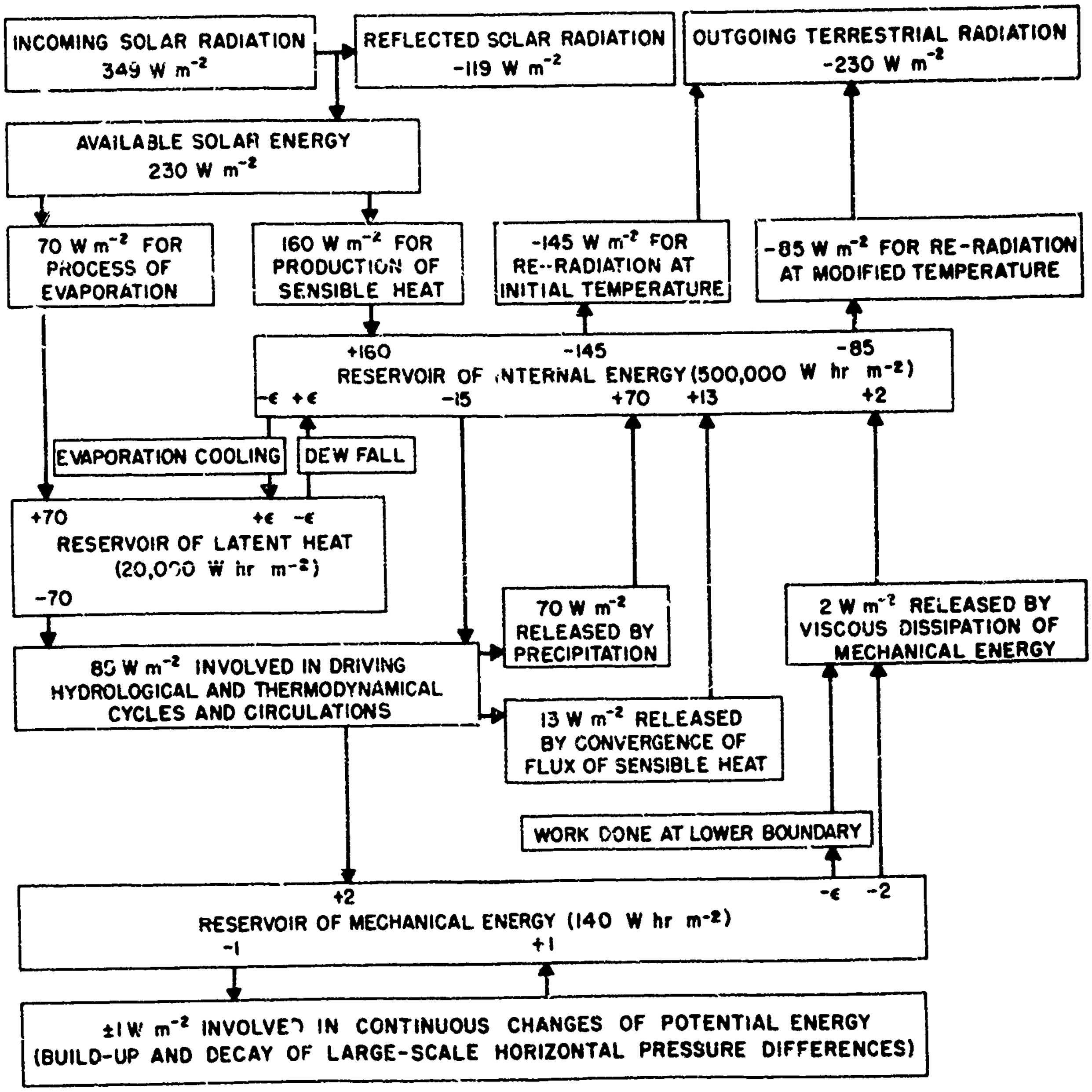
3-7 RAIN

Rain is a familiar natural environmental factor but this familiarity does not result in simplicity in the consideration of rain properties. The frequency with which rain falls and the magnitude of its effects have led to the definition and study of a variety of rain properties that are derived in large part from the effects of rain on materials and operations.

Properties of rain that are of interest to design engineers include the following (Ref. 19):

(1) Raindrop shape, size distribution, mass velocity, and impact energy and pressure

(2) Liquid water content



Note: A solar constant of 1395 W m^{-2} and a global albedo value of 0.34 are assumed. The average total incoming radiation to the globe is 1/4 of the solar constant. ϵ denotes an average rate of less than 0.5 W m^{-2}.

Figure 3-5. Estimated Mean Global Energy Flow (Ref. 16)

(3) Rainfall intensity.

(4) Physical and chemical properties of water in rain.

In addition to these properties of rain, the nature of rainfall throughout the earth is of interest, including characteristic intensity patterns, durations, and variations in the listed properties as they occur with geographical positions. With respect to geography, the heaviest rains are found in the tropical latitudes, and belts of frequent rainfall are found in the middle latitudes. Longitudinal variations in rainfall patterns are controlled almost completely by topography and prevailing wind directions over large water bodies. Thus, rainfall is more abundant at higher altitudes and near seacoasts. Different types of rain are derived from these topographic and meteorologic dependencies; e.g., convective rain, cyclonic rain, and orographic rain.

Data have been obtained on rainfall rates, frequency of occurrence of rainfall, the hours per year in which rain occurred, the frequency of rainfall occurrence in days per year, and other data bases for reporting rainfall. Extremes of rainfall are also available and are dependent upon the length of the time period employed. Thus, a rainfall of about 3.18 cm (1.25 in.) has been observed to occur in 1 min; for a 20-min interval, the record is a little over 20.3 cm (8 in.); for a 12-hr period, the record is 135 cm (53 in.); for 1 day, the record is 188 cm (74 in.); and for 1 yr, the highest recorded rainfall is 2,647 cm (1,042 in.) (Ref. 20). A graphical representation of record rainfalls, based on other data, is given in Fig. 3-6.

The effects of rain fall into three categories; those that occur while the rain is in the atmosphere, those occurring on impact, and those occurring after deposition of the rain on the surface of the earth. Rain while falling deteriorates radio communications, limits radar effectiveness, limits aircraft operations due to visibility restrictions, damages aircraft in flight, affects weapon accuracies, degrades or negates optical surveillance, and decreases the effectiveness of personnel in exposed activities. The impact of rain on surfaces causes erosion of surfaces, particularly exposed earth, and also imposes very large forces on structures. After deposition, rain has the essential properties of water in its deteriorative effects. Thus, it degrades the strength of materials, promotes corrosion, deteriorates surface coatings, decreases off-road mobility capabilities, causes destructive flooding, directly destroys certain types of exposed materiel, and can render electrical and electronic apparatus inoperative. Some of these effects of rainfall are common (i.e., the erosive effects of rainfall on exposed earth) while other effects are less well known (i.e., radar attenuation). All, however, have been subjects of many investigations and much data are available to aid the design engineer in his efforts to avoid these adverse effects of rain on Army materiel.

3-8 SOLID PRECIPITATION

This environmental factor includes all forms of ice that are derived from atmospheric moisture. Although snow is the most important of these precipitants, graupel, ice pellets (sleet), ice crystals, hail, glaze, rime, and hoarfrost also are included and are at times important environmental factors. Because those regions of the earth that are exposed to solid precipitants are also militarily important, the effects thereby have been developed for operating in snow-covered regions. Emphasis on this aspect of solid precipitants should not detract from the devastating effects of solid precipitants in the temperate zones. The disabling consequences of major snowstorms, widespread glaze, or intense hailstorms must not be overlooked, although they are transient in nature.

While both precipitant snow and deposited snow as well as other solid precipitants are of interest in this discussion, the deposited ice forms are more important because of their longer lasting effects. Snow in the atmosphere is characterized by its density, crystalline

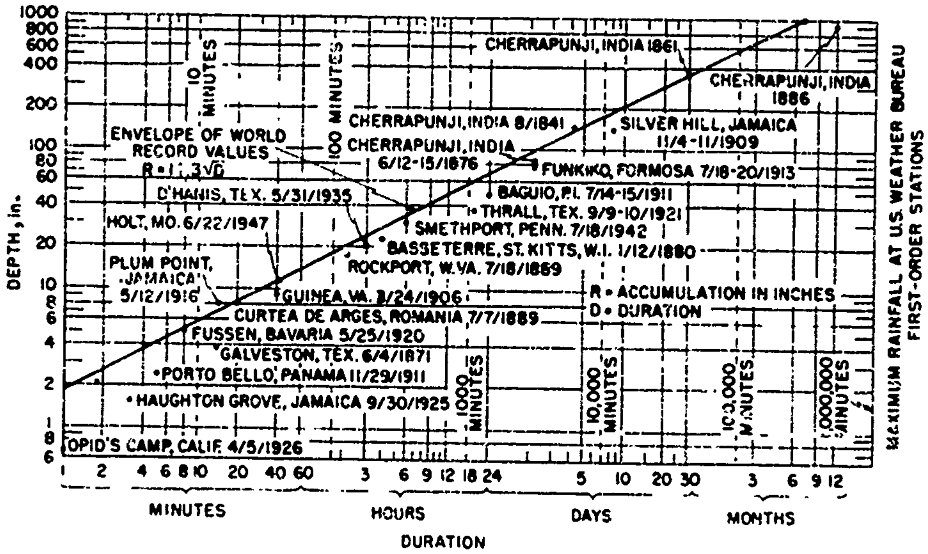


Figure 3-6. A Graphical Representation of World Record Rainfalls (Ref. 21)

structure, and its occurrence. Deposited snow, because of its diverse uses and effects, is subject to more intensive analysis (Ref. 22). Data are available on mechanical properties of snow such as density, porosity, permeability, hardness, grain size, elastic properties, creep, and sliding friction. The strength of age-hardened snow is illustrated in Fig. 3-7. Because snow is an excellent thermal insulator, its thermal properties also have been examined. Data are available on thermal conductivity, the latent heat of fusion, and thermal expansion. Electrical properties of snow are of interest with respect to electromagnetic propagation. This has led to accumulation of information on conductivity and dielectric properties. In similar fashion the optical reflectivity of snow is important with respect to its electromagnetic properties as well as its effect on the energy transfer and visibility in the cold regions.

The other solid precipitants have not been studied as intensely as has snow, but the properties that are important with respect to effects are documented. The important properties of hail, for example, are size, weight, and falling velocity. The largest hailstones reported in the United States, for example, are 13.7 cm in diameter and have a mass of about 450 g. Only one hailstorm in 100,000 would be expected to have hailstones this large, as indicated by extrapolation of the probability data in Fig. 3-8. Glaze, rime, and hoarfrost are forms of ice derived from atmospheric moisture under different meteorological circumstances, thus having distinct characteristics. Hoarfrost is a light, feathery deposit of ice consisting of interlocking ice crystals; rime is a white, opaque, granular deposit formed by rapid freezing of supercooled water drops as they impinge on a surface; and glaze is a hard transparent coating of ice formed by the freezing of supercooled rain or drizzle. An example of rime is shown in Fig. 3-9.

The annual snowfall in various regions of the world is well documented and, in addition to its latitudinal dependence, is affected by topological features such as mountains and water bodies. Annual accumulations in the Northern Hemisphere range from about 3.8 cm to over 3 m but this is not necessarily directly related to the thickness of the snow blanket on the ground. Metamorphic changes, thawing and freezing cycles, and the nature of the snowfall all affect the accumulated depth. A seasonal snowfall of 60 to 75 cm in the extreme cold regions may produce a maximum snow cover of 25 to 50 cm during the month of maximum depth. In the cold regions of the Northern Hemisphere, the greatest accumulation of seasonal snow occurs between 40 and 60 deg latitude. For construction purposes, snow accumulation is also reported in terms of maximum expected snow load on a horizontal surface. In those regions of the extreme cold climate where little or no summer melting occurs, the annual load accumulates from year to year (Ref. 24).

While hailstorms occur in those regions of the earth from the Equator to the 65th parallel, hail occurs sufficiently frequently in certain regions to characterize them as hail belts. These are in midlatitude continental regions. In similar fashions, in other regions the probability of occurrence of the other solid precipitants is large compared to the remainder of the globe (Ref. 25).

The effects of solid precipitants are listed:

(1) Transportation systems are slowed or completely disrupted.

(2) Personnel movements are slowed or stopped.

(3) Snow loading of exposed structures can result in damage.

(4) Obscuration of the terrain makes navigation and position location difficult.

(5) Camouflage is made difficult.

(6) Mechanical apparatus can be jammed or otherwise rendered inoperative.

Figure 3-7. Age-hardened Snow Produced by Sintering in an Undisturbed Winter Snow Pack (Snow is about 30 in. deep) (Photo in late January at Goose Bay, Canada – provided by R. W. Gerdel)

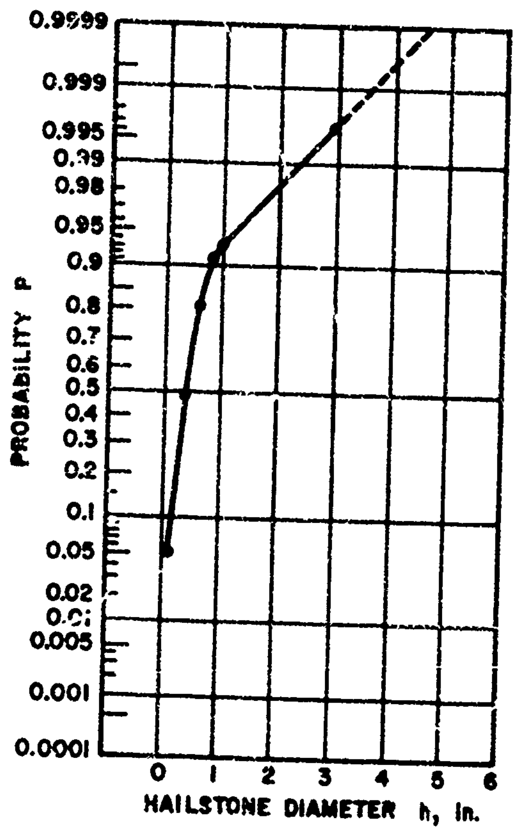


Figure 3-8. Estimate of Probability P That in a Given Hailstorm, the Maximum Hailstone Diameter Will Not Exceed a Certain Value h (Ref. 23)

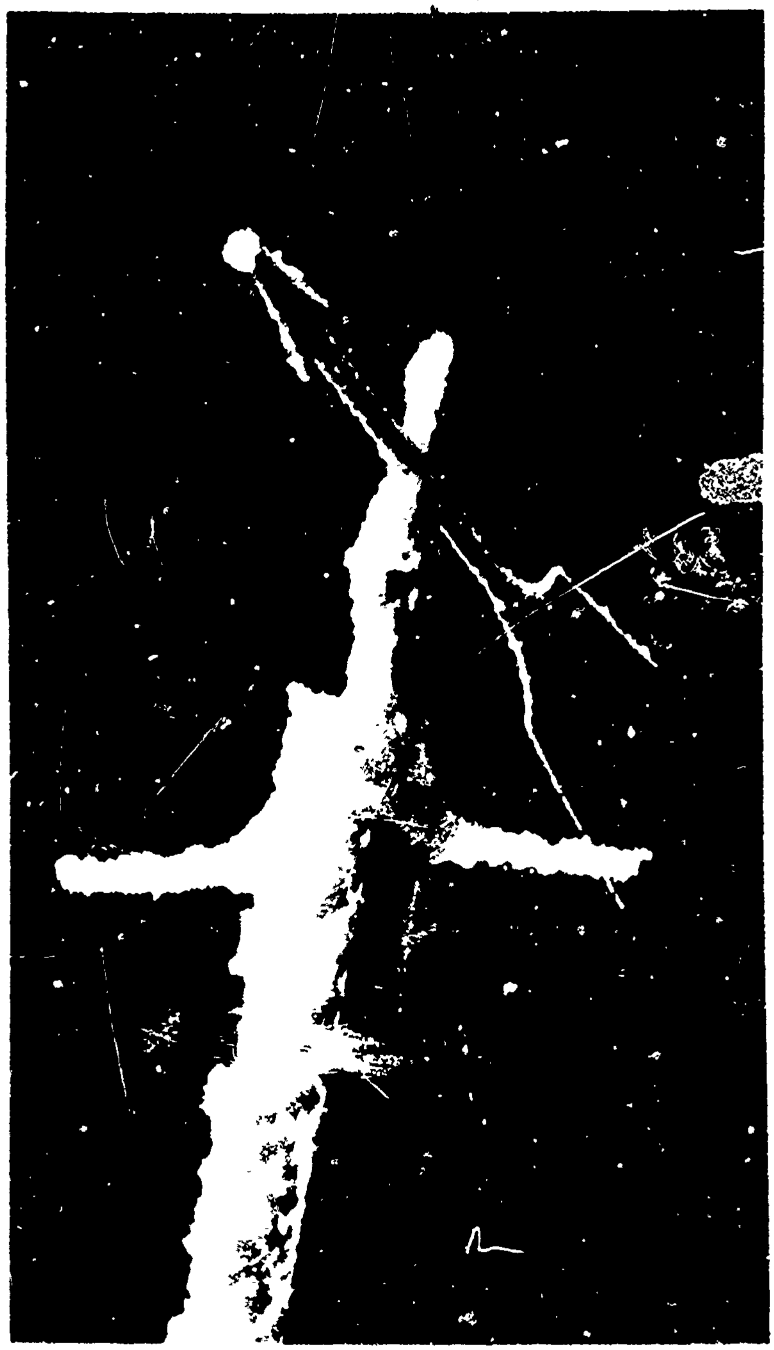


Figure 3-9. Rime on a Windvane Showing the Windward Development of This Form of Solid Precipitation (Photographed at Donner Summit, Calif., by R. W. Gerdel)

(7) The probability of personnel injuries increases.

(8) Electromagnetic propagation is affected by precipitating snow or by deposits on antennas.

(9) Weapon performance may be degraded; i.e.. contact fuzes can fail on a snow cover.

The damaging effects of hailstorms--particularly from the larger hailstones--are apparent. Effects of the deposited forms of ice--glaze, rime, and hoarfrost--are related primarily to the weight that they impose on various materiel items. The most important example of such damage is that occurring to suspended wires associated with power distribution or communication. Ice loadings on vegetation at times create a hazard and impede movements as a result of fallen limbs and trees. It is not uncommon for a large tree to be coated with 50 tons of ice in a glaze storm (Ref. 26).

The largest costs resulting from solid precipitants are associated with snow removal, oversnow transport, and control of drifting snow. A variety of snow removal equipment has been specifically developed and applied to road and airport clearance. Although much of this equipment receives only periodic usage, nevertheless it is required in order to maintain operating capabilities. In similar fashion much effort has been directed toward the development of specialized equipment for oversnow transport in the form of vehicles with tracks or runners. Drifting snow often creates major problems, thus stimulating continuing efforts to control it through use of suitable barriers.

In studies directed towards acclimatization of military operations to the snow-covered environment, the Army extensively has investigated the use of snow as a construction material, including not only snow pavements for aircraft runways and roads but also the use of snow to build structures. One of the more unique examples of snow construction was created at Camp Century in Greenland where the utility of living and working quarters built within the snow cover were demonstrated.

3-9 FOG AND WHITEOUT

Fog and whiteout constitute an environmental factor, their most important effect being the reduction of visibility. Other effects of these phenomena are almost identical to those produced by high humidity or rain and thus will not be discussed in this paragraph.

Fog is essentially a cloud whose base touches the surface of the earth. It consists of a visible aggregate of minute water droplets suspended in the atmosphere. Another form of fog, icefog, is composed of suspended ice particles. Whiteout is a weather condition occurring in extreme cold climates over a snow cover in which the combined effect of the snow cover and fog is such that light is completely diffused. In a whiteout no object casts a shadow, the horizon is not discernible, and light-colored objects are difficult to see (Ref. 27).

Some knowledge of fogs is derived from their formative processes. Thus, there are evaporation fogs, mixing fogs, and cooling fogs. The latter category is subdivided into radiation fogs, advection fogs, and upslope fogs. The small water droplets in fog range in size from 1 to 60 μm, although in most cases the largest diameter is closer to 20 μm (Ref. 28). Ice crystals in icefogs fall within the same range of diameters. The liquid water content of fogs ranges between 0.01 and 1.0 g^{-3}, and the droplet concentration ranges from about 10 to 600 cm^{-3}.

The visibility or visible range in a fog is one of the prime methods for parameterizing the fog and may range from essentially zero in a thick fog to 1 km in a light fog. If the visibility is greater, then the atmospheric moisture is not called a fog (Ref. 8).

Since fogs result from atmospheric condensation of water vapor on nuclei, the presence of small suspended particles or nuclei in the atmosphere is conducive to fog formation, and the nuclei constitute an important impurity source in fog. Condensation nuclei result from combustion processes, chemical reactions in the atmosphere, and entrainment of liquid and solid particles in the atmosphere by wind action.

Large regions of the earth are free from fog. Fog occurs most frequently along coastal regions of large landmasses and frequently is associated with ocean currents, both hot and cold. Ice fog results primarily from injection of water vapor into a cold atmosphere by combustion or other processes associated with man's activities and, therefore, is observed most frequently around habitation in the extreme cold regions (Ref. 29).

As mentioned, the primary effect of fog is on visibility. Efforts to alleviate its effects concentrate on more accurate prediction of fog and the various fog dissipation techniques that have been employed. A successful seeding operation is shown in Fig. 3-10. While land transportation systems are affected by fog, the main effect is on air transport.

3-10 WIND

Wind is another well-known and commonly observed environmental factor. The extreme winds associated with cyclones, thunderstorms, tornadoes, and similar violent meteorological disturbances produce the primary adverse effects. Lighter winds interact with military materiel to some extent, such as to enhance evaporation processes or to carry suspended sand and dust, but these effects are less important in themselves. Airborne sand and dust, being an important induced environmental factor, is discussed separately.

Since wind is a primary factor in meteorology, a large body of information has been compiled on it. The complexities of atmospheric motion as produced by energy exchange processes and as affected by the earth are well known. In discussing the distribution of wind, it is convenient to treat separately the surface layer closest to the earth—a planetary boundary layer—and the free atmosphere in which the jet stream is found. The horizontal distribution of wind is associated with so-called global wind systems and is also well known. Localized phenomena such as sea breezes, the urban heat island effect, and mountain wind systems play important roles in certain regions.

In most regions of the earth, the effects of normal winds on materiel are unimportant. In fact, the beneficial effects of wind in dispersing pollutants and in cooling the environment are very helpful. The adverse effects of extreme winds, however, are important and include the following:

(1) Damage to buildings, bridges, and other structures.

(2) Flooding by wind-driven waters.

(3) Damage to power distribution and communication systems.

(4) Damage to aircraft.

(5) Interference with ground-vehicle operations.

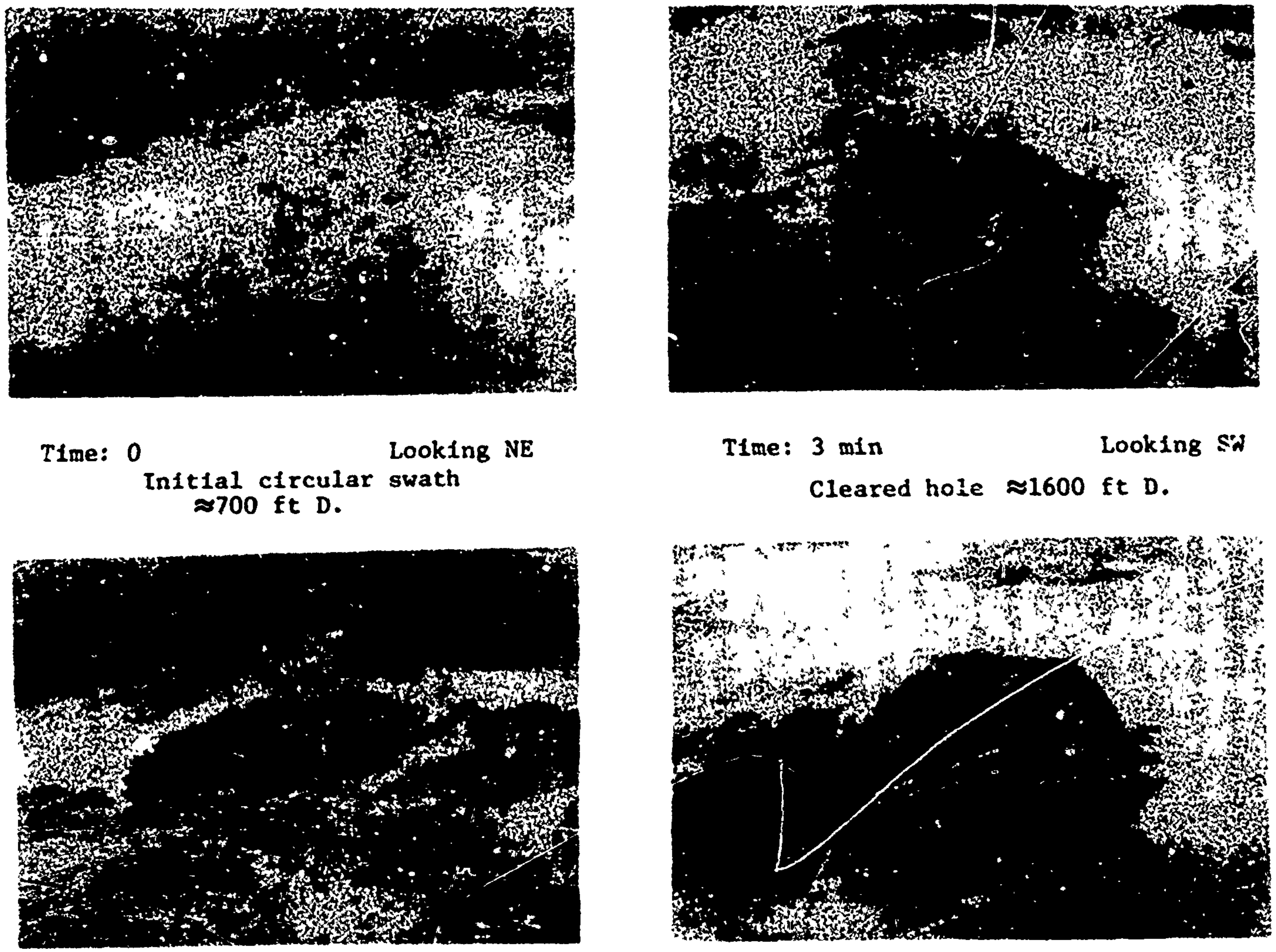
(6) Injuries and damage by windblown objects.

(7) Damage to vegetation and terrain.

(8) Restriction of visibility.

3-11 SALT, SALT FOG, AND SALT WATER

The widespread presence of salt in the environment and the acceleration of corrosion by salt are the reasons for focusing attention on salt as an important environmental factor. Salt, although relatively inactive chemically, is a strong promoter of electrochemical reactions in the presence of water. This property of salt has led to its strong association with corrosion and to the use of salt-spray, salt-water immersion, and salt-fog testing as



Time: 0 Looking NE
Initial circular swath
≈700 ft D.

Time: 3 min Looking SW
Cleared hole ≈1600 ft D.

Time: 5 min Looking NE
Cleared hole ≈2100 ft D.

Time: 6 min Looking SW
Cleared hole ≈2500 ft D.

Figure 3-10. Results of Seeding Ground Fog (Ref. 28) standard methods for determining corrosion resistance of materials.

Salt is used generically to identify sodium, chloride, sulfate, and magnesium ions such as occur naturally and as are entrained in the atmosphere as particles, condensation nuclei, salt fog, and saltwater droplets. In such circumstances, the airborne salt is measured as pounds of salt per cubic mile of air and, in particulate form, its size distribution is given in terms of diameter or weight. Another measurement parameter is saltfall, which is the amount of atmospheric salt deposited on land from the air, usually in units of pounds per acre per year.

Almost all airborne salt results from bubbles produced on the ocean surface or from the breaking of waves on the beach. This results in entrainment of the salt in the atmosphere. Salt is removed from the atmosphere by means of precipitation washout or by dry fallout. In unusual circumstances, sea salt particles from the air impinge on structures such that encrustment occurs (Ref. 30).

Most atmospheric salt is found in the vicinity of oceans or seas. Normal sea winds can carry from 10 to 100 lb of salt per cubic mile of air onto the land. This may increase to 1,000 lb in a storm. The amount of salt entrained in the air depends markedly upon the salinity and temperature of sea water in the particular region.

Salt fallout may be as high as 400 lb $acre^{-1}$ yr^{-1} in the immediate coastal region but drops off rapidly with distance from the seacoast. However, farther inland the salt fallout reaches a constant minimum value at about 2 lb $acre^{-1}$ yr^{-1}, which is characteristic of inland continental areas (Ref. 31).

Almost all of the effects of salt are the result of metal corrosion. Thus, even when paint blistering is observed or when electrical or mechanical equipment is affected by salt, the prime cause of damage is corrosion. A different but related mechanism occurs in salt attack on concrete structures in which vulnerable components of the cement are chemically converted, resulting in scaling and sometimes disintegration (Ref. 10).

3-12 OZONE

Ozone is a gas that occurs in the lower atmosphere in varying, usually low, concentrations coming from both natural and man-made sources. Since it is highly reactive and can be harmful to both people and materiel, its presence as an environmental factor is a concern to design engineers who are charged with providing protection for both materiel and personnel.

Ozone is classified as a natural environmental factor because the largest amount of observed ozone originates in the stratosphere and is transported to the surface of the earth by atmospheric circulation. These natural concentrations are unlikely to exceed 6 pphm. Ozone is produced in the stratosphere by absorption of solar ultraviolet radiation by oxygen molecules. In the troposphere, ozone is produced by photochemical reactions, usually involving pollutants. Ozone also can be produced by photochemical reactions with natural organic vapors and by electrical discharges, ultraviolet radiation, and nuclear radiation.

Only limited data are available on worldwide ozone concentrations. These data are insufficient to allow any general conclusions other than that higher altitudes, pollution, and active vertical airflow are conducive to high ozone concentrations. The diurnal variation in ozone concentration is illustrated in Fig. 3-11.

The effects of ozone on materials are those of a strong chemical oxidant. The most obvious of these effects is that on rubber, which is highly sensitive to ozone attack. This degradation of rubber is observed commonly as ozone-cracking wherein a large number of small cracks appear in the rubber, degrading its strength and ultimately causing it to fail.

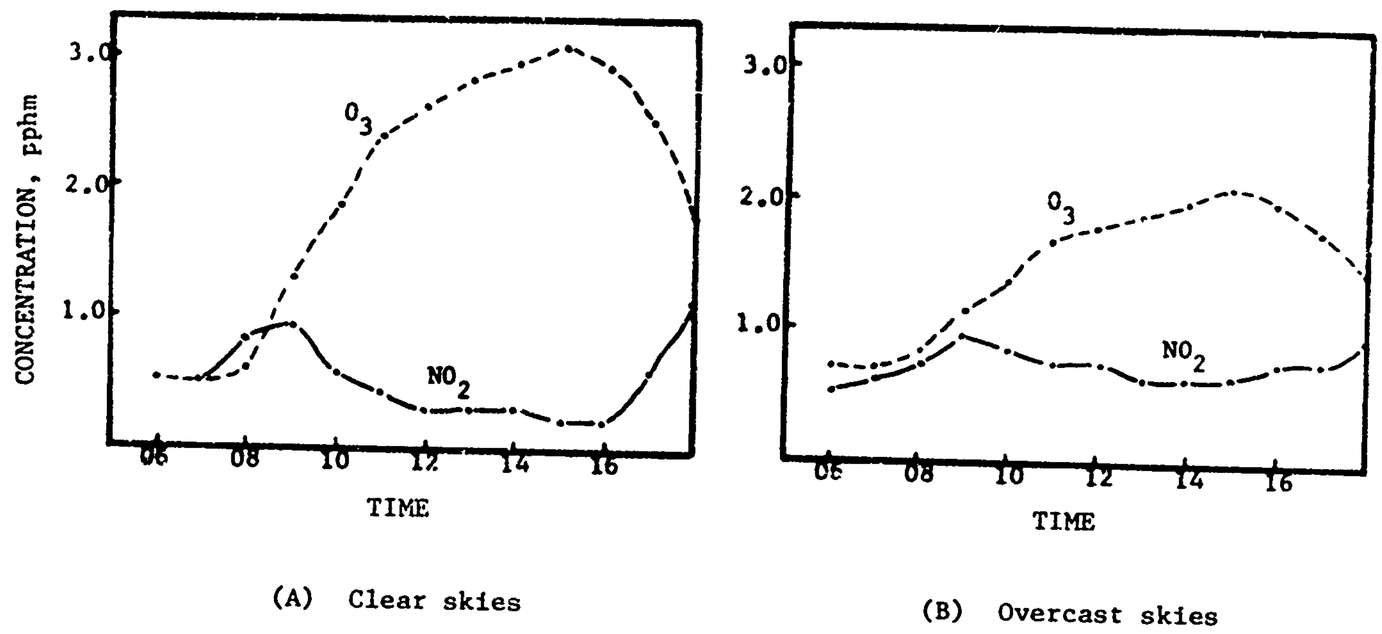


Figure 3-11. Diurnal Variation of Ozone Concentration (and That of Nitrogen Dioxide) in a Rural Environment (Ref. 33)

Ozone attack on an automobile tire is shown in Fig. 3-12. Ozone also attacks cellulose, such as is found in fabrics, and dyes, producing rapid deterioration in these materials (Ref. 32).

Design engineers also must be aware of the ozone-generating potential of some materiel. Electrical and electronic equipment in which high voltages are employed can serve as ozone generators when high voltage discharges occur. The sweetish smell of ozone is not uncommon in electronic equipment environments. Ultraviolet lamps used for germicidal or other purposes also generate ozone and can produce harmful amounts.

The health effects of ozone are important since as little as 1 ppm produces readily discernible effects, and exposure to 9 ppm can produce severe illness.

3-13 MACROBIOLOGICAL ORGANISMS

Macrobiological organisms include all those living things that individually can be seen with the unaided eye. In the animal kingdom this includes all of the insects, marine borers, rodents, reptiles, mammals, and birds. It also includes vegetation. That these types of living organisms do affect Army materiel is obvious. The effects range from materiel destruction by rats and mice to destruction of buildings by termites and damage to aircraft by birds. Macrobiological organisms that are important pests at military installations are listed in Table 3-2. Each type has its individual habits and produces individual effects. The more important macrobiological organisms and their effects are described in the discussion that follows.

The identification and brief discussion of the various major types of macrobiological organisms that affect military materiel and operations do not exhaust the cataloging of effects of this environmental factor. In a given location at a given time, other organisms not mentioned here may create important effects. In some regions of Africa, for example, it is possible that the large mammals may cause problems or that the reptiles may have a significant effect on military operations in some regions. Because such instances are isolated products of particular circumstances and because of the great diversity of macrobiological organisms, it is neither possible nor desirable to discuss all such possible effects.

(1) Termites are the most destructive of the biological agents, damaging wood and other cellulose-containing products. Once a wooden building or other wooden product becomes infested with termites, the damage they cause may be extensive before it is discovered. Fig. 3-13 shows an example. Of the two primary types of termites, the subterranean termites are found in both tropic and temperate areas in large colonies. They frequent warm, moist ground containing abundant food. Nonsubterranean termites do not require a ground contact and are less common. They are found in warm coastal areas in the tropics and subtropics. Termites infest structural timbers, furniture, utility poles, lumber, paper, cloth, fiber insulation panels, and numerous other items (Ref. 35).

(2) Powder-post beetles comprise several families of wood borers that honeycomb hard woods and softwoods. Their name is derived from the excreted flourlike powder deposited mainly in burrows formed by their larvae. At least some species of this insect can be found in all parts of the world and cause considerable damage to wood products (Ref. 36).

(3) Clothes moths damage unprotected animal fibers including wool, mohair, fur, hair bristles, feathers, and down. Damage consists of holes eaten into the materials, which often make an article unsuitable for further use. Clothes moths are distributed widely except in the tropics and are found throughout the United States. In order to flourish, they need an ample supply of suitable food, a temperature of about 27°C, and relative humidities in the 60- to 80-percent range (Ref. 37).

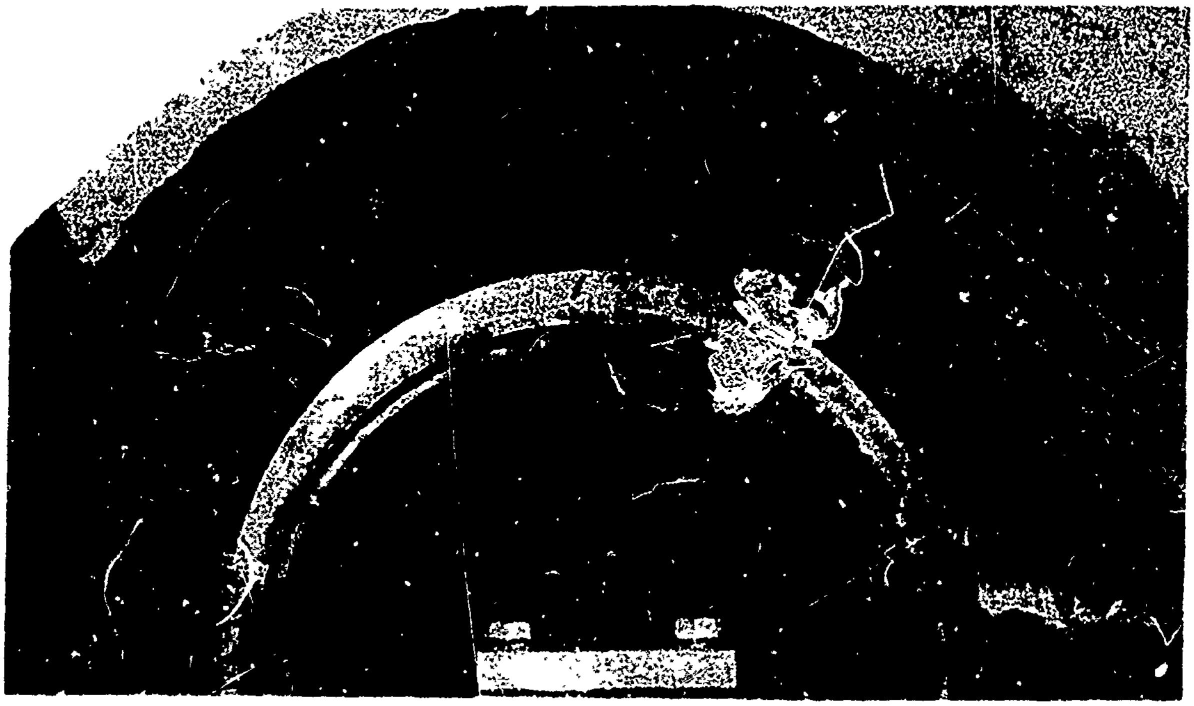


Figure 3-12. Tire Showing Ozone Effect on Unprotected Section Labeled "Control" (Ref. 34)

TABLE 3-2

IMPORTANT PESTS AT MILITARY INSTALLATIONS (Ref. 36)

Pest	Common name	Scientific name
Mosquitoes	Anopheline mosquito	*Anopheles spp*
	Culicine mosquito	*Aedes spp*
		Culex spp
		Mansonia spp
Flies	House fly	*Musca domestica*
	Greenbottle fly	*Lucilia spp*
	Bluebottle fly	*Calliphora spp*
	Stable fly or dog fly	*Stomoxys calcitrans*
	Deer fly	*Chrysops spp*
	Horse fly	*Tabanus spp*
	Latrine fly	*Fannia spp*
	Cluster fly	*Pollenia rudis*
	Fruit flies	*Drosophila melanogaster*
Gnats and Other Diptera	Sand fly	*Phelebotomus spp*
	Plunkie	*Culicoides spp*
	Black fly	*Simulium spp*
	Eye gnat	*Hippelates spp*
	Nonbiting midge	*Chironomus spp*
Bed Bugs	Bed bug	*Cimex lectularius*
		Cimex hemipterus
Lice	Body louse	*Pediculus humanus corporis*
	Head louse	*Pediculus humanus humanus*
	Crab louse	*Phthirus pubis*
Fleas	Human flea	*Pulex irritans*
	Dog flea	*Ctenocephalides canis*
	Cat flea	*Ctenocephalides felis*
	Oriental rat flea	*Xenopsylla cheopis*
Ticks	Rocky Mountain spotted fever tick or wood tick	*Dermacentor andersoni*
	American dog tick	*Dermacentor variabilis*
	Brown dog tick	*Rhipicephalus sanguineus*
	Relapsing fever tick	*Ornithodorus turicata*
	Pacific tick	*Ixodes pacificus*
	Rabbit tick	*Haemaphysalis leporis-palustris*
	Herms soft tick	*Ornithodorus hermsi*
Mites and Spiders	Chigger	*Trombiculidae*
	Itch Mite	*Sarcoptes scabiei*
	Black widow spider	*Latrodectus mactans*
	Food infesting mite	*Tyroglyphus spp*
	Clover mite	*Bryobia praetiosa*
	Chicken mite	*Dermanyssus gallinae*
Termites and Wood Borers	Subterranean termite	*Reticulitermes spp*
	Dry-wood termite	*Kalotermes spp*
	Old house borer	*Hylotrupes bajulus*
	Flat oak borer	*Smodicum cucujiforme*
	Ivory-marked beetle	*Eburia quadrigeminata*
	Lyctus beetles	*Lyctus spp*
	Furniture beetles	*Anobium punctatum*
	Death watch beetle	*Xestobium rufovillosum*
	Wharf borer	*Nacerda melanura*
	Rot fungi	*Merulius spp*
	Building poria fungi	*Poria incrassata*

TABLE 3-2 (continued). IMPORTANT PESTS AT MILITARY INSTALLATIONS (Ref. 36)

Pest	Common name	Scientific name
Cockroaches	German cockroach	*Blattela germanica*
	American cockroach	*Periplaneta americana*
	Oriental cockroach	*Blatta orientalis*
	Brown-banded roach	*Supella supellectilium*
	Brown cockroach	*Periplaneta brunnea*
	Wood roach	*Parcoblatta spp*
Ants	Argentine ant	*Iridomyrmex humilis*
	Red harvester ant	*Pogonomyrmex barbatus*
	Carpenter ant	*Camponotus spp*
	Odorous house ant	*Tapinoma sessile*
	Pharaoh ant	*Monomorium pharaonis*
	Thief ant	*Solenopsis molesta*
	Fire ant	*Solenopsis saevissima*
Stinging Insects	Yellow jackets	*Vespula spp*
	Polistes wasps	*Polistes spp*
Stored-Product Insects	Cadelle	*Tenebroides mauritanicus*
	Black carpet beetle	*Attagenus piceus*
	Confused flour beetle	*Tribolium confusum*
	Red flour beetle	*Tribolium castaneum*
	Saw-toothed grain beetle	*Oryzaephilus surinamensis*
	Indian meal moth	*Plodia interpunctella*
	Mediterranean flour moth	*Ephestia kuhniella*
	Casemaking clothes moth	*Tinea pellionella*
	Webbing clothes moth	*Tineola bisselliella*
	Silverfish	*Lepisma saccharina*
	Broadbean weevil	*Bruchus rufimanus*
	Pea weevil	*Bruchus pisorum*
	Rice weevil	*Sitophilus oryza*
	Larder beetle	*Dermestes lardarius*
	Hide beetle	*Dermestes maculatus*
	Red-legged ham beetle	*Necrobia rufipes*
	Cabinet beetle	*Trogoderma inclusum*
	Cheese skipper	*Piophila casei*
	Powder-post beetle	*Lyctus planicollis*
	Carpet beetle	*Attagenus piceus*
	House cricket	*Acheta domestica*
	Fire brat	*Thermobia domestica*
	Book louse	*Liposcelis divinatorius*
	Grain mite	*Acarus siro*
	Spider beetles	*Ptinus spp*
	Cigarette beetle	*Lasioderma serricorne*
Pests of Turf and Grasses	Japanese beetle	*Popillia japonica*
	Green June beetle	*Cotinus nitida*
	Carolina grasshopper	*Dissosteria carolina*
	Differential grasshopper	*Melanoplus differentialis*
	Red-legged grasshopper	*Melanoplus femur-rubrum*
	Long-winged grasshopper	*Dissosteira longipennis*
	Southern mole cricket	*Scapteriscus acletus*
	Armyworm	*Pseudaletia unipuncta*
	Chinch bug	*Blissus spp*
	Nematodes	*Heterodera spp*
	Rhodes grass scale	*Antonina graminis*

TABLE 3-2 (continued). IMPORTANT PESTS AT MILITARY INSTALLATIONS (Ref. 36)

Pest	Common name	Scientific name
Insects Damaging Schrubs, Shade Trees, and Forested Areas	Plant louse	*Aphis spp*
	Locust borer	*Megacyllene robiniae*
	Twig borer	*Saperda spp*
	Twig girdler	*Oncideres spp*
	Elm bark beetle	*Scolytus spp*
	Bagworm	*Thyridopteryx ephemeraeformis*
	Tent caterpillar	*Malacosoma spp*
	San Jose Scale	*Aspidiotus perniciosus*
	Euonymus scale	*Unaspis evonymi*
	Box wood leaf miner	*Nonarthropalpus buxi*
	Pine shoot moth	*Rhyacionia buoliana*
	Thrips	*Liothrips umbripennis*
	Plant bugs	*Leptocoris spp*
	Oak kermes	*Kermes spp*
	Oyster shell scale	*Lepidosaphes ulmi*
	Mealy bugs	*Pseudococcus spp*
	Red spider	*Tetranychus spp*
	White fly	*Trialeurodes spp*
	Leaf hopper	*Rhopalosiphum spp*
	Nematodes	*Xiphinema spp*
Rats, Mice, Field Rodents and Predatory Animals	Norway rat	*Rattus norvegicus*
	Roof rat	*Rattus rattus rattus, Rattus rattus alexandrinus*
	Meadow mouse	*Microtus spp*
	House mouse	*Mus spp*
	Ground squirrel	*Citellus spp*
	White-footed mouse	*Peromyscus spp*
	Pine mouse	*Pitymys spp*
	Prairie dog	*Cynomys spp*
	Pocket gopher	*Geomys spp, Cratogeomys spp, Thomomys spp*
	Western mole	*Scapanus spp*
	Eastern mole	*Scalopus spp*
	Bats	*Lasiurus spp*
	Skunks	*Mephitis spp*
	Coyote	*Canis latrans*
	Woodchucks	*Marmota spp*
	Cotton rats	*Sigmodon spp*
	Pack rats	*Neotoma spp*
	Kangaroo rats	*Dipodomys spp*
	Pocket mice	*Perognathus spp*
	Jack rabbit	*Lepus spp*

Figure 3-13. Termite Attack on Structural Lumber (Ref. 36)

(4) Carpet beetles attack materials containing animal products including fur, silk, wood, leather, feathers, meat, and milk solids. The larvae of these insects do the damage. They are common pests in dwellings, industrial plants, and warehouses (Ref. 36).

(5) Silverfish and fire brats, primitive insects flourishing at high ambient temperatures and relative humidities, travel a considerable distance to find their food, carbohydrates and protein. These insects are particularly destructive of paper products and often destroy books. They also attack cotton and are fond of linen and rayon, particularly those containing starch (Ref. 38).

(6) Ants are the most abundant of living creatures and a variety of species exists. Ants have a varied diet but are particularly fond of most of the same foods that man eats. The presence of ants on exposed rations often renders them unfit for human consumption. Ants also create a health problem, and their presence in buildings and equipment often causes difficulties. Argentine ants, found in the Southern United States, will bite people and cause much discomfort. Harvester ants have vicious stings and often cause indirect damage to roads and airplane runways by destroying soil-binding vegetation. Carpenter ants invade wooden buildings and can ultimately cause much destruction of the structure (Ref. 36).

(7) Marine borers cause tremendous damage throughout the world by attacking the timbers of unprotected piers (see Fig. 3-14) and vessels in immense numbers and riddling them to such an extent that they become worthless in a surprisingly short time. Some marine structures have been destroyed by marine borers in less than 1 yr. Marine borers consist of two distinct groups: the molluscan and the crustacean borers. The former, sometimes called shipworms, are more destructive (Ref. 39).

(8) Rats, mice, and other members of the rodent family constitute an environmental factor that, at times, has played an important role in world history and military operations. The major harmful effect of rodents has been the transmission of disease, but large quantities of materiel have been destroyed by their activities. The Norway or ground rat is the most common rodent species, but black rats, mice, and other rodents dominate in some localities. The importance of the rodents results from their prodigious appetites and their never-ending search for food to satisfy these appetites. This search usually leads them to inhabited areas and, when adequate food supplies are found, their population increases rapidly. Evidences of rat and mouse infestation are droppings, runways, tracks, and gnawings. Their population is greatest in eastern and southeastern Asia where they originated, but they have spread throughout the world from the tropics to the arctic regions and no doubt have the widest distribution of any mammal except man. In their efforts to obtain food, rats chew their way through packing cases, plastic containers, and other barriers, ruining stored materials in addition to the food that they seek. Plague is the bacterial disease most commonly associated with rats, but other diseases are carried with equal facility. Direct attack on human beings is fairly common (Ref. 36).

(9) Birds are attractive and useful contributors to the environment in which man lives, but they carry diseases and insects, create hazards for aircraft, create dirt and noise nuisances, contaminate food, deteriorate equipment, and destroy crops. Militarily, their most important effect is probably their hazard for aircraft. Airliners have crashed after passing through flocks of starlings, and the pilot of a jet trainer was killed as a result of a collision with a snow goose. Each year a large number of aircraft-bird mishaps are recorded with much costly damage resulting. The solution to bird problems has often been to

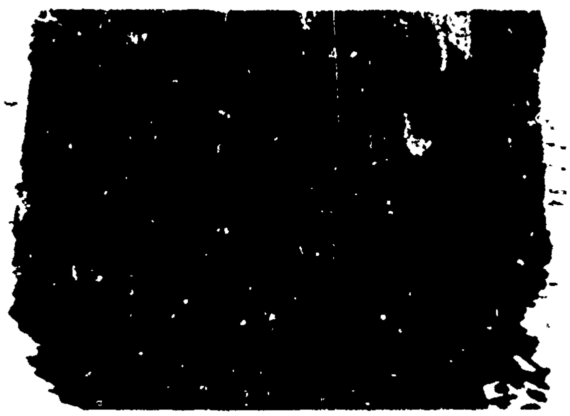


Figure 3-14. Piling Destroyed by Marine Borers (Ref. 36)

remove the particular attraction that an area has for the birds. Other more direct methods of removing bird populations have been only partially successful (Ref. 40).

(10) Vegetation is included in discussion of both terrain and macrobiological organisms. With respect to terrain, vegetation is considered as a physical feature of the landscape. inhibiting mobility and, at times, providing concealment or impeding visibility. Vegetation, as a macro-organism, creates effects on materiel through its harboring of microbiological organisms, its altering of meteorological conditions, its direct damage by thorns and spines, its contribution to fire hazards, and, at times, by its toxicity.

The distribution of the various classes of vegetation over the earth is determined by temperatures, soils, and rainfall. These factors have created reasonably well-defined forests, grasslands, tundra, and other regions characterized by some specific type of vegetation (Ref. 6).

3-14 MICROBIOLOGICAL ORGANISMS

Microbiological organisms (or microbes) constitute a more important environmental factor relative to material degradation than is recognized by the average design engineer. The design engineer may accept rot, decay, corrosion, and other microbiological deterioration processes without recognizing their causes or adopting optimal preventive measures. The degradative mechanisms associated with microbes are related closely to—often indistinguishable from—similar mechanisms discussed in other chapters of this handbook. Humidity, temperature, salt, solar radiation, and macrobiological organisms are factors that influence, accompany, or contribute to microbiological degradation processes (Ref. 10).

Microbes include bacteria, fungi, and other species. Bacteria are without chlorophyll and are present in soil, water, air, animals, and plants. Bacteria can survive wide extremes in the environment including boiling water, complete desiccation, or a vacuum. Fungi are plants without leaves, stems, or roots and include such well-known species as mushrooms, yeast, and molds. Fungi reproduce through generation of spores that are readily disseminated in nature and are present in virtually all environments. The growth and nourishment of microbes, since they are universally present, depend upon the availability of moisture and food under suitable environmental conditions rather than on the confirmed presence of a species.

The products of living microbial, plant, or animal cells do not accumulate on earth due to the ability of microbes to biodegrade and mineralize all components of living cells. The fact that the biological productivity of the oceans—about 30 billion metric tons per year—is biodegraded without any significant accumulation gives some idea of the numbers and biodegradative capacities of microbes. These organisms constitute an estimated 50 percent of all of the living material on the earth. Every gram of fertile soil contains between 10^6 and 10^9 microbes (Ref. 41).

The ubiquity of microbes and their metabolic versatility suggest that few materials are resistant to some form of attack or alteration by microbes. Examples of such attack include damage to concrete, bricks, electrical materials, glass, optical equipment, photographic products, fats, oils, waxes, minerals, metals, paints, petroleum fuels, oils, greases, asphalt, plastics, rubber, resins, sewage sludge, wool, linen, cotton, synthetic textiles, wood pulp, paper, and cork. The general types of microbial damage to materials are as follows (Refs. 42,43):

(1) Corrosion of metal surfaces, destruction of insulation on electrical wires, and deterioration of some lubricants result from microbial action.

(2) Microbes eat cellulosic materials and decompose foodstuffs. Fungal growth on lumber is shown in Fig. 3-15.

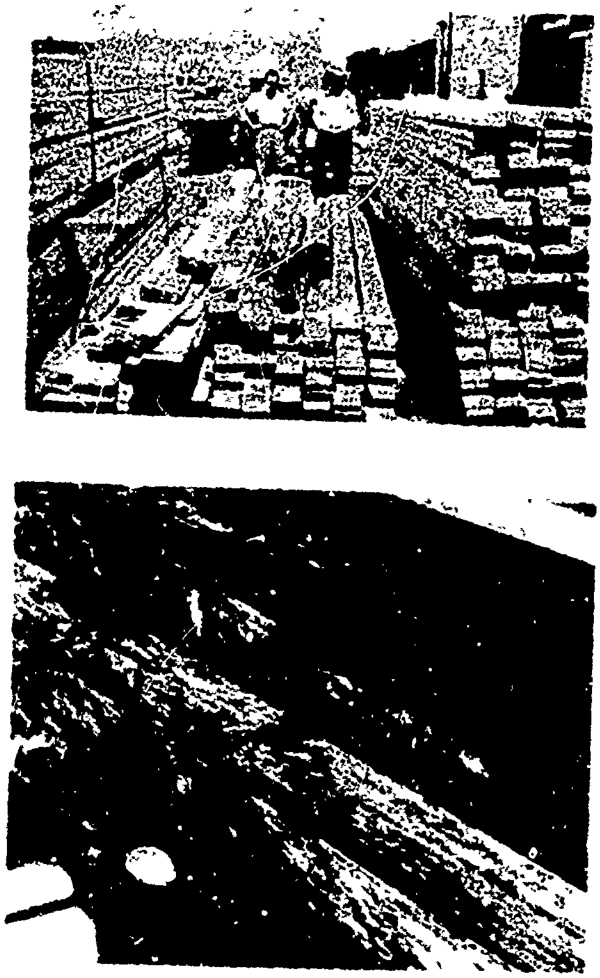


Figure 3-15. Fungous Attack on Lumber (Ref. 36)

(3) Excretory products including organic and inorganic acids produced by microbes corrode iron and attack many other materials.

(4) Mechanical mechanisms and pipes are clogged by growth of bacterial colonies; a specific example is the blocking of fuel lines by hydrocarbon-utilizing microbes in fuel tanks.

The destructive effects that microbes have on materiel is the composite result of a great number of environmental factors. Materiel degradation is dependent on the accessibility of the material to attack and on the environmental and nutritional factors that exist. The prime factors necessary for microbes include:

(1) *A compatible temperature*. Various microbes grow and flourish in fairly narrow temperature ranges although they survive extremes.

(2) *Light*. Light is necessary for some microbes to grow and flourish but ultraviolet light is lethal to all such microbes; however, fungi do not require light.

(3) *Oxygen*. Oxygen is very necessary for the growth of fungi, and most other microbes grow better with oxygen, although it will kill some species.

(4) *Water*. If the moisture content of a material is less than 10 percent and no moisture is available from other sources, little growth of microbes will occur.

(5) *Acceptable acidity*. Some microbes grow over a relatively wide range of acidity, although optimal levels of acidity or alkalinity prevail for particular species.

(6) *Nutritional factors*. Like all living organisms, microbes require copious supplies of the basic building block elements such as carbon, hydrogen, oxygen, and others as well as trace amounts of a variety of other chemicals in order to survive.

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CHAPTER 4

INDUCED ENVIRONMENTAL FACTORS

4-1 INTRODUCTION

Induced environmental factors include those for which man's activities constitute the major contribution insofar as their effects on materiel are concerned. It is notable that the importance of every one of the natural environmental factors may be altered by man and, in fact, often is when protection is provided. Those regions of the environment within modern buildings are almost completely controlled by man, for example. In similar fashion, the induced environmental factors are influenced and, at times, dominated by natural forces.

The environmental factors discussed in Chap. 3, "Natural Environmental Factors", include those of primarily natural origin. The induced factors discussed in this chapter complete the compilation of factors that are required to describe the environment. They are tabulated in Table 4-1.

Since these induced factors are derived from man's activities, they may be controlled to any extent deemed necessary and practical. The following discussion is intended to provide a perspective on the induced factors. Detailed information is provided in Part Three of the Environmental Series of Engineering Design Handbooks. In addition, an attempt is made to relate each factor to other environmental factors with which it has a strong interaction, to assess its importance, and to ascertain areas where the factor is of importance.

4-2 ATMOSPHERIC POLLUTANTS

Atmospheric pollutants are an induced environmental factor that is receiving increased attention because of the growth in pollutant concentrations and because of their adverse effects upon the overall quality of the environment. These adverse effects are related more closely to human health and environmental quality than to effects on materiel. However, it is well documented that the effects of air pollutants on materiel are of considerable economic importance to the civilian economy (Refs. 1,2). These effects are more pronounced if materiel is in the proximity of industrial activity or dense population centers. Certain military operations are also sources of air pollutants and the environment in the vicinity of such sources exhibits those same characteristics found in urban areas.

The important pollutants are listed in Table 4-2 along with their approximate concentration ranges. The lowest concentrations are found in regions remote from habitation while the higher extremes are associated with a high level of human activity.

The atmospheric pollutants of most importance include sulfur dioxide, carbon monoxide, hydrocarbons, and particulates. Sulfur pollutants, which are primarily derived from the combustion of fossil fuels, are responsible for a significant fraction of air pollution problems because of the chemical activity of these compounds in the atmosphere. Carbon monoxide is more abundant and more widely distributed than any other air pollutant and is the most important effluent from the internal combustion engine. Hydrocarbon gases in the atmosphere are important because of their high concentrations and because they are precursors of photochemical oxidants that

TABLE 4-1

CLASSIFICATION OF INDUCED ENVIRONMENTAL FACTORS

Contaminants
Air pollutants
Sand and dust
Mechanical factors
Vibration
Shock
Acceleration
Radiated energy
Acoustics
Electromagnetic radiation
Nuclear radiation

TABLE 4-2

ATMOSPHERIC POLLUTANTS (Ref. 1)

Pollutant	Typical concentration range
Sulfur dioxide	0.005- 2 ppm
Hydrogen sulfide	0.001- 0.003 ppm
Nitric oxide	0.01 - 0.4 ppm
Nitrogen dioxide	0.02 - 0.3 ppm
Carbon monoxide	0.1 -100 ppm
Hydrocarbons	0.1 - 40 ppm
Particulates	10 -200 μg m^{-3}

produce damaging effects. Atmospheric particulates are the most obvious of the atmospheric pollutants and include both inert particles with only a soiling effect and particulates with active chemical properties.

The effects of air pollutants on materials are observed primarily on surfaces where they may cause corrosion, discoloration, leaching, and similar effects. Pollutants also contribute to the deterioration of textiles, paper, dyes, and rubber products. Often, the effects of atmospheric pollutants are such as to accelerate deterioration processes that are associated with natural environmental factors such as solar radiation, humidity, temperature, microbiological organisms, and ozone. Patterns of deterioration have been associated with increased concentrations of pollutants in the vicinity of specific sources and with specific air pollution incidents. Several examples of air pollution damage to materials are shown in Fig. 4-1.

4-3 SAND AND DUST

An airborne sand and dust environment is associated most often with the hot-dry regions of the earth but also occurs seasonally in other regions. Naturally occurring sand and dust storms are an important factor but, with the increased mechanization of military operations, these cause less of a problem than does sand and dust associated with man's activities. Thus, the most important impact of sand and dust on materiel is as an induced environmental factor rather than as a naturally occurring factor (Refs. 3,4).

The parameters of sand and dust environments of interest to materiel designers include the concentration, particle size, size distribution, particle shape, and the composition and hardness of the particles. The normal concentration range of sand and dust particles is from micrograms to milligrams per cubic foot and the particle diameters are on the order of 1 to 150 μm. Larger size particles settle rapidly from the air while smaller diameter particles comprise a small percentage by weight of the total dust in the atmosphere. Shapes of sand and dust particles may vary from irregular jagged shapes to well-rounded smooth spheres. Silica comprises by far the bulk of the constituents of dust although smaller quantities of aluminum oxide and other metallic oxides are present in varying amounts depending upon the origin of the airborne particles (Refs. 5,6).

The adverse effects of sand and dust depend considerably upon the nature of the materiel they contact. When carried by the wind, sand and dust will abrade metallic surfaces, penetrate seals, and cause a variety of damage to equipment. Chemically, sand and dust particles may cause either acid or alkaline reactions in the presence of moisture, thus producing corrosion. All such damage can be classified as either abrasion, clogging and blocking, or corrosion. Readily apparent effects of sand and dust may be observed in the erosion of telephone poles in desert areas, the pitting of automobile windshields, the pitting of the surfaces of electrical insulators, and the soiling of exposed materiel. For example, it has been observed that helicopter rotorblades with wooden leading edges are severely worn after 20 min of hovering in dust-laden air (Ref. 7). Gas turbine engines have been destroyed by 15 hr of operation in dusty areas (Ref. 8).

The importance of airborne sand and dust as a detrimental, induced environmental factor varies considerably with circumstances. Off-road operations in dry regions are most damaging. Fig. 4-2 shows a typical vehicle-created dust cloud on an unpaved road. In urbanized areas, where the roads are paved, airborne sand and dust are more of a nuisance than a hazard for materiel. Materiel designers therefore must be alert to those circumstances in which sand and dust will be an important factor in the performance of materiel and take such precautions as are necessary when exposure would be expected to create problems.

(A) Glass window

Figure 4-1. Material Attack by Air Pollutants (Photograph courtesy of Environmental Protection Agency)

(B) Electrical insulator

Figure 4-1 (continued). Material Attack by Air Pollutants (Photograph courtesy of Environmental Protection Agency)

(C) Automobile door handle

Figure 4-1 (continued). Material Attack by Air Pollutants (Photograph courtesy of Environmental Protection Agency)

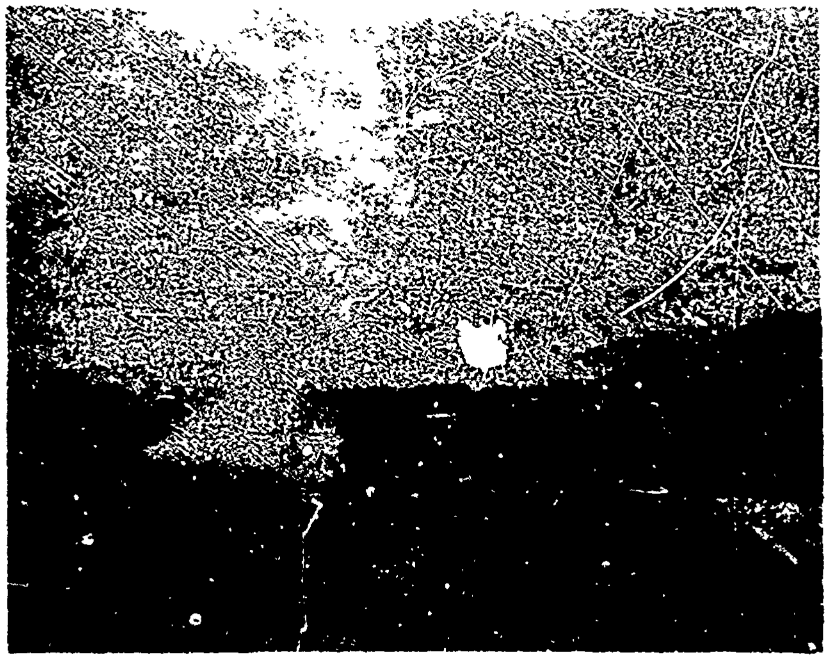


Figure 4-2. Truck at 15 mph Velocity on Typical Well-maintained Unpaved Road Illustrating Dust Problem (Ref. 3)

4-4 VIBRATION, SHOCK, AND ACCELERATION

Vibration, shock, and acceleration are induced environmental factors that interact with materiel through application of various types of mechanical forces. These factors have many similarities but are sufficiently unique in their characteristics and effects to warrant the separate consideration given them in Part Three of this handbook series. Vibration is a quasi-continuous oscillatory motion or force; shock is a short duration impact type of force or motion; and acceleration, while defined as the rate of change of velocity, is used to describe those forces acting on materiel as a result of a changing velocity and slowly varying with respect to time when compared to vibration or shock. These three induced environmental factors are described most often in terms of their motion parameters; i.e., the time dependencies of their velocity or acceleration (Ref. 9).

Natural manifestations of vibration, shock, and acceleration are sometimes important. Earthquakes, glacial activity, rock slides, and severe windstorms produce vibration and shock. The wave motion of the ocean produces a common form of low frequency vibratory motion. Hailstorms constitute another form of natural shock phenomena, and the almost constant force exerted by gravity is the most prevalent form of acceleration. However, these various natural mechanical forces are relatively unimportant in their effects on materiel when compared to similar forces that result from man's activities. Only in the rarely occurring catastrophic natural phenomenon is this situation reversed.

In considering the effects of vibration, shock, and acceleration on materiel, exposure may be categorized into two distinct categories. The first category is exposure to sometimes severe vibration, shock, and acceleration forces during normal operational use while the second category of exposure is that incidental to normal application of the materiel. In the first category, materiel usually is designed to survive the environmental stresses adequately. This applies to materiel employed in close proximity to guns, that used in the severe environment of tracked vehicles, or materiel that is a component of any vehicle.

The mechanical forces associated with the transportation and handling environment constitute the greatest stress on materiel in incidental exposure. All materiel, whether designed to survive a severe vibration, shock, or acceleration environment or not, must survive the transportation and handling environment. This environment produces the most materiel damage that can be associated with the mechanically induced environmental factors.

Rational design and test of material and equipment to insure survival in transit require that the salient shock and vibration conditions be identified and expressed in suitable engineering parameters. Where design requirements thus imposed are incompatible economically or technically with end function, protective packaging must be employed to bridge the differential between environment severity and equipment or material strength (Ref. 10).

Subjectively, it would not appear difficult to identify specific sources of vibration, shock, and acceleration in the environment; however, the shock and vibration aspect of transportation differs substantially from other environmental factors in that loads encountered by equipment in transit are not predetermined uniquely but result from interaction of the shipped item and the transportation equipment. An additional consideration is that, while shock and vibration may seem significantly different phenomena, in practice their separation may be difficult and may require arbitrary criteria for differentiation. At other times, classification of the different mechanical stresses is accomplished readily.

Thus, when a truck traverses a generally smooth road and strikes an isolated chuckhole, the truck and its contents are obviously subject to shock. The disturbance is transient, and the free vibrations of the truck and its cargo decay as the shock energy is dissipated. An accidental drop of a container or package onto an unyielding surface is a similarly discontinuous phenomenon, inducing severe transient vibration of the packaged item in the absence of protective cushioning. Additional typical examples of shock in transportation are the humping (forcible coupling) of rail cars, airdropping, and hard landing of aircraft. In-transit disturbances obviously satisfying the "continuous" criteria for vibration are the pulsating forces transmitted to airframe and cargo by aircraft engines, both turbojet (compressor and turbine) and reciprocating (crankshaft and propeller). Vibration induced in a truck traveling a coarse gravel road, while clearly continuous, would not be periodically repetitive, however, since the roadbed discontinuities generally would be of unequal size and spacing. If the road had developed a "washboard" surface, a periodic vibration may be introduced (Ref. 11).

Application of engineering disciplines to design of shock- and vibration-resistant equipment and packaging requires that the specific hazards be not only identified and classified but also quantified. Extensive measurement programs have accordingly been conducted under Government and industry sponsorship to quantify typical shock and vibration excitation.

Transportation shocks most frequently are described in the literature in terms of acceleration versus time or a specific total velocity change, while vibration conditions normally are reported in terms of motion amplitudes (usually acceleration or displacement) versus frequency, although measurement is made against a time base, as in the case of shock. Thus, an additional step in data reduction that is rarely performed for shock is routinely performed for vibration. The unfortunate inference is created that shock is intrinsically "different" and more simple. Actually, shock transients may be equally and aptly expressed in terms of an acceleration versus frequency spectrum, although the transposition is generally more tedious and requires more elaborate equipment for instrumental analysis.

Expression of both shock and vibration in terms of amplitude versus frequency spectra is advantageous, primarily because of resonance phenomena, a universal aspect of dynamic structural response. Briefly, the resonance phenomena are associated with an extremely wide variation in structural response as a function of the frequency of the forcing function. At forcing frequencies, where inertial and elastic forces cancel each other, the structural response is exaggerated and its damage susceptibility is high.

These aspects of shock excitation sometimes are combined in a single presentation because shock transients can be defined in terms of a continuous frequency spectrum, and structural response is frequency related. Shock transients thus are expressed in terms of the maximum motion response of an idealized resonator to the pulse as its frequency of resonance is varied across the frequency range of interest.

The wide variation in structural response to dynamic forces as a function of frequency is also reflected in the manner in which structures load the source of dynamic energy. The "motional impedance" of the structure at the point of loading similarly varies widely with frequency. The common specification of dynamic excitation in motional parameters alone effectively implies that the "sources" of the dynamic loading have "infinite" material impedance; i.e., that their motion while imparting energy is totally unaffected by the loading structure itself. The limited validity of this convention in many applications is recognized increasingly in efforts to define shock and vibration in terms of force parameters, or to supplement motion data with motional impedance measurement.

A common form of shock phenomenon associated with military operations is the shock wave that accompanies the detonation of either chemical or nuclear explosives. The shock wave associated with nuclear weapons is most important, of course, because the magnitude of all of the shock parameters are much greater than for other detonations. A shock or blast wave produces large transient forces on materiel in its path. Analysis of effects normally is accomplished by treating materiel structures as rigid bodies in describing the shock wave in terms of the peak overpressure, the overpressure impulse, shock velocity, its rise time, its decay characteristics, and its duration. All of these depend upon the particular type of detonation producing the shock wave. Most effects depend on the magnitude of the peak overpressure. If this exceeds 0.5 lb in.$^{-2}$, a majority of structures will suffer damage.

Vibration, shock, and acceleration are very important induced environmental factors constituting one of the major threats to the proper operation of materiel. Much effort has gone into designing materiel that will survive these stresses and into protecting materiel through packaging. In Fig. 4-3, the protection offered by one type of packing container is being subjected to a rough ride on a trailer. In Fig. 4-4, the complexity of the equations of motion of a tracked vehicle are illustrated, and the vehicle is shown undergoing a test to check the validity of the model. Improvements in transportation vehicles and handling procedures also are major contributions to the mitigation of such effects. All of these efforts, however, only serve to reduce the incidents of materiel failures attributed to vibration, shock, or acceleration. These still constitute major environmental stresses and warrant continued emphasis by design engineers.

4-5 ACOUSTICS

Inclusion of acoustics as an important induced environmental factor results from an increasing awareness of its importance to materiel design engineers. The acoustical aspects of the environment are related closely to vibration but, in this case, the concern is only with those vibratory excitations transmitted through the atmosphere. Acoustical energy can interact with materiel so as to cause deterioration; more importantly, acoustical energy—as noise—interferes with communications and also constitutes a hazard to personnel. The primary concerns of the design engineer with respect to the acoustical factor in the environment are to minimize the generation of noise or sound by materiel and to provide for the protection of personnel from the effects of noise (Ref. 14).

The most severe sources of acoustical energy are gunfire and other explosive detonations. Machinery of various types—particularly vehicular propulsion equipment—also constitutes an important source of noise. The sound pressure levels in the vicinity of a rocket test site are shown in Fig. 4-5. The effects of noise and blast on personnel are quantified in terms of temporary and permanent threshold shifts in hearing ability. Measurements have indicated that such deterioration in hearing ability is common in personnel exposed to severe noise environments. Personnel exhibiting hearing impairment are less able to detect low level sounds and are less efficient in their speech reception capabilities (Ref. 15).

Data on noise exposure limits, speech interference criteria, and workspace noise criteria are available for application to design, and methods for hearing protection are available. The constantly changing magnitude and spectrum of acoustical energy produced by modern materiel warrants increased emphasis on the acoustical factor in the environment by design engineers.

4-6 ELECTROMAGNETIC RADIATION

Electromagnetic radiation, a form of energy present everywhere in the environment, is an increasingly important environmental factor. This energy is in the form of varying electromagnetic fields propagating throughout the environment. The frequency of these variations—the complete set being referred to as the electromagnetic spectrum ranges over

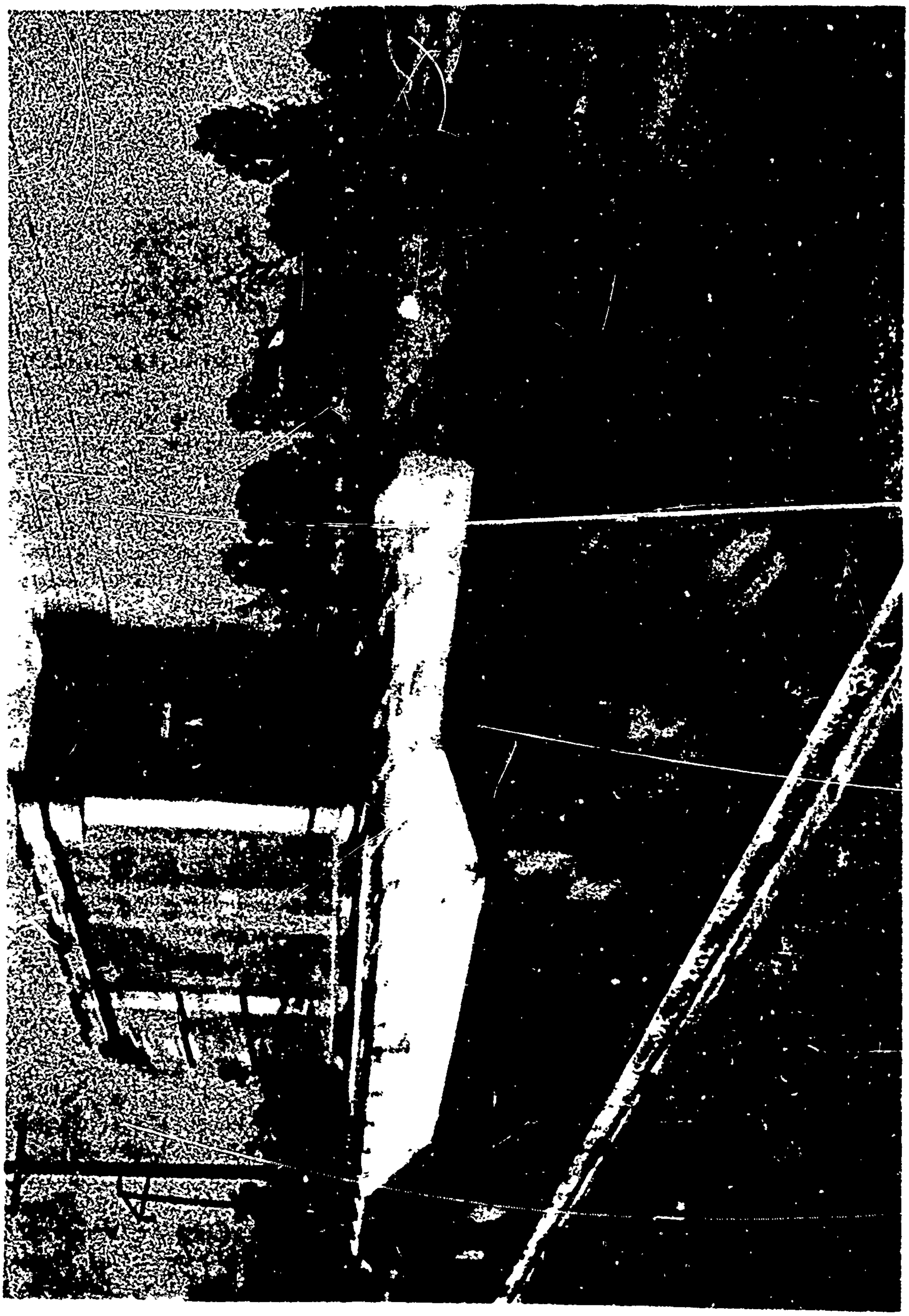
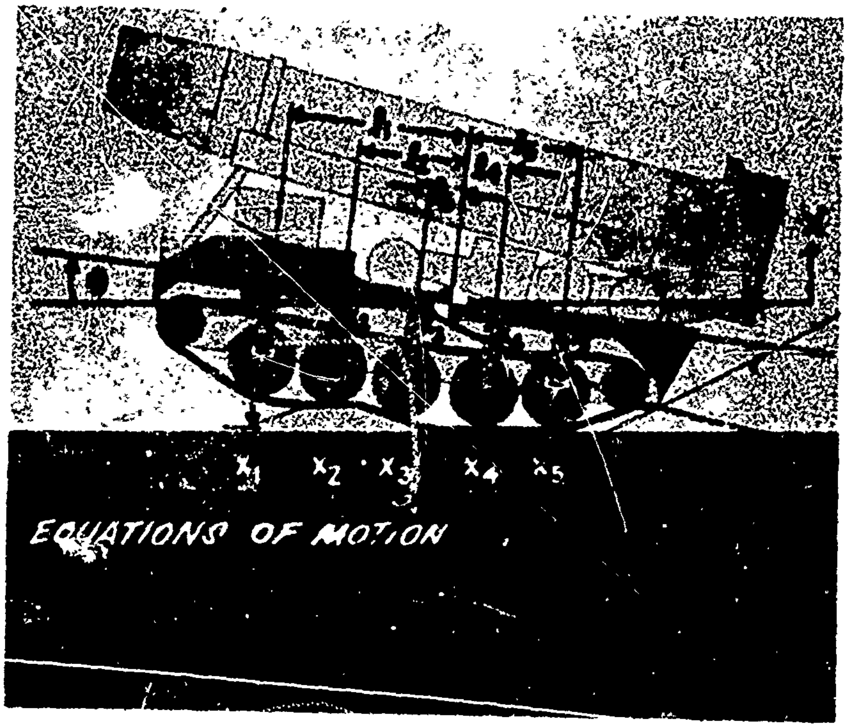


Figure 4-3. Testing Shipping Containers on a Flat-bed Trailer (Ref. 12)



(A) The model

(B) The test

Figure 4-4. Vibration Testing of Tracked Vehicle (Ref. 13)

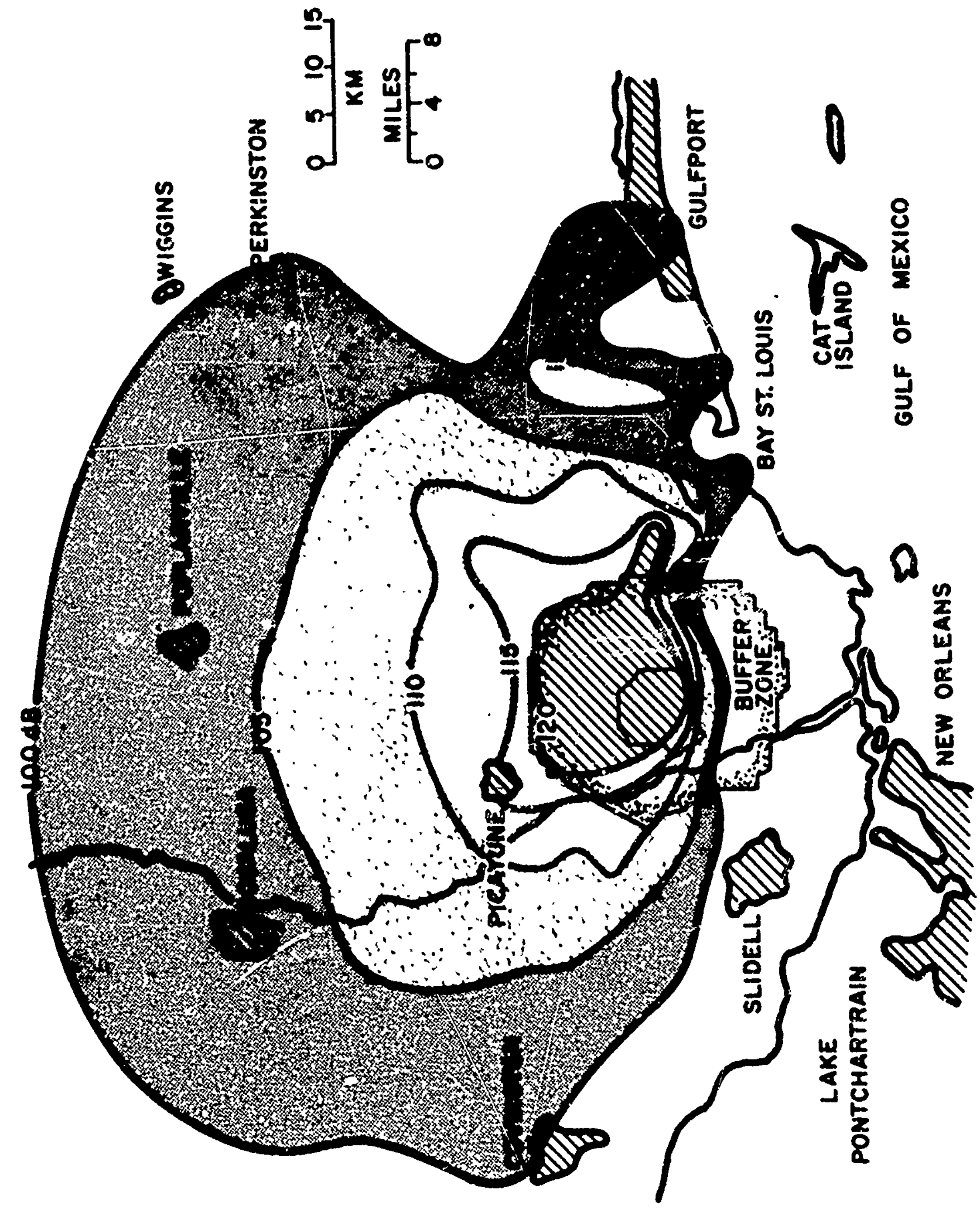


Figure 4.5. Sound Pressure Level Contours During Static Test of Large Rocket Motor (Ref. 16)

25 orders of magnitude (Ref. 17). The amplitude of these radiations and their characteristics vary considerably within this frequency range.

The most prevalent form of natural electromagnetic radiation is that associated with lightning (Ref. 18). It is estimated that lightning strikes the earth about 100 times each second, each stroke releasing large bursts of electromagnetic energy which encircle the globe. Most of this energy is concentrated at the low frequency end of the electromagnetic spectrum with the maximum power level being concentrated at about 3 kHz. Additional natural electromagnetic energy reaches the earth from the sun and is found at the very high frequency region of the spectrum. The importance of solar energy is sufficient to warrant consideration as a separate natural environmental factor.

Although natural electromagnetic energy dominates all other sources in the vicinity of a lightning stroke, manmade electromagnetic energy is of far greater importance when solar energy is excluded. This results not only from a low probability of being in the immediate vicinity of a lightning discharge but also to the complex and sophisticated use to which man is putting electromagnetic radiation. In Figs. 4-6 and 4-7, electromagnetic radiation sources of the modern Army are shown. Artificial electromagnetic radiators include power distribution systems, a multitude of uses in communications, and specialized detection and analytical applications. The development of lasers has introduced another intense source of electromagnetic radiation and, in military applications, the electromagnetic pulse associated with nuclear weapon detonations is of considerable importance.

The characterization of the electromagnetic radiation factor in the environment is difficult. Empirical measurement of the radiation is a complex task even for one point in space and is almost impossible on a synoptic basis. Calculation of the electromagnetic radiation at a point is also difficult unless one or two well-characterized sources are dominant. In most cases, the practical approach is to be aware of the nearby energy sources that will contribute significant power levels.

The production of a strong pulse of electromagnetic energy by a nuclear weapon is not surprising since even small detonations of chemical explosives produce electromagnetic signals. The two mechanisms by which electromagnetic pulses are produced in nuclear explosions are:

(1) The creation of an asymmetrical charge distribution in the detonation (the "Compton-electron model")

(2) The rapid expansion of the conducting plasma created by the explosion within the magnetic field of the earth (the field displacement model) (Ref. 20).

The first of these is the mechanism by which electromagnetic pulse (EMP) is generated by nuclear detonations on or slightly above the surface of the earth. In this model, high energy protons resulting from the explosion dislodge electrons from the atoms and molecules of the surrounding air. A large quantity of these Compton electrons move rapidly away from the center of the burst in a symmetrical fashion unless some obstacle exists. When the charge symmetry is destroyed by the presence of a boundary such as that of the earth, the net effect is to produce an instantaneous pulse of current in one direction which radiates electromagnetic energy just as it would if it were flowing in an antenna. Because the charge plasma of the nuclear fireball undergoes oscillations at characteristic frequencies, the radiated electromagnetic energy similarly oscillates.

The second mechanism, characteristic of underground or very high altitude explosions where spherical symmetry is maintained, depends on the immediate interaction of the charged plasma created by the explosion with the geomagnetic field of the earth.

Figure 4-6. Mobile Tropospheric Scatter Antenna (Ref. 19)

Figure 4-7. Octopuslike Array of Electromagnetic Emission Sources (Ref. 19)

The EMP spectrum is similar to that created by lightning with a maximum energy appearing at about 10 kHz but distributed with smaller amplitudes throughout a broad region of the frequency spectrum. EMP energy is of considerably greater magnitude than that observed in lightning and extends over a much larger area of the earth. Despite the similarities among EMP and lightning and other strong sources of electromagnetic energy, it cannot be assumed that protective measures consistent with these other electromagnetic radiation sources will protect materiel from the effects of EMP. The rapid rise time of the pulse associated with a nuclear detonation and the strength of the resulting pulse are unique (Ref. 21).

A variety of effects of electromagnetic radiation on materiel are known, probably a number of effects are still unrecognized, and there are some poorly understood effects on man. Of course, one of the most important effects of electromagnetic radiation in the environment is the interference it produces for the use of the electromagnetic spectrum (Ref. 22). Well-known examples are called radio interference and radar clutter. Another important effect in the military is the interaction of electromagnetic radiation with electroexplosive devices used as detonators (Ref. 23). Military as well as civilian explosives are provided with detonators that often depend on heating a small bridge wire to initiate the explosion. Absorbed electromagnetic radiation can accidentally activate such fuzes.

Most electromagnetic effects on material occur in close proximity to sources of large energy. In such cases, overheating and dielectric breakdown can occur. Devices particularly semiconductor devices can be damaged permanently by relatively small electromagnetic fields. Direct effects of electromagnetic radiation on human beings are not fully understood. It is accepted that certain thermal effects resulting from absorption of energy can be harmful, particularly to organs such as the eyes. Some investigators believe that additional effects result from direct interaction of electromagnetic waves with the nervous system.

Protection against the effects of electromagnetic radiation has become a sophisticated engineering field. The most direct approach to protection is, in most cases, to avoid the limited region in which high radiation levels are found. When exposure cannot be avoided, shielding and filtering are important protective measures. In other cases materiel design changes or operating procedural changes must be instituted in order to provide protection.

4-7 NUCLEAR RADIATION

Although a natural background level of nuclear radiation exists, the only nuclear radiation that is of interest to design engineers is that associated with manmade sources such as reactors, isotope power sources, and nuclear weapons. The most important of these sources is nuclear weapons, the effects of which can produce both transient and permanent damaging effects in a variety of materiel. A nuclear detonation is shown in Fig. 4-8.

X rays, gamma rays, and neutrons are the types of nuclear radiation of most concern. As opposed to charged nuclear particles, which also emanate from nuclear reactions, those forms of radiation listed have long ranges in the atmosphere; thus, they can irradiate and damage a variety of military materiel.

Among the nuclear effects that have been of most concern are those called "transient radiation effects on electronics", often referred to as TREE. These transient effects are due primarily to the nonequilibrium-free charged condition induced in materials primarily by the ionization effects of gamma rays and X rays. The separation of transient and permanent effects is made on the basis of the primary importance of the radiation effects. For example, a large current pulse may be produced by ionizing radiation, and

Figure 4-8. Low Altitude Nuclear Detonation Showing Toroidal Fireball and Dirt Cloud (Ref. 24)

this current pulse may result in permanent damage to a device by overheating. This is a transient effect because the permanent damage results from overheating due to excess current rather than to direct-radiation-induced materiel property change. A large amount of information is available on specific electronic components, circuits, and hardening methods.

It is impossible to completely protect materiel items from nuclear radiation as can be accomplished for some other environmental factors. The variety of effects produced by nuclear radiation for different materials and components makes protective design difficult. The procedure employed is to define a radiation hardness level in a given materiel item and to design and test the item to that level.

Nuclear radiation hardening is a large and complex field with a variety of specialists required to deal with different aspects of the problem. This subject is treated extensively in the *Design Engineers' Nuclear Effects Manual* (Refs. 25-28) and only briefly in this Environmental Series of Engineering Design Handbooks.

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CHAPTER 5

COMBINED ENVIRONMENTAL FACTORS—CLIMATES

5-1 INTRODUCTION

The discussion of natural and induced environmental factors in Chaps. 3 and 4 is an example of single-factor analysis wherein each of the environmental factors is considered independently. The advantage of single-factor analysis is that it allows attention to be focused on compartmented sets of information and thus avoids the almost intractable problem of considering all environmental stresses on materiel simultaneously. In the actual materiel environment, however, many of the factors do cooccur. This chapter is concerned with identifying combinations of environmental factors that frequently are observed and that are associated by natural coupling.

The fact that, in a given region of the environment, a number of environmental factors are working together to affect materiel does not necessarily imply that all such factors must be considered in every case. In the natural environment, for example, a set of environmental factors is associated with each major type of climate. The environmental factors associated with climates are discussed in subsequent paragraphs of this chapter. In those regions of the environment that are subject to control e.g., inside structures the number of environmental factors that must be considered is very much reduced from that found in most natural environments. Thus, in spite of the fact that the consideration of actual materiel environments may at first seem to be overly complex because of the multiplicity of factors involved, in actual circumstances the number of environmental factors that are active is very much reduced and may be discussed in a logical fashion. This is not to say that the environment is not complex the interactions between factors take many forms and exert complex stresses on materiel and exert large influences on materiel requirements.

In their effects on materiel, many environmental factors act in conjunction or in synergism. In the former case are found examples of factors in pairs or in multiple combinations that are characteristic of geographic regions or other circumstances. Thus, high temperature and high humidity often cooccur as do high temperature and airborne sand and dust. Synergisms create factor combinations of importance to materiel designers. Two or more factors that act together to produce effects that are more important than the separate effects of either constitute a synergistic action. An example of a synergism is that obtained with low temperatures and vibration. With this combination of factors, rubber shock mounts that can survive either the extreme cold or severe vibrations readily are destroyed by the combined action of these two factors. In similar fashion the appearance of one environmental factor may inhibit the action of another. High temperature inhibits solid precipitants and low temperature inhibits attack by microbiological organisms.

Time is extremely important in the consideration of the effects of environmental factors on materiel. Some factors produce effects rapidly and others require long periods of exposure. The various combinations of factors to which materiel is exposed change with the seasons and with the time of day. Some items of materiel are designed for repetitive use over long periods of time while others are consumed in use and thus have a short life cycle. Time is included in the consideration of environmental effects by calculation of duration of effect or duration of exposure, by probability of occurrence of a given effect, or by other time integration or summation procedures.

The life cycle of a given item of materiel includes time periods in which the item is in a storage environment, a transportation environment, or an operational environment. These time periods determine the degree of exposure to which the materiel item is subjected to the environmental factors that are active in those particular regions of the environment.

In this chapter two categories of information are introduced. The first of these involves the cooccurrence and combined effects of various natural and induced environmental factors, and the second is concerned with those combinations of environmental factors characterizing specific climatic regions. Because climates represent a long-term concern for which much information has been accumulated, the preponderance of this chapter is a catalog of climatic data based on the classifications established in AR 70-38 (Ref. 1).

5-2 MULTIFACTOR COMBINATIONS

Probable combinations of climatic, terrain, and induced factors have received much attention from climatologists, meteorologists, geographers, and materiel design engineers. Combinations of factors are based on climatic categories effects on materials, and synergisms, and on functional conditions, e.g., transportation, storage, or operational environments.

It is difficult to quantify objectively the effects that all combinations of environmental factors may have on every item. Depending upon the detail with which it is desired to analyze both the environment and function of an item, literally hundreds of thousands of possible combinations exist between the effects of the environment and the reaction of an item under exposure to this environment. Therefore, it is necessary that some relationships be established between logical combinations and the effect of these combinations on common properties of materials. As an example, it is well recognized that many materials exhibit increased rigidity and become more brittle as temperature is reduced. It is logical to assume that they will become more susceptible to failure by shock and by vibration under these conditions. Hence, the combination of the environmental factors of low temperature, shock, and vibration is significant. Similar examples could be presented describing many such distinct phenomena related to the probability of occurrence of various environmental factors. Studies have been made which have attempted to generalize such phenomena. It is emphasized, however, that these are generalizations and do not apply necessarily to every equipment item.

The occurrence of environmental factors in combination with each other is not as important as their probable intensities and frequencies. Certain obvious conclusions can be drawn from climatic data which serve to identify normal combinations of environmental factors occurring in various regions of the earth. The purpose of considering combined factors, however, goes beyond establishing frequency of occurrence of combinations and levels of intensity of individual factors. The primary purpose is to establish whether or not these conditions will have an effect on a given piece of equipment.

5-2.1 ENVIRONMENTAL FACTOR DESCRIPTORS

All of the environmental factors are capable of producing adverse effects on materiel but in most regions of the environment, only a limited number of factors actually produce effects because many factors either are absent from that particular region of the environment or are present in an intermediate range where they have no significant effects. Associated with each of the factors are factors that indicate the possible severity of materiel effects. As applied to a natural environmental factor e.g., temperature the descriptors employed are low, high, or intermediate. The first two descriptors would describe circumstances wherein materiel effects are important but intermediate temperatures would be less important. The descriptors employed with vibration, as an example of an induced factor, would most likely be severe, moderate, or none. With a number of factors, it is sufficient to note whether they are present or absent. In Table 5-1, descriptors are listed for each of the environmental factors.

5-2.2 TWO-FACTOR COMBINATIONS

Because of the frequency of their cooccurrence or because they have been found to affect adversely many items and materiel, a number of important two-factor combinations have been identified. One list of such combinations, which resulted from a study of combined effects on materiel, is given in Table 5-2. It may be noted that two environmental factors, free moisture and explosive atmospheres, are identified but are not included in those discussed in this handbook.

A number of naturally occurring two-factor combinations are not included in the tabulated list, including wind and sand and dust, wind and salt spray, vibration and acoustics, and high temperature and microbiological organisms This probably resulted from the nature of the materiel effects included in that specific study. At the same time, some environmental factors are independent of other factors. Strong acoustic, electromagnetic, or nuclear radiations are induced by man's activities and thus, are relatively independent of the other environmental factors although their effects may be either enhanced or reduced through the action of another factor.

5-2.3 FUNCTIONAL COMBINATIONS

The factor combinations cited in the preceding paragraph are those frequently observed to cooccur. In par. 5-3, the various factor combinations comprising natural climates are described In this paragraph, brief attention is given to factor combinations that occur as a result of the task or function being performed. The factor combinations listed do not include all such combinations or all conceivable functions but are deemed to represent adequately the types of such combinations possible.

From the examples of combinations of environmental factors by activities given in Table 5-3, it is apparent that no more than 10 of the 21 environmental factors are of importance in any given circumstance. During troop movement by foot, for example, acceleration is not present, and slow-acting factors such as ozone and microbiological organisms are insignificant. From the operational perspective, environmental effects may be limited to a few of the more important factors. The design engineer must consider all factors, however, so that the materiel he is designing will not have undue limitations on its applicability.

5-3 CLIMATES

The natural environment is composed of a large number of individual factors which occur in multitudinous combinations in various parts of the world. A number of environmental factors are completely absent in some regions and may occur only seasonally in others. Awareness and recognition of the common groups of natural environmental factors, where they are likely to occur, and their probable quantitative limits are necessary for materiel design engineers. The classification of climates into four broad types which are further subdivided into eight climatic categories is defined in AR 70-38 (Ref. 1). The basis for this subdivision is the range of temperatures and humidities typical of different regions. The four major climatic types are hot-dry, hot-wet, cold, and intermediate. The intermediate type of climate characterizes most of the land regions of the earth which do not experience extreme conditions. However, since the most important effects of environmental factors on materiel relate to extreme conditions, emphasis has been on the hot-dry, hot-wet, and cold climatic types. These often are referred to as desert, tropical and arctic environments. The characteristics

TABLE 5-1

ENVIRONMENTAL FACTOR DESCRIPTORS

Factors	Descriptors
Terrain	
Topography	Mountainous, hilly, flat
Hydrography	Tundra or swamp, lakes, rivers, arid
Vegetation	Mature forests, mixed, brush, grasslands, none
Temperature	High, low, intermediate, changing, range
Humidity	High, low, intermediate
Pressure	High, low, intermediate, changing
Solar radiation	Intense, weak, intermediate, none
Rain	Intense/frequent, moderate/occasional, light, rare
Solid precipitation	Permanent snowcover, seasonal snowcover, seasonal occurrence, none
Fog	Heavy/frequent, light/occasional, none
Wind	Severe, moderate, light, none
Salt	Heavy, light
Ozone	High, normal
Macrobiological organisms	Present, absent
Microbiological organisms	Quiescent, active
Atmospheric pollutants	Present (type), absent
Sand and dust (airborne)	Heavy, light, none
Vibration	Severe, moderate, none
Shock	Strong, weak, none
Acceleration	Strong, weak, none
Acoustics (radiation)	Loud, annoying, weak, or none
Electromagnetic radiation	Strong, moderate, weak
Nuclear radiation	Strong, moderate, background

TABLE 5-2

TWO-FACTOR COMBINATIONS OF IMPORTANCE TO MATERIEL (Ref. 2)

High temperature	with	Humidity Free moisture Low pressure Salt spray Sunshine Sand and dust Vibration Shock Acceleration
Low temperature	with	Humidity Free moisture Low pressure Sand and dust Vibration Shock
Humidity	with	Low pressure Sunshine Vibration Ozone
Low pressure	with	Vibration Explosive atmospheres
Sunshine	with	Sand and dust Vibration Ozone
Sand and dust	with	Vibration
Vibration	with	Acceleration

TABLE 5-3

COMBINATIONS OF ENVIRONMENTAL FACTORS ASSOCIATED WITH VARIOUS ACTIVITIES

Function	Significant factors
Troop movement on foot	Terrain, temperature, humidity, solar radiation, rain, solid precipitants, fog, wind, sand and dust
Air transport of men and materiel	Pressure, fog, wind, vibration, shock, acceleration
Long-term storage of materiel in warehouse	Temperature, humidity, salt, ozone, macrobiological organisms, microbiological organisms, pollutants
Arctic base operations	Terrain, temperature, solar radiation, solid precipitants, fog, wind, pollutants, vibration
Tropical air operations	Temperature, humidity, solar radiation, rain, wind, salt, microbiological organisms, vibration

of the intermediate climate are not considered here because the factors operative in it are less severe but are otherwise similar to those of the extreme climates.

The diurnal extremes of temperature, solar radiation, and relative humidity for both operational and storage/transit conditions are tabulated for all eight climatic categories in Table 1-3 of Chap. 1, "The Environment Faced by the Military". The subdivision of climatic types into climatic categories is tabulated in Table 1-2. In Table 5-4, the relationship between the 13 natural environmental factors and the eight climatic categories is indicated. This table serves to identify the importance of each factor for each category. In Fig. 1-1 the areas of occurrence of the eight climatic categories are given. In this same figure are plotted diurnal temperature and humidity cycles defined by AR 70-38 as climatic requirements for design purposes.

The diurnal variations in temperature for both operational and storage/transit conditions are plotted for all eight climatic categories in Fig. 5-1. It is important to note that these data represent a 1-percent risk policy. Materiel is not designed, developed, and tested to withstand such climatic conditions that more severe conditions are expected to occur only 1-percent of the time (hr) in the most extreme month in the most extreme parts of the appropriate areas. This 1-percent risk policy is established to avoid the cost and complexity of designing for the absolute extreme conditions that might occur in an area. Thus, the temperature data given in Fig. 5-1 and the humidity data given in Fig. 5-2 do not represent averages, norms, or typical diurnal cycles for the defined climatic categories but an extreme diurnal cycle based on a 1-percent risk policy.

The paragraphs that follow describe the principal climatic types.

5-3.1 HOT-DRY CLIMATE

Desert is often employed as a synonym for hot-dry climate although this is not completely accurate. (A desert is defined as a region that is generally vegetationless, rainless, and desolate.) Since desert regions are defined by a low precipitation level, the climate can be cold. The hot-dry climate is characterized by simultaneous occurrence of very high air temperatures, very low relative humidities, and intense solar radiation. There is no necessity for subdividing this climatic type into two categories; thus, hot-dry is also a climatic category. The hot-dry climate is found in low latitude deserts which, as indicated in Fig. 1-1, are found in northern Africa, West Pakistan, and India, a region on the Arabian peninsula around the Red Sea, north central interior of Australia, and a small region in the southwestern United States and northern Mexico. Many other regions of the earth are dry and are classified as deserts but these do not meet the combined criteria of high temperature and low precipitation that defines the hot-dry climatic type.

The hot desert climate is characterized by high incoming solar radiation, high outgoing ground radiation, clear skies, low relative humidity, large ranges of diurnal temperature, and infrequent and irregular rainfall. Visibility is generally good although it can be very restricted during sandstorms or duststorms and atmospheric shimmer. Mirages are not unusual. These climatic conditions are unique to the desert only in that they occur over long periods of time; it is not uncommon for high temperatures, radiation, etc.—characteristic of hot deserts—to occur in the more humid zones for a few days during the summer months. Vegetation in the desert is sparse although certainly not completely lacking. Woody shrubs exist in almost all areas with perhaps the singular exception of sand dunes which cover a relatively small percentage of the total desert area. The terrain of the desert varies widely from loose dune sands to stone- and rock-strewn surfaces, and from playas and flats to precipitous slopes and mountains. Playas are dry lake beds which may fill after a rainstorm. Flash floods occasionally occur, so that occupancy of dry washes should be avoided.

TABLE 5-4

ASSOCIATION OF NATURAL ENVIRONMENTAL FACTORS WITH CLIMATIC CATEGORIES

Factor	Climatic category						
	Wet-warm	Wet-hot	Humid-hot coastal desert	Intermediate hot-dry	Intermediate cold	Cold	Extreme cold
Terrain	2	2	2	2	2	2	2
Temperature	2	2	2	2	2	2	2
Humidity	2	2	2	2	2	2	2
Pressure	2	2	2	2	2	2	2
Solar radiation	2	3	2	2	2	2	2
Rain	2	2	2	1	2	2	0
Solid precipitation	0	0	0	1	2	3	3
Fog	1	1	1	0	2	2	2
Wind	2	2	2	2	2	2	2
Salt	2	2	3	2	2	2	1
Ozone	2	2	2	2	2	2	2
Macrobiological organisms	2	2	2	2	2	1	0
Microbiological organisms	3	3	3	1	2	1	1

0 Absent
1 Occasional
2 Common
3 Frequent or permanent

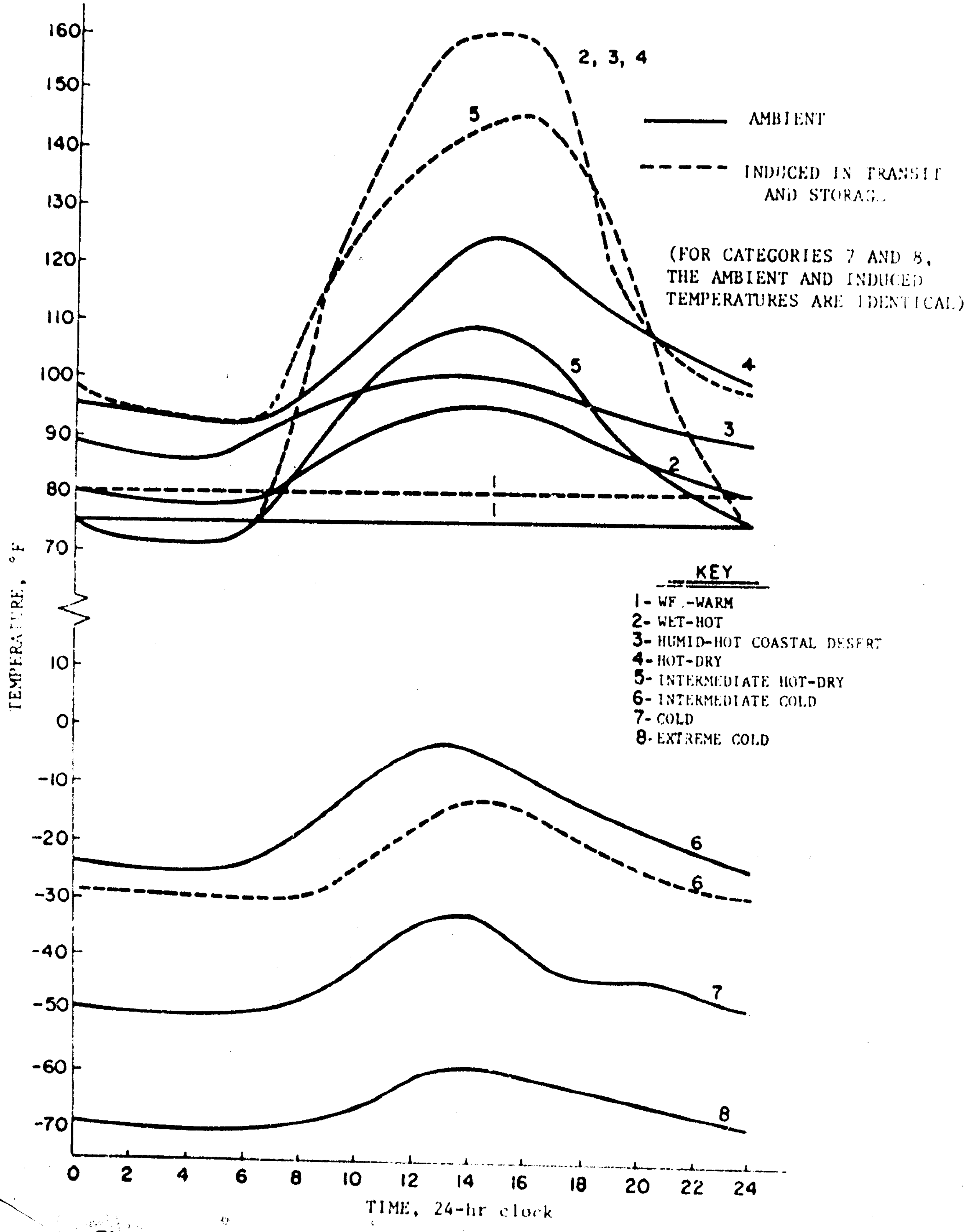


Figure 5-1. Diurnal Temperature Cycles for Various Climatic Categories (Ref. 1)

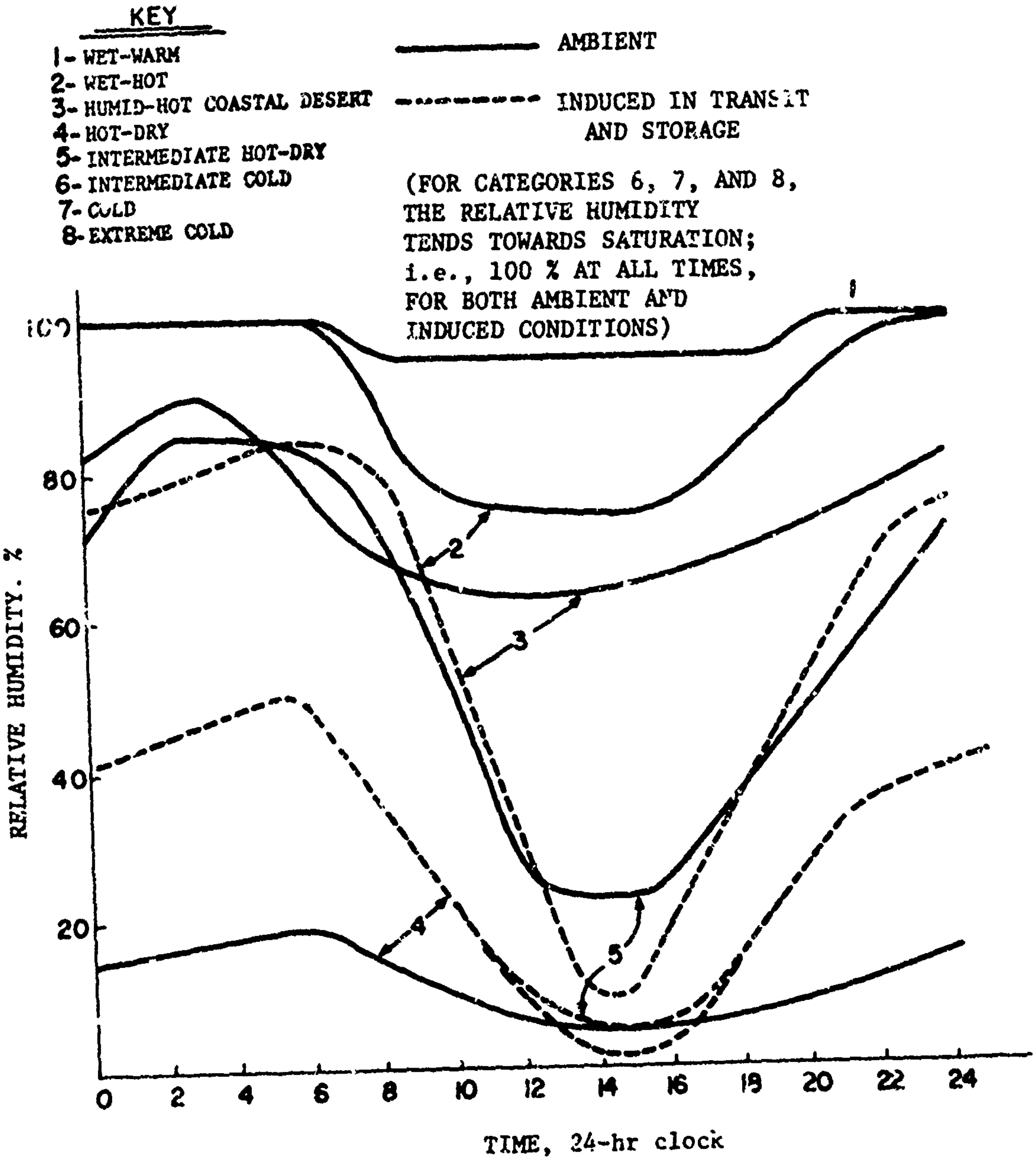


Figure 5-2. Diurnal Variations of Relative Humidity for Various Climatic Categories (Ref. 1)

The desert of the Yuma, Ariz., area is of particular interest to the Army because this is the locale in which the majority of Army materiel is field tested and evaluated. A series of reports comparing the Yuma climate with other desert areas of the world has been prepared and is very useful in evaluating or estimating probable deleterious effects to be expected in other deserts (Ref. 3).

5-3.1.1 TEMPERATURE

The highest ambient temperatures in the world are experienced in the hot deserts. The upper limit of high temperature defined in AR 70-38 for operations in hot desert areas is 53°C (125°F). One source has estimated that this temperature is exceeded approximately 2 percent of the time based on composite temperature data from stations located in Libya (Libyan Desert), Pakistan (Indian Desert), Death Valley (Mojave Desert) (Ref. 4), and Mali (Sahara Desert) (Ref. 5).

Temperatures of the hot desert commonly exceed 38°C (100°F) daily. During the warmest month, large portions of northern Africa and Saudi Arabia, for example, have a mean daily maximum temperature exceeding 38°C (100°F) on 95 percent of the days. Almost all of northern Africa, the eastern part of Saudi Arabia, the Mojave Desert, and the Gibson Desert in Western Australia have a mean daily maximum temperature of 38°C (100°F) on at least one-half of the days during the warmest month

Insofar as extremes are concerned, only Death Valley in the United States* and an area in northwestern Africa between latitudes 20 and 30 deg N. have temperatures equal or greater than 49°C (120°F) from 2 to 8 days during their warmest month. Southwestern Algeria is the only area in the world reporting temperatures above 38°C (100°F) more than 50 percent of the total hours during the warmest summer month. Conversely, stations within this so-called hot spot—such as Reggan, Bou-Bernous, and Aoulef, Algeria—reported January average daily maximum and minimum temperatures of approximately 22°C (72°F) and 6°C (43°F), respectively. Temperatures at Yuma Proving Ground, Ariz., exceed 49°C (120°) on less than 1 percent of the days; however, 29.9 days during July will have a maximum temperature of greater than 38°C (100°F). The mean maximum and minimum temperatures for Yuma during December and January are approximately 20°C (68°F) and 6°C (43°F), respectively, which compare quite closely with the temperatures cited in Algeria.

It may be seen that rather extreme seasonal variations exist between the summer and winter temperatures of the desert regions. The extreme high temperatures in the Northern Hemisphere generally occur in the season from May through September. Some stations in Libya and Algeria experience temperatures exceeding 38°C (100°F) during some portion of all months between April and October, and a few stations in Egypt (e.g., Aswan) report average daily maximum temperatures in excess of 38°C (100°F) from March through November. Therefore, temperatures in excess of 38°C (100°F) can be expected most of the year in many parts of northern Africa, during the summer months in Yuma, and for approximately 6 to 7 mo in the hotter portions of Arabia along the eastern boundary.

The clear, cloudless skies characteristic of the desert result in rapid nighttime radiation and often a wide diurnal temperature range—extremely wide in rare instances. Daily temperature excursions average 14 to 25 deg C (25 to 45 deg F), even 35 to 40 deg C (60 to 70 deg F). During the hot season, the lower nighttime temperatures are a distinct relief by contrast with the day, although they may not be cool by any means. For example, daily

*Because Death Valley is below sea level, -86 m (-282 ft), there is an additional temperature rise due to the adiabatic heating of the air as a result of the normal lapse rate with a change in elevation. As compared to the nearby Mojave Desert with an elevation of 610 to 915 m (2,000 to 3,000 ft), the temperature in Death Valley, with equal insolation, could be expected to range 4 to 6 deg C (7 to 10 deg F) higher as a result of the lower elevation.

maximum temperatures of over 38°C (100°F) at Phoenix, Ariz., are followed by minimum nighttime temperatures of 24°C (75°F), which may be considered typical temperature variations for hot desert areas. Wider extremes have been experienced, however, especially during low sun seasons. At Bir Milrha in the Sahara, a minimum of −0.56°C (31°F) and a maximum of 37.2°C (99°F) have been recorded on the same day in December. During this season, days are still warm but nights are distinctly chilly. Daily maximum temperatures may average 16° to 21°C (60° to 70°F), occasionally reaching 27°C (80°F). Average minimum temperatures in the area are about 4°C (40°F) (Ref. 6).

5-3.1.2 SOLAR RADIATION

Solar radiation at a locality is influenced primarily by sun position (latitude and hour), cloud cover, and atmospheric particulate matter. With clear skies the computed average daily solar energy reaching the surface of the earth is a maximum of 570 ly* (2,100 Btu ft^{-2} day^{-1}) at 0 deg latitude, decreasing less than 10 percent at latitude 30 deg N. (Ref. 7). Between latitude 30 and 70 deg N., however, it decreases roughly 10 percent for each 10-deg latitudinal interval. At Yuma during the months of July and August at 5:30 a.m. and at 8:30 p.m., total radiation including both solar and sky radiation is about 25 percent of maximum, which is almost 135 ly (500 Btu ft^{-2} day^{-1}) (Ref. 8). Between the hours of approximately 11 a.m. and 3 p.m., radiation remains within 5 percent of maximum, the actual maximum occurring about 1:30 p.m. Cloud cover in desert areas is of little consequence, ranging between 0.1 and 0.3, somewhat greater in winter than in summer. Atmospheric moisture attenuates radiation but usually not significantly in hot dry regions. Atmospheric sand and dust cause scattering and reflection, their occurrence and effects varying considerably with air movement and sand and dust storm characteristics of the area. Table 5-5 portrays computed annual average solar radiation at the ground surface with normal cloud cover in various latitudinal zones of the Northern Hemisphere.

*1 langley = 1 cal cm^{-2}.

Insolation, or solar radiation received, in hot-dry regions has severe indirect as well as direct thermal effects. To those effects on personnel and materiel of simply high ambient air temperature must be added heat absorption by direct exposure to solar radiation. Similarly, because of solar radiation effects, ground surface temperatures and air temperatures near the surface are considerably higher than ambient temperatures normally reported, measured at 200 cm above the ground. Ground surface temperatures as much as 20.5 deg C (37 deg F) above those at 200-cm level are reported in studies at Yuma (Ref. 8), and Trewartha (Ref. 6) mentions that temperatures may reach 90°C (194°F) for dry ground in desert regions.

5-3.1.3 PRECIPITATION AND MOISTURE

The most notable comment on precipitation is that stated by Trewartha: "It is a general rule, worthy of memorization, that dependability of precipitation usually decreases with decreasing amount" (Ref. 6). All areas of the hot desert will receive precipitation during some time period but it is highly unreliable and occurs in a most sporadic manner. While most hot desert weather stations record average annual rainfalls from a few millimeters to as much as 30 cm, 8 to 10 cm is a more common figure. Average annual precipitation figures have little meaning in the desert except that they do give some indication of the frequency of rainstorms. If precipitation is at the rate of 3 to 4 cm hr^{-1} or greater, storms of the order of 1 to 3 cm of rainfall can cause severe damage in the desert because of the rapid runoff. Stories of solid walls of rock and water rushing down dry stream beds are common and can be verified by surveying resulting damage to roads and bridges.

Average relative humidity in hot-dry regions is quite low although there is usually a

TABLE 5-5

COMPUTED ANNUAL AVERAGE SOLAR RADIATION AT GROUND SURFACE (Ref. 7)

Latitude, °N:	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Solar radiation, per day, ly (Btu ft^{-2}):	385 (1420)	445 (1641)	438 (1615)	395 (1457)	332 (1224)	243 (896)	195 (719)

moderate amount of moisture in the atmosphere. For example, the air at Yuma, Ariz., contains nearly as much moisture as that at Madison, Wis., in July and twice as much in January. Relative humidity at Yuma during these months, however, is only one-half to two-thirds that in Madison. In spite of the low relative humidity in desert areas, surface cooling during late evening and early morning hours is often sufficient to produce valley fogs and dew. Relative humidity may be quite high in morning hours, becoming extremely low during the heat of the day, as indicated in Table 5-6 for randomly selected hot-dry locations.

Monthly average morning relative humidities for Yuma are consistently fairly high, ranging from 56 to 68 percent. At Baghdad and Timbuktu, average highs are considerably above those at Yuma, and average lows are considerably below. Similarly, average midafternoon highs at Yuma are appreciably lower than those at the other locations. Generally, midafternoon lows—the relative humidity levels commonly associated with hot-dry regions—are below 20 percent.

5-3.1.4 WIND

In general, an average windspeed of 6 to 11 km hr^{-1} (3.7 to 6.8 mph) would be representative of the majority of desert locations. However, some desert areas characteristically have strong winds; an example is the "wind of 40 days" in southwestern Iran. Storms having higher winds occur in the desert which are serious for man and machine. In some interior regions in northeastern Africa the air is normally almost calm, with only occasional sandstorm disturbances particularly during the summer season. Coastal portions of northwestern Africa have prevailing winds with a mean speed of 25 km hr^{-1} (15.5 mph) during July, but winds in interior regions range from calm up to only 11 or 12 km hr^{-1} (6.8 or 7.5 mph). Personnel stationed in North Africa during World War II reported that in spite of low speeds the persistent wind had little cooling effect and often carried a sufficient amount of sand and dust to cause severe eye, nose, and throat irritations.

The dominant effect of wind in an arid region is the lifting of surface dust particles into air, or surface migration of sand particles. Porter et al. cite five types of duststorms and sandstorms distinguished in central Africa (Ref. 10):

(1) *Dust devil.* A small vortex of 3 to 15 m (10 to 49 ft) in diameter rotating rapidly. It occurs quite often and may upset light structures such as tents and scaffolding, but is generally of little importance and not likely to be recorded as a sandstorm.

(2) *Local rising sand.* A highly localized phenomenon of rising sand, resulting from wind velocity exceeding a critical level that varies widely according to locality.

(3) *Haboob.* A rainy season sandstorm or duststorm with strong wind occurring with thunderstorms. (Most frequent from May through September, but haboobs have occurred in every month except November (Ref. 11).)

(4) *Rainy season cold-front-type sandstorm.* A sandstorm followed almost invariably within a day or two by general rains.

(5) *Harmattan haze.* An intensified haze occurring when the dust content of the "harmattan", or northeast trade wind, is increased behind cold air invasions during winter. The harmattan blows consistently in the center of northwestern Africa and is normally dust laden at all seasons. Behind widespread cold fronts, its dust content is greatly increased, and "harmattan" haze persists for days. The same harmattan-type haze predominates over wide areas in French Equatorial Africa except during summer months.

Clements states that a windspeed of approximately 48 km hr^{-1} (30 mph) is required to produce a sandstorm (Ref. 12). He further states that perhaps not more than three or

TABLE 5-6

AVERAGE RELATIVE HUMIDITIES IN HOT-DRY LOCATIONS (Ref. 9)

Location (Country)	El., ft	Annual precip., in.	Time, hr	RH, Highest %	RH, Highest Month	RH, Lowest %	RH, Lowest Month
Yuma (U.S.)	141	3.4	0530	68	Aug	56	June
			1200	34	Dec	18	May-June
Baghdad (Iraq)	111	5.5	0600	84	Jan-Dec	32	July
			1500	52	Dec	12	July
Khartoum (Sudan)	1,279	6.2	0800	67	Aug	18	Apr
			1400	41	Aug	10	Apr
Timbuktu (Mali)	988	9.1	0600	83	Aug	27	Apr
			1200	57	Aug	15	Apr

four storms occur per year in most localities in the American deserts. This number of storms, particularly those of a violent nature, probably holds true for most of the African deserts. These storms rarely exceed two or three days in duration and are most likely to occur during the spring. Contrasted with these data are reports by some observers who have noted as many as 20 duststorms per year in Africa. Data show as many as 100 sandstorms in a year in the area of southern Algeria (Ref. 10).

5-3.1.5 TERRAIN

Elevations of the desert are quite varied, ranging from below sea level to around 1,000 m (3,000 ft). High mountains found in some desert regions generally are not considered true desert areas because of the low temperatures associated with their elevations. If they receive no appreciable rainfall, however, they take on aspects characteristic of dry regions. Clements has divided the desert surfaces of the southwestern United States into 10 types (Ref. 12):

(1) *Playas.* Dry lake beds occupying the lowermost portions of interior basins, perhaps the flattest physiological feature that can be found.

(2) *Desert flats.* Areas of very low relief varying widely in size and, except for playas, the flattest surfaces to be found in the desert.

(3) *Bedrock fields.* Smooth rock surfaces of varying size which may be of very low relief (hammadas), slightly inclined (pediments), or domed (desert domes).

(4) *Regions bordering through-flowing streams.* River bottoms and terraced areas adjoining streams in which the total relief from the river bottom to the highest terrace may be well over 30 m (100 ft).

(5) *Alluvial fans and bajadas.* Areas formed by the deposited materials washed out from higher elevations.

(6) *Dunes.* Mounds or hills of windblown materials ranging in size from clay to coarse sand, usually sand. They occupy from 1 percent of the American deserts up to 25 percent of the Sahara.

(7) *Dry washes.* Stream courses that contain water shortly after heavy rainstorms but are dry the remainder of the time.

(8) *Badlands.* Extremely rough terrain formed by the intricate dissection of soft rock by torrential run-off characteristic of desert areas.

(9) *Volcanic cones and fields.* Cones of loose volcanic material having slopes of about 30 deg, varying in height but recognizable above the surrounding desert. Fields consist of loosely packed cinder surfaces. Lava flows commonly have irregular surfaces consisting of basaltic blocks and tubes, and large pits resulting from collapse of tubes.

(10) *Desert mountains.* Mountains whose outstanding features are abundant rock outcrops and abrupt change from mountain slope to valley, as contrasted with rounded smooth slopes of mountains of more humid regions.

Surface materials may be mineral salts, lime, clay, silt, sand, gravel, boulders, or bare rocks. Occurrence of these surface conditions is highly irregular and requires extremely detailed mapping to indicate their locations. It is sufficient to state that desert surfaces can be negotiated relatively easily by man and machine, or almost impossible, depending upon location. It is only through detailed maps that locations of the "good and bad" areas can be established firmly.

There are occasional trails through almost all desert areas; camel routes, where used, normally follow the more sandy areas whereas stony surfaces most often are used by vehicles. Precise surface conditions that have a critical effect on movement are difficult to discuss in a general manner. Few areas in the hot deserts of the world cannot be traversed by man on foot provided that he has sufficient food and water. Vehicles, however, will be hampered almost continuously by steep-sided washes, boulder-strewn surfaces, and other impediments of the surface microrelief.

5-3.1.6 MATERIEL EFFECTS

The most important materiel effects observed in the hot-dry climatic regions result from the extremely high daytime temperature. Effects that closely follow this in importance are derived from the extreme ultraviolet radiation, the airborne sand and dust produced by sudden violent winds or by human activity, and the large daily temperature fluctuations.

A rule of thumb that often is employed is that the rate of chemical change doubles for each rise of 10 deg C in the temperature. Thus, at 50°C (112°F) chemical reactions occur 16 times as rapidly as they do at 10°C (50°F). High temperatures can have important effects on electronic apparatus in which such components as condensers and batteries deteriorate rapidly. The black finish often employed on electronic apparatus because of its excellent thermal radiation properties has the inverse effect in a hot climate. By efficiently absorbing direct sunlight, temperatures of black-finished objects may rise 50 percent above the outside temperatures and, with the added effect of heat generated within the equipment, surface temperatures may rise to 200°F, a temperature that will damage many types of equipment.

The sand and dust of the hot-dry environment will damage electromechanical equipment such as relays and switching gear; gasoline engines; any fine, lubricated moving parts of light and heavy equipment; and other materiel. The most injurious effects of sand and dust result from their adherence to oil-bearing surfaces, but all polished surfaces including glass and plastic window areas are etched by sand particles driven by high wind.

Tires wear out rapidly in desert areas, and surface finishes of all types crack, craze, and blister. Sunlight causes chemical changes in textiles, plastics, and rubber products.

The primary effects of sandstorms and duststorms are those of abrasion or erosion, visibility reduction, particle penetration through small apertures, and alteration or obliteration of surface landmarks. Less widely publicized and encountered but often spectacular are electrostatic effects (Ref. 10). Sandblasted paint and chrome, and frosted or pitted glass occur commonly with vehicles used in the desert. Sculptured effects are seen on wood posts and rocks projecting from the ground.

Although visibility often is reported as zero by desert inhabitants it is probably rarely less than 3 m (10 ft). Where the surface is alluvial with little or no sand, the dust rises in dense clouds to heights of several thousand feet (Ref. 13). In an erosion desert in which the only free dust consists of fine rock particles, the wind produces first a mist of both sand and dust. Later the mist disappears leaving only a low-flying cloud of sand. Where the ground consists of coarse grains, pebbles, or large stones, the top of the cloud may be as much as 2 m (6 ft) above the ground surface but is usually less. When the surface consists of fine sand, the height of the sand cloud is noticeably lower (Ref. 13).

Although 13 m s^{-1} (30 mph) is often used as the windspeed threshold for sandstorms, sand-sized particles will migrate at windspeeds as low as 5 m s^{-1} (11 mph) (Ref. 13). Within this range of speeds, particle movement may cause formation of ripples, ridges, and whalebacks; movement of considerable masses of sand; dune growth; and drifts of sufficient magnitude to cover small structures or objects.

The impact of windblown sand particles on metallic electrical conductors produces electrostatic charges of sometimes serious proportions. During the Dust Bowl conditions in the United States in the middle 1930's, some auto ignition systems failed to function unless the auto frame was grounded by means of a wire or chain to the ground. Breakdowns of insulators, transformers, and lightning arrestors in electric power systems have been reported during sandstorms even when no lightning discharges occurred. During construction of a telephone line in a sandstorm in the Imperial Valley of California, electrostatic voltages high enough to knock a man down were reportedly built up on a bare wire being laid. In Saudi Arabia, charges as high as 150,000 V have made telephone and telegraph communications of a railroad impossible during a sandstorm (Ref. 12).

In many ways the hot-dry environment is benign. Such natural environmental factors as solid precipitants, rain, and fog are completely absent and deterioration by microbiological organisms does not occur because of the lack of the moisture required for growth of such organisms. Macrobiological organisms such as insects exist in small numbers but do not create significant problems. While saltfall occurs in quantities from 0.05 to 0.5 g m^{-2} yr^{-1}, the lack of moisture prevents the occurrence of a significant corrosion problem. Equipment that was recovered from years of exposure to the hot-dry climate has been found to operate well.

5-3.2 HOT-WET CLIMATE

This climatic type often is described as tropical and is characterized by lush vegetation along with high temperature and humidity. Generally, tropical climates may be assumed to be those lying roughly between latitudes 25 deg N. and 25 deg S. Areas within this zone, however, may be hot or cold, wet or dry, and may have much or little vegetation. Major deserts occupy a considerable portion of the landmass in these regions and might be classed as tropical deserts. They are categorized more correctly and usefully as hot-dry regions, however, and are treated as such in this handbook. Much of the remainder of the lands in tropic latitudes are those areas considered truly tropic; i.e., wet-humid, wet-tropic, characterized by abundant moisture and relatively high temperatures, continuously or at least for some portion of the year.

In order to fully characterize the hot-wet climatic type, three climatic categories are identified in AR 70-38—the wet-warm, wet-hot, and humid-hot coastal desert (Ref. 1).

Wet-tropic climates cover approximately 15 percent of the land area of the earth and are found in all continents except Europe and Antarctica. The largest continuous areas are in the Amazon and Congo Basins. Asian and Australian wet-tropics are small by comparison and are mostly on tropical islands lying between the two continents (Ref. 14). Limits of the wet-tropics vary greatly, but several authorities agree on the location of sizable core areas in tropical latitudes (shown in Fig. 5-3), which constitute less than one-third of the total wet-tropic area. Moisture and temperature are constantly high, and tropical rain forest vegetation and lateritic soils predominate in these areas. Surrounding the core areas are broad transitional zones whose characteristics gradually change from core to periphery. Transitional areas characteristically have a dry season of some extent increasing in duration as the perimeter is approached. As aridity increases outward from the core area, the tropical rain forest yields to patches of scattered trees and grass and, finally, to expanses of tropical grassland and low shrubs.

Outstanding features of wet-tropical regions are heavy precipitation distributed throughout its year, a relatively small diurnal annual ter. ature variation, and overabundance of vegetation. The latter forms a closed canopy of leaves and branches above ground level and results in a microclimate below the canopy significantly different from ambient conditions above it. Although reliable data are scarce, approximate differences between the microclimate below the closed canopy of a mature wet-tropical forest and the climate measured in extensive clearings are outlined where pertinent in the paragraphs that follow. It may be assumed that the

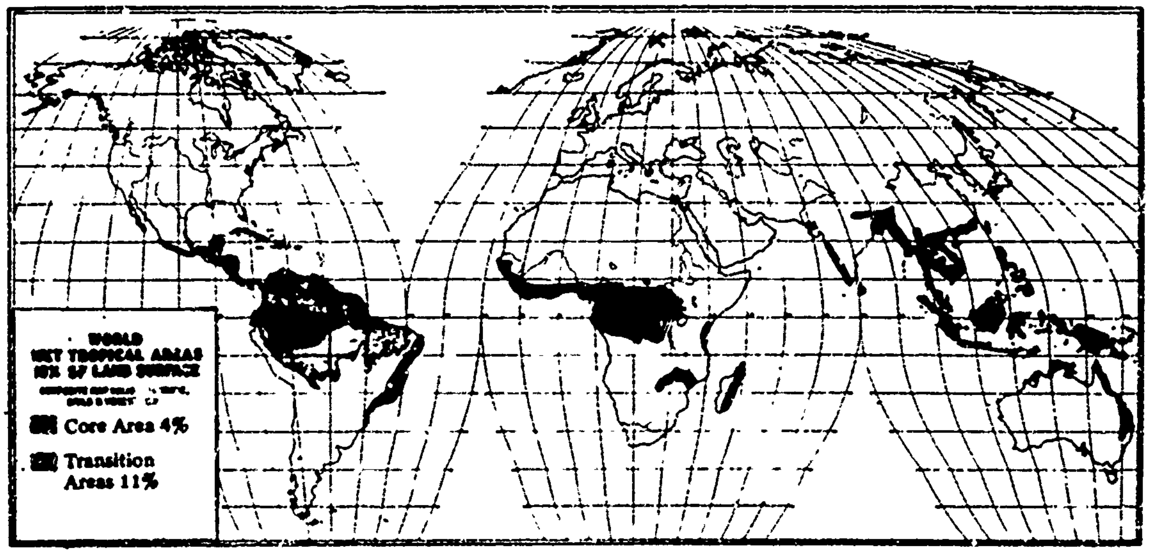


Figure 5-3. Core and Transitional Wet-Tropical Regions

climatic conditions measured immediately above the canopy are equivalent to those that would occur in extensive clearings.

Within the regions identified as wet-tropics, subregions may be differentiated on the basis of climate, vegetation, and soil. Chambers et al. treat wet-tropic areas in terms of interior plains mountains, and coastal lowlands (Ref. 14). Trewartha, classifying subregions on the basis of climate, identifies the tropical wet or tropical rain forest climate, the monsoon-rain forest climate, and the tropical wet and dry climate (Ref. 6). Similarly descriptive, and combining aspects of each of these systems, are the categories of tropical rain forest, tropical marine and tropical monsoon, described briefly in the subparagraphs that follow.

Tropical rain forests are constantly wet, with average monthly temperatures for the warmest and coolest months varying only about 2 to 4 deg C (4 to 8 deg F). They are typified by high rainfall, but the wettest month of the wettest season varies greatly from place to place. Moisture-laden prevailing winds forced to higher elevations by mountain ranges can create a situation of high rainfall, and hence, rain forests. On the lee side of the mountains, drought conditions may exist during part of the year so that the dry areas may be considered marginal to the true tropical rain forest. Distinct differences are observed between the environment beneath the forest canopy and in clearings and that above the canopy.

Although a tropical rain forest region usually is located on relatively large landmasses between latitudes 10 deg S. and 2 deg N., similar tropical conditions are found on isolated Pacific islands as far north as latitude 20 deg N. The islands exhibit a temperature range greater than the rain forests between the hot and cool months, but diurnal temperature variations are less than in the rain forest because of the surrounding ocean.

The tropical monsoon climate, which includes most of India and Southeast Asia, is entirely seasonal. Temperature extremes are high. Cloudless skies between mid-April and June are accompanied by afternoon temperatures averaging 40°C (103°F) with extremes to 45°C (113°F). With the clear skies and strong earth radiation of this period, the night air may cool to 27°C (80°F). Following rains in June until late September, cooling dry winds from the northeast result in daily temperatures from 9° to 21°C (48° to 70°F). Precipitation is concentrated in the months of June to September. During these months, the southwest monsoons bring in continual rain, drizzle, and cloudiness. Rainfall is light from September to April with less than 25 percent of the yearly precipitation occurring during this period. Aside from the seasonal variation, total rainfall varies widely between coastal or mountainous areas receiving about 250 cm (100 in.) annually and interior plains receiving only about 75 cm (30 in.).

5-3.2.1 TEMPERATURE

Mean annual temperatures of about 27°C (80°F) are common for continuously wet tropical areas. Seasonality is marked by a change in precipitation accompanied by a change in temperature of 6 to 8 deg C (10 to 15 deg F). Slightly lower temperatures are associated with the wetter months. The difference in average temperature between the hottest and coldest months for areas near the Equator is usually less than 5 deg C (9 deg F). In some areas mean monthly temperatures vary less than 1 deg C (1.8 deg F).

Although monthly variations in temperature are small in the wet-tropics, diurnal variations may be considered relatively large. Mean daily ranges of 3 to 14 deg C (5 to 25 deg F) can be expected for different areas. Mean monthly minimum temperatures are usually near 21°C (70°F) and mean monthly maximum temperatures are generally in the vicinity of 30°C (85°F). Maximum temperatures rarely exceed 35°C (95°F) in continuously wet regions.

Although insufficiently supported by data, a mean temperature of 18°C (64°F) for the coldest month has been used by many authorities as the minimum temperature for the megathermic type of vegetation* characteristic of the wet-tropics (Refs. 6, 15). Lower temperatures are found primarily in mountainous regions as indicated in Table 5-7, which also indicates a lapse rate (temperature decrease with altitude increase) of approximately 0.4 to 0.7 deg C/100 m (2.2 to 3.8 deg F/1,000 ft).

The closed canopy formed by leaves and branches effectively reduces the total amount of solar radiation reaching the forest floor. Mixing of the air above the canopy with air below also is impeded by the vegetation. These two influences result in lower maximum temperatures in tropical forests than in clearings. Table 5-8 provides data on temperatures within wet tropical forests. The maximum daily temperature is approximately 4 deg C (7 deg F) lower in the undergrowth of a mature tropical forest than above the main tree canopy. Minimum daily temperatures are not affected appreciably by the vegetation. Contributory factors are climatic; extensive cloud cover, high humidity, and frequent rain tend to reduce outgoing radiation and nighttime cooling.

5-3.2.2 SOLAR RADIATION

The belt of maximum solar radiation crosses the Equator twice during the year as seasons change (Ref. 6). Total daily solar radiation received by the surface of the earth at any given point depends upon a number of factors–the angle of solar rays, length of day, selective scattering of short wavelength blue light by molecules of air and fine dust, diffuse reflection of all wavelengths by large dust particles and cloud droplets, and absorption of principally the longer wavelength by water vapor. It is estimated that 35 percent of the total solar radiation entering the atmosphere of the earth is reflected back into space by scattering and reflection from the various components of the atmosphere and the surface of the earth. Two percent is reflected from the surface, 6 percent is reflected by the atmosphere; and the remaining 27 percent is reflected from clouds. Fourteen percent of the total radiation is absorbed by the atmosphere and only 51 percent of the total incoming radiation finally reaches the surface of the earth and is absorbed by it. [illegible] four percent of this 51 percent is in [illegible] of direct sunlight and the remaining 17 percent is diffused radiation or sky radiation (Ref. 6).

Landmasses at or near the Equator receive the greatest total annual solar radiation but do not necessarily receive the maximum daily radiation. Latitude 40 deg N., at the time of summer solstice, receives approximately 28 percent more radiation than the Equator (Ref. 17). This radiation level is 6 percent higher than the maximum at the Equator at the time of the vernal and autumnal equinoxes when incoming radiation is incident at 90 deg on the atmosphere at the Equator. Because of the greater amount of water vapor in the atmosphere over the wet-tropics, a larger amount of incoming radiation is absorbed annually by the atmosphere than in the higher latitudes or at higher elevations in the low latitudes. Consequently, the total solar radiation reaching the earth is reduced correspondingly.

The modifying effect of normal cloud cover on the amount of solar radiation received at the land surface is shown in Table 5-9 which represents only average annual conditions since the actual amount of solar radiation absorbed by the ground depends upon the geographical location, season of the year, type of soil and vegetation, and weather conditions. In comparing solar radiation for two specific sites–the Canal Zone (latitude 9 deg N.) and Amarillo, Tex. (latitude 35 deg N.)–it is interesting to note that the Canal Zone received 381 ly day^{-1} and Amarillo 471 ly day^{-1} (Refs. 18, 19). On a typical hot sunny day in May, a maximum of 615 ly

*A type of vegetation that requires high temperature and abundant moisture.

TABLE 5-7
TEMPERATURE CHANGES WITH ALTITUDE (IN NETHERLANDS EAST INDIES) (Ref. 16)

Location	Altitude, m (ft)	Av. temp., °C (°F)
Lowlands	0- 200 (0- 656)	25-27 (77-81)
Foothill belt	200-1000 (656-3280)	19-24 (66-75)
Mountain belt	1000-1800 (3280-5900)	13-18 (55-64)

TABLE 5-8

TEMPERATURES (°C) AT DIFFERENT HEIGHTS IN WET-TROPICAL FORESTS (Ref. 15)

Location	Temperature	Dry season		Wet season	
		(0.7 m) Undergrowth	(24 m) B Story*	(0.7 m) Undergrowth	(24 m) B Story*
Rain forest in southern Nigeria	Mean daily max	29.7	33.9	26.8	30.9
	Mean daily min	23.9	24.0	23.3	21.8
		Undergrowth	(35-40 m) Top of tall tree	Undergrowth	(35-40 m) Top of tall tree
Forest at 300 m on Mt. Maquiling in Philippines	Mean daily max	27.5	32.5	26.9	31.3
	Mean daily min	19.9	19.6	21.0	20.6

*The terms "A", "B", and "C" Stories are used to describe different tree strata in a tropical forest. "A" is the highest and "C" the lowest. A profile of this particular forest showed that the "B" Story formed the closed portion of the canopy and the trees of the "A" Story did not form a closed canopy.

TABLE 5-9
SOLAR RADIATION (ly day^{-1}) AT SURFACE OF EARTH WITH NORMAL CLOUD COVER (Ref. 7)

Conditions	Latitude			
	0°-10°N	10°-20°N	20°-30°N	30°-40°N
Solar radiation at surface with clear sky	567	556	534	494
Mean cloudiness	0.52	0.40	0.34	0.40
Solar radiation absorbed at ground surface	308	365	346	3[illegible]

day^{-1} was recorded in the Canal Zone while the monthly average in Amarillo for the month of May was 617 ly day^{-1}. The peak monthly average at Amarillo occurred in June with 654 ly day^{-1}.

Measurements of solar radiation in Java (Ref. 16) indicate a total radiation level considerably lower than Washington, D.C., during the time that the incidence of solar rays was at the same angle for the two locations. A study of radiation in the Congo Basin (Ref. 7) revealed that the maximum and mean total radiation levels in this area are approximately equivalent to those in temperate zones during summer. A marked deficiency in blue and ultraviolet wavelengths was also reported. It is suggested that the low total radiation for this part of the Congo is due to large quantities of water vapor and contaminants such as volcanic dust in the atmosphere.

5-3.2.3 RAINFALL

Depending on the seasonal distribution, high total annual rainfall can be associated with either continuously wet conditions or with alternating periods of heavy rainfall and prolonged drought. Table 5-10 presents rainfall data for two locations in the Tropics—Conakry, Guinea, and Padang, Sumatra. Both have approximately the same annual total precipitation of about 4.3 m (170 in.), but that for Padang is distributed more or less evenly throughout the year while rain falls predominantly from June through October at Conakry. Obviously, high annual rainfall does not always mean a continuously wet-hot condition.

A large portion of the total rainfall in the Tropics occurs as cloudbursts, a cloudburst being defined as a shower of rain intensity greater than 0.1 cm min^{-1} (0.04 in. min^{-1}) for not less than 5 min. Although a greater percentage of precipitation in the Tropics occurs as cloudbursts, intensity appears to be approximately the same as cloudbursts in temperate climates, 0.2 to 0.3 cm min^{-1}. Variations in amount of rainfall appear due to shorter or longer durations of showers rather than to any significant change in intensity (Ref. 20).

It is desirable to ascertain the total amount and distribution of rainfall necessary for continuously wet conditions. In this context a "wet" soil is defined as one receiving a net surplus of moisture; i.e., more than the amount that will evaporate from the soil and transpire through vegetation, a process termed "evapotranspiration". Under wet conditions, the soil cannot hold additonal water against gravity, and any excess runs off or percolates through the soil. Because of difficulties of measuring actual evapotranspiration, Thornthwaite developed methods of calculating it from mean monthly temperature (Ref. 21), leading to a method of calculating mean monthly precipitation necessary for wet conditions at various temperatures. According to this method, rainfall of at least 10 cm mo^{-1} is necessary to maintain wet-tropical conditions at 30°C (86°F) and above, and at least 7.5 cm mo^{-1} between 20° and 30°C (68° and 86°F) (Ref. 19)

The U.S. Army Corps of Engineers has measured soil moisture and rainfall in an effort to predict moisture content from climatic data (Ref. 22). Figs. 5-4 and 5-5 show the monthly variation of soil moisture content for two different sites in the Canal Zone. Both are in the same general area, but the vegetation on one site consisted of a spotty growth of tall grass while vegetation on the other was a dense semideciduous jungle forest. The denser vegetation resulted in less variation and higher moisture content during the dry season. Soil moisture content at both sites, however, remained remarkably constant from June through January. Absence of appreciable variation in soil moisture over a period of 9 mo, even though the recorded precipitation varied from 5.6 to 37 cm (2.2 to 14.5 in.) in that time, indicates that excess water either percolated down through the soil or ran off. It can be assumed that the soil was continuously wet from June through January,

TABLE 5-10

MONTHLY AVERAGE RAINFALL (in.) (Ref. 9)

Month	Padang, Sumatra	Conakry, Guinea
January	13.8	0.1
February	10.2	0.1
March	12.1	0.4
April	14.3	0.9
May	12.4	6.2
June	12.1	22.0
July	10.9	51.0
August	13.7	41.5
September	16.0	26.9
October	19.5	14.6
November	20.4	4.8
December	18.9	0.4
Total	174.3	169.0

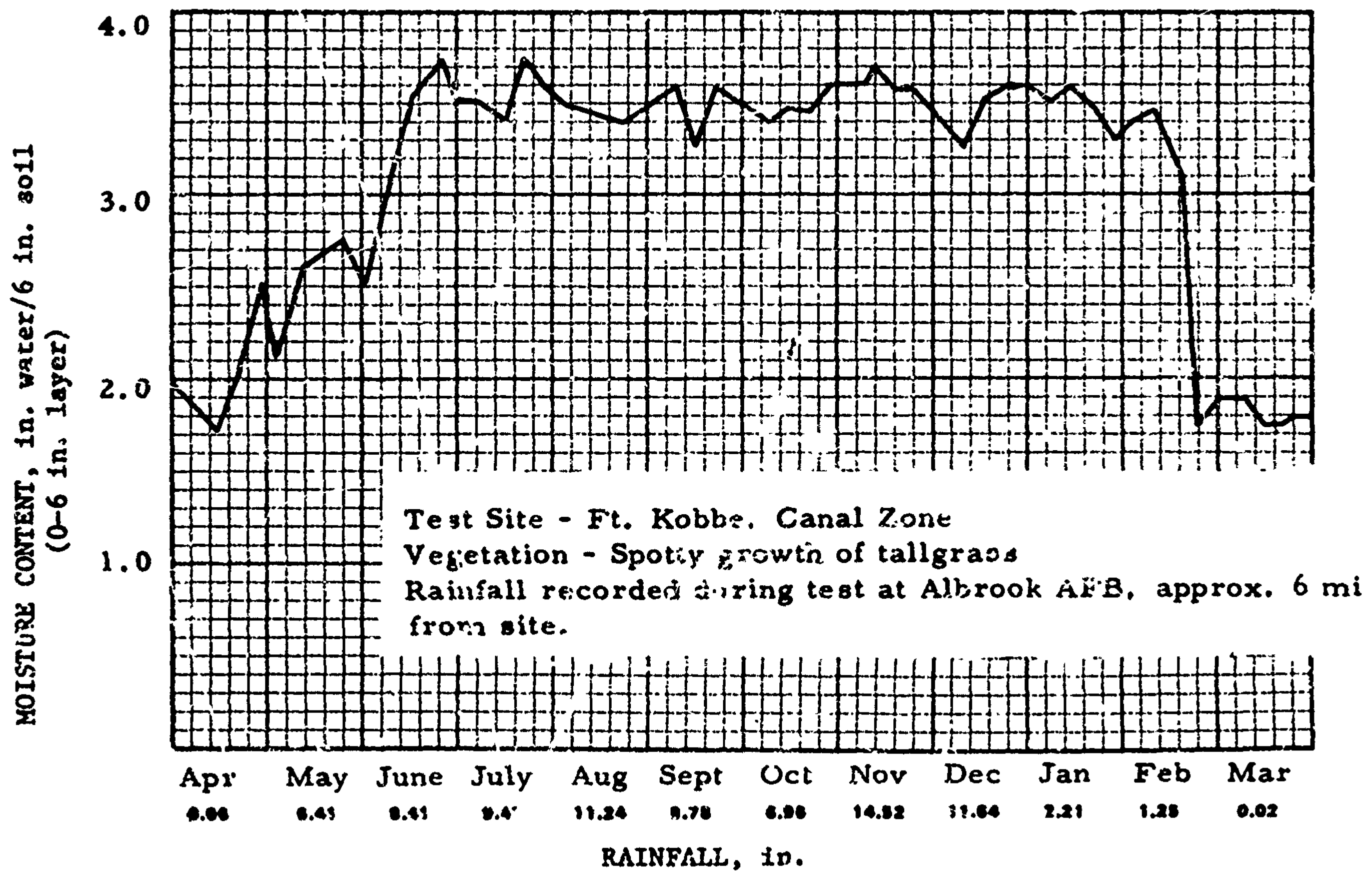


Figure 5-4. Measured Moisture Content of Soil in Tropical Forest (Ref. 22)

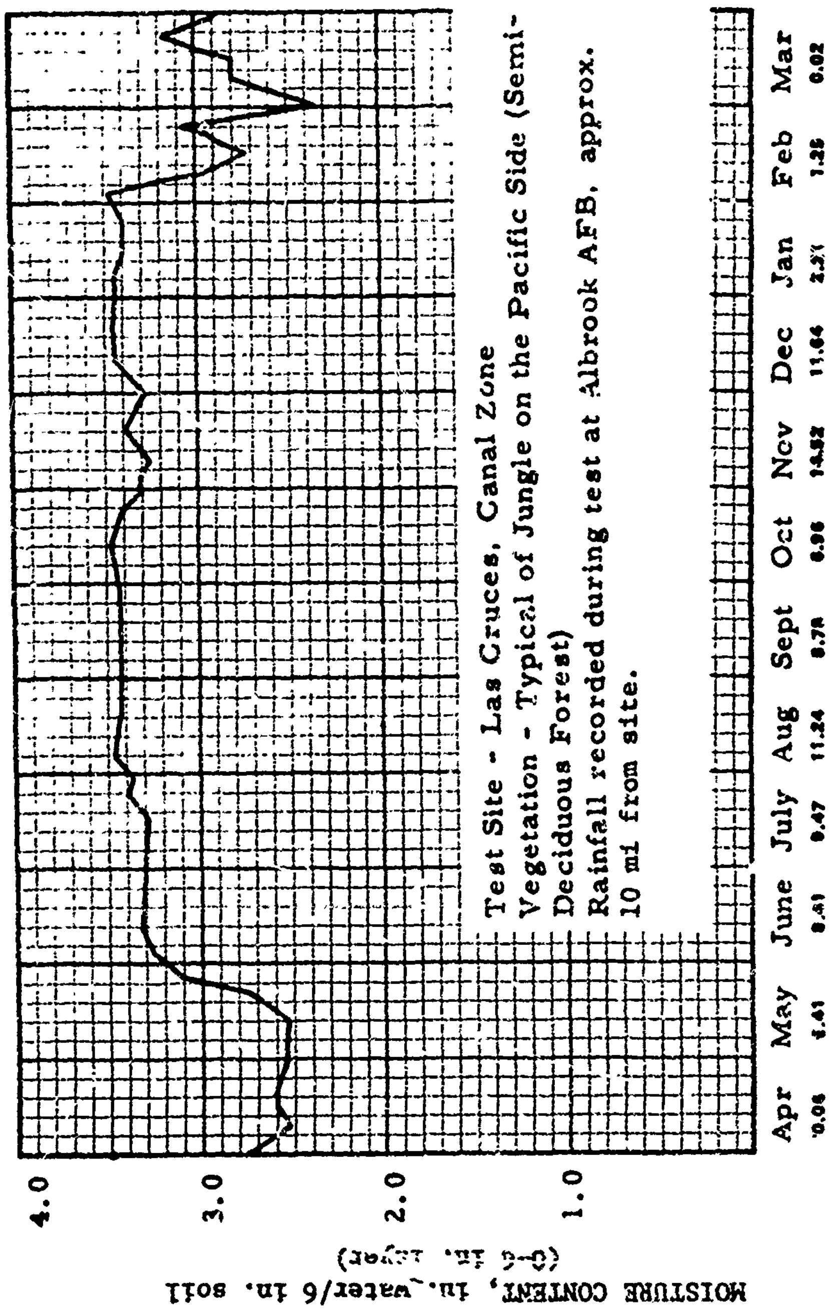


Figure 5-5. Measured Moisture Content of Soil in Tropical Grasslands (Ref. 22)

during which time monthly rainfall never fell below 5.6 cm (2.2 in.).

Köppen used vegetation for his criterion and concluded that a minimum of 6 cm (2.4 in.) of rainfall each month is required for continuously wet conditions in the Tropics (Ref. 15). Other investigations have reported higher values. It has been found that 10 cm (4 in.) is the minimum monthly precipitation requirement for rain forests to grow in the West Indies (Ref. 23).

It generally is agreed that high annual rainfall is not a guarantee of continuously wet conditions. Most authorities on plant ecology believe that with a minimum annual rainfall of approximately 165 to 180 cm (65 to 70 in.) the type of vegetative climax is influenced more by seasonal distribution than total rainfall. Exceptionally high totals do appear able to delay the effects of short drought periods; with high total rainfall, it is possible to have at least 1 mo with little or no rain before soils start to become noticeably dry.

Few consistent data are available for determining rainfall requirements for continuously wet conditions in the Tropics. Several different approaches to the determination include an empirical equation expressing evapotranspiration, field measurements by the Corps of Engineers of soil moisture content in the Canal Zone, and several attempts to use vegetation as an indication of moisture content. In spite of somewhat diverse results, a range of 5.5 to 10 cm (2.2 to 4 in.) appears to represent a monthly rainfall considered minimum for continuously wet conditions. The lower figure is probably applicable for a period of 1 to 2 mo preceded by considerably higher rainfall.

The canopy formed by the leaves and branches of mature wet tropical forests acts as a huge umbrella that prevents a considerable portion of each rainfall from reaching the ground. The amount of moisture intercepted appears to be dependent on the density and type of vegetation, and on the intensity and duration of the rainfall. The amount of moisture needed to wet the surface of the vegetation would represent a greater percentage of the total rainfall when the total is low (0.2 to 0.5 cm) than when it is high (2 to 5 cm). Frequent light showers should allow greater opportunity for evaporation from the foliage than would one deluge of the same total precipitation. It is difficult to reconcile the findings of different investigators in this respect because many of the pertinent variables are usually not reported. Also, several investigators have obtained divergent results concerning effects of intensity and duration of rainfall on this phenomenon. One author states that a greater percentage of rainfall was retained by the vegetation when the rain fell as thundershowers than when it fell as a long continued fine rain. Another group "found that relatively more rain reached the forest floor during the season of heavy downpours than during the season when rain is less heavy". These comments typify the information available. Data indicate that under a cover of dense forest roughly 70 to 80 percent of the precipitation falling on the forest canopy reaches the soil (Refs. 20, 24, 25); however, reliance on the judgment of experts in the fields of plant ecology and pedology is suggested for a more realistic estimate under specific conditions.

5-3.2.4 HUMIDITY

High relative humidity is a characteristic phenomenon of the wet Tropics. The daily range varies considerably, with highest humidity occurring during hours of minimum temperatures. In general, the air is near saturation (100 percent RH) during most of the night and early morning hours. Conversely, minimum relative humidities occur during the highest daily temperatures (usually around noon) and often may be as low as 60 to 65 percent in open areas, even during the rainy season.

Seasonal variations in relative humidity correspond to seasonal precipitation, in part because months with high precipitation are usually cooler than months with lower rainfall. Corrective action usually is occurring, and since the adiabatic rate of cooling usually exceeds the temperature lapse rate, condensation occurs.

Relative humidities as low as 60 to 65 percent during the rainy season may be experienced in such open areas as airfields and other similar locations for meteorological stations, but do not occur usually in the interior of a wet tropical forest. Fig. 5-6 is a replot of data for a rain forest in Southern Nigeria. Although the minimum relative humidity above the canopy was as low as 60 percent and stayed below 70 percent for an appreciable length of time, the air near the forest floor remained very close to saturation. Why 100-percent relative humidity was never reached at the lower level but was at the upper is not easily explained, but these results have been substantiated by other investigators.

5-3.2.5 WIND

Winds in most of the areas near the Equator are very light and variable. This is the area often called the doldrums or intertropical convergence zone. Average windspeeds are generally less than 5 km hr^{-1} (3 mph) and seldom exceed 13 km hr^{-1} (8 mph). Farther north or south of the Equator, winds are more brisk but, except for the hurricane zone of the West Indies, prevailing breezes are normally 16 to 24 km hr^{-1} (10 to 15 mph) during the day and somewhat less at night. Thundershowers in both of these areas usually are accompanied by high winds and occasional tornadoes.

In addition to the West Indies, other coastal regions of the Tropics experience cyclones. In the Western Hemisphere, they normally are referred to as hurricanes but in the vicinity of the Philippines Republic and the China Sea they are called typhoons. These storms may be as large as 800 km (1,500 mi) in diameter and have maximum windspeeds in the vicinity of 240 km hr^{-1} (150 mph). In the West Indies they occur at the end of late summer and early fall. Windspeed decreases quite rapidly as soon as the storms pass over appreciable landmasses although very heavy rainfall may occur many miles inland for several days after their passage.

Since the closed canopy of a mature wet tropical forest greatly impedes the movement of air, windspeeds are noticeably lower than above the canopy. Air circulation at night appears to be dependent primarily upon convection currents set up by thermal gradients due to radiation from the surface of the canopy.

Air movement within the forest is often so light that smoke appears to stand still. Measurement of airspeed under these conditions requires extremely sensitive instrumentation or the use of special techniques. As a result, reliable data on air velocities in wet tropical forests are almost nonexistent. Data of one investigator show that for an airspeed of 8 km hr^{-1} (5 mph) measured 150 m (500 ft) outside a forest in Brazil, it was 1.6 km hr^{-1} (1 mph) at a distance of 100 m (328 ft) inside the forest. At a distance of 1,100 m (3,600 ft) inside the forest, the windspeed was too low to be measured with an anemometer (Ref. 16).

5-3.2.6 TERRAIN

5-3.2.6.1 TOPOGRAPHY. In general, the topography of the wet-tropics is not much different from that in other parts of the world. Landforms vary from extensive flatlands--such as the Amazon Basin in Brazil--to high mountains. By far the most outstanding topographic feature is the large number of rivers, creeks, gullies, and ditches formed by the heavy runoff of tropical rains. These drainage ways vary in size and shape but usually are characterized by very steep and slippery banks. Flash floods are a constant danger in many areas. Rivers may rise many feet in a matter of hours or even minutes. Generally, there is no warning of such flash floods because they may be caused by heavy

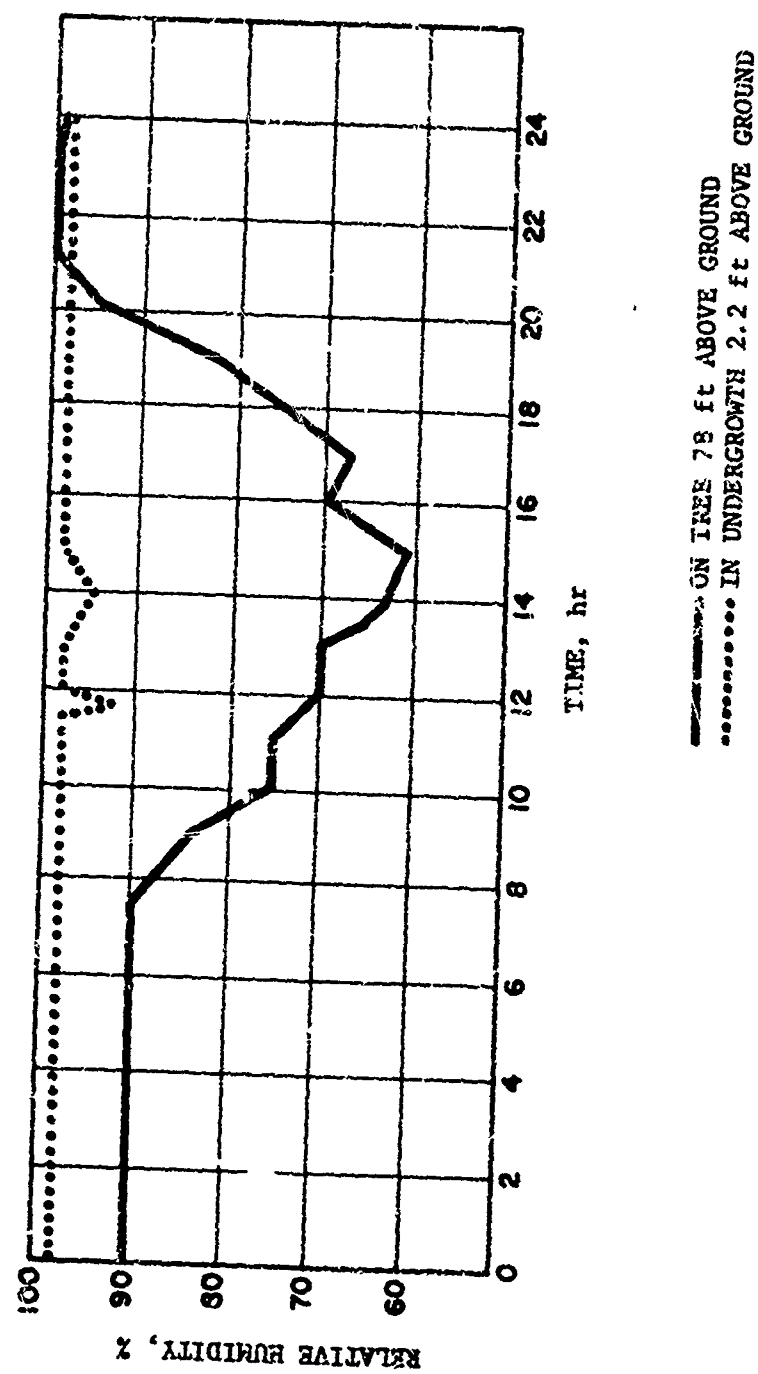


Figure 5-6. Relative Humidity Above and Below the Canopy of a Tropical Rain Forest (Ref. 16)

rains that have fallen a considerable distance upstream.

5-3.2.6.2 SOIL. Soils in the wet tropics vary as much in structure and physical and chemical properties as do *in situ* soils of temperate regions. Many of the wet tropical soils are red or reddish brown due to high iron content and contain sufficient clay minerals to create mobility problems when wet. In general, the principal soil of wet tropical areas is a highly leached, claylike material, and the soil stratum of interest usually is confined to the vicinity of flood plains.

Small differences in moisture content can cause drastic changes in the mechanical properties of soil. Surfaces of soils with excess water are firm but very slippery. With a slightly lower moisture content, the soil becomes sticky and may ball-up on shoes, wheels, and tracks.

Soils on steep slopes are usually quite shallow due to erosion and are often not more than a few inches deep. In many instances the parent material, which is usually partially weathered rock, may outcrop on steep slopes.

Soil conditions are also dependent on the type of natural vegetative cover. There is relatively little undergrowth in a mature tropical rain forest and—due to rapid decomposition of organic matter by fungi and bacteria—there is only a light covering of leaves and humus on the forest floor, which is easily removed to expose firm but often slippery soil. In a forest with more open canopy—such as deciduous or semideciduous forests—undergrowth is slightly heavier and forms a porous mat of fine roots and organic matter which is temporarily effective in increasing traction. Savannas (grasslands) are found often on poorer sandy soil, and are accompanied usually by hardpan. During the wet season, unsurfaced roads and trails in savannas become quagmires often impassable even to trucks with large tires and high ground clearances. In the dry season, the ground surface is reasonably firm, with ruts, chuckholes, and washboard surfaces if motor vehicle traffic is moderately heavy. Depth of mud usually does not increase, however, because of the hardpan characteristic of many wet tropical soils. "Bottomless" mud (more than 1 or 2 m deep) rarely exists except in peat swamps which are sometimes encountered between mangrove swamps and higher land. Peat swamps are not extensive though, and many swamp soils are very firm even though they may be covered by 30 to 60 cm (12 to 24 in.) of water. Some soils formed by yearly deposits of silt may become "bottomless" but are the exception rather than the rule.

5-3.2.6.3 VEGETATION. Continually moist soils and moderately high temperatures have been shown as representative of the wet-tropics. These climatic factors are necessary requirements for the luxurious, evergreen-type of vegetation that is probably the most outstanding feature of wet tropical regions. A detailed description on the various types of vegetation found in the wet-tropics is not warranted in this publication, and only the outstanding vegetative characteristics th[illegible] may have military importance are disc[illegible]

The tropic[illegible] rain forest (see Fig. 5-7) is the predominant vegetative climax in the wet-tropics, but adverse soil conditions or topography may result in slightly different forest types. Although deciduous forests are found more often in drier regions of the Tropics having a prolonged dry season (3 mo or more), poor soil may result in a semideciduous-type forest even though the soil is continuously wet. Swamp forests are a result of poorly drained soils; montane (mountain) forest characteristics reflect the influence of lower temperatures at higher altitudes.

The principal differences between the four types of forest (rain forest, semideciduous forest, swamp forest, and montane forest) appear to be in height of the trees and structure of the canopy, the closed roof of the forest formed by the crowns of its trees. Three strata of trees exist in a mature rain

(A)

(B)

Figure 5-7. Tropical Rain Forest, Ft. Sherman, C.Z.

forest (see footnote, Table 5-8). While it is quite possible for each strata to form a continuous canopy, the highest and middle stories more often combine to form a single canopy the height of which may vary from 15 to 45 m (49 to 147 ft) above the forest floor (Ref. 17). Taller trees are by no means uncommon, but are usually well scattered and do not form a continuous canopy.

Due to the closed canopy, the floor of a mature rain forest receives only a small fraction of available sunlight and, therefore, is relatively free of undergrowth. Lateral visibility at eye level is limited more by the spacing than foliage, and a person usually can be seen at a distance of 25 to 50 m (82 to 164 ft).

Trees of the semideciduous and montane forest are somewhat lower in height than those of the rain forest, and their canopy is slightly more open. This allows more light to penetrate to the forest floor which often results in heavier undergrowth. However, the increased cloudiness usually accompanying the montane forest counterbalances the slightly more open canopy so that it is relatively free of undergrowth. The swamp forest has a greater number of trees per unit area than does the rain forest canopy, and heavy undergrowth is common.

Except for occasional openings in the canopy caused by fallen trees, ground-to-air visibility in a rain forest usually is limited to the height of the closed canopy. In swamp forest and semideciduous forests, the canopy is often sufficiently open to allow low-flying aircraft to be seen if they are directly overhead. The converse of this is not true since the forest floor is only occasionally visible from the air.

Large trees often have enormous, buttressed root systems that may extend laterally 6 to 9 m (20 to 30 ft) along the ground, but most of the trees in the wet-tropics are shallow rooted.

The term "jungle" connotes a dense growth of vines, grasses, shrubs, and trees that form an almost impenetrable barrier. The term often is applied to any and all types of tropical vegetation and, as can be seen from the previous discussion, is certainly erroneous for mature forests. In reality, "jungle" or "bush" is second growth vegetation in the process of replacing a mature forest that has been destroyed.

Although destruction of the forest may be due to natural phenomena such as lightning-caused fires or windstorms, the most important cause is the widespread "slash-and-burn" agricultural practices common in the majority of wet tropical countries. This practice usually consists of felling and burning a majority of trees in an area. Crops are then grown for a period of 1 to 3 yr, but rapid leaching of humus and nutrients soon makes the soil infertile and it is abandoned. If the land is allowed to lie fallow, development of second growth will begin rapidly and, although 75 to 100 yr may be required, a mature climax closely resembling the original forest will be formed.

Second growth usually is initiated by rapid growth of weeds and grasses. A period of at least 2 to 3 yr is required before seedling trees can establish themselves. The first weedlike trees are characteristic of early secondary forests; they grow very rapidly and many species attain a height of 4 to 8 m (13 to 26 ft) in a period of 2 to 3 yr. Because of their rapid growth, these trees are very soft textured and of low density.

After the first 10 yr of its development, the "jungle" is perhaps at its densest. The numerous small trees are closely spaced and interlaced with vines and climbers. Razor grass and bamboo may add to the chaotic jumble to form an almost impenetrable barrier. Lateral visibility is often only a few feet, but vertical visibility is usually much better than in a mature forest because of the absence of a closed canopy. The fast-growing trees soon reach maturity and die. The time to reach maturity varies with the species, but a period of 15 to 20 yr seems to be a reasonable estimate for many. Because of their relatively short lifespan, such trees do not attain the size and proportions of the larger trees in the original forest. The largest trees of a young secondary forest rarely attain a height greater than 22 m (72 ft) and a diameter greater than 30 cm (1 ft), measurements which are considerably smaller than trees of a mature rain forest that often average 50 m (164 ft) in height and 1 m (3.2 ft) or so in diameter. By the latter stages of their maturity, these second growth trees have succeeded in shading out a considerable portion of the undergrowth, and many of the earlier aspects of the jungle have disappeared.

The original climax consists of numerous species of trees, possibly over several hundred, and crowns of individual trees can be readily distinguished from the air. In contrast, the secondary forest is made up of trees chiefly of a few dominant species, of which many may reach maturity simultaneously. From the air these even stands of secondary forest may resemble a well-cut lawn except for gaps left by trees fallen as a result of disease or windstorm. Such gaps admit sunlight and encourage dense coverage of the forest floor by heavy undergrowth until the next succession of slower growing trees fills them and closes the canopy. For the succeeding 10 to 20 yr, the secondary forest still retains many aspects of a jungle; the trees are polelike and closely spaced, and vine and climbers abound. After the forest has reached the age of 50 to 100 yr, it is usually indistinguishable from the original.

Savannas are essentially grassy plains with random trees and shrubs. They are often assumed to be an indication of a relatively dry tropical climate, but it is also theorized that the savanna climax is due primarily to adverse soil conditions or repeated burnings rather than climatic conditions (Ref. 16). It is generally recognized that, although various theories have been propounded to explain the nature and distribution of savanna vegetation, no single and convincing viewpoint has met with universal acceptance (Ref. 26).

In the preceding discussion of second growth, it was assumed that, after the forest had once been cleared, it was left undisturbed until it reached its final stage of maturity. If, instead, the process of slash and burn is repeated, a totally different or "deflected" climax usually results. For this reason, extensive savanna grasslands are often found in areas that previously have supported a tropical rain forest

Savannas usually are dominated by grasses. Although trees and bushes are seldom totally absent, the canopy typical of most wet tropical forests never is formed. The climate of the savannas is usually quite similar to the macroclimate reported by meteorological or weather stations. The majority of savannas formed by slash-and-burn agricultural practices are found on flat or gently rolling terrain, but they are by no means limited to flatlands because local economies often require the cultivation of very steep slopes.

In lowland savannas the soil usually becomes saturated during the wet season but dries out very rapidly and invariably shows the first signs of drought. It is this characteristic that leads to repeated burnings of savannas in many areas where the original vegetation rarely becomes dry enough to burn.

Lateral visibility is usually dependent on height of the grass and in many savannas is almost unlimited. If bushes and trees are numerous, an observer may be required to climb a vantage point such as a tree for an unobstructed view. Ground-to-air and air-to-ground visibilities usually are limited only by fog or low clouds.

Although coastal vegetation represents only a small percentage of the vegetation in the wet-tropics, the mangrove swamp is a formidable obstacle to movement of men and materiel. Mangroves are found mostly on tidal mud flats, bays, and inlets, and occasionally on sandy beaches and coral reefs. Depending on the topography, they may extend inland a few hundred feet to a few hundred yards and often may change abruptly into swamp forest or rain forest. They may vary in height from low shrubs to trees almost 30 m (98 ft) tall. Aerial roots, their most outstanding characteristic, extend as much as a meter or so above the surface at low tide and may seriously impede foot travel in addition to very efficiently catching debris and soil-forming materials.

5-3.2.7 MATERIEL EFFECTS

In the Tropics, the effects of high temperature, high humidity, and the accompanying microbes produce the primary effects on materiel. Metallic corrosion, wood rot, and fabric deterioration occur rapidly and may cause major problems. Reports from the Tropics are replete with examples of rapid deterioration—canvas tents having a lifetime of 6 mo, a complete issue of clothing being required every 2 weeks, and aircraft antenna wire being replaced every week.

If any feature dominates the hot-wet environment, it is the necessity for protecting materiel from moisture. Once materiel is wet, either fungous or corrosive deterioration occurs. Materiel protected from moisture by packaging, surface coatings, or shelter does not deteriorate so rapidly.

Other effects in the Tropics are well known. The tropical vegetation restricts visibility and mobility; macrobiological organisms such as termites, wood borers, rodents, and mosquitoes cause materiel problems; and the often oppressive high temperature-high humidity combination reduces the ability of personnel to counter or correct environmental effects.

5-3.3 COLD CLIMATE

The cold or arctic climate is separated into two climate categories—the cold and the extreme cold. These are differentiated by the minimum temperatures of -50° and -70°F, respectively.

The cold regions of the Southern Hemisphere are tempered by the influence of large ocean areas so that, with the exception of Antarctica, severe cold is not found there to any great extent. Accordingly, emphasis is on the climatic factors and related phenomena peculiar to the cold regions of the Northern Hemisphere. The stresses imposed by a cold environment influence engineering design, facility maintenance and operations, transportation, and human performance. Snow, ice, frozen ground, and low temperature during the cold months, and ice jams, floods caused by melting snow, mud, and thawed muskeg during the warmer months are characteristic phenomena with which man and his equipment must contend in the cold regions.

With minor exceptions, the 40th parallel is the southern limit of the cold regions in the Northern Hemisphere. Major ocean currents such as the Gulf Stream may ameliorate the climate of adjacent landmasses, accounting for the relatively mild climate of Great Britain and Ireland and the northwest coast of Europe. The warm ocean currents can create an anomalous situation, however; when the Gulf Stream is warmer than usual, the low atmospheric pressure associated with the large mass of warm water forces the major storm tracks to the south, bringing abnormally cold winters with much snow and ice to otherwise mild climates. Thus, large areas, which normally are included in the intermediate climatic categories of the Temperate Zone, frequently fall within the criteria for the cold climatic category during winter periods.

Elevation also has a marked effect on the climate. Vertical temperature gradients up mountain slopes are much steeper than latitudinal temperature gradients at sea level. The worldwide lapse rate (change of temperature with elevation) varies from 1 deg C/100 m (5.4 deg F/ 1,000 ft) for dry air to 0.5 deg C/100 m (2.8 deg F/1,000 ft) for saturated air. The latter rate commonly is used by climatologists when transferring temperature information from low elevations to higher elevations. The extension of the cold regions of the Northern Hemisphere south of the 40th parallel in Southeast Asia and in the mountain regions of North America is due mainly to the high elevation of these areas.

A high elevation regime in the Temperate Zone has certain similarities and many anomalies when compared with a high latitude regime. Annual temperature extremes may be similar in both regimes but the great difference in insolation has a marked influence on the diurnal temperature cycle. Snowfall volume and distribution patterns also are much different at high elevations. The orographic influence on precipitation may result in winter snow depths of tens of feet on the windward side and only a few inches on the lee or precipitation shadow side of a mountain.

5-3.3.1 TEMPERATURE

The basic concept of a cold region requires acceptance of the temperature as the dominant climatological factor. The cold climatic categories in AR 70-38 (Ref. 1) are defined by a 1-percent probability of occurrence of 6 continuous hours with a maximum ambient temperature (4 to 6 ft above the ground) of -25°, -50°, and -70°F for the intermediate cold, cold, and extreme cold categories, respectively.

Each of the three categories–intermediate cold, cold, and extreme cold–may be further subdivided into lowlands and highlands. The latter is typified by the Cordillera of western North America, the mountains of Europe, the Asian Highlands, and the Greenland ice dome. Latitudinal variation in temperature range and in average temperature for some typical lowland locations and comparative records for several highland sites are shown in Table 5-11.

The difference in range of average annual temperature (mean maximum for the highest month minus mean minimum for the lowest month) increases progressively as latitude increases from the intermediate cold zone to the extreme cold zone. Although seasonal temperature is lower at high elevations than at low elevations within the same latitude, the annual temperature range, as shown in Table 5-11, is little affected by change in elevation. The seasonal change in the temperature regime with latitude is influenced by the seasonal change in length of day and the available amount of solar radiation. At a given latitude, there is little change in the length of day or the amount of available solar radiation with change in elevation. Climatically, the highland (or Alpine) regions of the intermediate cold zone are not analogous to lowland regimes in the cold zone or the extremely cold zone although they frequently are considered as such for test and evaluation of equipment and staging of winter maneuvers. Any assumption that an Alpine climate is analogous to an arctic or subarctic climate ignores the difference in stresses created by length of daylight, diurnal temperature cycles, and diurnal differences in both solar and longwave radiation.

The average annual temperature range shown in Table 5-11 is far from the extreme range that may be expected in the cold areas. At Verkhoyansk, Siberia, the difference between the maximum and minimum of record is 87 deg C (157 deg F). At Snag, Yukon Territory, it is 77 deg C (139 deg F) and at Camp Century, Greenland, it is 41 deg C (74 deg F).

Both latitude and elevation temperature gradients must be taken into consideration when comparing climatic information from one part of the cold regions to another. The abundance of meteorological data available from the more populated regions of several cold zones permits extrapolation to analogous areas where records are lacking. In the higher latitudes and elevations, sparse or nonexistent meteorological records make identification of zonal boundaries and evaluation of elevation-temperature regimes difficult. It is sometimes possible to use low elevation weather records to estimate temperatures for higher elevations.

TABLE 5-11

COMPARATIVE TEMPERATURES FOR THE COLD CLIMATIC CATEGORIES

Climatic category	Station	Mean temperature, °F		
		Coldest month	Year	Annual range
Lowland regime				
Intermediate cold	Peoria, Illinois	24	51	52
	Bucharest, Romania	26	51	48
	Peking, China	24	53	55
Cold	Harbin, China	-2	38	74
	Moose Factory, China	-4	30	66
Extremely cold	Yakutsk, Siberia	-35	12	112
	Ft. Yukon, Alaska	-21	20	99
	Eureka, Canada	-38	-3	[illegible]
Highland regime				
Intermediate cold	Lake Moraine, Colo. 10,000 feet	20	38	57
Extremely cold	Camp Century, Greenland 6,000 feet (1961)	-44	-14	75

On the high Greenland Ice Cap where no melting occurs in most years, the amplitude of the annual temperature cycle approaches zero at 8 to 10 m (26 to 33 ft) below the surface (Refs. 27, 28). Comparison of the snow temperature at this depth with available synoptic data from a few stations on the Ice Cap that have been manned for a period of at least 12 mo shows that it is very close to the mean annual temperature as measured in a weather instrument shelter. By use of this and snow profile temperature data, a lapse rate of 0.7 deg C/100 m (3.84 deg F/ 1,000 ft) is found. This was used to construct the map of Fig. 5-8 showing the mean annual air temperature distribution on the Greenland Ice Cap.

The frequency at which a potentially deleterious temperature may occur is an important factor in operations in the cold regions. The percentage frequency of times that the temperature is below −31°C (−23.8°F) for the month of January in the Northern Hemisphere is shown in Fig. 5-9 (Refs. 29,30). The need for a rational interpretation of such maps is emphasized by the recorded occurrence of several consecutive days with temperatures above −1°C (30°F) accompanied by some rainfall in January 1958 at weather stations in the Canadian Arctic north of latitude 75 deg. At the same general latitude in north Greenland, as many as seven consecutive days with maximum temperatures of −45.6°C (−50°F) or lower have been recorded during winter. At Snag, Yukon Territory, a minimum of −48.4°C (−55°F) or lower has occurred on an average of 6 days yr^{-1} for the more than 50 yr of record.

The temperature-frequency map presented in Fig. 5-9 permits a reasonable evaluation of operational limitations. Where the ambient temperature remains below −31.6°C (−25°F) for several days, most operational capabilities are reduced by 50 percent. Several additional days can result in almost total immobilization. At that temperature so much time must be devoted to protection of facilities and equipment and to survival efforts that gainful activities are reduced to ineffectual levels.

Windchill adds to operational problems in a cold area. Low air temperature accompanied by wind increases the cooling effect of the atmosphere which increases human discomfort. Siple and Passel developed a windchill formula which has become widely accepted as the most satisfactory measure of potential human discomfort in the cold regions (Ref. 31):

$$K_o = (100V + 10.45 - V)(33 - T_a) \quad (6\text{-}1)$$

where

K_o = windchill, the cooling effect of the atmosphere, kcal m^{-2} hr^{-2}

V = windspeed, m s^{-1}

T_a = air temperature, °C

From experiments it was determined that windchill values could be associated with a subjective sense of cold by the human body but windchill has no meaning when used to indicate the cooling rate of inanimate equipment since it does not include all avenues of heat transfer that may be active during a test (Ref. 32).

The U.S. Air Force, recognizing that the subjective approach has some value in connection with survival of aircraft crews, prepared the windchill chart presented in Fig. 5-10. This chart in one form or another generally is used by the Armed Forces in planning arctic activities

Frequent and persistent temperature inversions are a characteristic of the cold regions. Normally, the temperature of the lower level of the atmosphere (troposphere) decreases with height. The lighter warm air near the ground rises through the dense cooler air, setting up convectional processes which induce a thorough mixing of the air. When the ground surface is chilled by radiation heat losses or evaporative cooling, or when there is inflow or intrusion of a low temperature layer of air near the surface, an inversion develops.

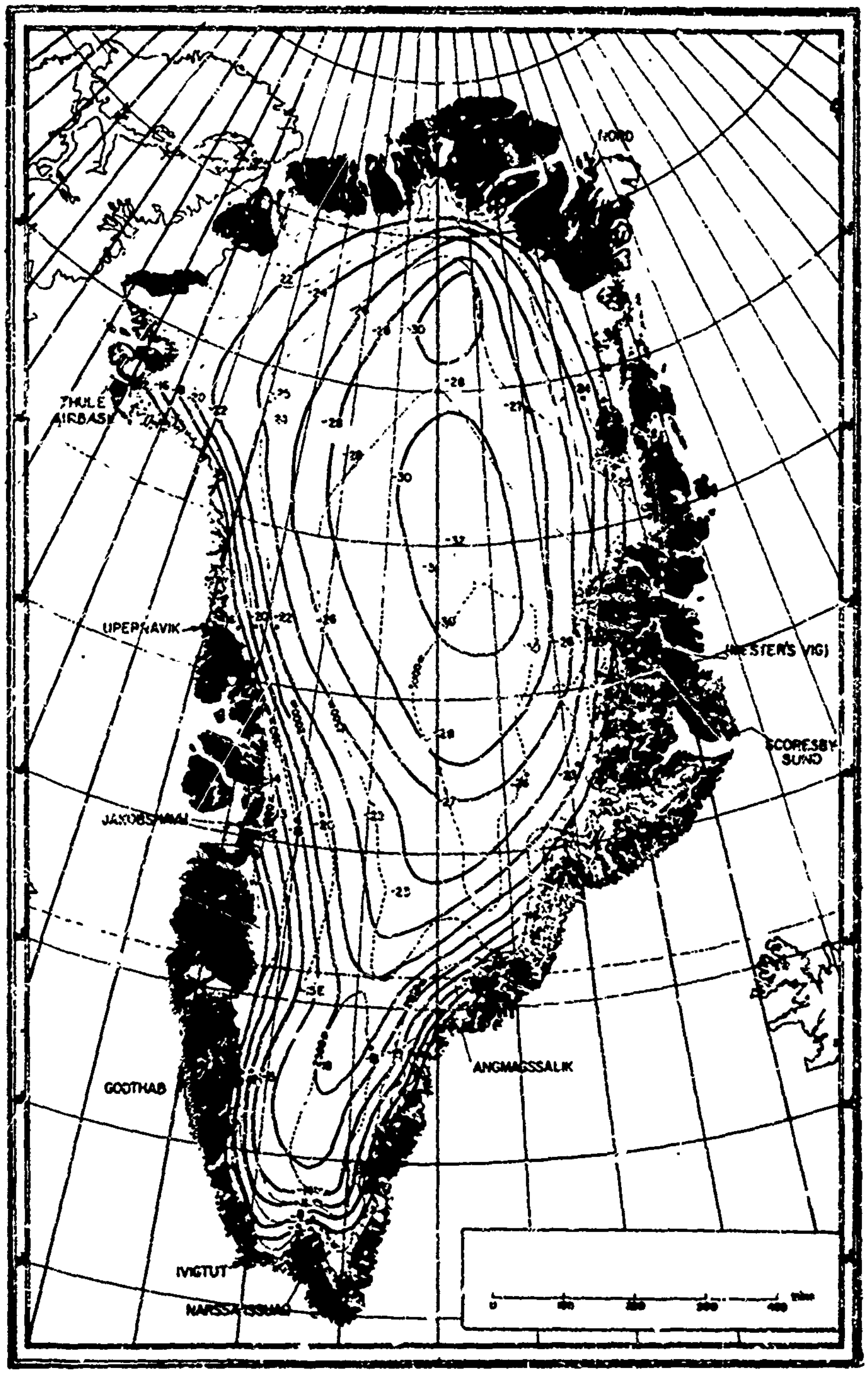


Figure 5-8. Mean Annual Air Temperature on the Greenland Ice Cap (°C) (Ref. 27)

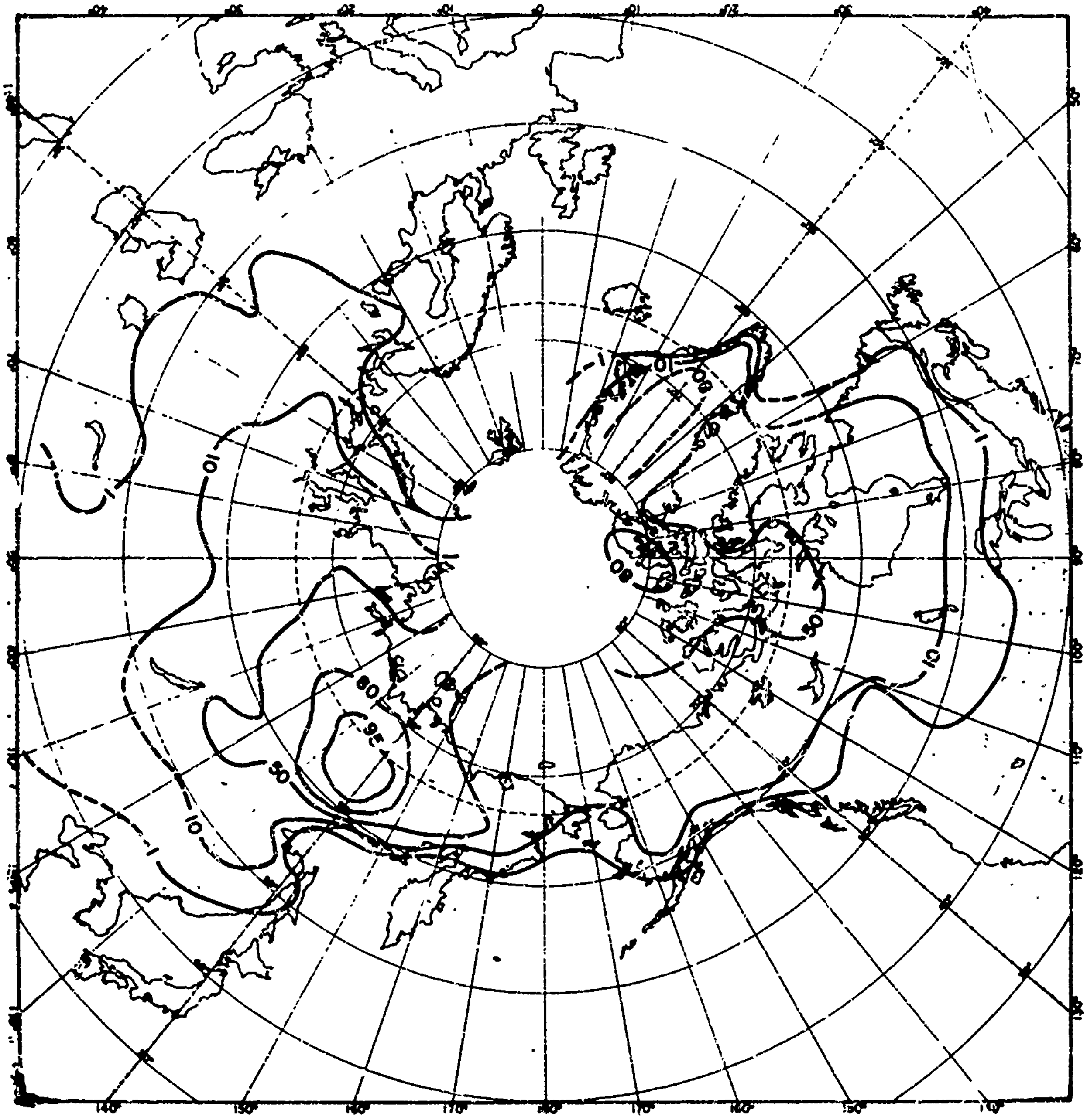


Figure 5-9. Percent Frequency of Temperatures Below −31.6°C (−25°F) During January in the Northern Hemisphere (Refs. 29, 30)

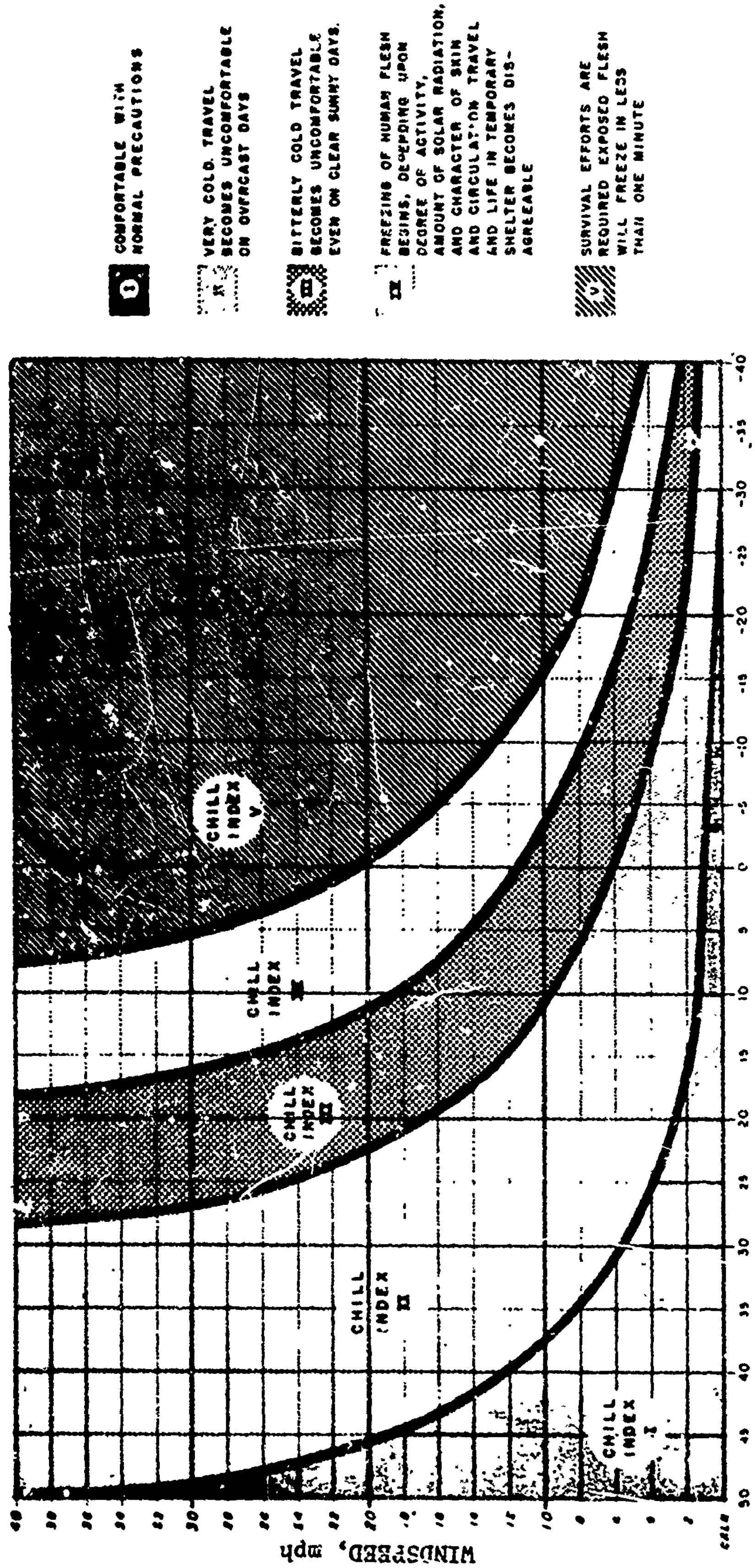


Figure 5-10. Windchill Index and Related Levels of Human Discomfort

The cool air in contact with the ground, being heavier and denser than the warm air above, establishes a stagnant condition which may prevail for days. With radiational or convectional warming of the ground surface at a minimum, the air temperature may be lowered to the dewpoint temperature and fog may form.

If the ground is warmed by solar radiation during an inversion without sufficient energy being developed to establish normal convective processes, the inversion may lift a few tens of feet above the ground. If the ground is covered by snow, diffused sunlight penetrating the overcast and reflected between the snow surface and the fog or cloud base produces the classic whiteout.

Typical temperature inversions measured at several stations in the Arctic are shown in Fig. 5-11. Steeper gradients than illustrated in this figure are not uncommon. A statistical survey of inversions at a number of stations located in the extreme cold zone showed that inversion thickness–i.e., height above ground at which normal lapse rates are reestablished–is much greater during cold months of the year than during warm months (Ref. 33). Inversions with their bases at ground surface occur more frequently during the cold months, and whiteouts with the fog or cloud base at some elevation above the snow surface occur most frequently during warm months. The steepness of inversions is greater during the cold months than in the warm season. Winter inversions of more than 9.1 deg C/100 m (50 deg F/1,000 ft) have been measured in Greenland and at the South Pole. These steep inversions were associated with a surface temperature of -55°C (-67°F) in the Arctic and -74.5°C (-102°F) in the Antarctic. Such steep gradients do not occur where inversions and fogs are associated with temperature differences between land or extensive ice sheets and open water, nor where a maritime, albeit low-temperature, climate dominates the environment.

5-3.3.2 SNOW

Solid precipitation, primarily in the form of snow, is an important environmental factor in the cold regions. Often, activities are stopped completely by snow. Materiel can be ineffective or damaged when operated in snow.

Annual snowfall in the cold regions of the Northern Hemisphere varies from as little as 25.4 cm (10 in.) to more than 20.3 m (800 in.). In water equivalent terms, this is equal to about 3.8 cm to 3.05 m (1.5 to 120 in.) of precipitation. Orography plays an important part in distribution of snowfall. The north-south axis of the Western Cordillera imposes a barrier to inflow of warm moist air from the Pacific Ocean into the continental area of North America. Some of the largest snow storms of record are reported from locations along the west slope of the Sierra Nevada, Cascades, and mountains of Alaska. The single storm snowfall in this highland regime probably is not exceeded anywhere else in the world. At Donner Pass in the High Sierra, 2.1 m (83 in.) of snow fell in 24 hr, the highest snowfall rate on record. At Tamarack, Calif., also on the west slope of the Sierra, 9.9 m (390 in.) of snow fell in 1 mo. At Thompson Pass, Alaska, on the Richardson Highway, 24.8 m (975 in.) of snow fell in one winter. All of these events occurred in recent times.

The Himalayas, with their east-west axis, intercept the northward flow of warm moist air from the Indian Ocean. Since the Himalayas are located close to the Tropics, moist air must be lifted to a greater elevation before snowfall occurs. Here the winter snowline is located at approximately 2,130 m (7,000 ft), while on the west slope of the Sierra Nevada, it is about 1,220 m (3,900 ft). The orographic influence on snowfall also may be observed in the Alps, the Appalachians, the mountains of central Quebec, and on the Greenland Ice Cap.

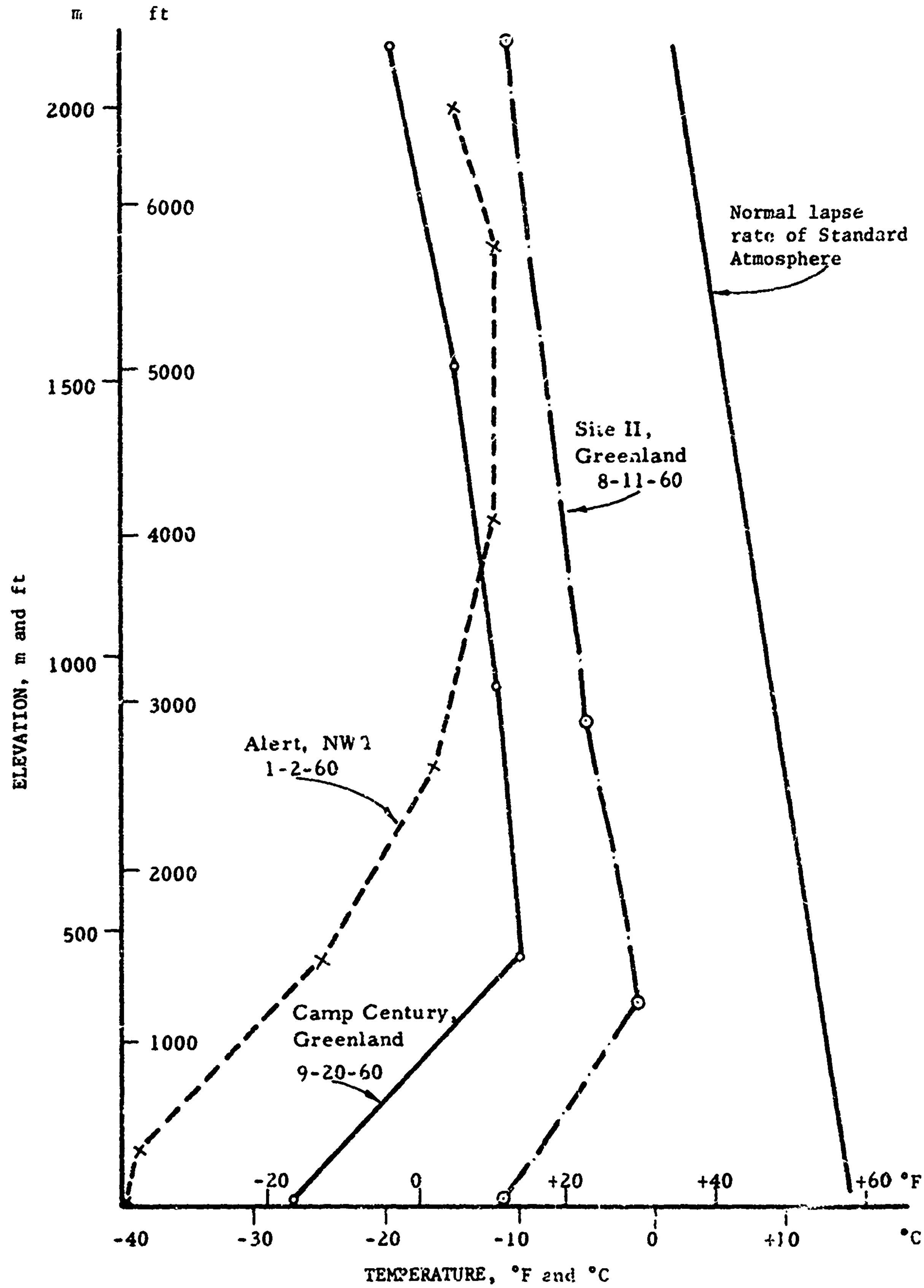


Figure 5-11. Temperature Inversions Observed at Arctic Weather Stations

Lesser annual precipitation in the form of snow during winter in midcontinental areas of both the Eastern and Western Hemispheres may be due to the precipitation shadow effect of mountains, to the low initial moisture capacity of the airmasses associated with the major winter storms, or to the long trajectory of storm paths over dry continental areas with little opportunity for moisture pickup.

5-3.3.2.1 SNOW COVER. Accumulation of seasonal snow cover is a function of the seasonal volume of precipitation and temperature cycles. In the extreme cold zone, the mean snow depth during the month of maximum depth on the ground may equal or exceed the mean depth for the corresponding period in the intermediate cold zone in spite of much greater annual snowfall in the latter zone. Frequent winter thaws in the intermediate cold zone may reduce the seasonal snowfall of 102 to 152 cm (40 to 60 in.) or more to an actual maximum seasonal cover of 30.5 to 45.8 cm (12 to 18 in.) in undisturbed areas. In the extreme cold zone where no melting occurs for 4 to 8 mo, a seasonal snowfall of 61 to 76.3 cm (24 to 30 in.) produced a maximum snow cover of 25.4 to 50.8 cm (10 to 20 in.) during the month of maximum depth. The difference between recorded annual snowfall and actual depth of snow on the ground in the extreme cold zone is due to settling, consolidation, and metamorphosis of the snow grains, not to melting as in other zones of the cold regions.

World distribution and duration of seasonal snow cover are shown in Fig. 5-12. This shows that the major snow-caused problem areas of the world are in the northern cold regions. The location of the zero-duration snow cover isoline in this figure does not identify the southern limit of snowfall. Snowstorms of sufficient magnitude to create traffic and communication problems do occur occasionally south of this line.

The average seasonal maximum snow depth on the ground in the cold regions of the Northern Hemisphere is shown in Fig. 5-13. This shows the maximum depth on the ground as recorded at the end of the month with maximum snow on the ground. Data used in the preparation of this map were derived from climatological records covering periods up to 30 yr.

The largest monthend depth of snow as reported for the winter season is usually less than winter maximum since the heaviest snowfall producing the maximum winter depth may have occurred early in the month (Ref 34). Settling and possibly some melting with no subsequent snowfall during the month may reduce the record monthend depth to less than winter maximum.

In Canada, a factor of 1.236 must be used to convert monthend maxima to annual maxima where such information is needed for operational or design purposes (Ref. 34). This conversion factor appears to be particularly applicable where the only available records of snow depth are those obtained from periodic snow surveys made for hydrologic purposes.

Although the maps in Figs. 5-12 and 5-13 give some idea of the world distribution of depth and duration of snow cover, they fail to illustrate adequately snow accumulation in the highlands of the cold regions. In the mountains, seasonal snowfall may accumulate to as much as 9.3 m (30 ft) or more and persist for 4 to 5 mo. Keeping highways, railroads, and airports open and maintaining communication services in these areas is a costly process suitable only to a high level of industrial economy or military necessity.

In the cold regions of the Northern Hemisphere, the greatest accumulation of seasonal snow occurs between latitudes 40 and 60 deg N. The decrease in accumulation northward is due to lesser annual precipitation and southward to intermittent melting during the winter. Seasonal accumulation also decreases with altitude above some elevation determined by the orographic and meteorological features of the region. The decrease in depth of snow on the ground at higher elevations may be

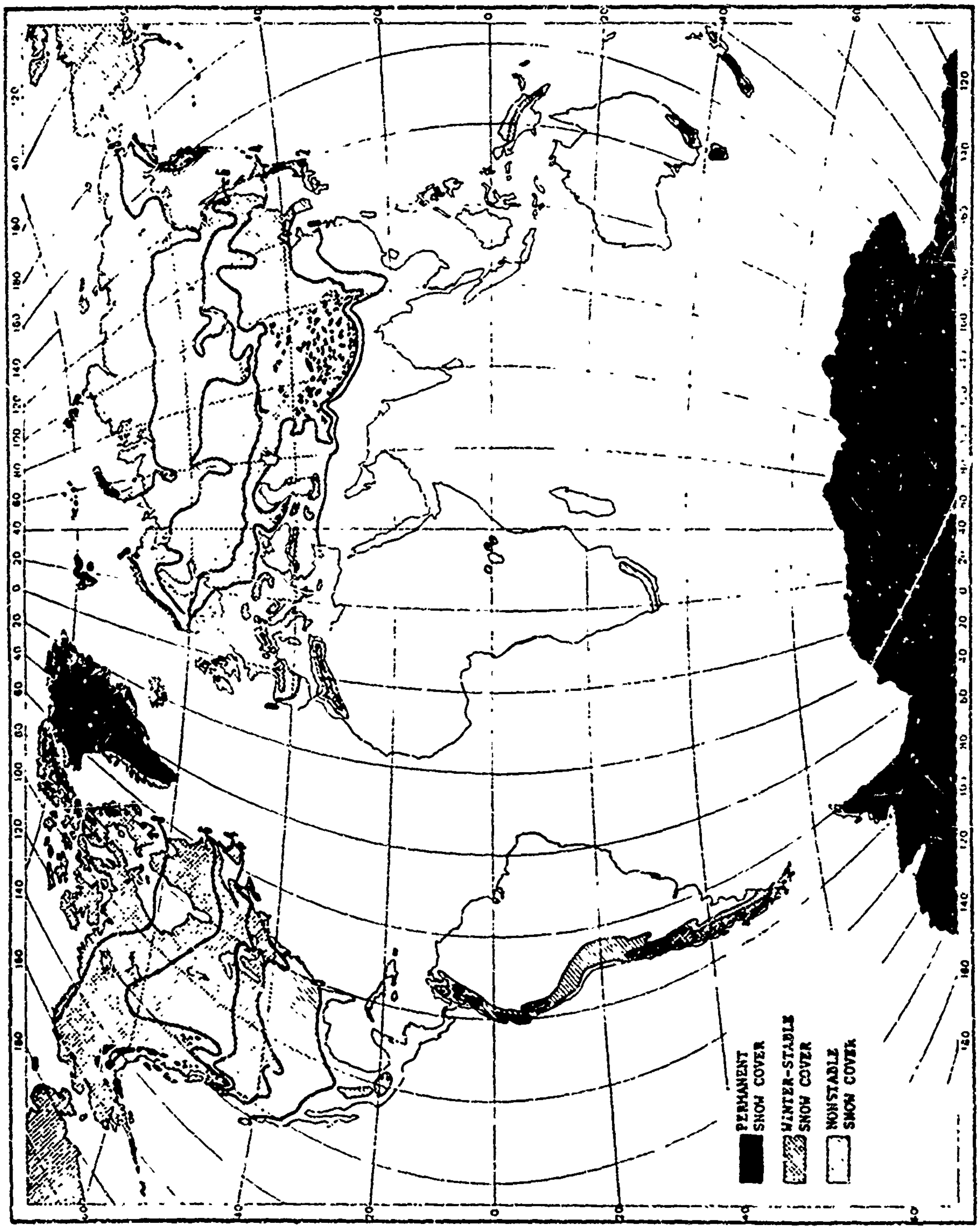


Figure 5-12. World Distribution and Duration of Seasonal Snow Cover (Ref. 34)

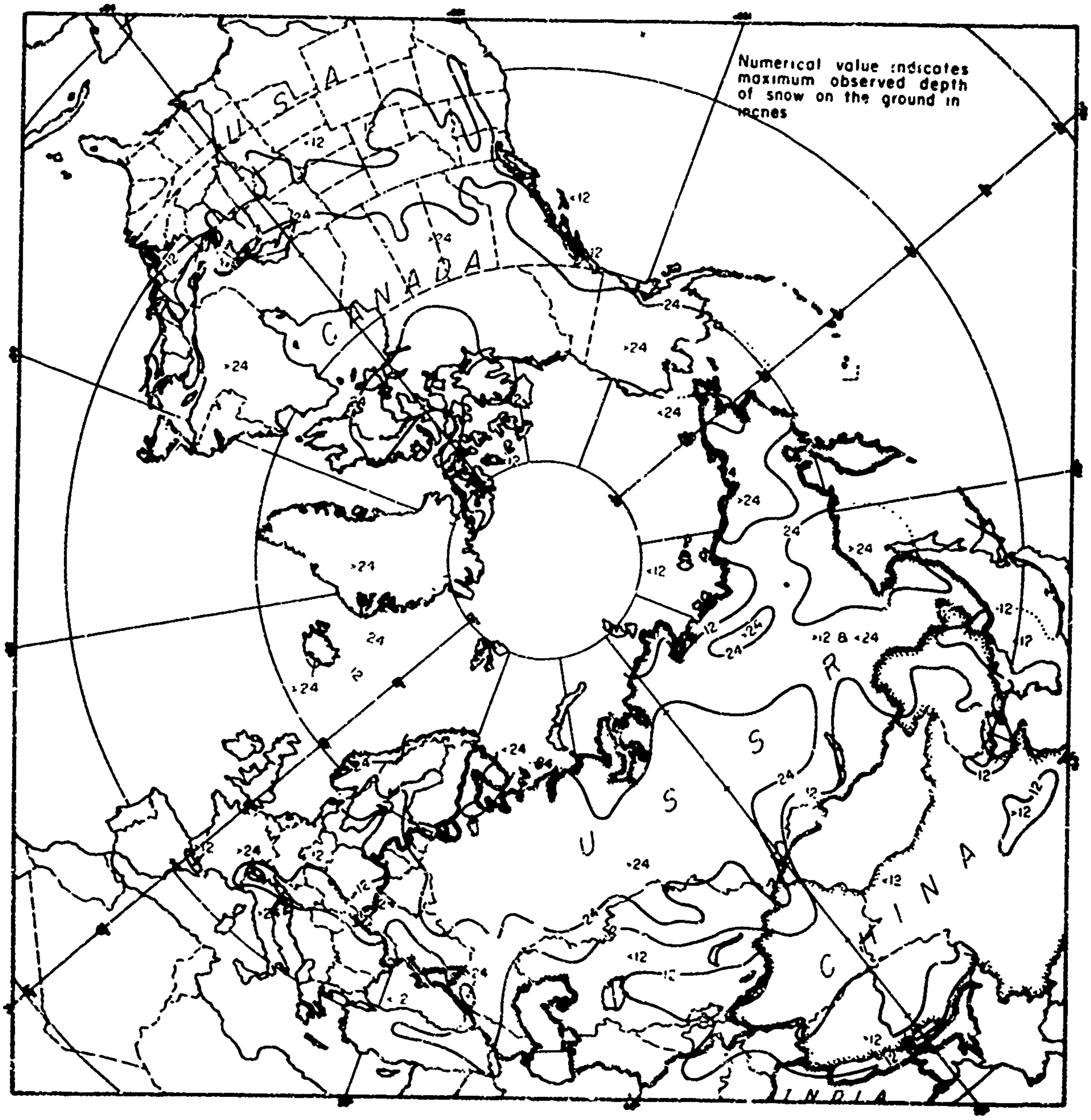


Figure 5-13. Maximum Annual Snow Cover in the Northern Hemisphere (Ref. 35)

masked by the effects of topography and exposure. High winds may sweep exposed areas clear of snow and deposit it in protected areas to depths several times the normal snowfall for the locality. Fig. 5-14 shows how exposed peaks at high elevations may be denuded of snow by frequent periods of high winds.

An excellent illustration of the effect of elevation, latitude, and exposure to prevailing storm tracks on seasonal snow accumulation is shown in Fig. 5-15. It is apparent from this map that there is an increase in the annual accumulation of snow from about 30 cm (11.8 in.) of water equivalent near sea level to 60 cm (23.6 in.) water equivalent at an elevation of about 2,500 m (8,200 ft) and then a decrease to 20 cm (7.9 in.) water equivalent snow about 3,000 m (9,850 ft) across central Greenland. This change in annual accumulation of snow with elevation along the westward face of the Ice Cap exhibits a uniform pattern that is illustrative of the orographic influence of the Ice Cap on the prevailing westerly storms that pick up large supplies of moisture as they cross the open waters of the Labrador Sea and Davis Strait. The effect of latitude is illustrated by the change in accumulation from about 90 cm (35.4 in.) water equivalent south of latitude 60 deg N. to 30 cm (11.8 in.) near 70 deg N. and 10 cm (3.9 in.) along the crest of the Ice Cap.

5-3.3.2.2 SNOW LOAD. Although depth of snow on the ground imposes a physical barrier to mobility, it is the weight of the snow, or the snow load, that must be taken into consideration for design criteria in the cold regions. Conversion of depth of snow on the ground to weight from which snow-load values may be computed is difficult. Newfallen snow may have a density of less than 0.01 g cm^{-1}, and older snow density may exceed 0.05 g cm^{-1}. The map of Fig. 5-16 shows the maximum probable snow load to be expected in Canada and the United States.

The isopleths in Fig. 5-16 are indicative only of the probable maximum snow load in any locality. Rain on snow can add appreciably to the load, particularly if the snow is cold enough to cause freezing of the rain in the snow cover. High winds may clear the snow load from some structures, or transfer and even increase the load on portions of other structures. Where the snow load is not removed by wind, the increased surface area created by accumulated snow may result in the snow load being augmented by wind pressure. Figs. 5-17 and 5-18 are photographs of snow-loaded roofs with creep-type and wind-type cornices, both of which caused damage before the end of the winter to the eaves, sidewalls, and windows of the building shown.

In the extreme cold zone, the annual snow load may accumulate year after year. On the Greenland Ice Cap, above the firn line where there is little or no summer melting, the snow load increases at rates of 146 to 489 kg $m^{-2} yr^{-1}$ (30 to 100 lb $ft^{-2} yr^{-1}$). Similar load accumulation problems are encountered at higher elevations in Alaska, Canada, and in the Antarctic.

Most available records on snow cover that may be used for computing regional snow loads are for snow depth only. Density or water equivalent values essential to satisfactory evaluation of potential snow loads are seldom measured or reported in standard climatological summaries. To compute snow loads from the regular weather station reports of depth on the ground, Boyd (Ref. 34) assumed that 2.5 cm (1 in.) of snow corresponds to a pressure of 4.88 kg m^{-2} (1 lb ft^{-2}).

Snow load specifications in AR 70-38 for the intermediate cold, cold, and extreme cold climatic categories are 195 kg m^{-2} (40 lb ft^{-2}) for semipermanent installations. As shown in Fig. 5-16, this value may be far too low for many parts of the cold categories.

5-3.3.3 GLAZE, RIME, AND HOARFROST

Surface deposits of ice in the form of glaze,

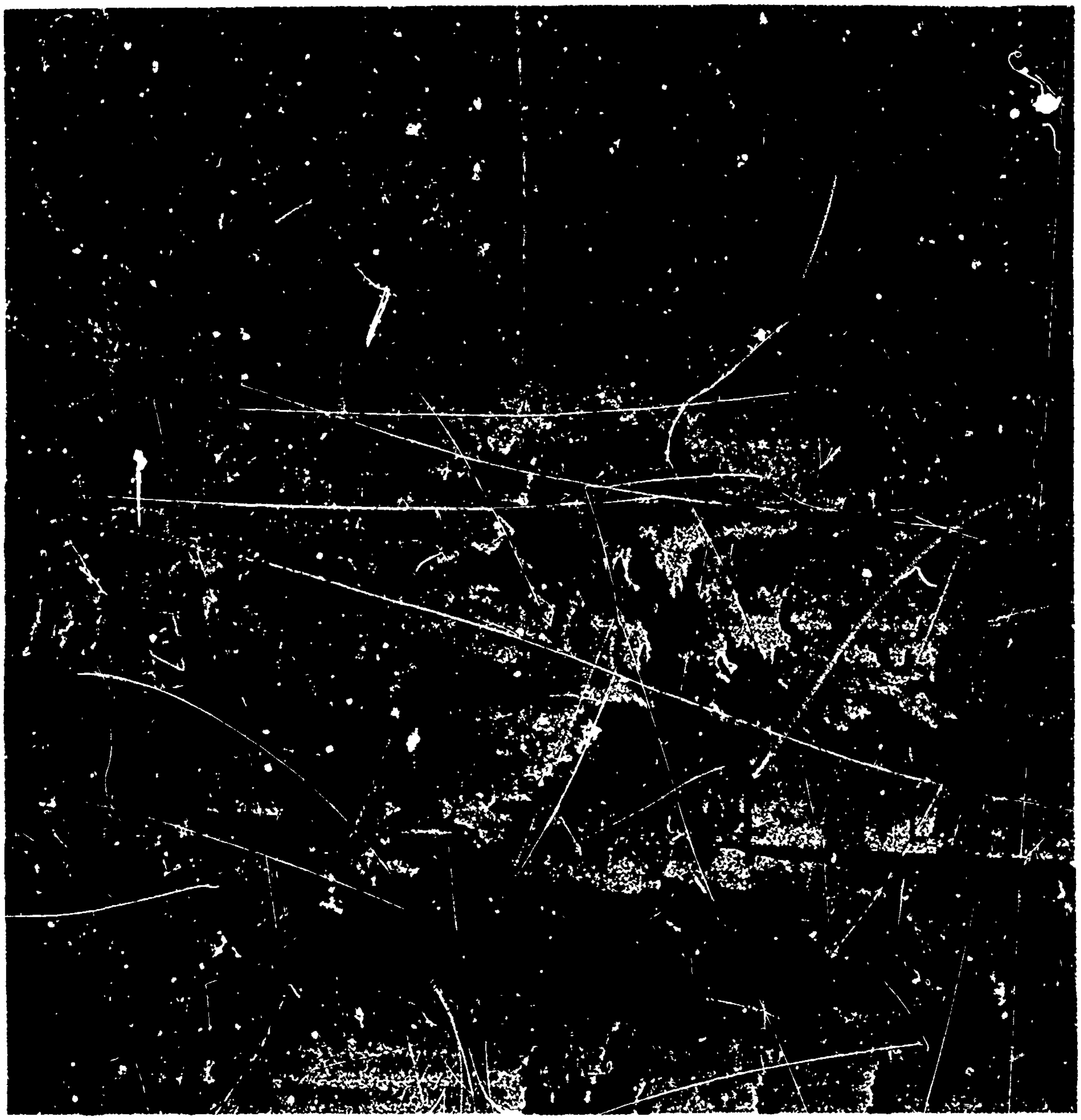


Figure 5-14. Windblown Snow From High Elevations Increasing the Snow Burden at Lower Levels (The "snowsheds" shown in this photograph protect the transcontinental railroad crossing Donner Summit, Calif., from the 20- to 60-ft drifts which often block the parallel interstate highway.)

(Photo by R. W. Gerdel)

Figure 5-15. Annual Accumulation of Snow Cover in Greenland (Ref. 37)

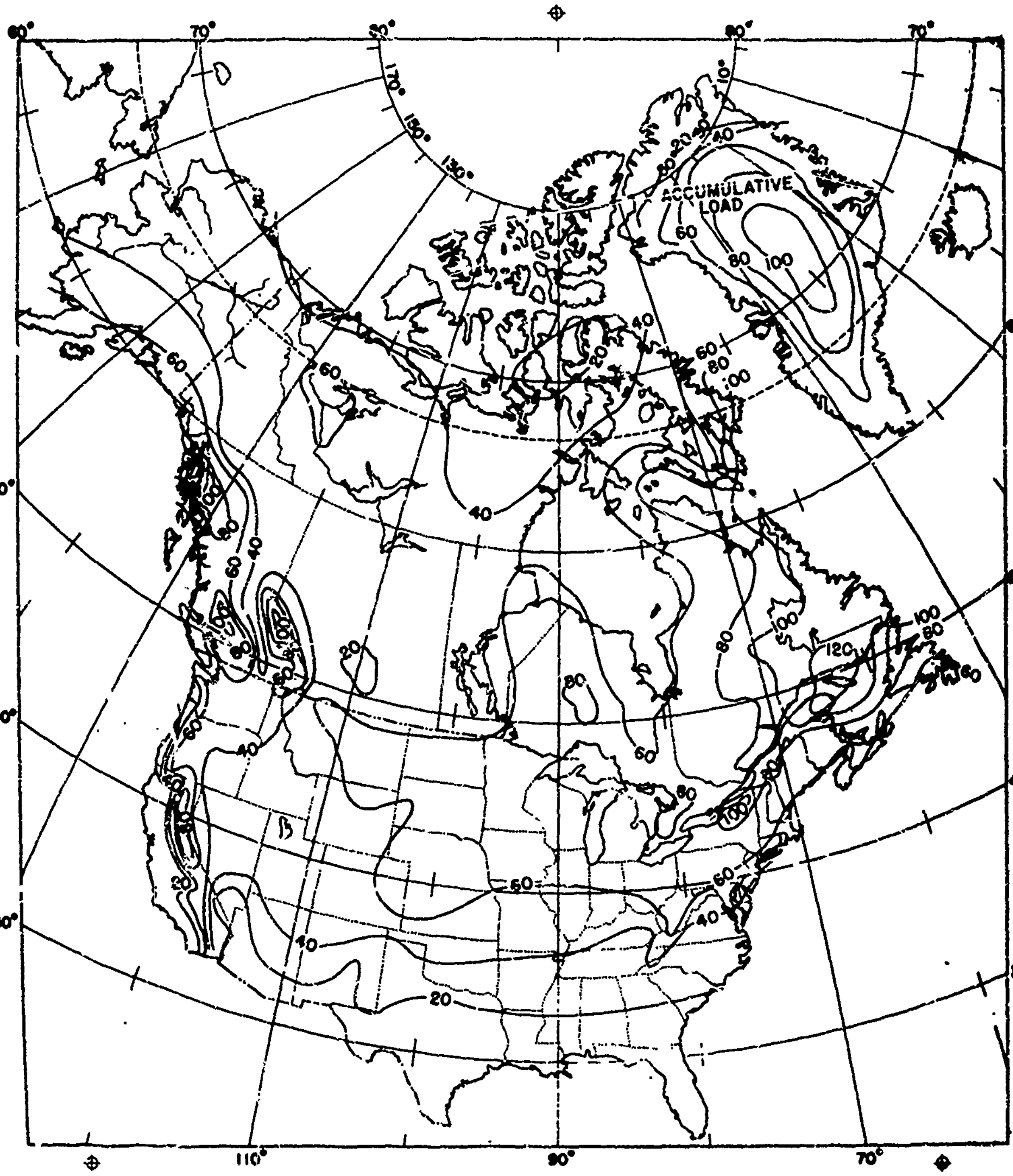


Figure 5-16. Maximum Probable Snow Load on a Horizontal Surface (lb ft⁻²) (Refs. 36, 38)

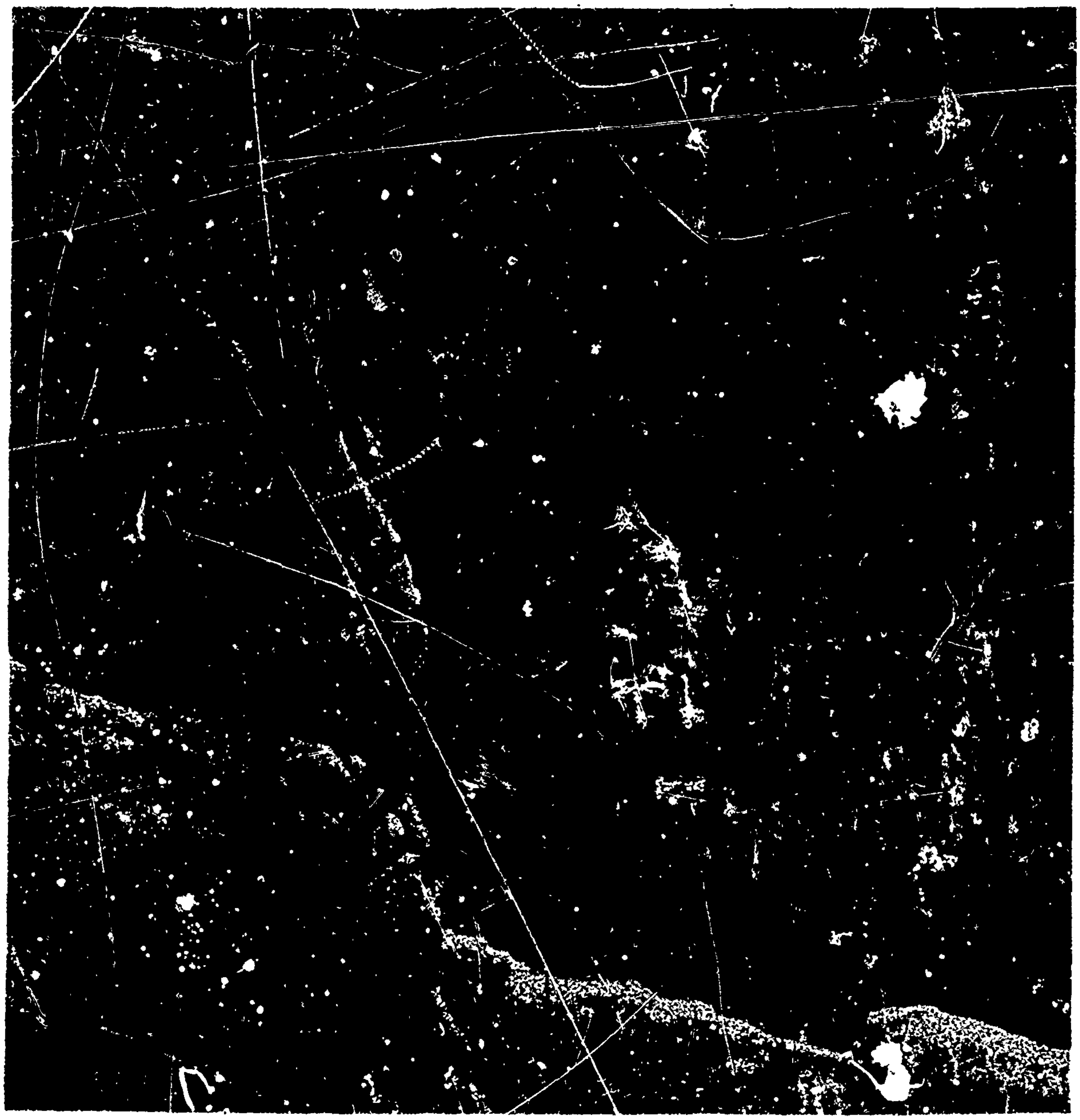


Figure 5-17. Snow Load With a Plastic-creep Cornice (Heated building with wood shingle roof)

(Photo by R. W. Gerdel)

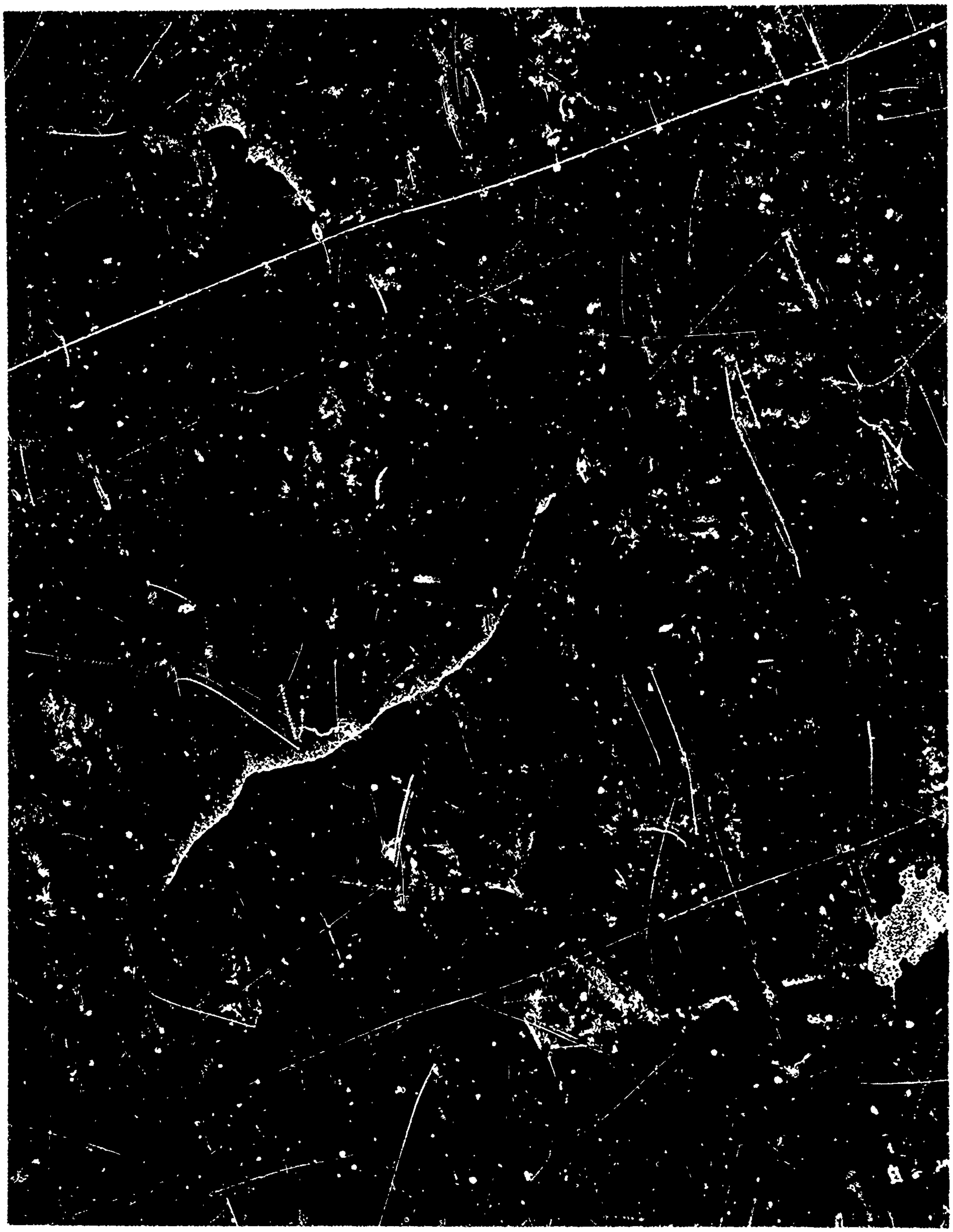


Figure 5-18. Snow Load With Wind Cornice on End-eaves (Heated building with sheet-metal roof)

(Staff Photo, Central Sierra Snow Laboratory)

rime, and hoarfrost are characteristic of the cold regions. A coating of glaze ice develops when rain falls on a surface that is below freezing. Rime is produced by cloud particles freezing to cold surfaces and is usually distinguishable from glaze by the opacity and lower density of the deposit. Rime commonly forms on the windward side of an object. This windward development of rime on a tree is shown in Fig. 5-19. Similar and frequently much more massive forms of rime develop on all types of exposed structures in maritime climates and at high elevations in cold regions. Hoarfrost is a sublimational product characterized by a feathery network of fragile crystals with a very low mass density. It is deposited commonly on cold surfaces in clear, calm air. It may be considered the winter equivalent of a heavy dew.

Glaze is usually transparent to translucent and has a density approaching that of pure ice (0.9 g cm^{-3}). Rime is translucent to opaque and the density usually falls within the range of 0.1 to 0.6 g cm^{-3} (6.2 to 37.5 lb ft^{-3}). The mass density of hoarfrost is almost impossible to measure, but it is probably less than 0.2 g cm^{-3} although the single "blades" or "cups" that give hoarfrost its striking patterns will have a density approaching that of pure ice.

Some idealized temperature curves associated with formation of precipitation as snow, glaze or sleet, and rain are shown in Fig. 5-20. Too little is known about temperature stratification in the lower atmosphere during formation of glaze and sleet to identify the actual conditions contributing to deposition of one or the other of these forms of precipitation.

Probably the most comprehensive treatment of glaze, rime, and hoarfrost from the standpoint of meteorological occurrence, geographical distribution, economic damage, and control practices is presented by Bennett (Ref. 39). Fig. 5-21 is a map of the Northern Hemisphere showing the "glaze belt" of the cold regions. It has been prepared largely from maps and other information presented by Bennett and supporting material from many quasi-technical sources and news articles. Lack of satisfactory meteorological records prevents extension of the glaze belt on this map through Asia, but probably much of interior Asia is relatively free of ice storms. Rime may be expected frequently in the southern Asian Highlands. Although data are sparse and inconclusive, it appears that heavy ice storms are frequent in Japan and along the Asian coast.

The frequency of occurrence of ice storms and extent of damage produced by them is difficult to evaluate from official weather records. Conditions in urban areas where weather stations usually are located may not indicate the extensive coverage of freezing rain in the open country during a major ice storm.

5-3.3.4 SOLAR RADIATION

Solar radiation in the cold regions has several unique characteristics. In winter, the long winter night with zero solar radiation lasts for longer than 2 mo at a latitude of 70 deg N. In contrast, the solar radiation of the long summer day provides the polar regions with a higher level of daily solar radiation than occurs elsewhere on the earth. In addition to this wide range of solar radiation levels, other phenomena such as the "greenhouse effect", whiteout, and atmospheric refraction contribute to a diverse solar radiation environment.

The "greenhouse effect", which is most pronounced in the cold regions, results from the confinement of radiation to the surface of the earth by atmospheric absorption and reflection. Incident solar radiation penetrates the atmosphere and is absorbed at the surface of the earth. Long wavelength radiation from the surface provides thermal energy to heat the atmosphere, and some portion of it is radiated into space. The arctic cloud cover, primarily in the summer, reduces the amount of long wavelength radiation that escapes to space to under 3 percent (Ref. 40). This

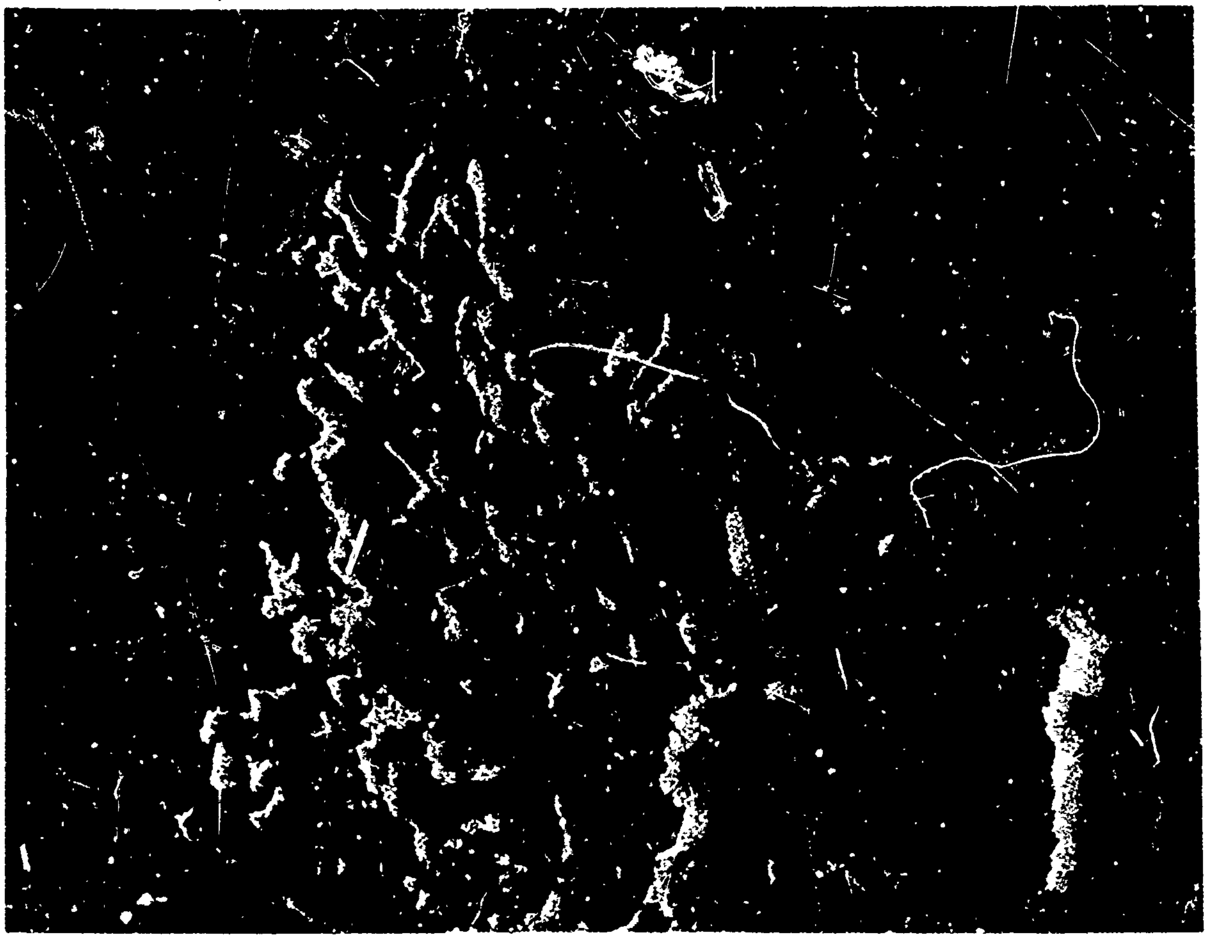


Figure 5-19. Rime Formation on Tree Branches

(Photo by R. W. Gerdel)

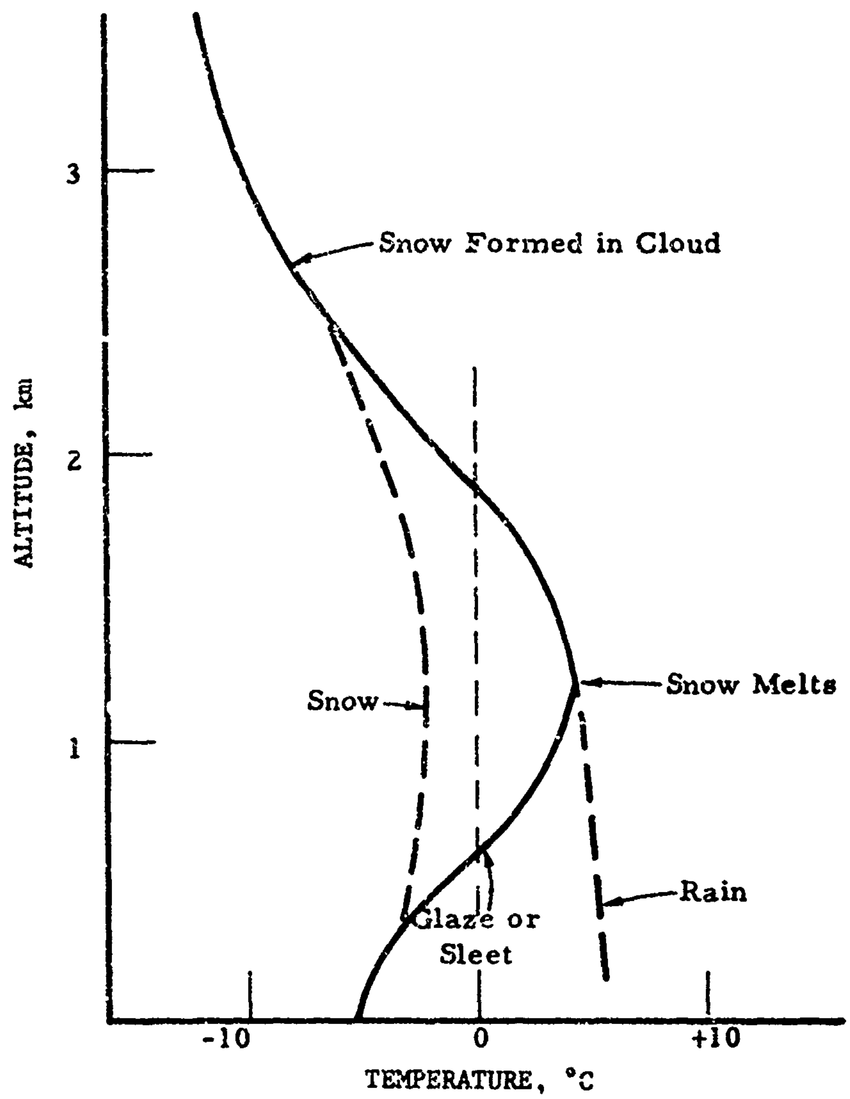


Figure 5-20. Idealized Air Temperature Profile Associated With Precipitation Falling as Snow, Rain, or Glaze or Sleet

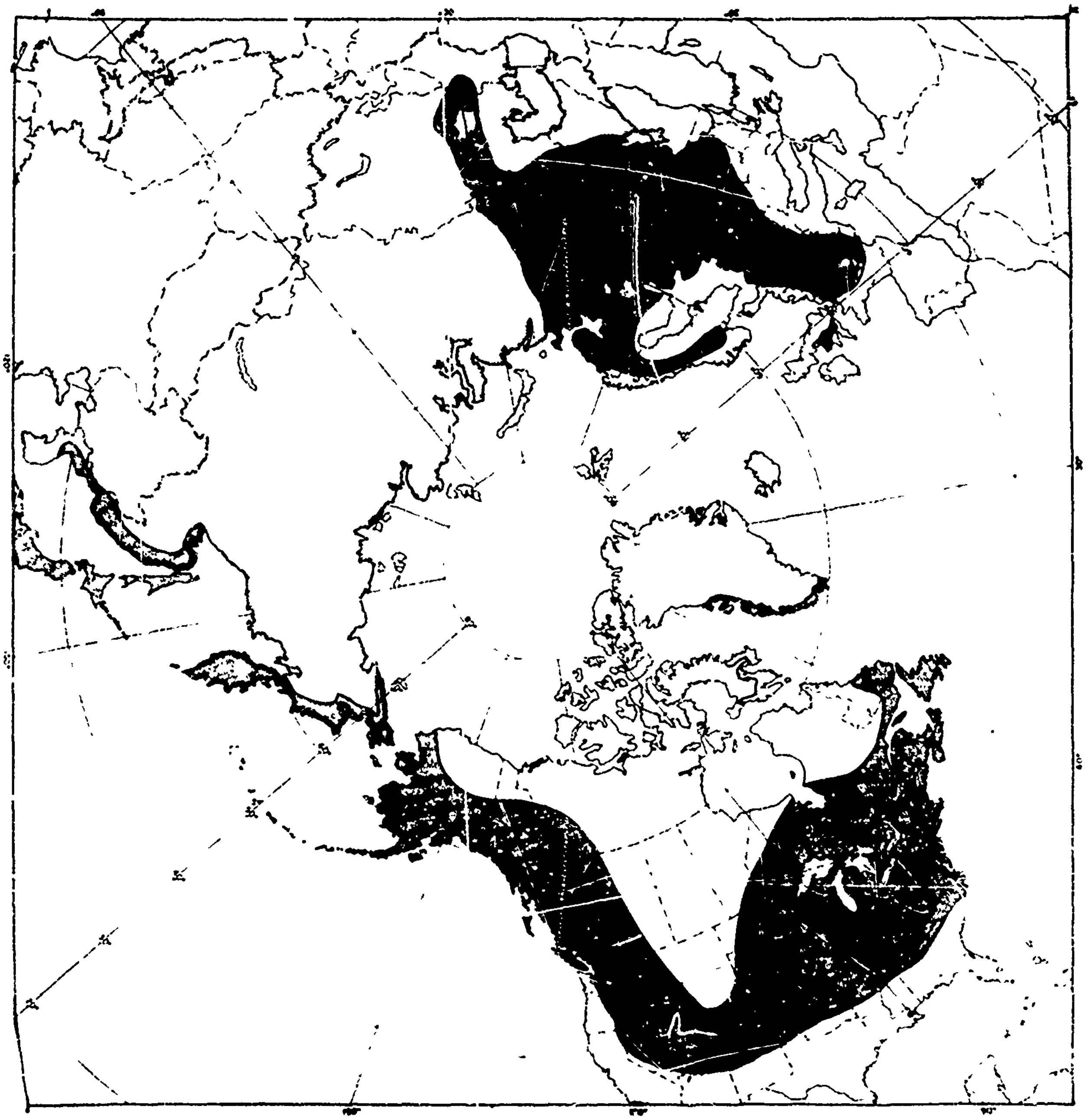


Figure 5-21. Glaze Belts of the Northern Hemisphere (Ref. 39)

causes rapid melting of the snow cover and arctic ice sheet and produces a wet, often impassable, terrain during the spring thaw and ice breakup period.

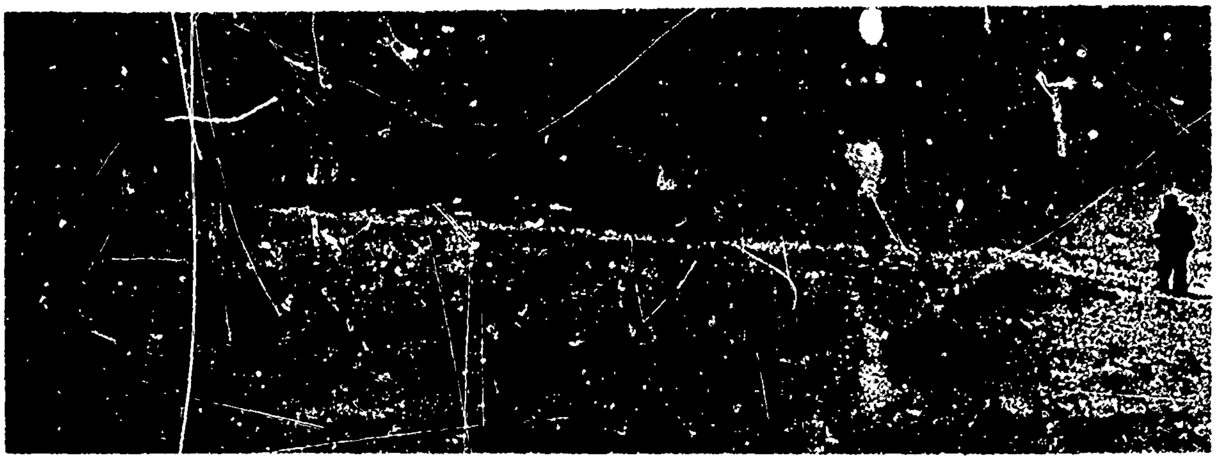
The strong, persistent inversions that are characteristic of higher latitudes produce extraordinary atmospheric refraction phenomena. Mirages are common, sharply defined, and frequently so extensive, particularly in coastal areas, that explorers have reported large landmasses where none exist. In the presence of two or more inversion layers, which is not uncommon in the Arctic, a mirage may consist of multiple or vertically elongated images which give a false impression of the height of coastline features and mountains. The term "ice blink" has been applied to mirages produced by refraction of snow-covered landforms or massive ice features.

Atmospheric refraction phenomena (variously referred to as "terrestrial scintillation", "atmospheric boil", and "shimmer") may influence object recognition and surveillance capabilities in cold regions. Image distortion and apparent, though not real, image motion are caused by propagated turbulence and fluctuations in atmospheric density along the line of sight. Optical shimmer in a horizontal path above snow cover may be greater than over any other type of surface (Ref. 41). The optical perturbations that cause deterioration in visual resolution are the product of incomplete turbulent mixing of thermally stratified layers of air near the ground. Visual resolution deteriorates systematically as the vertical temperature gradient increases. Under clear skies, deterioration of resolution increases as windspeeds increase up to 8 km hr^{-1} (5 mph) and then improves with further increases in windspeed. Optical shimmer is at a minimum and visual resolution at an optimum under low overcast. However, low overcast above an unbroken snow surface also creates the optimum condition for whiteout with the accompanying lack of contrast and depth perception.

When sunlight is diffused through an overcast with multiple reflection between the cloud base and a continuous snow cover, the environment becomes almost uniformly "whitened", a condition in which there are no shadows and visual orientation is difficult. This is the characteristic cold region phenomenon called "whiteout". In a typical, full-scale whiteout, under continuous overcast, there is total lack of contrast between the sky and the snow surface. Since there is no horizon usable for reference, perspective involving judgment of distance is limited to a few feet although actual horizontal visibility of dark objects is not materially reduced. The uniform, spatial albedo or reflectance of snow surface for diffused light obliterates all surface features so that drifts, wind etchings, footprints, and tracks produced by sleds or vehicles are not visible. Reduction in visual contrast may be sufficient to cause a man to stumble over a 5-cm (2-in.) "mountain" or into a 5-cm (2-in.) "gully", as one polar explorer is reported to have remarked in describing a whiteout. Fig. 5-22 illustrates the conditions typical of a whiteout on polar ice sheets. A similar condition occurs on ice-covered lakes or seas when there is an unbroken expanse of snow cover.

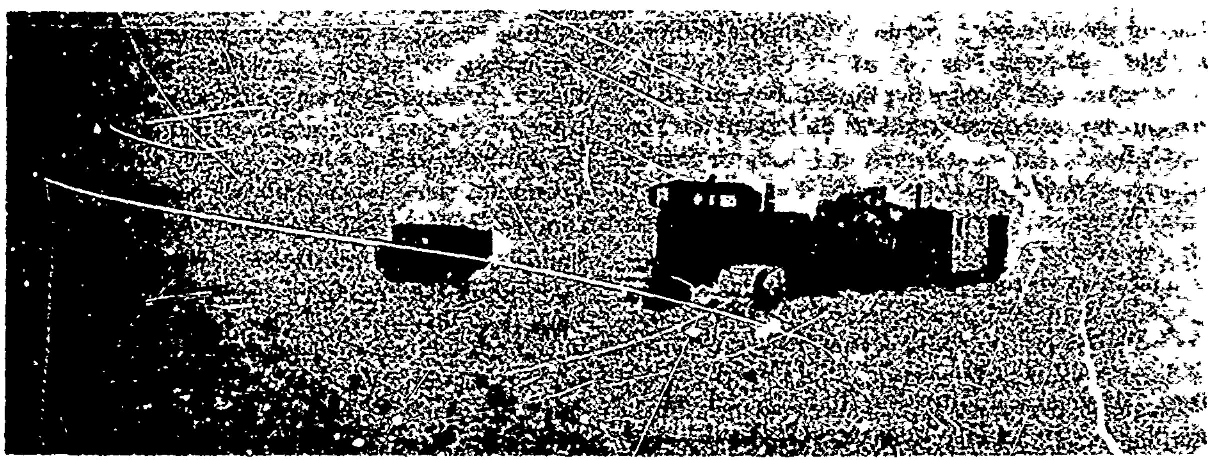
Contrary to a somewhat common assumption, the color of an object does not affect its visual range in whiteout. The color contrast between an object and its background falls below the chromaticity threshold when the distance between the observer and object approaches the visual range limit (Ref. 42). Colored trail markers, colored paints, and color-tinted glasses are ineffective as aids to improvement in visibility during whiteouts. As distance increases, colored objects appear gray long before they merge into the background and become invisible.

The high albedo of snow-and-ice-covered areas produces a background of very high luminance under clear skies. The high luminance may contribute to an increase in contrast between an observable object and the background with some improvement in visual range and recognition. Atmospheric boil or scintillation may attenuate details, however,



(A) Example of typically clear day. Note presence of horizon, high contrast of surface features, tractor swing elements, and all parts of the aircraft.

(B) Onset of whiteout with light diffusion and loss of shadow effects



(C) Complete whiteout with no horizon and all surface features obliterated by full spatial diffusion of light

Figure 5-22 Whiteout Development on the Greenland Ice Cap
(Photograph by R. W. Gerdel)

so that any improvement in contrast may be more than offset by loss in resolution. In nonturbulent, clear air, the absolute visual range maximum is attained with a black object against a white background. In nature, there is no whiter background than a new snow surface. Any dark, nonreflective object that does not lose its "blackness" by reflecting light from the surroundings will be highly visible with a snow background. A dark, olive-colored tent and a vehicle painted the usual olive or dark green color are examples of objects that are essentially black when viewed against a snow background. Very white or bright objects with high albedo will reflect light and blend into a snow-covered background. Moving, light-colored objects are more readily detectable than stationary ones. When the sun is behind the observer, the object may be less readily detected than when the sun is behind the object being viewed. This is due, in part, to the mixed contrast effect produced by the lower reflectance of the snow surface in the shadow created on the snow surface by the object. Over snow or ice, from the air or from the ground, under conditions of high surface albedo and high luminance, improvements in visual acuity may be achieved by making observations over the widest possible angle.

5-3.3.5 OBSCURANTS

Water fogs, ice fogs, and blowing snow are the most common obscurants that reduce visibility in cold regions. Steam fogs occur over open leads on the Arctic Sea at all seasons but are most prevalent during summer and often create a navigational hazard. Sea fogs and low stratus inflowing over coastal areas impede both air and ground transportation in the Arctic during summer months. At high elevations, radiational and advectional fogs may persist for several days, immobilizing all surface and air movements; as low fogs, they are additive in their effect on reduction of visibility and target recognition during whiteouts. Fig. 5-23 shows the effect on visibility of fog over a snow surface. It should be compared with Fig. 5-22 which shows visual conditions in a typical overcast whiteout.

Ice fogs may form at temperatures below -30°C (-22°F) and probably will form at temperatures below -40°C (-40°F) when atmospheric moisture is provided by combustive or explosive processes. They are most common during the dark period of the arctic winter when the essential extreme low temperature conditions prevail for several days. Ice fogs may vary from a light fallout of minute ice crystals called diamond dust to a dense manmade fog caused by pollution of the atmosphere with water vapor from automobile exhaust and residential and industrial effluence. A dense ice fog over Fairbanks, Alaska, during a period when the air temperature was about -40°C (-40°F) was sustained by a water supply of 600 kg min^{-1} (1,300 lb min^{-1}), delivered to the atmosphere from local residential and industrial heating plants, cooling ponds of thermal generating stations, and automobile exhausts (Ref. 43).

Visibility during an ice fog may be reduced to as little as 3 m (10 ft). The slowly falling particles may consist of well-formed ice crystals or spherical crystals with only rudimentary faces. When well-formed hexagonal or columnar ice crystals predominate, there is a spectacular scattering of light in an ice fog. Vertical and horizontal rays extend from automobile headlights and street lights, and the scattering of light by the crystals makes judgment of distance almost impossible.

Because of their small (2 to 20 μm) average diameter, ice crystals fall very slowly. With an increasingly available supply of water vapors and nuclei as products of combustion in densely inhabited areas during extremely cold weather, there is a continuing concentration and increase in density of ice fog, which usually will not dissipate fully until the atmospheric temperature rises above -18°C (0°F). The crystals may sublime into warmer air or they may aggregate, growing into snow crystals with sufficient mass to fall out.

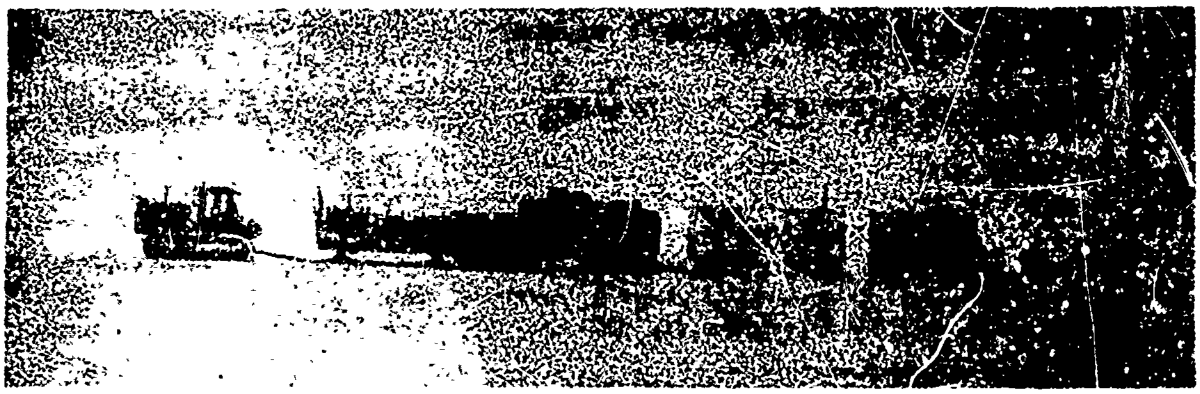


Figure 5-23. Attenuation of Visibility by Fog (In this photograph, the fog is a physical obscurant, additive to an optical whiteout illustrated in Fig. 5-22.)

(Photograph by R. W. Gerdel)

At high elevations, a form of ice fog develops at comparatively high temperatures. It usually is associated with hoarfrost or rime formation at a few degrees below freezing. Crystals suspended in the air appear to have been formed originally as frost or rime on trees or other objects exposed to supersaturated or supercooled saturated air, and cooled by longwave radiational heat loss. Some of the crystals appear to be attached so lightly that only a light breeze is required to scatter them through the air, creating a condition similar to the diamond dust fallout of the high Arctic. The small crystals frequently adhere to the windshields of automobiles traveling over a mountain pass, creating a visibility problem far greater than their actual mass in the atmosphere would imply. Frequently these high temperature ice fog crystals are sufficiently tenacious to cause icing similar to that occurring during a freezing rain.

Blowing snow is an atmosphere-borne obscurant common to all parts of cold regions. Reduction in visibility by blowing snow may occur during a snowstorm, or when recently deposited, unconsolidated snow is lifted from the surface by high winds. The reduction in contrast and visual acuity during a blowing snowstorm is shown in Fig. 5-24. As shown in this photograph, the presence of objects that may channel the wind and increase its velocity aggravate the condition. The usual combination of blowing snow and low temperature with extremely high winds results in almost total immobilization of all forms of transportation. Heavily populated metropolitan areas are as susceptible to traffic delays caused by blowing snow as are the highways through mountain passes. Tractor trains carrying supplies to industrial and military facilities in the far north may be stalled for days, waiting for the end of a blowing snowstorm and improvements in visibility.

5-3.3.6 TERRAIN

Terrain in the cold regions is characterized by snow cover and ice. Vegetation varies from forests to barren, permanently snow-covered soil. Tundra and muskeg are unique terrain features of the cold regions. While overall precipitation is not large, the spring thaw, the huge glaciers, and the permafrost create a land of lakes, streams, and swamps that creates a formidable mobility problem.

5-3.3.6.1 GLACIERS. Geologists and physical geographers recognize two basic types of glaciers—mountain glaciers and continental ice sheets. Mountain glaciers occur throughout the cold regions. In the extreme cold zone, glaciers may extend from the highest peaks down to sea level. In the southern highlands of the intermediate cold zone, they may be limited to inactive, cirque-confined ice remnants. Where they flow out of valleys and spread out on plains at the foot of mountains, piedmont glaciers often provide trafficable access routes to high elevation sites that may have strategic importance. An example of a mountain glacier discharging onto a coastal plain is shown in Fig. 5-25. High mountain glaciers are the major source of water for many of the northern rivers that provide navigable access to inland regions in summer, and ice-covered natural highways in winter.

Continental glaciers cover the Antarctic, Greenland, and a part of Ellesmere Island in Canada. They are dome- or shield-shaped masses of ice which in the Antarctic and in Greenland are more than 3,000 m (10,000 ft) thick near their center. The Greenland ice sheet occupies more than 1,800,000 km^2 (700,000 mi^2) of the total 2,200,000 km^2 (850,000 m^2) of land area. It reaches the sea or coastal plain in the form of valley glaciers, high, steep ice cliffs (Fig. 5-26), and floating ice shelves. The Humboldt Glacier in North Greenland (Fig. 5-27) is an ice shelf 20 km (50 mi) wide and 90 m (300 ft) above sea level where it reaches the sea. Tabular icebergs or small ice islands, 90 m (300 ft) thick and up to several square miles in area, constantly break off the ice shelf during the summer and float southward into the sea lanes of the Atlantic.

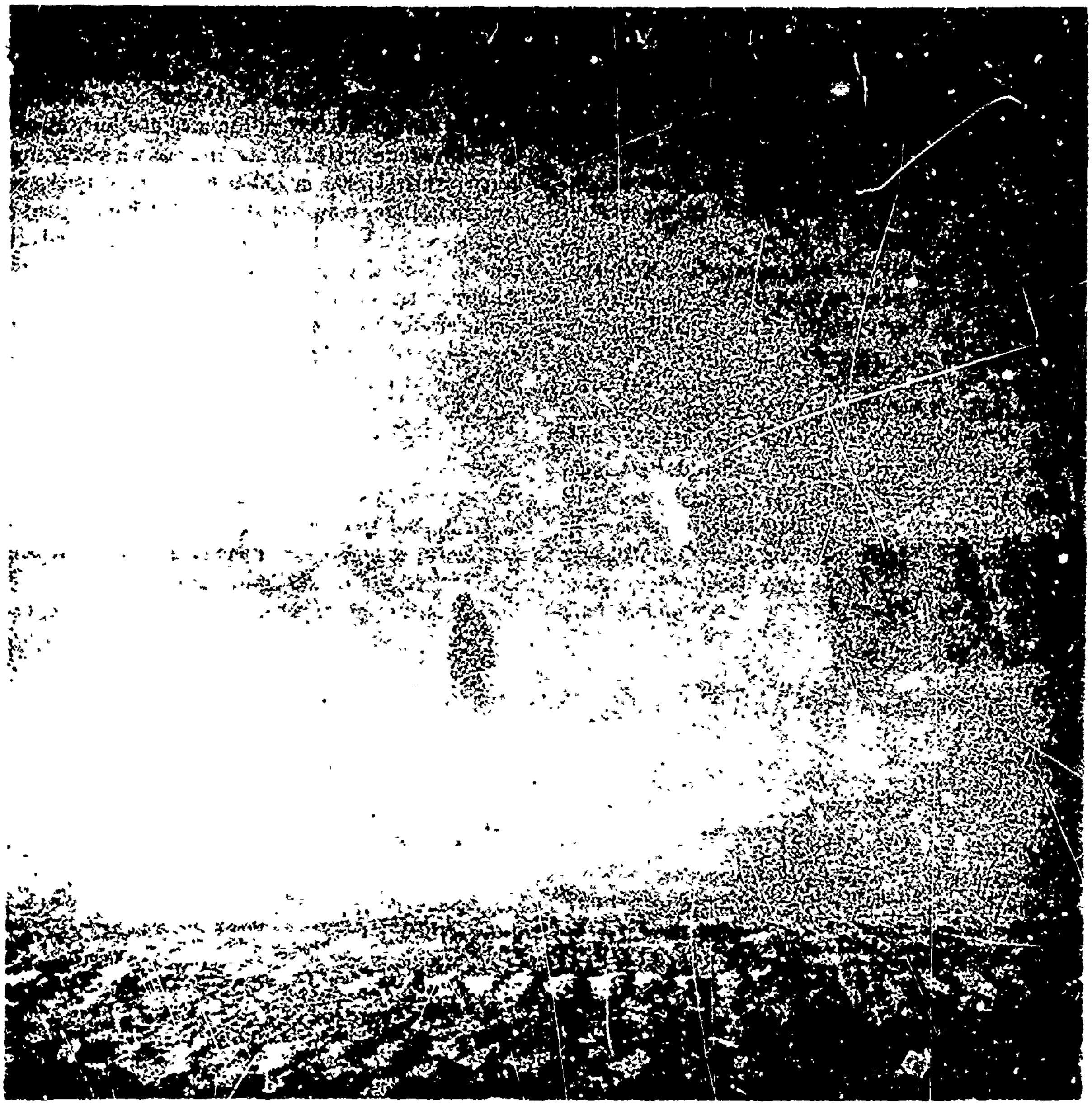


Figure 5-24. Attenuation of Visibility by Blowing Snow (In this photograph the diffusion of sunlight is additive to the obscuration caused by the blowing snow.)

(Photograph by R. W. Gerdel)

Figure 5-25. Mountain Valley Glacier Debouching Onto a Coastal Plain

(Photograph on Ellesmere Island by R. W. Gerdel)

Figure 5-26. Ice-cliff Front of a Continental Glacier With Terminus on Land

(Photograph in North Greenland by R. W. Gerdel)

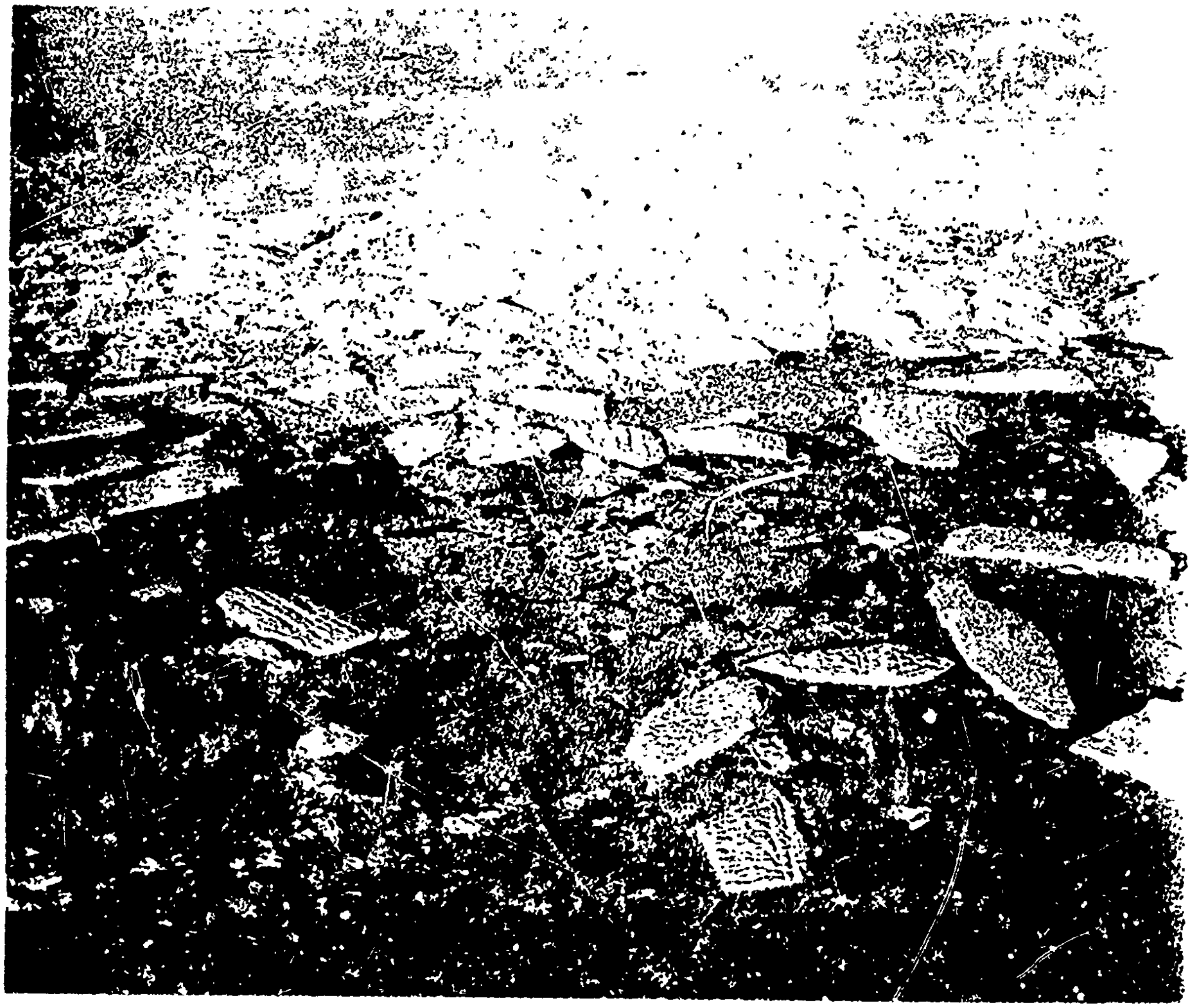


Figure 5-27. Tabular Icebergs Calved at the Sea Terminus

(Photograph of Humboldt Glacier, North Greenland by R. W. Gerdel)

In contrast to mountain glaciers which may move downslope at rates of a meter to several meters (several feet to several yards) per day, the continental ice sheets are relatively stable. Movement at higher elevations in the interior regions is on the order of several centimeters per year. The slow horizontal movement permits the establishment of reasonably permanent facilities on or within the ice such as Camp Century in Greenland. Such facilities will be destroyed by the pressure of accumulative snow loads as they become submerged in the ice long before any appreciable damage develops from horizontal shifting of the continental ice sheet.

5-3.3.6.2 ICE COVER. In most cold regions, an ice cover forms on open water during winter months sufficiently to interfere with, or totally halt, navigation for 2 to 4 mo each year. Ice does not form on the open sea in the intermediate cold zone, but coastal harbors may become icebound and require special efforts to maintain navigation. A notable example of heavy ice cover on a major harbor occurred in 1844 when hand labor was required to cut a channel about 7 mi long through the ice in Boston Harbor to release outbound and inbound ships. In 1852 an ice cover at the headwaters of Chesapeake Bay was so thick and persistent that it interfered with navigation for 2 mo.

Ice jams, formed when heavy rains and rapid melting break up ice cover in upper reaches of a stream, cause development of ice floes larger than the channel can contend with. Such floes can have material effect on navigation and hydroelectric installations. The Mississippi River was totally blocked by ice jams at New Orleans in 1899.

Ice-related damage to property and interference with transportation probably cause greater annual economic loss in southern parts of the cold regions of the Northern Hemisphere than all of the ice cover—several orders of magnitude greater in thickness and volume—that is formed during a single winter season in the cold and extremely cold zones.

Since the freezing point of sea water is approximately -2°C (28°F), extensive ice cover develops on ocean water only in cold and extreme cold zones. In the extreme cold zone, sea ice cover reaches a thickness of 1 to 3 m (3 to 10 ft) annually. In summer the continuous cover breaks up into floes which drift with wind and current.

Fig. 5-28 shows the area of ice cover and its duration in terms of navigability for the cold regions of the Northern Hemisphere (Ref. 36). Navigability occasionally may be affected by ice jams and ice covers produced by abnormally low temperatures some 10 deg of latitude south of the 100-day isoline on this map.

By taking advantage of open leads that develop in the arctic pack ice for several weeks each summer and with the assistance of large icebreaker ships, strategically located stations around the perimeter of the Polar Basin are receiving annual logistic support by sea. With under-ice navigation by nuclear-powered submarines having been proved feasible and with continuing improvement in aircraft operational capabilities in the extreme cold zone, routine support and maintenance of Arctic- and Antarctic-based establishments, including those on floating islands are now feasible.

When ice cover develops on calm water in lakes, pools, and the quiescent reaches of a stream, crystallization usually starts from the shore or solid objects projecting above the water surface. If the water surface is not greatly disturbed, a stable ice sheet rapidly forms by outward growth from the initial region of crystallization.

In turbulent streams and on lakes and the sea where the water surface is disturbed by wind and wave action and kept in contact with cold air, a layer of water several inches to several feet in thickness may be supercooled before freezing takes place. Under suitable conditions of turbulence and rate of supercooling, the morphological form of ice

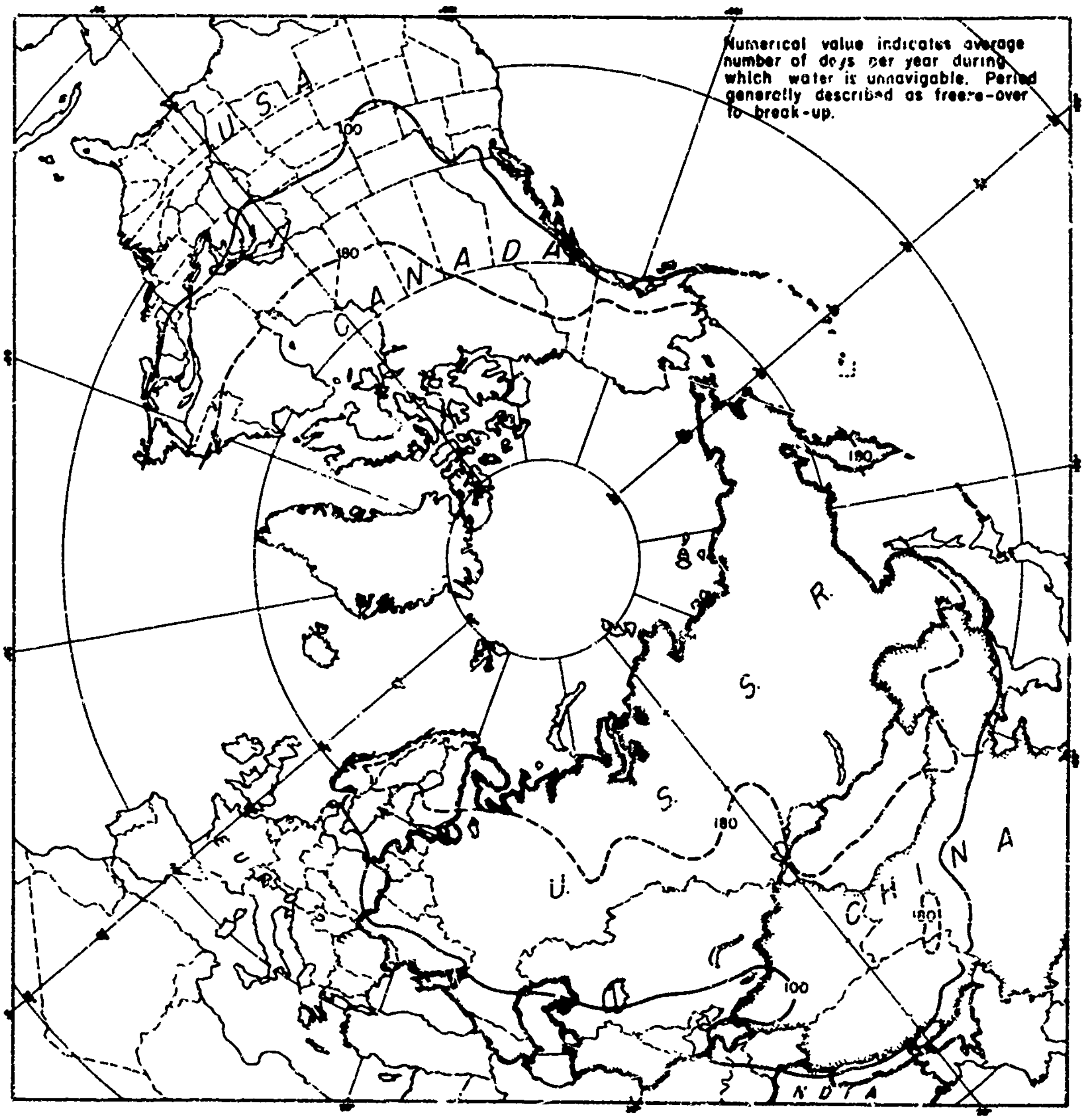


Figure 5-28. Average Number of Days Per Year in Which Water is Unnavigable (Ref. 30)

particles called "frazil ice" develops throughout the supercooled layer. Frazil particles are initially disc shaped with a lobate perimeter and are usually less than 1.0 mm (0.04 in.) in diameter. They continue to form and grow with some transition toward crystal shape if the rate of supercooling remains fairly constant.

Frazil ice particles are very buoyant, and, under turbulent action of stream flow or waves, they remain in suspension below the surface or even to the bottom of streams and shallow lakes.

When frazil ice forms in rivers, it clogs water intakes and leads to formation of ice jams which may cause heavy upstream damage by flooding, and downstream damage to bridges, piers, levees, and jetties.

Since the water in which frazil ice is forming or in which it is being transported in suspension remains slightly supercooled, wood, metal, stone, and other objects in the water will have a surface temperature at or slightly below freezing. This leads to adherence and eventual buildup of frazil ice into a cohesive mass or coating of ice on underwater objects and on rocks in the riverbed. This form of submerged ice is called "anchor ice".

5-3.3.6.3 FROZEN GROUND. An arbitrarily selected depth of seasonal frost penetration into the ground is an engineering criterion for identification of the cold regions. Fig. 5-29 shows the southern boundary of the cold regions of the Northern Hemisphere as defined by a 0.3-m (1-ft) depth of frost penetration. A criteria of 100-degree days of freezing temperature was used as an equivalent for frost penetration of 0.3 m (1 ft) and a recurrence of at least once in 10 yr to identify this southern boundary of the northern cold regions.

Since the actual depth of frost penetration is not observed regularly, cumulative degree days* frequently are used as a measure of potential frost penetration into the ground. Several other methods have been used to derive the cumulative degree-day value for computing a freezing index. Some are described in the Corps of Engineers publication, *Freezing Index in the United States* (Ref. 44). Fig. 5-30 shows how the cumulative degree day curve is used to derive the freezing index for Caribou, Maine. Maps showing the distribution of mean freezing indexes for Canada Alaska, Greenland, and northern Eurasia are presented in TM 5-852-1 (Ref. 45).

Application of the freezing index to estimation of frost penetration into the ground is complicated by many other factors that affect surface heat losses and thermal conductivity. Moisture content, and structural and textural composition of soil have a marked influence on penetration of the freezing isotherm and on actual freezing of water in the soil. The insulating effect of vegetation and snow cover reduces depth of frost penetration. Under pavement from which snow has been removed during winter months, freezing may penetrate to a depth twice as great as in adjacent brush or snow-covered fields. The average depth of frost penetration under different types of surfaces and ground cover at Duluth, Minn., which has a freezing index of about 2,900, is shown in Table 5-12. In that area, frost penetrated to 1.75 m (69 in.) under a concrete pavement but to only 0.75 m (30 in.) where approximately 1 m (3 ft) of snow cover insulated the ground.

In general, for soil of uniform texture and moderate moisture content, frost will penetrate about 0.3 m (1 ft) for a freezing index of 100 and 1.8 to 2.4 m (6 to 8 ft) where the

*An accumulation of 100 degree days of freezing temperature is obtained when the sum of the differences between the freezing temperature and the mean daily temperature reaches 100 in a given season. Thus, a mean daily temperature of 27°F has a value of 5 F degree days and a mean daily temperature of 34°F has a value of -2 F degree days. The cumulative total for these 2 days would be 3 F degree days of freezing temperature. It requires 20 consecutive days of 27°F mean temperatures to accumulate 100 degree days of freezing temperatures.

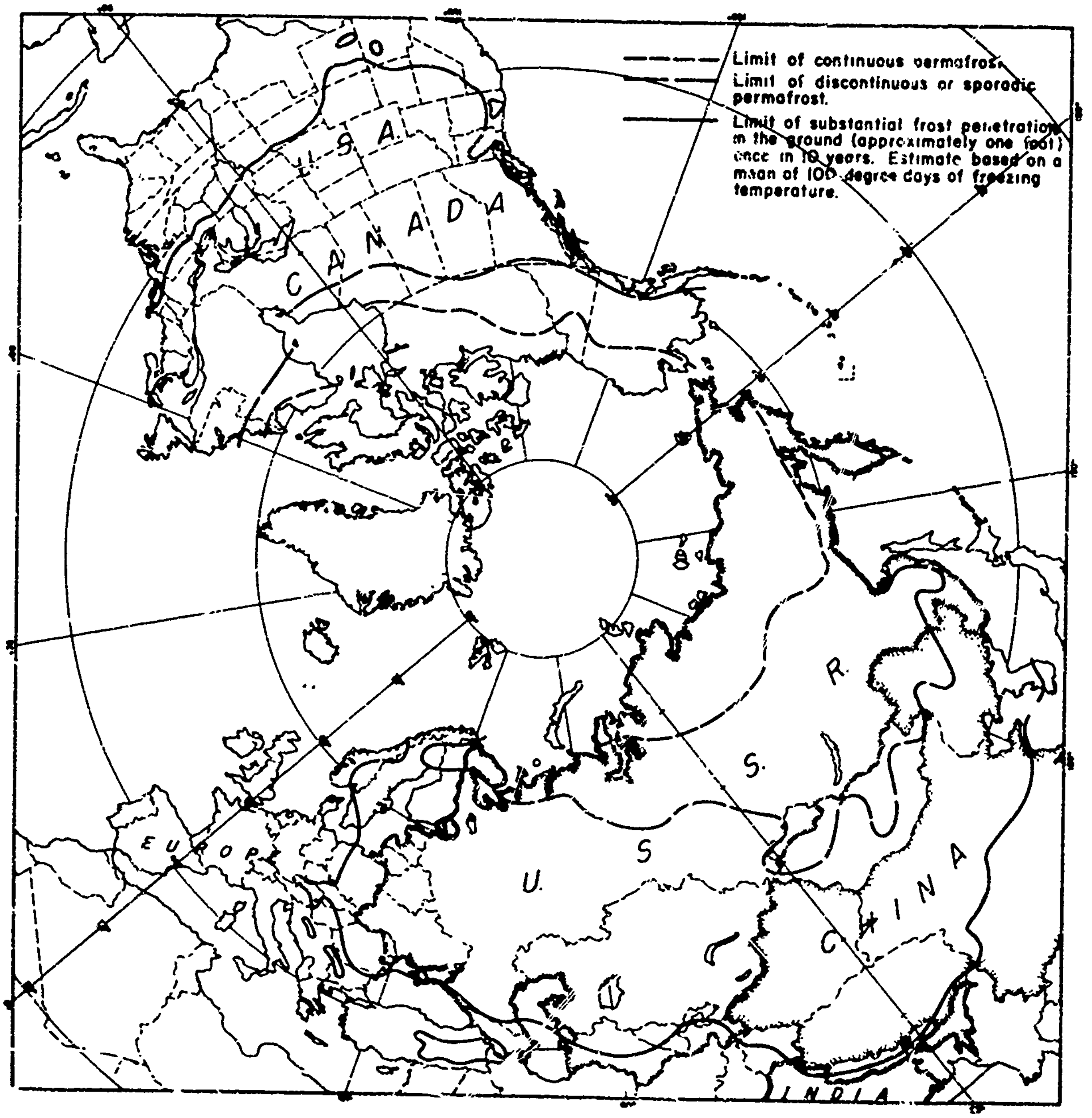
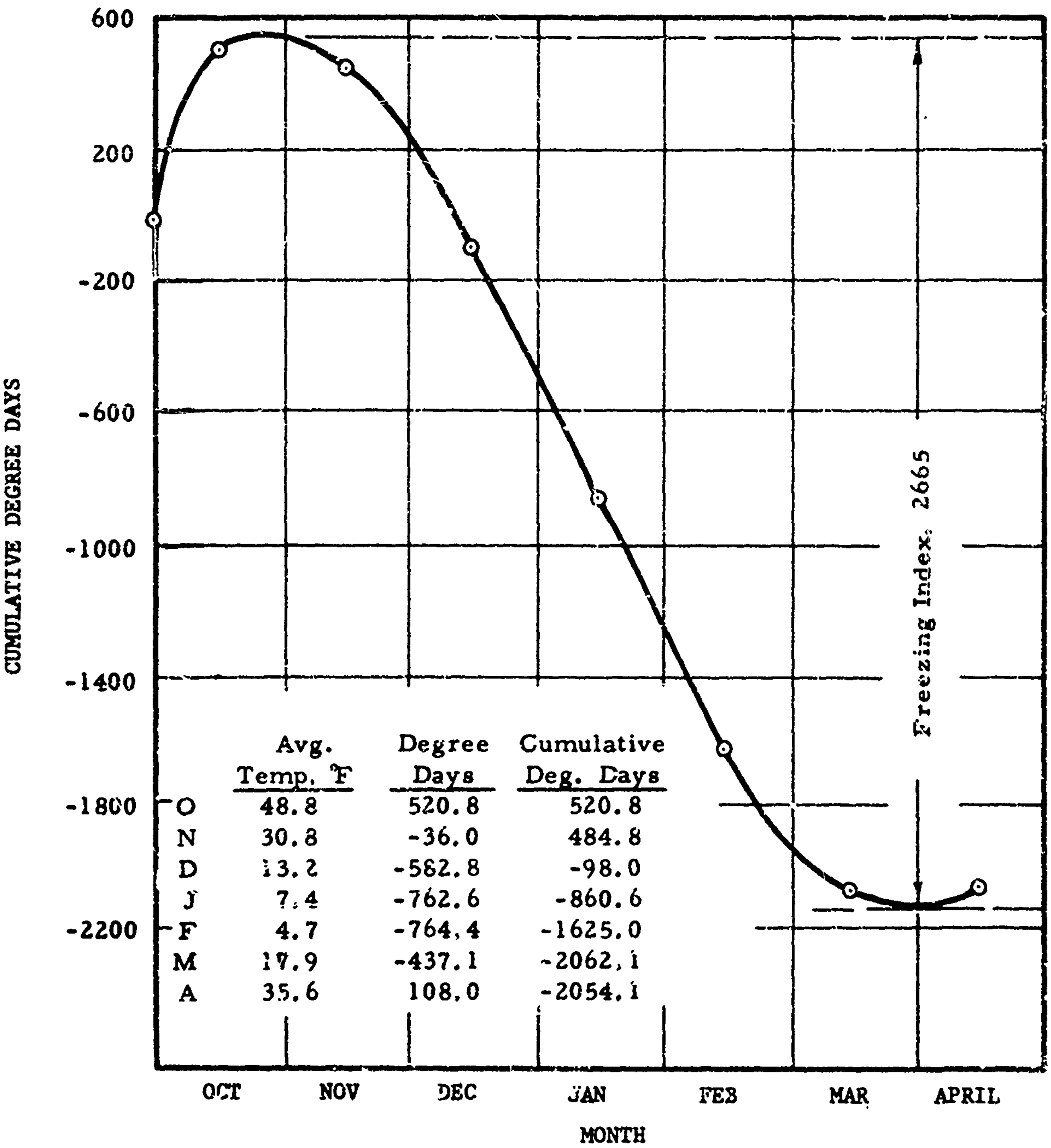


Figure 5-29. Distribution of Frozen Ground in the Northern Hemisphere (Ref. 43)



	Avg. Temp. °F	Degree Days	Cumulative Deg. Days
O	48.8	520.8	520.8
N	30.8	-36.0	484.8
D	13.2	-582.8	-98.0
J	7.4	-762.6	-860.6
F	4.7	-764.4	-1625.0
M	17.9	-437.1	-2062.1
A	35.6	108.0	-2054.1

Figure 5-30. Determination of Freezing Index by Cumulative Degree Days (Ref. 44)

TABLE 5-12

FROST DEPTHS (FOR DULUTH, MINN.) (Ref. 46)

Condition	Frost depth, in.
Bare concrete on sandy soil	69
Bare asphalt on sandy soil	68
Bare sandy soil	68
Grass on sandy soil	66
1 ft of snow on grass and sandy soil	47
Brush cover on sand, no snow	47
Brush and 1 ft of snow on sand	36
2 ft of snow on sandy soil	37
3 ft of snow on sandy soil	30

freezing index is 5,000. Frequently, amplitude and duration of freeze-thaw cycles, capacity of the surface for absorbing and retaining solar radiation, and infiltration of rain and melt water are factors that influence the depth of seasonal frost penetration. Use of the freezing index in the development of design criteria for road construction, utilities installation, or foundations in the region of seasonal freezing requires a thorough understanding of the local environment.

Permafrost is defined as a thickness of soil or other superficial deposit or even of bedrock, at a variable depth beneath the surface of the earth in which a temperature below freezing has existed continuously for a long time (from two to tens of thousands of years) (Ref. 11). The definition is based exclusively on temperature, irrespective of texture, degree of induration, water content, or lithologic character. A readily drained soil, rock, or boulder mantle may be frozen with little or no ice present in the voids. Such permafrost will not have the hardness that develops in an ice-cemented material and can be excavated readily. Waterlines buried in such dry permafrost will freeze as quickly as those installed in ice-bonded permafrost of the same temperature. Any construction or operational practice that will permit infiltration of water into dry frozen ground will produce the characteristic ice-bonded permafrost.

An organic form of dry, nonindurated permafrost may be produced if an area of muskeg is drained artificially or if the water table is lowered through some change in the natural hydrology of the region.

Permafrost is universal throughout the extreme cold zone of the Northern Hemisphere. It is prevalent, although really discontinuous, in the northern part of the cold zone. It is present, below the seasonal freeze-thaw layer, at a depth of several inches to 8 or 10 ft and extends from a few feet to several thousand feet below the bottom of the seasonally frozen ground. Fig. 5-29 shows the distribution of the frozen ground zones in the Northern Hemisphere.

Thickness, distribution, and temperature of permafrost are not consonant with present day climate in many areas. In the region where permafrost is discontinuous, it often does not re-form if disturbed. In the region of continuous permafrost, it may not re-form to the original depth or acquire the same temperature following large-scale disturbance. Since permafrost is predominantly a relic of the Ice Age, its distribution cannot be defined readily by the freezing index. It does appear that a freezing index of at least 7,000 degree days is required to maintain a continuous permafrost regime.

Permafrost underlies about one-fifth of all the land surface of the earth with most of it in the Northern Hemisphere (Ref. 47). Three-fourths of Asiatic Russia and 45 percent of all the U.S.S.R. is underlain by permafrost (Ref. 48). The permafrost region of northeastern European Russia has the most severe climate in Europe with not more than 100 frost-free days in the year and a mean annual low temperature of -50°C (-58°F). Lack of precipitation in summer and rapid evaporation of the small amount of moisture in the thin seasonally thawed layer inhibits plant growth. A mean maximum temperature of 36°C (96.8°F) in this barren, water-deficient region makes the summer climate less endurable than the cold winters.

Most of Alaska and at least one-half the land area of Canada lie within the continuous and discontinuous permafrost zones (Fig. 5-29). In Alaska, the Brooks Range is the approximate dividing line between the region of continuous permafrost which extends northward to the Arctic Ocean, and the region of discontinuous permafrost extending southward almost to the Gulf of Alaska.

5-3.3.7 MATERIEL EFFECTS

In the cold climates, the most important effects of the environment are immediate. When a heavy snow occurs, surface mobility is immediately degraded and with sufficient accumulation becomes zero; if the temperature drops below -25°F for several days, operational capabilities are reduced 50 percent. If the low temperatures persist for several additional days, then all effort is spent on survival and operational capabilities are zero. Field operations in much of the cold regions are difficult, even in the summer months, because of the wet, unstable terrain. When the temperature drops below -40°F, ice fog forms due to combustion products emanating from vehicles, power stations, and heating facilities. The result is an obscured atmosphere which persists until the temperature rises or the wind blows. These examples, however, represent only the extreme. In the densely inhabited intermediate cold regions, incursions of the cold climate impede activities, cause great expense, and do much damage.

Low temperatures, by themselves, are not damaging to materiel. Items that had been exposed to severe cold for years have been found to operate well. In fact, man creates the arcticlike conditions to preserve perishable food for future consumption. Most direct materiel damage results from changing temperatures or from cold temperatures combined with other environmental factors. Plastics, rubbers, and metals are embrittled at low temperatures. If they are subjected to shock or vibration, they may fail. Melting and refreezing of ice often causes mechanical linkages to be jammed. Freezing of the ground can cause accumulation of water and can lead to displacement of structures and roadways. The properties of fluids change with low temperature; lubricants can become ineffective and batteries will cease to store electrical power.

In summary, the cold climate has little deteriorative effect on materiel, but when the materiel is used at low temperatures, its performance may be degraded. Operationally, the combined effect of the many environmental factors associated with a cold climate present formidable problems, restricting capabilities and creating a requirement for much specialized equipment or for modifications of operational procedures.

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CHAPTER 6

QUANTITATIVE ENVIRONMENTAL CONCEPTS

6-1 GENERAL

The description of the environment of Army materiel, if it is to be useful to design engineers, must be in quantitative terms. It is difficult to design and test materiel for a hot, humid region unless temperature and humidity data for the region are available in understandable terms. The need for quantification extends to all environmental factors but the success in doing so is limited for many factors. Macrobiological and microbiological organisms, for example, are not readily parameterized.

Equally important to the quantitative description of environmental factors is the quantitative description of the effects of these factors on materiel. Thus, voluminous data have been collected on the relationships between operating temperature and the time-dependent properties of electronic components, on corrosion rates of various materials as a function of time and environmental conditions, and on deteriorative effects of various forms of radiated energy.

Both types of data—that on environmental factors and that on their effects—require measurements that in turn depend on the availability of standardized measurement procedures, instrumentation, calibration standards, and data processing techniques in order that the measurements yield useful data. Without attention to these matters and their careful recording, erroneous use may be made of the data.

Examples of the pitfalls in data collection and interpretation are not difficult to find. In one such case, a decrease in skin cancer incidence was attributed to decreased solar radiation which in turn was attributed to increased air pollution (Ref. 1). The decreased solar radiation was based on pyranometer data over a 20-yr period for which regression analysis showed a 20-percent decrease in the annual average of daily incoming solar radiation. The analysis, however, failed to account for deterioration of the absorbing surface in the pyranometer and the fact that the pyranometer had been relocated twice during the period of the record. These factors introduced uncertainties in the data sufficient to invalidate the analysis and conclusions.

Time is an important parameter in data on environmental factors and their effects. Steady-state conditions rarely exist in the natural environment. Changes may occur in seconds—such as when a cloud passes the sun; or in hours—such as when a weather front passes through; or in days—as when the synoptic weather pattern changes. The effect of an environmental factor may depend on the intensity of the factor and the time of exposure in a highly nonlinear relationship.

The nature of the environment and its effects may be embodied in models that provide logical relationships between the occurrence of environmental factors or relate effects to factor values. Although such models are often poor approximations to the actual occurrences, they serve very useful functions in environmental analyses. Examples of models would include:

(1) The quantitative descriptions of climatic categories given in AR 70-38, which provide temperature and humidity ranges and cycles as well as limits on other factors (Ref. 2)

(2) Descriptions of typical days based on accumulations of weather records (Ref. 3)

(3) A mathematical relationship between raindrop size and rainfall intensity (Ref. 4)

(4) The Arrhenius equation for the temperature dependence of reaction rates, which serves as a model for the temperature-dependent changes in materials (Ref. 5)

(5) The U.S. Standard Atmosphere, which serves as a model for atmospheric parameters (Ref. 6).

There are many such models for many purposes. Some are purely conceptual, while others are based on a large quantity of data. They are necessary for quantitative analysis of the environment and its effects.

6-2 QUANTITATIVE FACTOR PARAMETERS

In order that measurements can be made, the measurable parameters associated with each environmental factor must be identified. In some instances, one factor may have a number of such parameters and those of greatest usefulness must be identified. In other instances, it is difficult to identify even one measurable parameter. In the subparagraphs that follow, quantifiable parameters are discussed for each of the 21 environmental factors. The general references for these descriptions are AMCP 706-116 and AMCP 706-117 (Refs. 7,8).

6-2.1 TERRAIN

Terrain, for quantitative study, is subdivided into four elements--soil, hydrographic features, vegetation, and topography. Table 6-1 lists the measurable parameters associated with each of these elements. Soils being of greater engineering importance have been studied more intensely and have a larger number of measurable parameters identified, 16 contrasted with 4 for vegetation.

Topography or surface geometry includes the macrorelief and microrelief of the land surface. Techniques for presenting surface geometry vary widely and are largely a function of the use to be made of the data. Relief maps drawn to various scales commonly are used to express surface geometry but have little value in depicting surface irregularities that, for example, a vehicle suspension designer may require. Therefore, microrelief and macrorelief normally are not presented in the same terms or units because of scalar differences. Microrelief commonly is reported in terms of frequency per unit length of several hundred feet or yards and amplitude in inches since this basically describes surface roughness. Data reduction techniques often are applied to make such information more useful. Macrorelief is concerned with the gross land features and refers to slopes in percent, elevation, or altitude, and the frequency of occurrence of these in terms of miles.

Surface composition or soil factors are considered here to be the characteristics of the surface of the earth which determine its load-bearing capacity, relative negotiability, stability, and workability. While the scientist is concerned with soil type or geologic formation, the engineer has more need of physical characteristic data that will determine, for example, the load-carrying ability of the surface. Soil characteristics regarding strength under static loads are reasonably well defined, and several systems for classifying soils have been developed. The Unified Soil Classification System developed by the U.S. Army Corps of Engineers is one of the more widely used systems and classifies soils on the basis of grain size and distribution, liquid limit, and plastic limit.

For purposes of mobility assessment, it generally is accepted that the soil reaction to dynamic loading must be determined. Many methods of measuring soil dynamic strength have been proposed and evaluated but as yet the development of a group of soil measurements that will positively determine the

TABLE 6-1

TERRAIN PARAMETERS

Terrain element	Parameters	
Soil	Particle size Allowable pressure Permeability Chemical composition Layer thickness Water content Plasticity Shear strength	Density Deformation modulus Cohesive strength Cone index Grain size distribution Atterberg limits Penetration resistance Bearing capacity
Hydrographic features	Water depth Stream width Bank height Bank slope	Lake area Stream flow velocity Differential bank height
Vegetation	Height Stem diameter	Stem spacing Recognition distance
Topography	Slope Obstacle approach angle Obstacle vertical dimension Obstacle spacing	Obstacle width and length Power spectral density Elevation

mobility of current vehicles has not been perfected.

Hydrological factors are the characteristics that define the nature of landmass surface water and the surface underlying it. An important hydrological factor is simply the location of rivers, streams, lakes, swamps, or other bodies of water. Others are the characteristics of a body of water such as its velocity, temperature, impurity content, amount of flow, depth, and width, and the seasonal variation of each. Descriptions of water basins sometimes include bottom and shoreline characteristics as well as obstacles that may hinder navigation.

Locations of bodies of water normally are presented on maps drawn to suitable scale. Characteristics of the water and flow are usually obvious from these maps but seasonal variations are often important enough to be noted specifically. Stream bed and bank geometry are presented in a manner similar to that of terrain relief; i.e., frequency and height of obstacles as well as slopes. Characteristics of the bed of a stream or river and bank conditions should be reported in terms that will allow an estimate to be made of vehicular and personnel mobility in crossing.

Vegetation factors comprise the physical characteristics of earth surface plants, trees, brush, and undergrowth. Characteristics of vegetation are of importance to the environmental engineer when considering the design of earth-moving equipment or special vehicle design. Obviously, vegetation characteristics are of utmost importance in activities that require a vegetated area. Thus, characteristics that define the physical geometry rather than the botanical specifics are important to the environmental engineer. One system for expressing these physical characteristics has been developed by the U.S. Army Engineer Waterways Experiment Station. The terms used in this system are:

(1) Crown shape

(2) Height

(3) Stem diameter

(4) Stem habit

(5) Branch habit

(6) Root habit

(7) Stem hardness

(8) Stem succulence

(9) Special properties (spines, cutting edges, etc.)

(10) Leaf size

(11) Leaf shape

(12) Leaf texture

(13) Leaf presence

(14) Leaf activity

(15) Plant distribution characteristics.

Each of the preceding major characteristics is broken down into subcharacteristics, and a symbological system is developed whereby presentation can be made in chart form (vegatation structure diagrams).

Each of the separate terrain parameters is of importance to some activity. Cross-country mobility, construction, communication, and other activities require different types of information on soils and topography. In some cases, the parameter is of interest to the field engineer, and for other cases, the design engineer or scientist.

Obviously, the parameterization of terrain as given in Table 6-1 is incomplete. Variations in hydrography with the seasons is often of overriding importance. Terrain parameters are difficult to associate in analytical expressions and a complete description of a complex terrain would require excessive data.

6-2.2 TEMPERATURE

Temperature is a measure of the thermal state of a solid, liquid, or gas. It is expressed in units that are related to absolute zero or to the freezing and boiling points of pure water.

The four scales or units used to indicate temperature are rankine (°R) and fahrenheit (°F) in the British system of measurement, and kelvin (K) and celsius or centigrade (°C) in the metric systems. The absolute scales, rankine and kelvin, are used primarily when dealing with thermodynamic expressions. Fahrenheit and celsius or centigrade commonly are used to express relative thermal conditions. The relationships among these scales can be expressed by the following:

$$\left.\begin{aligned} {}^\circ R &= {}^\circ F + 459.69 \\ K &= {}^\circ C + 273.16 \\ {}^\circ F &= (9/5){}^\circ C + 32 \\ {}^\circ C &= (5/9)({}^\circ F - 32) \end{aligned}\right\} \quad (6\text{-}1)$$

The climatic temperature in which the environmental engineer is most interested is the ambient or surrounding air temperature in degrees fahrenheit or celsius (centigrade). The ambient temperature in no way completely defines the thermal regime, but is a strong index of its general magnitude. Ambient air temperature normally is measured in a ventilated enclosure approximately 4 ft above the soil surface, shielded to minimize heat transfer to the measuring instrument from solar and surface radiation. Ambient temperature will vary considerably depending upon local terrain features and height above the surface, which is the case whether macroclimatic or microclimatic conditions are of interest. One of the more useful techniques in estimating temperatures for locales not in the immediate vicinity of measuring instruments is the application of lapse rate, or the variation of temperature with altitude, usually stated in terms of degrees per unit change in elevation. Generalized lapse rates have been computed for the major climatic zones of the world.

There is no fixed or standard manner in which ambient temperature data are presented. Since temperature is an instantaneous measurement, many types of data reduction are used to provide more useful forms for its expression. These include frequency, average, mean, extreme, probability, deviations, etc. Table 6-2 lists quantifiable temperature parameters

Temperature data are extremely sensitive to measurement technique and the instrumentation employed. Temperatures as measured in a standard weather instrument shelter differ from temperatures measured in exposed locations, at different heights, or with a different sensor. A low thermal mass thermistor exposed to air currents will record rapid temperature fluctuations while a large thermal mass bimetallic thermometer will not respond to fluctuations but will indicate some average value of temperature.

Recorded temperature data are subject to variations related to the location of the measurement instruments, their care and use, as well as less obvious factors (Ref. 1). The network of climatological stations of the National Weather Service includes 13,000 stations operated by cooperating observers who record daily maximum and minimum temperatures. One observer, whose observing record was continuous for 25 yr without a missed day, carried her instruments with her on a trip in order to preserve the record. It was noticed that her reported data were not consistent for the station location and, after investigation, the cause was found and the data were corrected. However, weather records throughout the world are subject to similar variability.

In the space of less than 10 mi, temperature variations in excess of 20 deg F have been observed and, at a given location, fluc-

TABLE 6-2

TEMPERATURE PARAMETERS

Air temperature
Soil temperature
Average temperature
Temperature lapse rate
Temperature range
Extreme temperatures
Exceedance probabilities
Diurnal temperature cycle
Annual temperature cycle

tuations over a 2-deg-F range are readily observed in a 10-min time span. These observations make it clear that reading and recording atmospheric temperatures to an accuracy exceeding 1 deg F is not worthwhile. This is not to imply, however, that temperature variations even less than 1 deg F are not important in many atmospheric phenomena.

6-2.3 HUMIDITY

Humidity is a general expression referring to the amount of water vapor present in the air. In its several forms, humidity is either defined or its extent established by the quantifiable parameters listed in Table 6-3.

Humidity data can be presented in numerous ways, providing the proper identification is used; i.e., relative humidity as a percentage, dewpoint in degrees fahrenheit or celsius (centigrade), etc. Some care must be taken when averaging data because relative humidity, dewpoint, and wet-bulb temperature are not linear functions of specific humidity and vapor pressure. Since dewpoint and wet-bulb temperature generally are regarded as the better indicators of the amount of water vapor in the air, the averaging of relative humidity, dewpoint, and wet-bulb temperature data per se may be considered to be in error.

The most common expression of humidity is relative humidity. This term is much maligned by the scientific community but remains popular nevertheless. It is an admittedly poor indicator of the absolute amount of water vapor in the air unless it is associated with a dry-bulb temperature, but it is one of the most simple and practical expressions regarding the likelihood that an object will give up or absorb moisture from the atmosphere. Wet- and dry-bulb thermometers are the most common devices for measuring humidity; through the use of semiempirical psychrometric charts or slide rules, wet- and dry-bulb temperatures can be converted into relative humidity or most of the other humidity indices. Other devices for measuring humidity include (1) dewpoint hygrometers, which determine the temperature at which the water vapor will condense on a solid surface, (2) instruments for determining the amount of water vapor based on infrared absorption, and (3) several types of hygrometers using physical changes in, or the hygroscopicity of, salts to detect moisture.

As with other meteorological factors, humidity data are dependent on the procedures, instrumentation, and locations used in their collection. Rapid changes in atmospheric water content result from transient showers, wind direction changes, and solar radiation variation. Instruments for measuring humidity are not as accurate as could be desired and, in general, humidity measurements can be greatly improved.

6-2.4 PRESSURE

Atmospheric pressure is the pressure exerted by the atmosphere due to the gravitational attraction of the earth at the point of interest, or the pressure of the "column" of atmosphere above the point of interest. In engineering terms, pressure is force per unit area; e.g., psi or dyn cm^{-2}. Atmospheric pressure or barometric pressure often are measured and recorded in terms of the height of a column of mercury which the atmosphere will support. The following units and values are commonly used to define standard atmospheric pressure:

Standard atmospheric pressure	
Millimeters of mercury	760
Inches of mercury	29.92
Pounds per square inch	14.696
Millibars	1,013.2

Standard atmospheric pressure also is known as sea-level pressure, and pressure sometimes is noted as "corrected to sea level". Station pressure or pressure measurements made at elevations different from sea level or zero-feet elevation are corrected by means of standard atmospheric charts which are tables listing the variation of standard pressure with elevation.

TABLE 6-3

HUMIDITY PARAMETERS

Vapor pressure
Relative humidity
Mixing ratio
Absolute humidity
Mole fraction
Dewpoint temperature
Wet-bulb temperature
Diurnal cycle
Altitudinal variations
Humidity extremes
Cooccurrence with high temperature

Absolute pressure is pressure measured from a base of zero pressure, while gage pressure is measured (and corrected) from a base of standard pressure. Thus, gage pressure equals absolute pressure minus 14.696 psi at standard atmospheric pressure.

Parameters associated with this factor include only pressure and its extreme values, averages, and distribution.

The largest errors in pressure data result from the effects of wind and a lack of knowledge of the temperature of the measuring instrument.

6-2.5 SOLAR RADIATION

Solar radiation is commonly restricted to the radiation that is received at the surface of the earth. This generally is reported in terms of heat energy per unit area per unit time. These units may be presented as langley (cal cm^{-2}) per unit of time or Btu ft^{-2} per unit time, or W per unit time. The data appear in totalized form over time units of hours, days, months, or even years. Solar radiation is a spectrum of wavelengths with different energy levels at each wavelength. Instruments or radiometers for measuring solar radiation have different spectral responses which are reflected in the data. Fortunately, the differences are very small and can be ignored for most design and operational purposes.

One important aspect of solar radiation is the amount of radiation reflected back to space by the earth, which is a function of the albedo of the earth, estimated to be about 35 percent. A number of factors such as time of year, latitude, elevation, and atmospheric dust and moisture determine the amount of solar radiation that reaches the surface of the earth at any particular location. Therefore, solar radiation data should contain references to the conditions of measurement to be meaningful. Generalized values of solar radiation versus latitude and climatic zones are available. The quantitative parameters listed in Table 6-4 are commonly used.

6-2.6 RAIN

When water vapor condenses in the atmosphere, the drops or droplets large enough to overcome convection fall from the formation and are observed as rain. The American Meteorological Society defines a raindrop as having a diameter above 0.5 mm (0.02 in.). Falling drops having diameters of 0.2 to 0.5 mm are referred to as drizzle (Ref. 9). Water vapor that condenses but does not form large enough droplets to precipitate remains suspended as fog, mist, or haze.

Rain is measured most commonly in rate of accumulation, as inches of water per unit time. It very often is averaged or totaled into monthly, seasonal, or yearly rates. Important climatic data are amount, intensity, duration, and number of days on which rainfall occurs. The amount of rainfall required for a bona fide rainfall to be recorded is arbitrary; the National Weather Service records amounts less than 0.01 in. as a trace. Rain parameters are listed in Table 6-5.

When rain is collected in a rain gage, the quantity collected is subject to various instrumental errors. However, these errors are small compared to those resulting from the way in which the data are used. One 8-in. diameter gage, exposed to a 0.5-mi diameter local shower, may be used to indicate the average rainfall for a 1,000 mi^2 land area. In such cases, the data are useful only as averages over large areas and long time intervals which decrease the impact of the many short range variations.

6-2.7 SOLID PRECIPITANTS

Snow is measured in rate of fall, or accumulation per unit time, such as inches per hour or inches per year. Accumulation in terms of inches of water equivalent per unit time is also important in calculating resultant runoff. Amount, intensity, duration, and number of days on which snowfall occurs are important climatic parameters. Although an effect rather than a measure of the intensity

TABLE 6-4

SOLAR RADIATION PARAMETERS

Sunshine intensity
Mean daily solar radiation
Maximum solar radiation
Mean monthly solar radiation
Spectral distribution
Sunshine duration
Cloud cover

TABLE 6-5

RAIN PARAMETERS

Raindrop size
Raindrop mass
Raindrop size distribution
Raindrop velocity
Liquid water content
Intensity
Chemical composition
Frequency
Average: monthly, annual
Probability
Extremes
Number of days with measurable precipitation
Amount
Duration
Radar reflectivity
Raindrop impact energy
Electrical conductivity

of the factor itself, an important aspect of snowfall is the accumulation or snowload on surface objects, reported in pounds per square inch or grams per cubic centimeter. Parameters associated with snow are given in Table 6-6.

Hail, like snow, is reported in terms of depth of accumulation. An obviously important characteristic of hail is the diameter of the individual hailstones. Because of the damage hail can do, the frequency of occurrence of hail is important, and maps indicating areas commonly experiencing hail have been prepared. The other solid precipitants are less subject to quantitative data collection, their occurrence is the primary record obtained.

6-2.8 FOG AND WHITEOUT

Visibility is the most common measure of the intensity of fog or whiteout. Fog is characterized by its constituents and by its occurrence and effect on visibility using parameters such as those given in Table 6-7. Whiteout is less definitively measurable since effects are more subjective than objective, although limits of horizontal visibility distance, horizontal extent, frequency of occurrence, and duration may be reported. Atmospheric pressure, dry-bulb and dewpoint temperatures, and wind velocities are pertinent to studies of fog and whiteout but are not measures of their intensity.

6-2.9 WIND

Wind is movement of the atmospheric airmass in relation to the surface of the earth, most often horizontally. From an engineering standpoint, the most useful description of wind is in terms of velocity and duration. Usually either miles per hour or knots are used to indicate speed. Observers may in some cases use qualitative terms such as hurricane force, strong, light, etc., which are identified in the Beaufort Scale of Table 6-8. The meaning of the word "force" as used in this scale is indicative of gross windspeed. The figures tabulated in the fourth column, "Force", indicate the unit pressures exerted on a surface transverse to the wind direction for the various Beaufort numbers and corresponding windspeeds. Although they are measures of effects rather than the intensity of the factor itself, they are useful for engineering applications. Often when windspeeds are high, maximum speeds reached in gusts as well as maximum sustained speeds are reported or predicted. Wind direction is also important and is recorded in terms of compass points or as degrees of azimuth. Many operations make use of data describing the frequency with which the wind blows from the several points of the compass on a seasonal or yearly basis. Wind parameters are listed in Table 6-9.

A useful means for showing the prevailing wind direction is the "wind-rose", a diagram designed to show the distribution of wind direction experienced at a given location over a considerable period of time. The most common form consists of a circle from which 8 or 16 lines emanate, one for each compass point. The length of each line is proportional to the frequency of wind from that direction; the frequency of calm conditions is entered in the center (Ref. 9).

6-2.10 SALT, SALT FOG, AND SALT WATER

Salt as dry fallout from the atmosphere, as contained in water droplets in salt form, or in water constitutes an important environmental factor because of its effects on materials. Parameters employed to characterize salt in its various forms are given in Table 6-10.

6-2.11 OZONE

Ozone is a naturally occurring as well as induced atmospheric constituent. It is measured in terms of a mixing ratio; i.e., an expression of the amount of ozone in a given amount of air where both are expressed in the same units; e.g., parts per million (ppm) or micrograms per gram ($\mu g\ g^{-1}$) of air. Alterna-

TABLE 6-6

SNOW PARAMETERS*

Snowfall rate	Young's modulus
Snowflake mass	Poisson's ratio
Snowflake falling velocity	Strength
Grain size	Creep rate
Density	Sliding friction coefficient
Porosity	Viscosity
Permeability	Thermal conductivity
Hardness	Dielectric constant
Annual snowfall	Reflectance
Mean snow depth	Extinction coefficient
Snowcover duration	Snow load

*With the exception of the first three entries, these parameters apply to snow on the surface of the earth.

TABLE 6-7

FOG PARAMETERS

Droplet size	Visible range
Droplet size spectra	Chemical composition
Liquid water content	Vertical depth
Droplet concentration	Duration
	Frequency

TABLE 6-8

BEAUFORT SCALE OF WIND (Ref. 10)

Beaufort number	Beaufort descriptive term	Velocity, mph	Force, psf
0	Calm	Less than 1	0.00
1	Light air	1 to 3	0.01
2	Light breeze	4 to 7	0.08
3	Gentle breeze	8 to 12	0.28
4	Moderate breeze	13 to 18	0.67
5	Fresh breeze	19 to 24	1.31
6	Strong breeze	25 to 31	2.30
7	Moderate gale	32 to 38	3.60
8	Fresh gale	39 to 46	5.40
9	Strong gale	47 to 54	7.70
10	Whole gale	55 to 63	10.50
11	Storm	64 to 75	14.00
12	Hurricane	Above 75	17.00+

TABLE 6-8.

WIND PARAMETERS

Windspeed	Vertical distribution
Wind direction	Extreme windspeeds
Gustiness	Average windspeed
Wind trajectory	Storm frequency

TABLE 6-10

SALT PARAMETERS

In water	Atmospheric
Salinity	Saltfall
Specific gravity	Particle size
Electrical conductivity	Particle weight
Chemical composition	Distribution
Freezing temperature	Transport

tively, ozone may be measured as concentration per unit volume, which is the absolute quantity of ozone in a given spatial volume; e.g., 10^{-6} moles of ozone per liter or 10^{-3} g of ozone per cubic meter.

6-2.12 MACROBIOLOGICAL ORGANISMS

Quantitative descriptors of macrobiological species are difficult to define and data are difficult to obtain. Since vegetation as well as all forms of animal life is included, the most obvious parameters are population density in a given area of a given species. Additional capabilities and other parameters are required only in special circumstances and then only for one or several species.

6-2.13 MICROBIOLOGICAL ORGANISMS

The population of microbiological organisms (microbes) is not important. The spores which lead to rapid growth under favorable conditions are always available. Although few data are available, those of potential value to design engineers concerned with microbes are the temperature, humidity, and chemical conditions favoring rapid growth.

6-2.14 ATMOSPHERIC POLLUTANTS

Atmospheric pollutants are manmade solid, gas, or liquid contaminants of the atmosphere. Pollutants usually are confined to deleterious contaminants and may include nitrates, nitrites, oxides, sulfates, and other metal salts, oils and tars; sulfur dioxide and trioxide; hydrogen sulfide; oxides of nitrogen; hydrocarbons; and fly ash (Refs. 11, 12).

For the most part, pollutants exist at relatively low concentrations. Gases may be reported in parts per million, parts per hundred million, or parts per billion. Particulate matter may be reported in milligrams per cubic foot (mg ft^{-3}), micrograms per cubic meter ($\mu g\ m^{-3}$), or grams per cubic foot (g ft^{-3}) (Ref. 13). Fallout may on occasion be reported in such cases as micrograms per square meter per unit of time. Opacity effects usually are reported in terms of some visual measurement. The Ringelmann numbering system is used but is subjective and yields inconsistent results. Various light-obscuring smokemeters are more precise measuring devices but, nevertheless, yield an arbitrary number that must be converted to qualitative units to be usable in many applications. Chemical identification of pollutants is essential, and other climatic data often are reported with concentration when found to be determining factors in their presence or transport. Frequency of occurrence and duration are of major interest.

6-2.15 SAND AND DUST

Although the definition of sand and dust is highly arbitrary, some authorities define dust as particles emanating from the surface of the earth and having diameters between 1 μm and 150 μm (Ref. 14). The coarser sand particles range from 150 μm up to 5,000 μm (0.0006 to 0.2 in.).

As with other atmospheric particulates, identification of the particles is mandatory. Concentration in terms of weight per unit volume of air, wind velocity, and particle shape are important characteristics of airborne sand and dust. Concentration is normally reported in grams per cubic foot (g ft^{-3}), although some references can be found to the number of particles per cubic foot; particle shape is reported in qualitative terms such as round, subround, and angular; velocity is most often in feet per second or miles per hour. Blowing sand and dust may be reported in terms of weight passing a unit area, such as grams per square centimeter per minute (g $cm^{-2}\ min^{-1}$). Further definitions of the particles may include hardness based on Mohs' scale. Size of the particle is commonly a measure of diameter in micrometers where the diameter is Stokes' equivalent diameter; i.e., diameter of sphere that would settle at the same rate as the particle. The parameters are listed in Table 6-11.

TABLE 6-11

SAND AND DUST PARAMETERS

Particle size	Concentration
Size distribution	Vertical distribution
Particle shape	Pickup speed
Composition	Settling velocity
Hardness	Frequency

6-2.16 VIBRATION, SHOCK, AND ACCELERATION

These environmental factors are discussed together since their parametric descriptions are very similar. Parameters for vibration are given in Table 6-12. The time-dependence of the phenomena associated with each factor is the most important basis for their differentiation

The characteristics describing mechanical factors may be presented in any of several different ways. Basically, vibration is defined in terms of repeated displacement versus time; shock is defined in the same units but is not repetitive; and acceleration is presented in gravitational units.

There are many characteristics of conditions producing shock and vibration that are difficult, if not impossible, to list in a simple comprehensive form. They are concerned largely with the form of the wave versus a time function and conditions under which measurement is made or data gathered. Much time and effort have been devoted to determine characteristics such as the shock and vibration associated with transportation. Because of the many factors involved, however, there is often much disagreement between investigators regarding application and reliability of the data. Further, limitations of instrumentation and data analysis techniques tend to introduce new factors into the data that are subject to question.

6-2.17 RADIATION: ACOUSTICS, ELECTROMAGNETIC, AND NUCLEAR

These three environmental factors comprise various forms of energy flow through the atmosphere that are induced primarily by the activities of people. Acoustical radiation consists of movement of air molecules and is described by the parameters given in Table 6-13. One parameter, hearing threshold shift, is an example of a measurement based on an effect; i.e it is the integrated acoustical power required to shift the hearing threshold by the amount given.

Electromagnetic radiation normally is reported in units of wavelength (μm) or of frequency (Hz). The energy of radiation is indicated by the amplitude of the wave, and may be measured in W cm^{-2}, erg s^{-1} cm^{-2}, or cal min^{-1} cm^{-2}. One important aspect of electromagnetic radiation is attenuation of the signal (or radiation) by absorption and scattering in the propagation medium. Quantifiable electromagnetic radiation parameters are given in Table 6-14.

Nuclear radiation is either pure energy such as X rays or gamma rays, or particulate energy such as alpha or beta particles, or neutrons. Nuclear radiation intensity is expressed as unit energy per unit time, such as erg s^{-1} or eV s^{-1}. Radiation received usually is measured in rads where a rad is a unit of absorbed dose equal to 100 ergs g^{-1} of absorbing material (Ref. 14). Ionization and electromagnetic wave interference are measured in terms of electron density; i.e., electrons per cm^3. Neutrons are measured in number of neutrons per cm^2 (flux) or neutrons per cm^2 per unit of time (fluence). There are many other units of measurement essential to this very broad subject. Identification of the type of radiation, intensity, duration (half-life), and dose rate are all of primary importance.

6-3 DATA QUALITY

There is a tendency to ascribe the ultimate in precision to printed data. The less that is known about the data source, the more confidence is given to it This tendency is not supported by experience. An example is given wherein the Eckman Spiral theory was examined (Ref. 1). This theory postulates that the horizontal wind vector turns with increasing height due to a decrease in the effect of surface friction. Since the effects are studied best over oceans to avoid terrain effects, data from ocean station vessels were employed to test the theory and it was found to be valid. The data, however, had been collected using measurement techniques incapable of sufficient resolution at the lower wind levels. Observers had compensated for this lack of resolution by using the Eckman Spiral theory

TABLE 6-12

VIBRATION PARAMETERS

Spectra	Acceleration
Displacement	Natural frequencies
Velocity	Duration

TABLE 6-13

ACOUSTICAL PARAMETERS

Sound-pressure level	Peak pressure level
Duration	Attenuation
Frequency spectra	Hearing threshold shifts

TABLE 6-14

ELECTROMAGNETIC RADIATION PARAMETERS

Spectrum
Intensity
Duration
Energy
Radiation
Patterns
Lightning frequency
Pulse shape
Power

to correct low level data, unbeknown to the theoretician. It is not surprising that the theory was validated; such a result could not be avoided.

For quantitative manipulations, it is necessary to know something about the instrumentation and measuring process. The resolution (the smallest change in the quantity being measured that will produce a detectable change in the indication of the instrument) of a resistance thermometer, for example, is readily degraded by that of the recorder with which it is used. For example, if the resistance thermometer has a span of 100 K and the recorder potentiometer has 1,000 turns, the resolution of the two is ± 0.1 K corresponding to one turn of the potentiometer. However, when the sliding contact of the potentiometer becomes worn, the resolution might decrease to ± 1 K (Ref. 15). Other attributes of the instrumentation are equally important—accuracy, sensitivity, speed of response, linearity, reporting increment, repeatability, and reliability are among these. The sensor itself may be subject to hysteresis effects, a dead band, a time constant, a delay distance, or other factor that will affect the nature of the data. Modern instrumentation storage media can introduce biases of various types in data which must be guarded against. When properly employed, complex data acquisition systems provide much higher quality data than is possible with manual collection.

It is seldom difficult to obtain accuracy in laboratory measurements of meteorological parameters or to obtain accuracy in the open air with new instruments. The problem is in maintaining that accuracy over long periods of time.

It was pointed out in par. 6-2.2 that accuracy of atmospheric temperature data in excess of 1 deg F is of little use in analysis. In similar fashion, there are limits on the useful accuracy of measurements for each of the environmental factors. These limits are determined by the environment and the use to be made of the data.

6-4 DATA SOURCES

Quantitative environmental data are available in a variety of forms and from a variety of sources. Specific sources are identified in the discussions of individual factors in Parts Two and Three of the Environmental Series (Refs. 7,8). Some of the more important sources of data are listed:

(1) *U.S. Army environmental data sources:*

(a) U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Va. 22060

(b) Atmospheric Sciences Laboratory, U.S. Army Electronics Command, White Sands Missile Range, N. Mex. 88002

(c) U.S. Army Waterways Experiment Station, Vicksburg, Miss. 39180

(d) U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N. H. 03755

(e) Frankford Arsenal, Philadelphia, Pa. 19137

(f) U.S. Army Natick Laboratories, Natick, Mass. 01760

(g) Land Locomotion Research Laboratories, U.S. Army Tank-Automotive Command, Warren, Mich. 48090

(h) Army Materials and Mechanics Research Center, Watertown, Mass. 02172

(i) U.S. Army Human Engineering Laboratories, Aberdeen Proving Ground, Aberdeen, Md. 21005

(j) U.S. Army Transportation Engineering Agency, Newport News, Va. 23606

(2) *Other organizations*

(a) Air Force Cambridge Research Laboratories, Bedford, Mass.

(b) Naval Ship Research and Developments Center, Carderock, Md.

(c) U.S. Naval Oceanographic Office, Suitland, Md.

(d) Smithsonian Institution, Washington, D.C.

(e) Environmental Data Service, Asheville, N.C.

(f) Environmental Protection Agency, Washington, D.C.

(g) Davidson Laboratory, Stevens Institute of Technology, Castle Point Station, N.J.

(h) National Research Council of Canada, Ottawa, Ontario, Canada

(i) Highway Research Board, National Academy of Sciences, Washington, D.C.

(j) Muskeg Research Institute, University of New Brunswick, Fredericton, New Brunswick, Canada

(k) Arctic Meteorology Research Group, McGill University, Montreal, Quebec, Canada.

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CHAPTER 7

TESTING AND SIMULATION

This chapter is concerned with environmental tests and the simulation of the environment required to carry out such tests.* To some extent, any test is an environmental test since some type of environment is always present. As discussed herein, however, environmental testing pertains to selecting and simulating the various environmental conditions of temperature, vibration, radiation, humidity, etc., for the express purpose of determining or verifying the capability of an item to operate satisfactorily when subjected to them. As such, it is not a basic test method itself but it is a way of implementing basic testing approaches. Strength, life, and performance tests as well as other basic test types may all involve environmental testing. Some hardware development programs designate a particular phase of their testing program formally as environmental testing. In this chapter the basic problems and considerations for testing and simulating environmental test conditions are considered.

The effect of environmental conditions, either natural or induced, on equipment is an important aspect of reliability. Environmental testing provides a method of investigating these effects. It is emphasized that environmental testing is done not because of the uncertainty of the environment but because of the uncertainty in the effects of the environment. The uncertainty of the environment can only be accounted for by conservative design practices to render it unimportant, by field testing to verify the success of the conservative design, or by increasing knowledge of the environment.

*This discussion employs as a general reference *Practical Reliability*, Vol. III, *Testing* (Ref. 1) and *Philosophy of Environmental Testing* (Ref. 2).

In environmental testing, conditions such as ambient temperature, vibration, and electromagnetic radiation are generated and controlled. In some cases there is a deliberate attempt to simulate as closely as possible the environmental profile during intended equipment operation. This occasionally is done, for example, in reliability demonstration with samples of prototype hardware. More frequently the emphasis is on simulating certain critical features of the total operational environment at specific severity levels. This is typically the approach in design qualification and acceptance testing of components and systems, and serves the useful purpose of uncovering design and material weaknesses and workmanship errors. In still other cases (such as development tests), the operational environment may not be known and test conditions consequently cover a wide range to explore the capabilities of an item.

All uses of environmental testing have as common objectives either determining the effect of the environmental conditions on an item or verifying that the item is capable of withstanding environmental stresses. It is employed in all phases of hardware programs from the parts and materials level of item complexity to fairly large systems. In programs that rely primarily on a "build and test" approach, it provides the major source of confidence in operational hardware. It also remains a necessity in a complementary role in programs where greater emphasis is placed on analytical design procedures.

A logical alternative to environmental testing is testing under field conditions. This alternative can provide the desired confidence but usually costs more (especially in the case of complex expensive items) and often delays the desired information. In field or flight testing, test conditions generally are not controlled as well as environmental testing permits; hence, cause and effect relationships may be more obscure.

Environmental testing ranges in sophistication from very crude methods such as using an improvised temperature chamber to testing in very elaborate facilities that enable switching between many combinations of conditions. Tests may be purposely destructive (as in strength and life testing), or nondestructive (such as proof tests and burn-in).

Selection of the appropriate test conditions is the major problem associated with environmental testing. Basic factors that affect this selection are:

(1) The possible environmental conditions during intended use of the equipment.

(2) The subsets of these that need to be treated by a testing approach.

(3) The capability for generating and controlling them.

The crux of the problem lies in determining which environmental features can affect the behavior of the item during intended use and in employing environmental simulation to investigate these features to the extent feasible within the constraints of cost, schedule, and testing capability. Not all environmental conditions that affect behavior can be simulated readily, and very rarely can all be generated simultaneously to account for interaction effects. Trade-offs are thus necessary in selecting the test conditions to make the best use of available capability in obtaining environmental performance information.

7-1 ENVIRONMENTAL FACTORS AND THEIR EFFECTS

Environmental conditions may be natural, induced, or combinations of these. Natural environments are those that exist in nature such as the weather, solar radiation, and low pressure in deep space. Induced environments are manmade and include such things as mechanical shock during transportation and handling, air conditioned rooms for computers, and electromagnetic radiation. An example of a combined natural and induced environment is the set of conditions surrounding a tracked vehicle operating under two sources of vibration—that induced by the vehicle and that resulting from the terrain.

The set of environmental conditions in proper sequence and combination that an item encounters during its lifetime is its environmental profile. The total profile begins during item fabrication and continues throughout its life. Therefore, environmental testing must consider the environments encountered in manufacturing, storage, transportation, and handling, as well as those experienced during operational use.

Descriptions of the environmental conditions are not always available in explicit form. No one knows precisely, for example, the environmental profile that a helicopter will experience throughout its life including all types of environmental factors and their severity levels. Through various sources of data on environments,* it is often possible to select representative characteristics, such as averages or maximum levels of major factors, for adequately describing conditions for a test.

Environmental conditions of greatest interest from the reliability viewpoint are those that have detrimental effects (i.e., those that cause drift, degradation, failure, wear, etc.) on equipment operation. Some conditions have no significant effect; some even may be beneficial.

*AR 70-38 defines climatic criteria for Army materiel (Ref. 3), and MIL-STD-810 describes standard environmental test methods (Ref. 4).

Table 7-1 lists detrimental effects of several environmental factors. In many cases, effects not detectable when the factors are encountered singly show up when two or more are present simultaneously. For example, some electronic components function properly in either a low temperature or a vibrational environment, but when the environments are combined, component leads may break.

Some conditions cause cumulative nonreversible changes in equipment; therefore, when considering equipment behavior at any point during its useful life, the history of environmental exposures should not be ignored. For example, heating from welding and soldering can cause permanent shifts in device characteristics; mechanical shock can result in permanent dislocation of a lead or a part; and nuclear radiation can cause permanent defects in semiconductor devices. The possible need for conditioning items prior to environmental testing to simulate the historical effects should not be ignored. This conditioning is sometimes necessary to assure that the response during the test is representative of that in operational use. Knowing the environmental history is not important when the effects were reversible, but knowing whether all pertinent responses are reversible can be determined only through careful consideration. Ignoring the nonreversible effects that have occurred in previous testing and operations can lead to very misleading environmental test results. Admittedly, they are not always easy to assess or to simulate, but just knowing of their possibility often can be informative in testing.

In selecting the environmental factors, the severity levels, and combinations of them to be treated, experience is usually the most reliable guide. For instance, a designer of a vehicle component may know that the combination of vibration and high temperature is far more likely to harm his component than low pressure and high ozone content. He may also know that the most severe conditions to consider for testing are determined by the operation environment rather than by the transportation and handling environment. Such prior knowledge and experience can help reduce the number of environmental tests needed to insure the successful operation of the item.

The problems associated with common environmental factors such as temperature, vibration, and thermal shock nearly always receive attention. Less familiar factors sometimes can be equally or even more important. Effects of ice fog, for example, are more likely to be strange to most engineers than the effects of high temperature. For arctic operations, the employment of artillery may be considerably influenced by creation of ice fog during firing. The characteristics of ice fog for environmental testing purposes, however, are the same as for other atmospheric obscurants. Factors for which tests are less common, such as hail or insects, if they are to receive attention in testing, require the determination of test characteristics and intensity levels that are representative of the test objectives. With hail, for example, if mechanical impact damage is the major effect of interest, then the size, shape, velocity, and number per unit area of the simulated hailstones are the characteristics of concern. On the other hand, the vibration induced by the incident hail may be the most significant factor. Insects can cause both mechanical and chemical damage, and both characteristics demand consideration when insects reasonably can be expected in large numbers.

When there is little available knowledge about the operational environment or its effect on an item, it is often simpler and more economical to test and see what happens instead of spending a great deal of time and money on an independent study. This is essentially the "build-and-test" approach but it has its limitations for large and expensive items. When used with discretion, it can be applicable especially to certain new designs or new applications of old designs.

TABLE 7-1

RELATIONSHIPS SUBJECT TO TESTING (Ref. 1)

Environment	Effects
Winds: gust and turbulence	Applies overloads to structures causing weakening or collapse; interferes with function such as aircraft control; convectively cools surfaces and components at low velocities and generates heat through friction at high velocities; delivers and deposits foreign materials which interfere with functions
Precipitation: sleet, snow, rain, hail, dew, frost	Applies overloads to structures causing weakening or collapse; removes heat from structures and items; aids corrosion; causes electrical failures; causes surface deterioration; damages protective coating
Sand and dust	Finely finished surfaces are scratched and abraded; friction between surfaces may be increased; lubricants can be contaminated; clogging of orifices, etc.; materials may be worn, cracked, or chipped
Salt atmosphere and spray	Salt combined with water is a good conductor which can lower insulation resistance; causes galvanic corrosion of metals; chemical corrosion of metals is accelerated.
Humidity	Penetrates porous substances and causes leakage paths between electrical conductors; causes oxidation which leads to corrosion; moisture causes swelling in materials such as gaskets; excessive loss of humidity causes embrittlement and granulation
Sunshine	Causes colors to fade; affects elasticity of certain rubber compounds and plastics; increases temperatures within enclosures; can cause thermal aging; can cause ozone formation

TABLE 7-1 (continued).

RELATIONSHIPS SUBJECT TO TESTING (Ref. 1)

Environment	Effects
High temperature	Parameters of resistance, inductance, capacitance, power factor, dielectric constant, etc., will vary; insulation may soften; moving parts may jam due to expansion; finishes may blister; devices suffer thermal aging; oxidation and other chemical reactions are enhanced; viscosity reduction and evaporation of lubricants are problems; structural overloads may occur due to physical expansions.
Low temperature	Plastics and rubber lose flexibility and become brittle; electrical constants vary; ice formation occurs when moisture is present; lubricants gel and increase viscosity; high heat losses; finishes may crack; structures may be overloaded due to physical contraction.
Thermal shock	Materials may be instantaneously overstressed causing cracks and mechanical failure; electrical properties may be permanently altered.
High or low pressure	Structures such as containers, storage tanks, and buildings may collapse, explode, or rupture; seals may leak, air bubbles may form in materials causing damage; the flight characteristics of shells, aircraft, or missles may be altered; some instruments such as altimeters may give erroneous data; electrical characteristics may change.
Gases	Corrosion of metals may be enhanced; dielectric strength may be reduced; an explosive environment can be created; heat transfer properties may be altered; oxidation may be accelerated.
Acceleration	Mechanical overloading of structures; items may be deformed or displaced; mechanical functions may be impaired.

TABLE 7-1 (continued).

RELATIONSHIPS SUBJECT TO TESTING (Ref. 1)

Environment	Effects
Vibration	Mechanical strength may deteriorate due to fatigue or overstress; electrical signals may be mechanically and erroneously modulated; materials and structures may be cracked, displaced, or shaken loose from mounts; mechanical functions may be impaired; finishes may be scoured by other surfaces; wear may be increased.
Shock	Mechanical structures may be overloaded causing weakening or collapse; items may be ripped from their mounts; mechanical functions may be impaired.
Nuclear/cosmic radiation	Causes heating and thermal aging; can alter chemical, physical, and electrical properties of materials; can produce gases and secondary radiation; can cause oxidation and discoloration of surfaces, damages electrical and electronic components, especially semiconductors
Thermal radiation	Causes heating and possible thermal aging. surface deterioration, structural weakening, oxidation, acceleration of chemical reactions, and alteration of physical and electrical properties.
RFI	Causes spurious and erroneous signals from electrical and electronic equipment and components; may cause complete disruption of normal electrical and electronic equipment such as communication and measuring systems.
Solar radiation	Effects similar to those for sunshine, nuclear/cosmic radiation, and thermal radiation
Albedo radiation	Albedo radiation is reflected electromagnetic (EM) radiation; amount depends on the reflective capabilities of illuminated object such as a planet or the moon; effects are the same as for other EM radiation.

TABLE 7-1 (continued)

RELATIONSHIPS SUBJECT TO TESTING (Ref. 1)

Environment	Effects
Zero gravity	Disrupts gravity-dependent functions; aggravates high-temperature effects
Magnetic fields	False signals are induced in electrical and electronic equipment; interferes with certain functions; can induce heating; can alter electrical properties
Insects	Can cause surface damage and chemical reactions; can cause clogging and interference with function; can cause contamination of lubricants and other substances
Clouds, fog, smog, smoke, haze, etc.	Can interfere with optical and visual measurements; deposition of moisture, precipitation, etc.; enhances contamination; can act as an insulator or attenuator of radiated energy
Acoustic noise	Vibration applied with sound waves rather than with a mechanical couple; can cause the same damage and results as vibrational environment, i.e., the sound energy excites structures to vibrate.

7-2 SIMULATING THE CONDITIONS

The emphasis on environmental testing has led to the development of elaborate facilities; e.g., the huge NASA dynamic test facility which can accommodate a 6-million pound replica of the complete Apollo-Saturn V vehicle in tests involving six degrees of motion (Ref. 5). Other facilities have even more versatility in terms of the number of different conditions that can be generated simultaneously. Detailed descriptions of methods for simulating various environmental conditions are given by Peeler (Ref. 6). The most frequently cited standard for methods in military procurement is MIL-STD-810 (Ref. 4). A tabulation of Government-operated environmental testing facilities is available (Ref. 7).

Given that certain environmental conditions need to be treated by a testing approach, it is not always possible to generate similar conditions even with the most elaborate facilities. No single facility, for example, can generate at once all of the types, energies, and intensities of Van Allen radiation for the space environment. Air turbulence, gases, and insects typically can present similar problems for environmental conditions not related to space. Many facilities are limited even in their capability to generate complex temperature profiles.

The realization of such problems has been the motivation for creating more sophisticated simulation capability. But there are often other ways of resolving the question at hand. It is the effect of the environmental conditions that is of interest, not just the conditions themselves. Thus, is there a suitable substitute? For example, pebbles might substitute for hailstones if mechanical damage from impact is the effect of interest. Or if vibration induced by hailstones is of interest, then a vibration test already scheduled may be adequate.

Some effects often are investigated more easily from a more fundamental level. The effect of ionizing radiation is studied most often at a materials or parts level than at the level of assembled equipment. Also, the environmental conditions themselves sometimes may be separated into more fundamental components. Typically, a temperature profile is simulated by high and low levels and thermal shock; cosmic radiation may be separated into components composed separately of protons and beta particles. In such cases, one must be alert that there is proper accounting for nonreversibility, interactions, and aging.

Elaborate environmental test facilities not always are needed to resolve certain problems. Simply heating individual electronic circuit components with a soldering iron may in some cases be more informative than testing the entire circuit or assembly in an oven. In the absence of certain capabilities, an answer from an improvised test may be better than no answer at all; e.g., when concerned about mechanical shock testing, simply dropping from a prescribed height is better than ignoring the effects of shock altogether.

With the increased emphasis on generating conditions for different factors simultaneously, a very important question concerns whether to use single or combined environments. When facilities do not exist for generating combined environments, there is, of course, no choice but to generate single environments. Multiple environmental factors must then be treated as single environments in sequence. If the severity levels of the environments are not purposely damaging, as in a sequence of screening tests, the order of application is determined by whatever is most convenient. Tests that are purposely damaging, as in certain qualification tests and acceptance sampling, demand careful consideration of order of environments, especially where only one or just a few test specimens are available. The basic criterion to employ in this case is to apply first the conditions that are least likely to damage the specimen. Thus for a mechanical part, humidity and salt-spray tests logically would be applied before vibration or a mechanical load test. An electronic part more likely would be tested by applying vibration before high temperature. Such test sequencing allows the maximum amount of information to be obtained before damage occurs.

Ordering of environments for items composed of both mechanical and electrical parts is not as clear cut. Although the same basic criteria still apply, ability to repair the item can greatly influence the ordering.

When capability exists for generating both single and combined environmental conditions, it does not follow necessarily that combined environmental testing is preferable. The decision depends mainly on what is to be accomplished with the test and is influenced strongly by factors such as time, cost, skills, and instrumentation.

Combined environmental testing has two significant advantages over single environmental testing. First and most significant is the ability to investigate the synergistic effects of multiple conditions; i.e., combined testing in most instances more closely approximates the real environment. Second, several conditions usually can be applied simultaneously in a shorter time than in sequence due to savings in set-up time. Therefore, combined testing often saves money. The major disadvantage is that the initial cost of the equipment for combined testing is higher.

In qualification and acceptance tests, combined environmental testing is preferable to testing with single environments. The increased confidence derived from the knowledge that synergistic effects are accounted for usually allows use of smaller safety factors in application.

In testing to relate cause and effect, the combined environmental test is used as an extension of single environment testing (Ref. 8). Testing during development usually emphasizes learning the effects of single environments. Combined environments are employed after single environment effects have been determined and synergistic effects become of interest. Employing combined environments first can be impractical. Single environment testing also can be preferable in long duration tests due to the impracticality of committing combined environmental test facilities for long periods of time.

7-3 ACCELERATED TESTING

In accelerated testing, items are subjected to conditions more severe than those encountered in normal use in an attempt to speed up aging and hence obtain degradation and failures in less time. It is thus a technique to shorten test time but applicable only to those tests in which aging is important. It is a very loosely defined concept; attempts to make it rigorous generally run into problems.

Accelerated testing means roughly, "Let's treat it worse than we expect it to be treated in ordinary practice and then see what happens". One difficulty is that "treating it worse" is not always clearly defined. For example, electrical contacts behave better as voltage and current are increased (up to a point) and some heating may improve the performance of electronic equipment by driving off moisture.

Because there is a reasonably firm qualitative foundation for much of accelerated testing, accelerated testing often is used beneficially and without too much difficulty in qualitative roles such as failure mode investigation. It is in the quantitative interpretation and application such as predicting performance and life of items under normal operating conditions that it begins to run into the greatest difficulty.

The most familiar ways of programming the conditions for accelerated testing are constant-stress and step-stress. Another approach frequently recognized is the progressive-stress method; however, this is no different from the step-stress approach when the steps are small.

Temperature is the most popular and probably the most important environmental factor for accelerated testing. The equations used in the literature to describe the accelerated behavior are a matter of some controversy. There are many experimental situations wherein temperature is changed, the results are recorded at each level, then the logarithms of the results are plotted versus $1/(kT)$ (or against $1/T$). This is often done because the conceptual model being used to describe the process suggests that the resulting line will be nearly straight (neglecting random variations). Many of these situations have nothing to do with the Arrhenius or Eyring equations. For example, the product of the electron and hole concentrations (n and p, respectively) in a semiconductor is given by:

$$np = P(T) \times \exp[-E_g/(kT)] \tag{7-1}$$

where

$P(T)$ = a polynomial in T (or similar expression containing fractional exponents)

E_g = the bandgap energy

k = Boltzmann's constant

T = temperature.

The form of this equation has its roots in the Maxwell-Boltzmann distribution. There are thermodynamic equations which have been put in the form

$$y = \exp[-E/(kT)] \tag{7-2}$$

where E is some thermodynamic energy. One of the reasons this form is preferred is that it turns up in the rather tractable analysis for perfect gases.

The Arrhenius equation often is cited as the classic example for temperature dependence of reaction rates and can be written*

$$rr = A \exp[-E/(kT)] \tag{7-3}$$

While we do not have access to the personal thoughts of Arrhenius, undoubtedly he was influenced for the form of the equation by the thermodynamic forms mentioned previously. The Arrhenius equation has enjoyed an appreciable amount of success for both interpolation and extrapolation.

The Eyring equation or, as it is more often known in physical chemistry, the equation for absolute reaction rates, seems to have assumed a strong image in some of the reliability-physics/accelerated-testing literature. The specific reaction rate may be written as

$$rr = \frac{\kappa kT}{h} \exp\left(\frac{-\Delta G\dagger}{kT}\right)$$

where

$\Delta G\dagger$ = the Gibbs free energy of the activated complex

κ = a transmission coefficient (usually virtually unity)

h = Planck's constant.

This equation has been developed for an elementary reaction and should be applied only to such a reaction. It is equally useful in considering the rates of the very rapid reactions that occur in a flame as well as the rates of reactions that under ordinary conditions require geologic ages.

*Sometimes an R is used in place of the k. R is the universal gas constant; k is Boltzmann's constant. Chemists tend to use the former and physicists the latter, the difference being per mole or per molecule, respectively. When R is used, E is usually given in kilocalories per mole, whereas when k is used, E is usually given in electron volts per molecule. Very often the per molecule or per mole is dropped. A is often called the frequency factor because the earliest reactions considered were of the first order. This name does not apply to reactions of other orders. The specific reaction rate is also called the reaction rate constant.

Electronic components are complex engineering systems from the point of view of theoretical chemistry-physics and, for practical purposes, use of absolute reaction rate theory will offer little if anything over the Arrhenius equation. One of the biggest obstacles to its use is the tremendous scatter in the data. Another is that the specific reaction rate is not observed, but some complicated function of it is. By the time one is discussing failure rates, he is a long, long way from a specific reaction rate.

7-4 TESTING IN THE OPERATIONAL ENVIRONMENT

It often is said that the only way really to determine whether an item will function as intended in its operational environment is to put it there and see. This is basically true, but it is not always possible nor necessarily desirable to do this prior to the real mission. One significant shortcoming of this approach, for example, is that certain cause and effect relationships may be obscured because of lack of knowledge about operating conditions.

Field tests, flight tests, commercial marketing tests, and in-service evaluation tests are all examples of testing in the operational environment. Typical reasons for wanting to test in this manner are.

(1) Increase confidence in the ability of the item to perform in actual operational environment

(2) Inability to simulate particular environmental conditions in the laboratory

(3) Obtain response data as a basis for future laboratory tests

(4) The item is too large and complex for environmental conditions in the laboratory.

Sometimes, it may be simply less expensive or easier than simulating conditions. However, if the capability to simulate conditions already exists, it is usually less expensive to use environmental simulation. As illustrated by the second and fourth reasons, there is often no choice but to resort to the operational environment.

There are often certain shortcomings in the approach. A simple test of a vehicle, for example, gives response to only a particular set of conditions. and the behavior is not known to be representative of the population of operational items. The extent of other shortcomings depends considerably upon how much control is maintained over the tests. If the items are merely put in the hands of customers to operate and are checked from time to time, the results may only indicate how well they survived this environment. Items may be used for purposes other than those intended or operated under conditions not included in the design criteria. Unless these are known, the results can have only limited utility. An even worse situation occurs when the reporting of behavior is left to the customer. Usually, he considers it the least important of his jobs and it often gets done poorly if at all.

Even when more control is maintained by the manufacturer, there can be disadvantages. Some cause and effect relationships may be obscured because of lack of detailed knowledge of the conditions. Measurements are often not as thorough or as accurate. Typically, there are delays in reporting results.

When the individual items are simple and inexpensive, such as hand tools, turning them over to the customer for testing in his environment can be a good way of evaluating the product. When they are as expensive as tanks, the controlled approach is usually better. Basic procedures for planning such tests are no different than others. The rewards must be evaluated with respect to costs in time, money, and effort.

7-5 APPLICATIONS OF TESTING IN HARDWARE PROGRAMS

As a design evolves from its initial concept through design and production to final operational form, numerous tests are required The tests at a particular stage usually can be associated with some general problem area such as development, design qualification. and verification of the final product. Whether the program is concerned with developing a piece-part, an equipment, or a large system, the types of problem areas to be treated are basically the same.

An illustration of how these applications relate to product evolution is presented in Fig. 7-1. The designations such as feasibility, development, and qualification are common terminology found in most programs, but meanings used here generally are based on concepts defined or implied by a number of sources (Refs. 8-10).

Note that in this representation the cycle of evolution ends following production; the testing and operation following production are associated with either the evolution cycle of a higher level of assembly or the operational use of the end item. For example, installation and checkout are simply in-process activities during fabrication of higher levels of assembly. Even though the manufacturer's major attention to a product may terminate with customer acceptance, the post-production tests and operations often can provide good feedback information for improving other items in production or in aiding new or modified designs. Some programs even provide for field personnel in support of this.

7-6 TEST CLASSIFICATIONS AND PLANNING

A significant barrier to the understanding of testing is the plethora of test names in common use. A given test name often means different things to different people, and two tests with the same objectives sometimes have different names.

Any form of classification is simply a way of viewing testing, and a variety of classifications are shown in Table 7-2.

Sound planning is critical to efficient testing. Facilities, personnel skills, instrumentation, and methods of reducing and analyzing data are typical of things considered, but has anyone considered, for example, what happens if the power fails during the test?

Test planning involves the prior consideration of as many of the practical test factors as possible. There are many of these and Table 7-3 illustrates the magnitude and complexity of them.

A basic question concerns the proportion of total test effort to devote to planning. The answer depends on schedules, experience, cost, and complexity of test specimens. It often is stated in testing literature that more test planning is needed, but clear justification for such statements usually is missing. Nevertheless, situations have arisen when it became obvious that more thought to test planning could have provided significant benefits.

A satellite once toppled several feet from its mount onto a concrete floor during a high temperature test of a flight acceptance test series because someone had failed to consider the effect of high temperature on the mount. This illustrates just one of many practical aspects of proper design for a test.

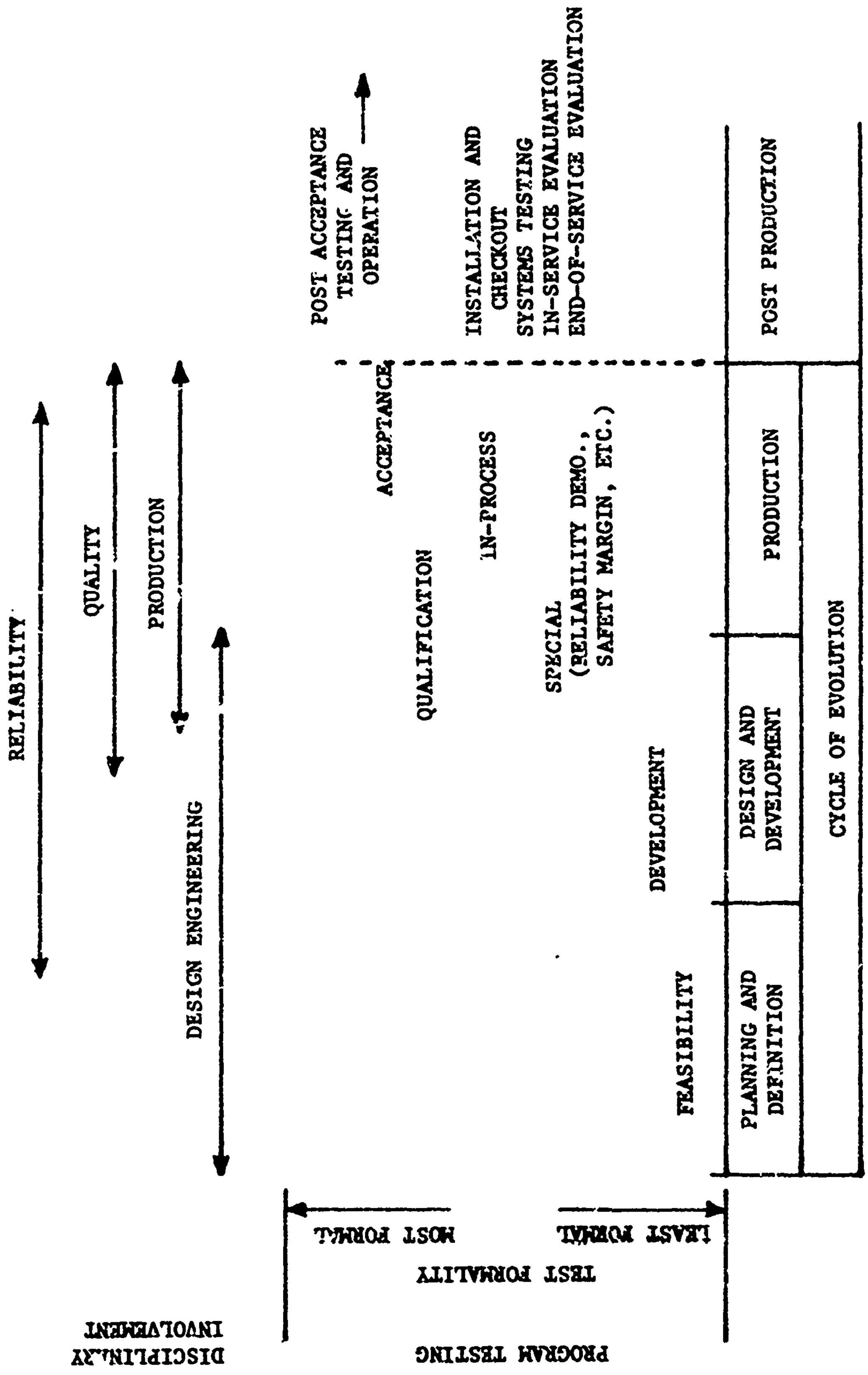

Figure 7-1. Environmental Testing in Hardware Development

TABLE 7-2

ENVIRONMENTAL TEST CLASSIFICATIONS (Ref. 1)

Basis of classification	Types of tests		
Classification by specific purpose	proof life strength	go, no-go run-in failure mode	burn-in functional check performance check
Severity of test conditions	overstress peripheral low voltage	accelerated understress	normal stress high temperature
Test design	nonsequential up-and-down method Robbins-Monroe design	random balance design 20 zil design Langlie design split-the-difference design	matrix factorial design Alexander design probit design
Method of analysis	linear discriminant sequential analysis Dixon-Mood analysis	probit method hypothesis testing maximum likelihood analysis	
Proportion of population tested	sampling 100-percent screening screening (title alone implies 100 percent)		
Level of assembly	material subassembly system	part assembly	component subsystem
Degree of formality	formal informal exploratory (indicates informality)		probe (informal) search (informal)
Degree of destruction	destructive nondestructive (general sense) nondestructive (special methods to circumvent destruction)		

TABLE 7-2 (continued).

ENVIRONMENTAL TEST CLASSIFICATIONS (Ref. 1)

Basis of classification	Types of tests		
Type of hardware function	electrical structural mechanical		
Method of terminating test	time-truncated failure-truncated sequential (implies that termination depends upon cumulative results) stress-to-failure (test-to-failure)		
Type of measurement	variables attributes		parameter go, no-go
Item maturity	breadboard engineering model production model		boiler-plate model prototype
Method of applying test conditions	constant stress step-stress progressive stress profile		programmed stress random stress stress-to-failure (test-to-failure)
Program applications	feasibility development qualification acceptance	reliability quality control systems preoperational	in-service end-of-service

TABLE 7-3

PRACTICAL FACTORS RELATED TO TESTING

Responses

- Reversible vs nonreversible
- Aging important vs aging not important
- Single vs multiple
- Correlation of responses
- Duration
- Continuity (discrete, intermittent, or continuous)
- Degree of destruction

Nature of items

- Interruptable response vs noninterruptable response
- One-shot vs repeated shot
- Repairable vs nonrepairable
- Hardware type (electronic, electromechanical, structural, etc.)
- Level of assembly (material, piece-part, system, etc.)
- Level of design maturity (breadboard, experimental model, production item, etc.)
- Stage of life cycle (during fabrication, pre-application, during application, etc.)

Use of results

- Estimation vs hypothesis testing
- Basic use (measure strength, performance check, burn-in, etc.)
- Program related application (development, reliability, acceptance testing, etc.)
- Proportion of items tested
- Degree of formality

Test conditions

- Stress vs nonstressing condition
- Effect of stress
- Severity of stress
- Relation to conditions during normal use
- Single vs multiple factors
- Importance of control or measurement
- Control or measurement at test termination
- Control or measurement precision

Analysis of Data

- Measurement accuracy
- Measurement precision
- Importance of variability
- Statistical model (normal distribution, constant hazard, "white" noise, etc.)
- Statistical confidence
- Engineering confidence
- Necessity of replications

Measurements

- Attributes vs variables
- Duration
- Continuity (discrete vs continuous)
- Single vs multiple
- Precision
- Accuracy
- Frequency
- Variability and uncertainty
- Instrumentation and capability
- Calibration of instruments

Resources

- Time
- Cost
- Personnel skills
- Test facilities
- Item availability

Other

- Safety
- Equipment dependability

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CHAPTER 8

MATERIEL CATEGORIZATION

Effects of the environment on materiel and materiel requirements are the basis of the Environmental Series of Engineering Design Handbooks. Previous chapters in this handbook introduce the importance of the environment; e.g., its effects, the factors of the environment, the complex combinations of environmental factors that cooccur, quantitative environmental concepts, and the testing of materiel and simulation of the environment. In this chapter, materiel is discussed. Emphasis is on the categorization of materiel as it exists and relates to environmental effects.

A variety of materiel categorization systems are employed, each tailored to a particular purpose. In discussions of the effects of environmental factors, material type is a commonly used basis for categorization. In other cases, the level of complexity of the item is used as a categorization basis. However, the most common materiel categorization is that used by the supply system. This will be examined in order to discern the information available in it that relates to environmental effects.

8-1 SUPPLY SYSTEM CATEGORIZATION

The purpose of materiel categorization based on the ways in which items are handled in the logistic system is to aid in the procurement and supply cycle. The existence of a uniform item classification system that is understood by both the suppliers and users of the items allows the total logistic system to function effectively and efficiently.

Materiel categorization systems are usually of little interest to the user but are necessary for the management and operations of the logistic system. The majority of materiel categorization systems used by the Army have originated with procurement and supply organizations.

One way to categorize materiel is based on the nature and importance of the individual items (Ref. 1). An example of this is given in Table 8-1. Another, more often used type of materiel categorization is based on the nature of the acquisition and distribution functions. An example of this type of materiel categorization is given in the Army Field Manual on logistic management and is shown in Table 8-2 (Ref. 2).

The most widely used materiel categorization system is the Federal Supply Classification (FSC) (Ref. 3). This system has been adopted by the DOD for use in classifying items of supply. The FSC is a commodity classification system designed to serve the functions of supply and is sufficiently comprehensive to permit classification of all items of personal property. In order to accomplish this, groups and classes have been established for the numerous commodity items with emphasis on the items known to be in the supply system of the Federal Government. The Federal Supply Classification System consists of 76 groups which are divided into 590 classes. A group is a broad category such as engines, turbines and components, or weapons. Table 8-3 contains a list of FSC groups arranged in alphabetical order. Each materiel class covers a relatively homogeneous area of commodities that are related with respect to their physical or performance characteristics or to otherwise related factors for supply management purposes.

The Federal Catalog System is designed to

TABLE 8-1

MATERIEL CATEGORIZATION BASED ON NATURE AND IMPORTANCE OF ITEMS (Ref. 1)

Principal items	Table of equipment items, the supply of which is, or is about to be, increasingly active, a high value item, or an item whose procurement will be difficult due to long lead time, shortage of strategic materials, or difficulty of manufacturing. Principal items represent less than one percent of the items stocked by the Army yet account for 60 percent of the procurement funds.
Secondary items	All other supplies except repair parts, clothing, and subsistence. They are categorized by short lead times, low value, and ease of procurement.
Repair items	All essential elements, materials, components, assemblies or subassemblies required for the maintenance and repair of an end item
Off-the-shelf items	Items regularly stocked by commercial organizations to supply normal demands; either principal, secondary, or repair items
Bulk procurement items	Items normally shipped in bulk form, and not sent through depot facilities; usually secondary items

TABLE 8-2

MATERIEL CATEGORIZATION BASED ON METHOD OF HANDLING ITEMS IN LOGISTIC SYSTEM (Ref. 2)

Class	Description
I	Subsistence
II	Clothing, individual equipment, tentage, organizational tool sets and tool kits, hand tools, administrative and housekeeping supplies and equipment
III	POL: petroleum fuels, lubricants, hydraulic and insulation oils; preservatives; liquid and compressed gases; bulk chemical products; coolants; deicing and antifreeze components and additives of such products; and coal
IV	Construction; construction materials to include all installed equipment and all fortification/barrier materials
V	Ammunition: ammunition of all types including chemical, radiological, and nuclear ordnance; bombs; explosives; mines; fuzes; detonators; pyrotechnics; missiles; rockets; propellants; and other associated items
VI	Personal demand items (nonmilitary sale items)
VII	Major end items; a final combination of end products which is ready for its intended use; e.g., launchers, tanks, whole machines, and vehicles
VIII	Medical materiel; including medical peculiar repair parts
IX	Repair parts (less medical peculiar repair parts); all repair parts and components to include kits, subassemblies and assemblies, repairable and nonrepairable, required for maintenance support of all equipment
X	Materiel to support nonmilitary programs; agricultural and economical development

TABLE 8-3

FEDERAL SUPPLY CLASSIFICATION MAJOR GROUPS
(excluding space vehicles) (Ref. 3)

FSC group number	Class
37	Agricultural machinery and equipment
87	Agricultural supplies
15	Aircraft and airframe structural components
16	Aircraft components and accessories
17	Aircraft launching, landing, and ground handling equipment
63	Alarm and signal systems
13	Ammunition and explosives
31	Bearings
76	Books, maps, and other publications
80	Brushes, paints, sealers, and adhesives
68	Chemicals and chemical products
79	Cleaning equipment and supplies
84	Clothing and individual equipment
58	Communication equipment
38	Construction, mining, excavating, and highway maintenance
56	Construction and building materials
81	Containers, packaging, and packing supplies
61	Electric wire and power and distribution equipment
59	Electric and electronic equipment components
28	Engines, turbines, and components
29	Engine accessories
12	Fire control equipment
42	Firefighting, rescue, and safety equipment
73	Food preparation and serving equipment
91	Fuels, lubricants, oils, and waxes
44	Furnace, steam plant, and drying equipment; and nuclear reactors
71	Furniture
14	Guided missiles
51	Hand tools
53	Hardware and abrasives
72	Household and commercial furnishings and appliances
66	Instruments and laboratory equipment
62	Lighting fixtures and lamps
88	Live animals
55	Lumber, millwork, plywood, and veneer
49	Maintenance and repair shop equipment
39	Materials handling equipment
52	Measuring tools
30	Mechanical power transmission equipment
65	Medical, dental, and veterinary supplies and equipment

TABLE 8-3 (continued)

FEDERAL SUPPLY CLASSIFICATION MAJOR GROUPS
(excluding space vehicles) (Ref. 3)

FSC group number	Class
95	Metal bars, sheets, and shapes
34	Metal working machinery
99	Miscellaneous
23	Motor vehicles, trailers, and cycles
77	Musical instruments, phonographs, and home-type radios
94	Nonmetallic crude materials
93	Nonmetallic fabricated materials
11	Nuclear ordnance
74	Office machines, visible record equipment, and data processing equipment
75	Office supplies and devices
96	Ores, minerals, and their primary products
67	Photographic equipment
47	Pipe, tubing, hose, and fittings
45	Plumbing, heating, and sanitation equipment
54	Prefabricated structures and scaffolding
43	Pumps and compressors
22	Railway equipment
78	Recreational and athletic equipment
41	Refrigeration and air conditioning equipment
40	Rope, cable, chain, and fittings
35	Service and trade equipment
19	Ships, small craft, pontoons, and floating docks
20	Ship and marine equipment
36	Special industry machinery
89	Subsistence
83	Textiles, leather, and furs
26	Tires and tubes
85	Toiletries
24	Tractors
69	Training aids and devices
48	Valves
25	Vehicular equipment components
46	Water purification and treatment equipment
10	Weapons
32	Woodworking machinery and equipment

classify, describe, and assign one, and only one, Federal Stock Number to each item of supply. The listing of classifications and descriptions is too extensive to include here. However, it is useful to describe the nature of the catalog number.

The Federal Stock Number (FSN) is composed uniformly of 11 digits and is always written in a 4-3-4 digit format with a dash after the fourth and seventh digits to facilitate reading; e.g., 8105-290-0345. The first four digits (8105) are the Federal Supply Classification code and the last seven digits (290-0345) are the Federal Item Identification Number (FIIN). The whole Federal Stock Number never is separated to run into a second line. In the Federal Supply Classification code (8105), the first two digits identify the broad group of material; i.e., group 81 covers containers, packaging, and packing supplies, and the last two digits identify a particular class within the group. Class 05 covers bags and sacks.

As an example of groups and classes, the first page of cataloging handbooks H2-1 is shown in Fig. 8-1. This includes the entries under Group 10, Weapons, and part of those under Group 11, Nuclear Ordnance. Descriptions of the other groups and classes are included in the reference.

The Federal Item Identification Number (290-0345) serves to differentiate each item of supply from all others within its class. In the example being used, the number identifies a 9-1/2- X 14-1/2-in. paper, cushioned shipping sack. Each Federal Item Identification Number applies to one, and only one, item of supply. They are assigned serially without regard to the name of the item, its description, or its classification.

8-2 EVOLUTION OF ARMY MATERIEL CATEGORIZATION

In order to understand materiel categorization and classification systems, it is instructive to examine the evolution of supply classification systems (Ref. 4). In World War I, supply was grouped into the four classes shown in Table 8-4. Prior to then, the Quartermaster Corps (established in 1775 to furnish supplies to sustain the individual soldier) and the Ordnance Corps (established in 1812 to furnish munitions) constituted the only military supply agencies and the only recognized supply classes. Before World War II, the classification offici lly was expanded to the five classes defined in Table 8-5 (Ref. 5).

During World War II the Army Air Corps required the addition of two more classes requiring the redefinition of classes as given in Table 8-6 (Refs. 6,7). The Quartermaster General was concerned with the lack of flexibility in this classification system. Parts associated with a basic item were in a different class from that of the basic item. Some items could be in two different classes (notably II and IV); an item could be classified as equipage or regular supply and require different handling; and Army exchange items were not separated from the general classifications. The Quartermaster General desired classification by use rather than classification by the nature of the item and recommended that the classifications be changed to those shown in Table 8-7. Apparently, no action was taken on this recommendation and at the end of World War II the official supply classification remained as shown in Table 8-6.

When the Air Force was established as a separate branch, it had the effect of increasing the number of supply classes that were recognized officially to nine as defined by the 1949 issue of FM 100-10 and as shown in Table 8-8. The 1954 issue of FM 100-10, however, reverted to the original five classes of 1940 (Ref. 11). However, the 1958 *Dictionary of United States Army Terms*, AR 320-5 again defined the nine classifications essentially as given in Table 8-8 (Ref. 12). In fact, the nine classes never had dropped out of common usage and officially were confirmed in a number of documents (Refs. 13-16). The reasons for this vacillation are unclear. In every case the classification was influenced by

FEDERAL SUPPLY CLASSIFICATION—Part 1

Groups and Classes

GROUP 10

Weapons

Note.—This Group includes both offensive and defensive weapons. Excluded from this Group are fire control and night vision devices classifiable in Groups 12 or 58.

1005 Guns, through 30 mm

Includes Machine Guns; Bayonets; Brushes, Machine Gun and Pistol.

Excludes Turrets, Aircraft.

1010 Guns, over 30 mm up to 75 mm

Includes Breech Mechanisms; Mounts.

1015 Guns, 75 mm through 125 mm

Includes Breech Mechanisms; Mounts; Rammers.

1020 Guns, over 125 mm through 150 mm

Includes Breech Mechanisms; Power Drives; Gun Shields.

1025 Guns, over 150 mm through 200 mm

Includes Firing Platforms; Mounts; Gun Shields.

1030 Guns, over 200 mm through 300 mm

Includes Gun Yokes; Rammers; Reflectors.

1035 Guns, over 300 mm

Includes Breech Mechanisms; Training Gears; Power Drives.

1040 Chemical Weapons and Equipment

Includes Flame Throwers; Smoke Generators.

1045 Launchers, Torpedo and Depth Charge

Includes Depth Charge Tracks; Torpedo Tubes.

1055 Launchers, Rocket and Pyrotechnic

Includes Airborne Rocket Launchers adaptable to guided missile use.

Excludes Specifically designed Airborne Guided Missile Launchers; Jettisonable Rocket Launchers; Launcher Fairings designed for specific airframes.

1070 Nets and Booms, Ordnance

Note.—This class includes nets and booms for harbor defense only.

1075 Degaussing and Mine Sweeping Equipment

1080 Camouflage and Deception Equipment

Includes Dummy Artillery, Aircraft and Vehicles; Garnished Nets.

1090 Assemblies Interchangeable Between Weapons in Two or More Classes

Includes Components and Accessories used on or with weapons falling in two or more classes of Group 10.

1095 Miscellaneous Weapons

Includes Line Throwing Guns; Catapult Guns; Saluting Guns; Signal Guns; Flare Guns; Barrage Balloons; Accessories, not elsewhere classifiable, for Weapons in this group; Expendable Bomb Dispensers.

GROUP 11

Nuclear Ordnance

Note.—This group includes, in particular, nuclear ordnance training weapons, practice ballistic units, and all components specially designed therefor, when not specifically classified elsewhere. Also included in the group are specially designed simulators and mockups, which are integral parts of the above. Excluded from this group are general purpose nose cones, case sections, flare sections or center sections designed to carry payloads other than nuclear and/or for use on a missile, rocket, or re-entry vehicle to attain the necessary aerodynamic configuration.

1105 Nuclear Bombs

Note.—This class includes nuclear weapons (including bombs), which are designed to be dropped from an aircraft.

Includes Ballistic cases, tail assemblies, retardation devices, and other peculiar components which are not classifiable elsewhere.

Excludes Parachute canopies and canopy hardware.

1110 Nuclear Projectiles

Note.—This class includes nuclear weapons which are designed to be propelled from a recoilless rifle, gun, howitzer, or the like, and which are not designed to be self-propelled.

Includes Ogive sections, body sections, bases, and other peculiar components which are not classifiable elsewhere.

1115 Nuclear Warheads and Warhead Sections

Note.—This class includes nuclear warheads (without or assembled with case sections, adaption kits, and/or fuzing and firing components) which are to be used in or with bombs, rockets, projectiles, missiles, demolition charges, or the like. Also includes case sections, nose cones, flare sections, center sections, and auxiliary structural components of missiles, rockets, and re-entry vehicles which are designed or constructed for exclusive use with or for housing of nuclear warheads and/or warhead sections.

Includes Components and parts peculiar to the warhead or warhead section, which are not classifiable in more specific classes.

Excludes Such components as fuzing and firing devices, nuclear components, high explosive components, classifiable in more specific classes, and items such as projectiles and bombs which include the entire outer case of a weapon.

1125 Nuclear Demolition Charges

Note.—This class includes nuclear weapons which are designed to be emplaced in or near a structure, area, or the like, which is to be destroyed. The weapons may include accessories.

Includes Outer cases, case sections, and other peculiar components, which are not classifiable elsewhere.

1

Figure 8-1. Typical Entries From Federal Supply Classification (FSC) (Ref. 3)

TABLE 8-4

SUPPLY CLASSIFICATION (DECEMBER 1917) (Refs. 8,9)

Class	Description
I	Food, forage, and other articles of automatic supply
II	Shoes, clothing, and similar equipment necessary for a soldier
III	Trucks, tarpaulins, axes, shovels, and other equipment authorized for individuals or organizations
IV	Items depending on the character of operations; exceptional items not part of the equipment of troops

TABLE 8-5

SUPPLY CLASSIFICATION (DECEMBER 1940) (Ref. 4)

Class	Description
I	Articles consumed at an approximately uniform daily rate, such as rations and forage
II	Authorized allowances, such as clothing, gas masks, arms, trucks, radio sets, tools, and instruments
III	Engine fuels and lubricants, such as gasoline for all vehicles and aircraft, diesel oil, fuel oil, and coal
IV	Supply related to operations in hand (except for articles in classes III and V), such as fortification materials, construction materials, and machinery
V	Ammunition, pyrotechnics, antitank mines, and chemicals

TABLE 8-6.

SUPPLY CLASSIFICATION (NOVEMBER 1943) (Ref. 6)

Class	Description
I	Supplies consumed at an approximately uniform daily rate under all conditions and issued automatically, such as rations and forage
II	Supplies for which allowances are fixed, such as clothing, weapons, and vehicles
III	Supplies of fuel and lubricants for all purposes except aviation
III(A)	Aviation fuel and lubricants
IV	Supplies for which allowances are not prescribed or which require special measures of control, such as fortification materials, construction materials, and articles of similar nature
IV(E)	Complete airplanes and all spare parts and supplies required to maintain the complete airplane in commission
V	Ammunition, pyrotechnics, antitank mines, and chemical warfare agents

TABLE 8-7.

SUPPLY CLASSIFICATION, QM RECOMMENDATIONS (NOVEMBER 1945) (Ref. 10)

Class	Description
I	Rations and ration accessories, and items used exclusively in the handling of rations, such as bread sacks, solidified alcohol heating units, and coffee bags
II(A)	Individual or organizational clothing and equipment with authorized allowances
II(B)	Expendables such as cleaning and preserving material, and office supplies
II(C)	Spare parts such as field range parts and tools that would be in excess of authorized allowances
III	Gasoline, oil, lubricants, and solid fuels and items used exclusively in the handling of these items, such as gasoline cans and hose
IV(A)	Distinctive items of clothing and accessories
IV(B)	Items specifically for supernumerary personnel, such as Red Cross personnel and war correspondents
IV(C)	Special supplies of a nonrecurring nature, such as American flag armbands and nausea bags
IV(D)	Medals and decorations
IV(E)	Materials-handling equipment not contained in allowance
PX items	Items procured by the QM and turned over in wholesale lots to the Army Exchange Service, Navy, and Red Cross

TABLE 8-8.

SUPPLY CLASSIFICATION (SEPTEMBER 1949) (Ref. 11)

Class	Description
I	Supplies consumed at an approximately uniform daily rate under all conditions and issued automatically
II	Supplies for which allowances are fixed for the Army
II(A)	Supplies for which all allowances are fixed for the Air Force
III	Fuel and lubricants for the Army
III(A)	Fuel and lubricants for aviation
IV	Supplies, except Air Force supplies, for which allowances were not prescribed. Classes I, II, III, and V may be subject to class IV issue when issued in excess of prescribed allowances or for purposes not regularly authorized
IV(A)	Air Force supplies for which allowances were not prescribed
V	Ammunition, pyrotechnics, antitank mines, and chemical warfare agents
V(A)	Aviation ammunition

the method of distribution and issue, the assignment of supply responsibilities, the storage and use of the item, and, to some extent, by the user of the item and its anticipated consumption and life. The classification system apparently took no appreciable cognizance of procurement, source of issue, cost, and obsolescence. In 1966, the supply classification was that given in Table 8-9 but has now been superseded by those given in Table 8-2.

8-3 ENVIRONMENTAL EFFECTS AND MATERIEL CATEGORIZATION

The current supply classification (Table 8-2) as defined in FM 38-1 (Ref. 2) includes all materiel that is supplied to the Army. Its interface with the Federal Supply Classification is mixed. For example, Class I materiel that is subsistence corresponds to FSC Group 89, but Class VII materiel, major end items, includes at least 10 FSC groups. The 10 materiel classes defined in Table 8-2 have an equally complicated relation to environmental effects as discussed by materiel class in the subparagraphs that follow.

Subsistence, Class I, is characterized by foodstuffs, many types of which are perishable. Fresh foodstuffs require controlled environments. while dried, canned, or prepared items have various degrees of environmental susceptibility that generally require special consideration. One unusual incident relates to a quantity of canned goods stockpiled in a humid location wherein their packaging materials and labels deteriorated so that the cans could not be handled without repacking and the individual items could not be identified. They were a total loss.

Generally Class I materiel is most susceptible to temperature, humidity, solar radiation, rain, macrobiological organisms, and microbiological organisms. The more slowly acting factors such as ozone, salt, and atmospheric pollutants; the mechanical factors; the various forms of radiated energy; and factors such as fog, wind, and pressure have little or no direct effect on subsistence.

Class II materiel includes clothing and a variety of small items such as tools, office supplies, and housekeeping equipment. Because of this variety, little coherence can be obtained in discussion of environmental effects. Generally, such materiel is packaged for normal handling and protected warehousing; hence little deterioration is observed. If packaging is compromised, open storage employed, or if long-term storage is required, the materiel is degraded by various natural environmental factors.

Class III materiel is largely petroleum products which require special handling both in transportation and storage. Characteristic environmental problems include evaporative losses at high temperature, moisture contamination caused by condensation, and microbiological attack.

Construction materials, which are Class IV supplies, interact directly with the natural environmental factors. Because engineering personnel consider environmental effects as major factors in any construction activity—a large amount of attention is given to such effects—little can be added here. However, engineering personnel must be alerted to those peculiarities of specific operating areas that call for special procedures or materials.

Class V includes all types of ammunition and explosives. Because of the nature of their use, these items are designed to resist environmental effects.

Materiel in Classes VI through X is insufficiently homogeneous in type, use pattern, or construction to allow any discussion of environmental effects by class.

It can be seen that the major materiel categorization systems in use relate poorly to classification of environmental effects.

In consideration of environmental effects, there is considerable emphasis on classes of materials as listed in Table 8-10. The advantages of this approach are that it is tractable in a one-

TABLE 8-9

SUPPLY CLASSIFICATION (FEBRUARY 1963) (Ref. 18)

Class	Description
I	Supplies such as rations, forage, and PX supplies that are consumed at an approximately uniform daily rate under all conditions
II	Clothing, organizational equipment, and vehicles, including spare parts for which allowances, tables of organization and equipment, or other appropriate lists or tables, and which are not included in classes II(A), IV, or IV(A)
II(A)	Aviation supplies and equipment for which allowances for initial issue to organizations are prescribed by appropriate tables-of-allowance lists
III	Fuels and lubricants for all purposes except for operating aircraft or for use as ammunition in weapons such as flame throwers
III(A)	Aviation fuels and lubricants
IV	Items not otherwise classified and for which initial issue allowances are not prescribed by approved issue tables. Normally such supplies include fortification and construction materials, special machinery and equipment, and other special supplies, as well as additional quantities of items identical to those authorized for initial issue (class II), such as additional vehicles
IV(A)	Aviation supplies and equipment for which allowances for initial issue to organizations are not prescribed by appropriate tables-of-allowance lists, or which require special measures of control
V	Ammunition of all types (including chemical), explosives, antitank and antipersonnel mines, fuzes, detonators, and pyrotechnics
V(A)	Aviation ammunition, bombs, rockets, pyrotechnics, and similar expendable accessories

TABLE 8-10

MATERIAL CLASSES

Plastics and rubber
Metals
Ceramics
Transparent materials
Textiles
Casting materials
Adhesives and sealing compounds
Magnetic materials
Gasket materials
Hydraulic fluids
Chemicals
Hydrocarbon fuels and lubricants
Wood and wood products
Explosives
Paint and other surface-protective coatings

TABLE 8-11

MATERIEL CATEGORIZATION BY TYPE

Mechanical assemblies
Electrical and electronic equipment
Optical equipment
Construction materials and equipment
Bulk materials
Weapons
Personal subsistence, clothing, and supplies
Small items

factor, one-material-class-type of analysis and that it provides information that is useful in design. Its disadvantage is that, since most end items include a variety of such materials, it is not always apparent which will be affected most in a given complex environment.

An alternative categorization system is given in Table 8-11 based on the type of materiel. This is also commonly employed because the interactions of electrical and electronic equipments with environmental factors, for example, differ from interactions of mechanical assemblies. Most of the data available on effects on end items is presented in these categories. Each category provides a distinct set of environmental effects which is observed, tested, and analyzed independently of the other categories.

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