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ENVIRONMENTAL HANDBOOK FOR DEFENCE MATERIEL

PART 4: NATURAL ENVIRONMENTS

Reprinted April 2000
Incorporating Amendment 1

This Defence Standard is progressively superseding AvP35 and supersedes DEF STAN 07-55 and DEF STAN 00-1

AMENDMENT RECORD

AMENDMENT NUMBER	**DATE OF ISSUE**	**TEXT AFFECTED**	**SIGNATURE & DATE**
Amendment No 1	Apr 00	Part 1 Ch 1-01 Re-issued Part 4 '02' Chapters added Part 6 added	

Revision

Part 4 of the standard has been amended to include the supplementary '02' chapters aligned to Part 6. Part 6 issued.

The content of this part of the standard has been revised to include previously published material.

Historical Record

This standard supersedes AvP35.

In 1963 a specification defining standard tests and test methods for Service Equipment was published in DEF 133 - Climatic, Shock and Vibration Testing of Service Equipment. This was revised and re-issued in 1975 as DEF STAN 07-55 Environmental Testing of Service Materiel.

In 1969 DEF STAN 00-1 was published and contained climatic environmental information agreed by the ABCA Force of the Quadripartite organisation in QSTAG 200. In 1977 the Standard was re-issued to implement STANAG 2831.

AvP 35 was progressively issued over the period 1966 to 1974 as the 'Environmental Handbook for Guided Weapons".

The material on environments and environmental categories has developed from that published in AvP 35 and DEF STAN 00-1.

Defence Standard 00-35 was previously published as a complete document as Issue 2 and is now issued in separate parts to facilitate easier reference, amendment and distribution.

Arrangement of Defence Standard 00-35

Defence Standard 00-35 comprises six Parts with each Part being divided into Sections and Chapters. The six Parts are:

Part 1	Control and Management
Part 2	Environmental Engineering Rationales
Part 3	Environmental Test Methods
Part 4	Natural Environments
Part 5	Induced Mechanical Environments
Part 6	Induced Climatic, Chemical and Biological Environments

DEFENCE STANDARD 00-35
ENVIRONMENTAL HANDBOOK FOR DEFENCE MATERIEL

Part 4 Natural Environments

PREFACE

This Defence Standard contains environmental data and a range of tests representing conditions which may be encountered during the life of defence materiel. The environmental data should be used to select test methods and test severities to simulate the service, storage and transportation environments for the materiel. The information available from the test results and subsequent assessments should be capable of providing sufficient evidence to demonstrate compliance with the specified environmental requirements for the materiel.

Defence Standard 00-35 is in six parts. More than one part may apply to the environmental requirement and may cross reference to other parts of the Defence Standard. It is essential that all parts be considered and used where appropriate. Users of this Defence Standard should make reference to Defence Standard 00-00 Part 3 Section 4 to ensure the latest issue of each part is in use.

Part 4 has been amended to implement STANAG 2895 Edition 1. This issue provides guidance to materiel procurement agencies on the specification of natural climatic environments to be anticipated in Service. It also provides general information and guidance for dealing with those climatic conditions that occur naturally; that is, those generated by the forces of nature, such as temperature, humidity, pressure, rain, dust and sand.

The technical material in this Standard has been prepared by the Joint Technical Requirements Committee (JTRC) Sub Committee 00-35. The JTRC is composed of representatives from the Ministry of Defence, the Defence Research Agencies, the Federation of Electronic Industries, and the Society of British Aerospace Companies.

In accordance with HM Government policy the maximum use has been made in this Standard of materiel, particularly in the field of environmental testing, published in British Standards and internationally agreed standards. Where these standards are suitable they are invoked in this Standard.

This Standard has been agreed by the authorities concerned with its use and is intended to be used whenever relevant in all future designs, contracts, orders etc. and whenever practicable by amendment to those already in existence. If any difficulty arises which prevents application of this Defence Standard, the Directorate of Standardisation shall be informed so that a remedy may be sought.

Any enquiries regarding this Standard in relation to an invitation to tender or a contract in which it is incorporated are to be addressed to the responsible technical or supervising authority named in the invitation to tender or contract.

This Standard has been devised for the use of the Crown and its contractors in the execution of contracts for the Crown. The Crown hereby excludes all liability (other than liability for death or personal injury) whatsoever and howsoever arising (including, but without limitation, negligence on the part of the Crown its servants or agents) for any loss or damage however caused where the Standard is used for any other purpose.

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DEF STAN 00-35

ENVIRONMENTAL HANDBOOK FOR DEFENCE MATERIEL

PART 4

NATURAL ENVIRONMENTS

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CHAPTER 1-01
GENERAL

1 SCOPE

1.1 Part 4 (Natural Environments) of Def Stan 00-35 describes the meteorological and biological environments likely to be experienced by defence materiel in the earth's atmosphere, and the effects of each environment on such materiel. This Part implements STANAG 2895 Edition 1 (Ref.1). In the first two chapters, climatic categories and the diurnal cycles of temperature, humidity and solar radiation in each category are described. These cycles are used in several climatic test methods in Part 3.

1.2 To facilitate the identification of climatic conditions for inclusion in the Staff Target or Staff Requirement, eleven climatic categories have been chosen to represent distinctive types of climate found on the land surfaces of the world, and a further three have been selected to describe the conditions found at sea away from land. The definition of each climatic category is given in Table 1 together with the identification of some of the more important regions upon which the categorization is based.

1.3 The eight categories, A1 to A3 and C0 to C4, relating to the land surface are defined with temperature as the principal consideration, while the remaining three, B1 to B3, represent climates in which high humidity accompanied by a warm temperature is the outstanding characteristic. With respect to the sea surface, two categories M1 and M3 are defined with temperature as the principal consideration; whilst the third, M2, represents a sea climate in which a warm temperature is accompanied by high humidity.

1.4 The geographical locations to which these climatic categories apply are illustrated approximately in Figures 1A, 1B and 1C. It is considered impractical to attribute categories to specific sea areas, but as a general guide, M1 and M2 apply to regions which experience tropical or temperate conditions respectively, while M3 is representative of arctic conditions.

1.5 The highest or lowest temperature ever reliably recorded in the location of various climatic categories is given in Table 2.

1.6 The delineation of the geographical areas in Figures 1A-C is not intended to imply that the climate at each and every location within that area complies exactly with the annual distributions and diurnal cycles appropriate to the indicated climatic category. The maps are provided only as a guide when determining the climatic environmental criteria. If data applicable to a specific region or location are required, then reference should be made to the appropriate sections in this part of the Defence Standard, or the Meteorological Office should be consulted. However, to avoid limitations in deployment, the geographical areas should be used as frequently as possible.

1.7 The diurnal cycles and annual distribution of temperature, solar radiation and humidity appropriate to each climatic category are summarised in Chapter 1-02 of this section and also discussed in Chapters 2-01, 3-01, and 4-01 respectively of this part. The data cover both meteorological and storage conditions (see Chapter 1-02 for definitions).

1.8 Although temperature, solar radiation and humidity are the principal environments affecting each climatic category, additional factors may need to be considered. Table 3 lists these other climatic factors and the categories affected.

2 WARNING

2.1 The Ministry of Defence (MOD) like its contractors are subject to both United Kingdom and European laws regarding Health and Safety at Work, without exemption. All Defence Standards either directly or indirectly invoke the use of processes and procedures that could be injurious to health if adequate precautions are not taken. Defence Standards or their use in no way absolves users from complying with statutory and legal requirements relating to Health and Safety at Work.

TABLE 1
DEFINITIONS OF CLIMATIC CATEGORIES

CATEGORY		APPLIES TO:
A1 -	EXTREME HOT DRY	Areas which experience very high temperatures accompanied by high levels of solar radiation, namely, hot dry deserts of North Africa, parts of the Middle East, Northern India and South Western USA.
A2 -	HOT DRY	Areas which experience high temperatures accompanied by high levels of solar radiation and moderately low humidities, namely, the most southerly parts of Europe, most of the Australian continent, South Central Asia, Northern and Eastern Africa, coastal regions of North Africa, southern parts of USA and most of Mexico.
A3 -	INTERMEDIATE	In strict terms, this definition applies only to those areas which experience moderately high temperatures and moderately low humidities for at least part of the year. It is particularly representative of conditions in Europe except the most southern parts, Canada, the northern United States and the southern part of the Australian continent.
B1 -	WET WARM	Areas which experience moderately high temperatures accompanied by continuous very high relative humidity. These conditions are found in rain forests and other tropical regions during periods of continuous cloud cover, where direct solar radiation is not a significant factor. Geographical regions covered include the Congo and Amazon basins, South East Asia including the East Indies, the north east coast of Madagascar and the Caribbean Islands.
B2 -	WET HOT	Areas which experience moderately high temperatures accompanied by high humidity and high direct solar radiation. These conditions occur in exposed areas of the wet tropical regions, such as the coastal region of the Gulf of Mexico.
B3 -	HUMID HOT COASTAL DESERT	Areas which experience moderately high temperatures accompanied by high water vapour content of the air near the ground in addition to high levels of solar radiation. These conditions occur in hot areas near large expanses of water such as the Persian Gulf and the Red Sea.
C0 -	MILD COLD	In strict terms, this definition applies only to those areas which experience mildly low temperatures such as the coastal areas of Western Europe under prevailing maritime influence, South East Australia and the lowlands of New Zealand. However for the purposes of this standard, this definition is considered to apply to all land masses except those designated as Category C1, C2, C3 or C4.
C1 -	INTERMEDIATE COLD	Areas which experience moderately low temperatures such as central Europe, Japan and central USA.
C2 -	COLD	Colder areas which include northern Norway, the prairie provinces of Canada, Tibet and much of Russia.
C3 -	SEVERE COLD	The coldest area of the North American continent.
C4 -	EXTREME COLD	The coldest areas of Greenland and Siberia.
M1 -	MARINE HOT	The tropical bulk sea areas where high ambient air temperature is the predominant climatic characteristic.
M2 -	MARINE INTERMEDIATE	The warmer, mid-latitude, regions of the seas, particularly temperate sea areas where high humidity combined with moderately high temperatures are together the principal climatic characteristics.
M3 -	MARINE COLD	The colder regions of the seas, particularly the Arctic zone where low ambient air temperature is the predominant climatic characteristic.

TABLE 2
EXTREME TEMPERATURES IN CLIMATIC CATEGORIES

Highest temperatures		Lowest temperatures	
A1	58°C	C0	-26°C
A2	53°C	C1	-42°C
A3	42°C	C2	-56°C
M1	51°C	C4	-68°C
		M3	-38°C

TABLE 3
ADDITIONAL CLIMATIC FACTORS AND RELATED CATEGORIES

CLIMATIC FACTOR	CATEGORY AFFECTED
Atmospheric pressure Wind Ozone Hail	All Categories
Blowing sand and dust Rain Drip hazard	A1, A2, A3, B1, B2, B3, M1 and M2
Ice accumulation Snow loading	C0, C1, C2, C3, C4 and M3
Temperature of surface sea-water Sea states	M1, M2 and M3

3 FACTORS AFFECTING THE SELECTION OF CLIMATIC CATEGORIES

3.1 Initially, the Service sponsor should decide on the planned geographical areas for the storage and use of the materiel, and specify this information in terms of one or more of the 14 climatic categories. Where materiel is intended for use at either fixed locations, or a restricted region within one of the geographical areas indicated, this should also be stated.

3.2 In respect to land use, it should be noted that the earth's surface is mountainous in many areas. Any requirements for exposure at high ground levels will need to be identified.

3.3 For use or storage at sea, it may be appropriate to specify all three 'M' categories, since ships may enter tropical, temperate and arctic waters during their service life.

3.4 Each requirement for land-service materiel is to be considered on its merits. In determining the climatic categories, care must be taken when including a little-used climatic area that this does not adversely affect in terms of cost or performance the development of the materiel, especially where little operational benefit will be gained. In particular, the following guidelines should be borne in mind:

(a) Materiel which is unlikely to be required for service outside the NATO European area should be designed to operate in categories A2, A3, C0, C1 and C2 only, unless it is considered that the inclusion of specific additional climatic categories would be relatively inexpensive to achieve in design.

(b) Exceptionally, materiel intended only for tropical use should be designed to operate in categories A1, A2, B1 and B3.

(c) Similarly, materiel intended only for arctic use should be designed to operate in categories C0, C1 and C2, and in particular cases C3 and C4.

(d) All other materiel should normally be designed, either directly or by the addition of arcticization or tropicalization kits, to operate in all climatic categories except C3 and C4.

3.5 In the case of aircraft, their armament and externally mounted equipment, consideration needs to be given to the likely operational deployments, including any restrictions on altitude, since aircraft may be deployed world-wide during their service life. Ground-based and mobile supporting equipment need to be considered in relation to the aircraft operations they support.

3.6 It is not MOD policy to require materiel to be necessarily safe and/or capable of acceptable performance when exposed to the highest and lowest temperatures ever reliably recorded in the geographical areas in each climatic category specified for the materiel. In most instances it is only required that the materiel be safe and/or capable of acceptable performance when exposed to those conditions which on average will be attained or exceeded for a small portion of each year from a few days to a few hours or less.

3.7 For materiel containing explosives, propellants and pyrotechnics, temperature and humidity levels should be based on a probability of being exceeded for 1% of one month in the worst period of the year, normally 3 to 4 days a year. This criterion is applicable for much materiel but, in other circumstances, for instance where a temperature-induced equipment defect will not present a hazard or cause a major system malfunction, the risk situations should be assessed so that temperatures derived from related percentage values representing the optimum compromise can be adopted. This assessment should be carried out during the compilation of the Environmental Requirement in accordance with Part 1 of this Standard.

(FIGURE 1A LOCATION OF CLIMATIC CATEGORIES [A])

(FIGURE 1B LOCATION OF CLIMATIC CATEGORIES [B])

(FIGURE 1C LOCATION OF CLIMATIC CATEGORIES [C])

4 REFERENCE

STANAG 2895, Apr 1985(Edition 1). Extreme Climatic Conditions and Derived Conditions for use in defining Design/Test Criteria for NATO Forces Materiel.

FIGURE 1(A)

LOCATION OF CLIMATIC CATEGORIES

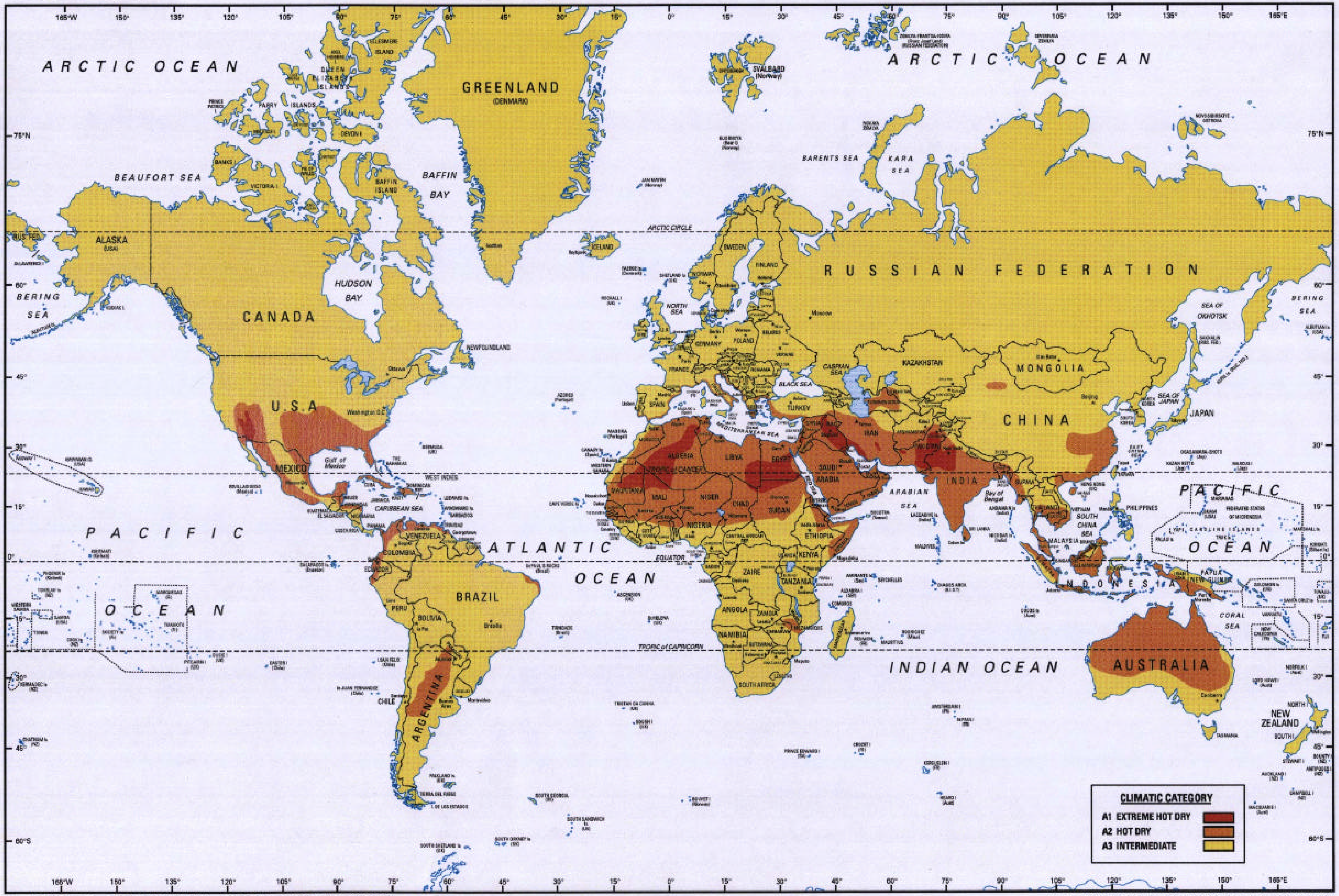

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FIGURE 1(B) **LOCATION OF CLIMATIC CATEGORIES**

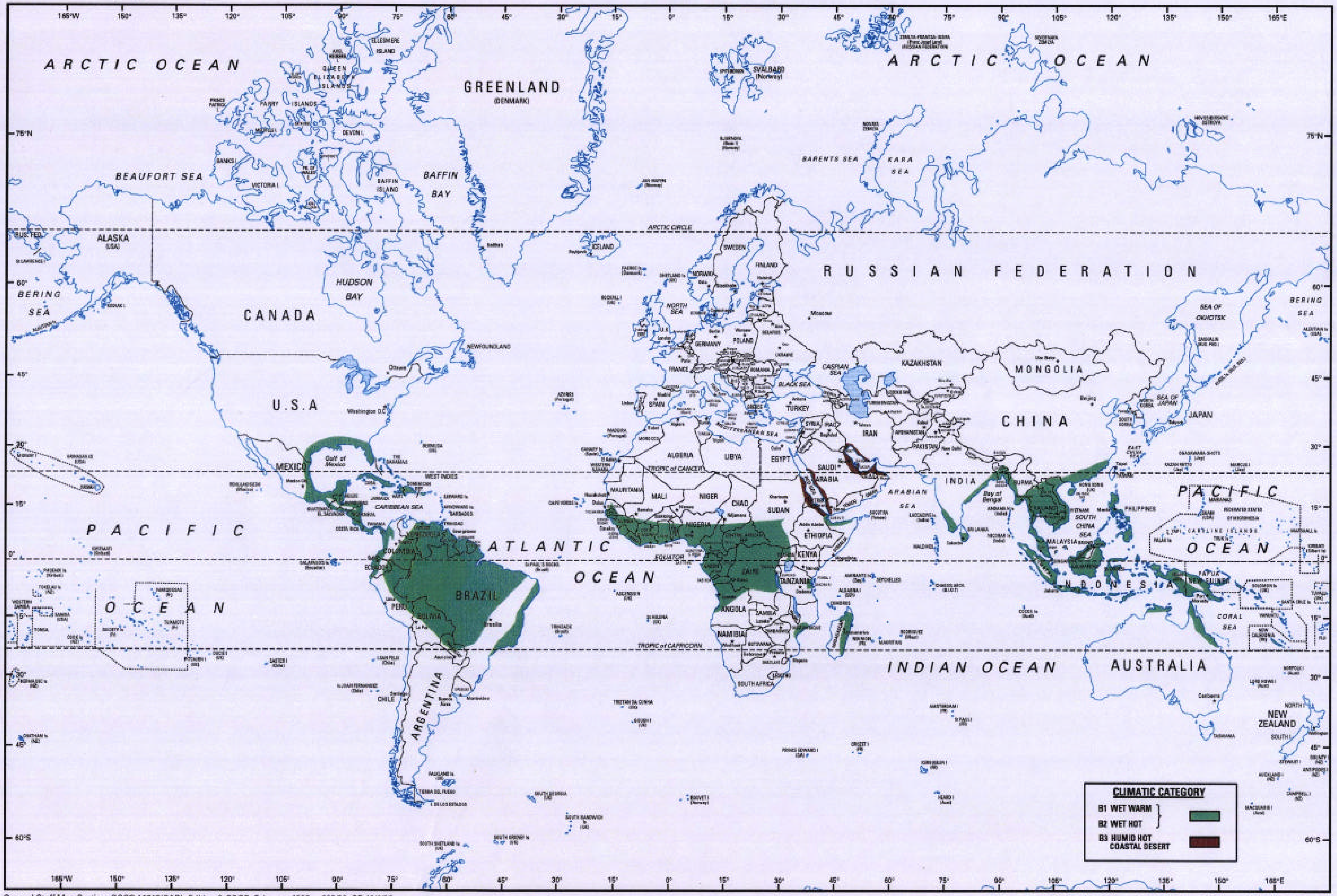

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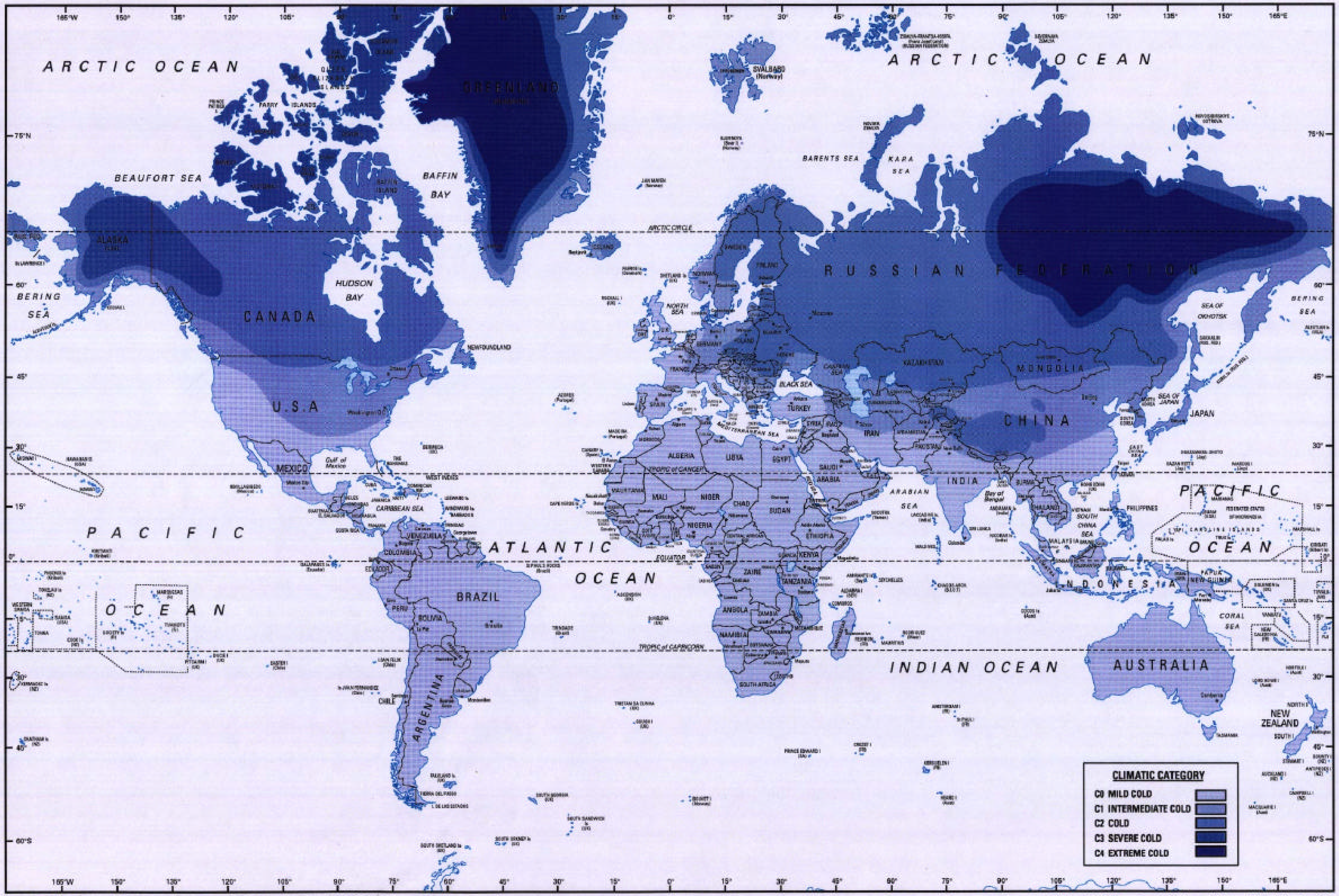
FIGURE 1(C) LOCATION OF CLIMATIC CATEGORIES



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CHAPTER 1-02

TEMPERATURE, HUMIDITY AND SOLAR RADIATION DIURNAL CYCLES FOR EACH CLIMATIC CATEGORY

1 INTRODUCTION

1.1 This chapter specifies the ambient (meteorological) temperature, humidity and direct solar radiation conditions occurring over the land and sea surfaces for the 14 climatic categories defined in Chapter 1-01 of this Part, together with the associated storage and transit conditions.

1.2 These data should be taken into account by Operational Requirements branches when preparing the Service environment, and by the appropriate authority when deriving the Environmental Requirement and determining design criteria for materiel, particularly materiel containing explosives, propellants or pyrotechnics.

1.3 To ensure that there is an acceptably low risk of adverse effects, due to climatic factors, on much materiel including that which contains explosives, propellants or pyrotechnics, the values for temperature, humidity and solar radiation used for the diurnal cycles are those which are exceeded on average for approximately 7 hours per year (1% of one month) in the worst month. For the design of other materiel, additional data are provided and guidance given on how to derive values for 5% and 10% (of one month) occurrence from the 1% data.

2 DEFINITIONS

2.1 The following definitions apply to the data provided in this chapter:

(a) Meteorological temperature. The meteorological temperature is the ambient air temperature measured under standard conditions of ventilation and radiation shielding in a meteorological screen at a height of 1.2 to 2.0 m above the ground.

(b) Storage and transit conditions. The storage and transit conditions are the induced air temperature and humidity measured inside a temporary unventilated field shelter, for example under tarpaulin covers or in a railway boxcar, which is exposed to direct solar radiation. Temperature of materiel can be derived by using data from previous similar storage conditions, by actual or simulated exposure to the appropriate diurnal cycle, or by the development and use of suitable mathematical models. Where more severe conditions than those quoted are known to occur these should be specified.

(c) Solar radiation. Solar radiation is the infra-red, visible and ultra-violet radiation from the sun. The spectral energy distribution of solar radiation at midday at sea level when the sun is directly overhead is given in Table 1.

TABLE 1
SPECTRAL ENERGY DISTRIBUTION OF SOLAR RADIATION AT SEA LEVEL

Spectral region	Ultra-violet		Visible		Infra-red	
Waveband (µm)	0.28-0.32	0.32-0.40	0.40-0.52	0.52-0.64	0.64-0.78.	0.78-3.00
Irradiance (W/m^2)	5	63	200	186	174	492

NOTE: The values of demarcation between the ultra-violet, visible and infra-red quoted in some reference documents differ slightly from those in the above table.

3 CLIMATIC DATA

3.1 For each climatic category, the following data are provided:

(a) The diurnal meteorological temperature cycle representative of conditions on days when near-extreme temperatures occur. The near-extreme temperature values are those temperatures exceeded at the hotter/colder locations in the category, on average, for a total of 1% of one month during the hottest/coldest period of the year.

(b) Transit and storage diurnal cycles, representative of the additional effects on induced temperatures of direct solar radiation on days when near-maximum ambient air temperatures occur, for the A1, A2, A3, B2, B3, M1 and M2 categories. On days when near-minimum ambient air temperatures occur for the C and M3 categories there is negligible direct solar radiation.

(c) A plot of the number of days of the year on which, on average, a given meteorological temperature is exceeded in the 5 to 10 per cent of the regions of each category which are climatically least hospitable.

(d) A plot of the dew points associated with the temperatures quoted at (c).

(e) A plot of the total number of hours in the year, based on (c) and (a), that a given temperature is just exceeded.

(f) Plots similar to (c) and (e) for storage temperatures.

3.2 The diurnal ambient temperature, humidity and solar radiation cycles for each climatic category are given in Tables 7 to 10 together with the associated transit and storage cycles. Background notes on the climatic categories are given in Table 11. The upper and lower values of each diurnal temperature and humidity cycle are summarized in Table 2.

TABLE 2
SUMMARISED WORLD-WIDE TEMPERATURE AND HUMIDITY CYCLES

Category	Meteorological		Storage	
	Temperature °C	Relative Humidity %	Temperature °C	Relative Humidity %
A1	32 to 49	8 to 3	33 to 71	*
A2	30 to 44	44 to 14	30 to 63	*
A3	28 to 39	78 to 43	28 to 58	*
B1 (7 days	24	100	24	100
(358 days	23 to 32	88 to 66	23 to 32	88 to 66
B2	26 to 35	100 to 74	30 to 63	75 to 19
B3	31 to 41	88 to 59	33 to 71	80 to 14
C0	-19 to -6	Tending to	-21 to -10	Tending to
C1	-32 to -21	Saturation	-33 to -25	Saturation
C2	-46 to -37	"	-46 to -37	"
C3	-51	"	-51	"
C4	-57	"	-57	"
M1	29 to 48	67 to 21	30 to 69	64 to 8
M2	25.5 to 35	100 to 54	30 to 63	78 to 13
M3	-34 to -23	Tending to Saturation	-34 to -23	Tending to Saturation

* Humidities for the A1, A2 and A3 storage conditions vary too widely between different situations to be represented by a single set of conditions.

3.3 Figures 1 to 4 provide diurnal ambient temperature maxima and associated dew point data in terms of the number of days per year. Figures 5 to 8 present the air temperature distribution in terms of hours per year. Finally, Figures 9 to 16 present the corresponding temperature data relating to the storage and transit conditions for each climatic category

3.4 The curves in Figures 1-16 are fixed by their values at the left-hand side of each graph, which are the extremes for the respective climatic category. The values on the right-hand side are the temperatures in the less-extreme season, and because of differences in latitude and continentality between the representative stations, may not be in the same order as the categories. Thus the A2 and A3 curves cross because the A3 station is the more maritime, with milder winters.

3.5 Figures 17 to 24 are schematic diagrams illustrating the diurnal cycles given in Tables 7 to 10. For test purposes, use the tabulated values.

4 DERIVATION OF DIURNAL CYCLES FOR OTHER PROBABILITIES OF OCCURENCE

4.1 The figures depicting the diurnal temperature maxima or minima in terms of the number of days per year are intended to provide background information for both meteorological and storage and transit conditions, and indicate the average number of days on which these conditions occur.

4.2 In order to derive the diurnal cycles for probabilities other than those given for the 1% case in Tables 7 to 10, the hourly temperature plots of Figures 5 to 8, 10, 12, 14 and 16 are provided. From one of these graphs the appropriate temperature maximum or minimum can be determined by noting the temperature that relates to the number of hours corresponding to the percentage probability in one month: thus for a 10% of one month probability of occurrence, 74 hours would be used.

4.3 To obtain the required diurnal cycle, the temperatures in the 1% cycle are modified in the following way:

(a) Hot categories. Each temperature in the 1% diurnal cycle is reduced by the difference between the new temperature maximum and the maximum for the 1% case quoted in the cycle and in Table 2.

For the A3 category diurnal cycles for 5 and 10% risk, the upper limit temperature should be derived as above, but for practical reasons the lower limit should remain the same as for the 1% risk situation. Intermediate temperatures in the cycle are then derived proportionally.

(b) Cold categories. Each temperature in the 1% diurnal cycle is increased by adding the algebraic difference between the new temperature minimum and the minimum for the 1% case quoted in the cycle and in Table 2.

4.4 It should be assumed that the diurnal cycles for relative humidity and solar radiation are not modified for other probabilities of occurrence.

5 CORRECTION FACTORS FOR ELEVATION AND ALTITUDE

5.1 The data presented in Tables 7 to 10 and Figures 1 to 16 relate to conditions found over the land at or near sea level and at the sea surface. For conditions above sea level these data have to be modified and the following paragraphs provide information and guidance on how the data should be corrected to take into account the effects of altitude.

5.2 Temperature moderating factors for elevated ground

5.2.1 The temperatures quoted for Categories A1, A2 and A3 relate to ground elevations from sea level to 900 m, and for Categories B1, B2 and B3 to elevations from sea level to 1200 m. For higher elevations the appropriate moderating factors quoted in Table 3 should be applied.

TABLE 3
TEMPERATURE MODERATING FACTORS FOR ELEVATED GROUND

Climatic category	Ground elevations above MSL	Moderating factors
A1, A2, A3	900 m	-1°C per 100 m
B1	1200 m	-2°C per 300 m
B2, B3	1200 m	-1°C per 100 m

5.3 Ambient air temperature at altitude - world-wide

5.3.1 Table 4 presents for a range of altitudes ambient air temperatures which, on a world-wide basis, are estimated to be exceeded for 7.4 hours (1 per cent of a month) of the hottest period of the year at the hottest location and for all but 7.4 hours of the coldest period of an average year at the coldest location. The highest and lowest temperatures ever reliably recorded at these altitudes are also given. The temperatures at other altitudes can be calculated by linear interpolation.

TABLE 4
AMBIENT AIR TEMPERATURE AT ALTITUDE - WORLDWIDE

Altitude km	Highest temperature ever recorded °C	Value of 1% high temperature occurrence level °C	Value of 1% low temperature occurrence level °C	Lowest temperature ever recorded °C
0	58	49	-61	-68
1	41	40	-53	-54
2	32	30	-41	-47
4	19	17	-48	-53
6	8	6	*-57	-61
8	-4	-5	-66	-68
10	-13	-13	-74	-74
12	-22	-22	-73	-80
14	-30	-30	-75	-77
16	-35	-37	-86	-87
18	-35	-37	-86	*-87
20	-33	*-32	*-86	*-86
22	-34	*-30	-84	-85
24	-33	*-33	-85	-86
26	*-28	*-28	-84	-84
28	*-23	*-23	-83	-83
30	*-18	*-18	*-83	*-83

NOTE: Values marked with an asterisk are taken from MIL-STD-210C. It should be noted that not all these highest (or lowest) temperatures at the various altitudes occurred simultaneously not necessarily at the same location and the set of values given in Table 4 does not represent a specific temperature/altitude profile. See MIL-STD-210C for such profiles.

5.4 Ambient air temperatures at altitude - over open seas

5.4.1 The range of ambient air temperatures over open seas at any altitude below 16 km is significantly less than the range over land masses. The high and low values over open seas, calculated in a similar manner as those for the world-wide condition, are given in Table 5.

TABLE 5
AMBIENT AIR TEMPERATURE AT ALTITUDE - OVER OPEN SEAS

Altitude km	Highest temperature ever recorded °C	Value of 1% high temperature occurrence level °C	Value of 1% low temperature occurrence level °C	Lowest temperature ever recorded °C
0	51	48	-34	-38
1	34	33	-29	-31
2	26	25	-31	-32
4	16	14	-39	-40
6	2	1	-46	-47
8	-8	-9	-56	-58
10	-20	-21	-69	-70
12	-36	-39	-74	-75
14	-35	-37	-75	-76
16	-35	-37	-86	-87

NOTE: It should be noted that not all these highest (or lowest) temperatures at various altitudes occurred simultaneously nor necessarily at the same location and the set of values given in Table 5 does not represent a specific temperature-altitude profile.

5.5 Humidity at altitude - world-wide

5.5.1 The humidities, expressed in terms of dew points, which, in an average year, are exceeded for a total of 7.4 hours during the most humid month at various altitudes up to 8 km are quoted in Table 6 together with the highest values ever recorded.

TABLE 6
HUMIDITY AT ALTITUDE - WORLDWIDE

Altitude km	1% high humidity occurrence level of dew point °C	Highest recorded dew point occurrence level °C
0	31	34
1	29	30
2	24	26
4	16	18
6	3	3
8	-8	-7

5.6 Direct solar radiation at altitude

5.6.1 Although the thermal effect of direct solar radiation at altitude is somewhat greater than at sea level, for the purpose of this chapter the values that apply at sea level are also taken to apply at altitude.

TABLE 7
DIURNAL CYCLE FOR CATEGORY `A` ENVIRONMENTAL CONDITIONS

	METEOROLOGICAL CONDITIONS									TRANSIT AND STORAGE CONDITIONS		
Category	A1			A2			A3			A1	A2	A3
Local Time Hours	Ambient Air Temperature °C	Relative Humidity %	Solar Radiation W/m²	Ambient Air Temperature °C	Relative Humidity %	Solar Radiation W/m²	Ambient Air Temperature °C	Relative Humidity %	Solar Radiation W/m²	Induced Air Temperature °C	Induced Air Temperature °C	Induced Air Temperature °C
0100	35	6	0	33	36	0	30	69	0	35	33	31
0200	34	7	0	32	38	0	29	72	0	34	32	29
0300	34	7	0	32	43	0	29	74	0	34	32	29
0400	33	8	0	31	44	0	28	76	0	33	31	28
0500	33	8	0	30	44	0	28	78	0	33	30	28
0600	32	8	55	30	44	55	28	78	45	33	31	29
0700	33	8	270	31	41	270	29	74	170	36	34	31
0800	35	6	505	34	34	505	30	67	500	40	38	35
0900	38	6	730	37	29	730	31	29	800	44	42	40
1000	41	5	915	39	24	915	34	51	960	51	45	44
1100	43	4	1040	41	21	1040	36	47	1020	56	51	50
1200	44	4	1120	42	18	1120	37	45	1060	63	57	54
1300	47	3	1120	43	16	1120	38	44	1020	69	61	56
1400	48	3	1040	44	15	1040	38	43	915	70	63	58
1500	48	3	915	44	14	915	39	43	660	71	63	58
1600	49	3	730	44	14	730	39	44	250	70	62	56
1700	48	3	505	43	14	505	38	46	70	67	60	53
1800	48	3	270	42	15	270	37	48	15	63	57	50
1900	46	3	55	40	17	55	35	50	0	55	50	46
2000	42	4	0	38	20	0	34	53	0	48	44	41
2100	41	5	0	36	22	0	34	56	0	41	38	37
2200	39	6	0	35	25	0	32	59	0	39	35	34
2300	38	6	0	34	28	0	32	63	0	37	34	33
2400	37	6	0	33	33	0	31	66	0	35	33	32

NOTES 1 Humidities for A1, A2 and A3 storage conditions vary too widely between different situations to be represented by a single set of conditions.

2 The vapour pressure in hot dry areas will vary according to the distance from the sea or other large expanse of water, but is likely to be within the range 3 to 12 mbars for category A1 and 12 to 25 mbars for category A2. The diurnal variation is likely to exceed 3 mbars for category A1 or 2 mbars for category A2.

TABLE 8
DIURNAL CYCLE FOR CATEGORY `B` ENVIRONMENTAL CONDITIONS

	METEOROLOGICAL CONDITIONS									TRANSIT AND STORAGE CONDITIONS						
Category	B1			B2			B3			B1		B2		B3		
Local Time Hours	Ambient Air Temperature °C	Relative Humidity %	Solar Radiation W/m^2	Ambient Air Temperature °C	Relative Humidity %	Solar Radiation W/m^2	Ambient Air Temperature °C	Relative Humidity %	Solar Radiation W/m^2	Induced Air Temperature °C	Relative Humidity %	Induced Air Temperature °C	Relative Humidity %	Induced Air Temperature °C	Relative Humidity %
0100				27	100	0	31	88	0			33	69	35	67
0200				26	100	0	31	88	0			32	70	34	72
0300	23	88	21	26	100	0	31	88	0	23	88	32	71	34	75
0400				26	100	0	31	88	0			31	72	34	77
0500				26	100	0	31	88	0			30	74	33	79
0600				26	100	45	32	85	45			31	75	33	80
0700	23	88	21	27	94	230	34	80	315	23	88	34	64	36	70
0800				29	88	460	36	76	560			38	54	40	54
0900	28	76	23	31	82	630	37	73	790	28	76	42	43	44	42
1000				32	79	800	38	69	920			45	36	51	31
1100				33	77	900	39	65	1040			51	29	57	24
1200	31	66	24	34	75	970	40	63	1080	31	66	57	22	62	17
1300				34	74	990	41	59	1000			61	21	66	16
1400				35	74	915	41	59	885			63	20	69	15
1500	32	67	25	35	74	795	41	59	710	32	67	63	19	71	14
1600				34	76	630	41	59	460			62	20	69	16
1700				33	79	410	39	65	210			60	21	66	18
1800	29	75	24	32	82	230	37	69	15	29	75	57	22	63	21
1900				31	85	45	36	73	0			50	32	58	29
2000				29	91	0	34	79	0			44	43	50	41
2100	26	84	23	28	95	0	33	85	0	26	84	38	54	41	53
2200				28	96	0	32	85	0			35	59	39	58
2300				27	100	0	32	88	0			34	63	37	62
2400	24	22	22	27	100	0	31	88	0	24	88	33	68	35	63

NOTES 1 The meteorological, storage and transit conditions quoted for Category B1 relates to 358 days per year. For the other 7 days, the ambient and induced air temperatures at 24 °C, relative humidity at 100%, and the dew point at 24 °C are nearly constant throughout the 24 hours

2 The solar radiation may be considered as negligible for the diurnal cycles quoted for Category B1, both for the 7 day period and for the remaining 358 days of the year

TABLE 9
DIURNAL CYCLE FOR CATEGORY `M` ENVIRONMENTAL CONDITIONS

	METEOROLOGICAL CONDITIONS							TRANSIT AND STORAGE CONDITIONS				
Category	M1			M2			M3	M1		M2		M3
Local Time Hours	Ambient Air Temperature °C	Relative Humidity %	Solar Radiation W/m^2	Ambient Air Temperature °C	Relative Humidity %	Solar Radiation W/m^2	Ambient Air Temperature °C	Induced Air Temperature °C	Relative Humidity %	Induced Air Temperature °C	Relative Humidity %	Induced Air Temperature °C
0100	32.5	51	0	26.5	100	0		32	52	33	71	
0200	31.5	53	0	26.5	100	0		31	56	32	73	
0300	31	55	0	26	100	0	-34	31	56	32	70	-34
0400	29.5	60	0	26	100	0		30	58	31	75	
0500	29	64	0	25.5	100	0		30	60	30	78	
0600	29	67	55	26	100	45	-34	30	64	31	75	
0700	31.5	61	270	28	90	170		33	56	34	63	-34
0800	34.5	51	505	29.5	82	470		38	42	38	51	
0900	38	38	730	31	74	710	-28	42	31	42	40	-28
1000	40.5	32	915	32.5	70	920		48	22	45	36	
1100	43	28	1040	33.5	67	1040		53	18	51	27	
1200	47.5	25	1120	34	63	1080	-23	61	12	57	20	-23
1300	46.5	22	1120	35	58	1040		67	9	61	16	
1400	48	21	1040	35	55	930		68	8	63	13	-23
1500	48	21	915	35	54	710	-23	69	8	63	13	
1600	47.5	23	730	34	57	470		68	9	62	14	
1700	46.5	27	505	33	62	190		65	11	60	15	
1800	45	33	270	32	71	15		61	15	57	20	-26
1900	42.5	37	55	30	77	0	-26	53	20	50	26	
2000	40.5	41	0	29	82	0		45	32	44	36	
2100	38	43	0	28	88	0	-31	40	39	38	51	-31
2200	36.5	45	0	27.5	90	0		36	45	35	60	
2300	35	47	0	27.5	92	0		34	50	34	63	
2400	34	49	0	27	94	0	-34	33	51	33	67	-34

NOTES 1 The relative humidity tends to saturate at all the ambient and induced air temperatures quoted for category M3

2 Solar radiation may be considered as negligible for the diurnal cycles quoted for Category M3

TABLE 10
DIURNAL CYCLE FOR CATEGORY 'C' ENVIRONMENTAL CONDITIONS

	METEOROLOGICAL CONDITIONS			TRANSIT AND STORAGE CONDITIONS		
Category	C0	C1	C2	C0	C1	C2
Local Time Hours	Ambient Air Temperature °C	Ambient Air Temperature °C	Ambient Air Temperature °C	Induced Air Temperature °C	Induced Air Temperature °C	Induced Air Temperature °C
0300	-19	-32	-46	-21	-33	-46
0600	-19	-32	-46	-21	-33	-46
0900	-15	-26	-43	-19	-33	-43
1200	-8	-21	-37	-12	-28	-37
1500	-6	-21	-37	-10	-25	-37
1800	-10	-25	-39	-14	-29	-39
2100	-17	-28	-43	-19	-32	-43
2400	-19	-32	-45	-21	-33	-45

NOTES: 1 The ambient and induced air temperatures are nearly constant at -51°C for category C3 and -57°C for category C4 throughout the 24 hours.

2 The storage temperatures are slightly lower than the corresponding meteorological temperature as storage shelters are often better radiators to the night sky than either the ambient air or the ground.

3 The relative humidity tends to saturate at all the ambient and induced air temperatures quoted for categories C0 to C4.

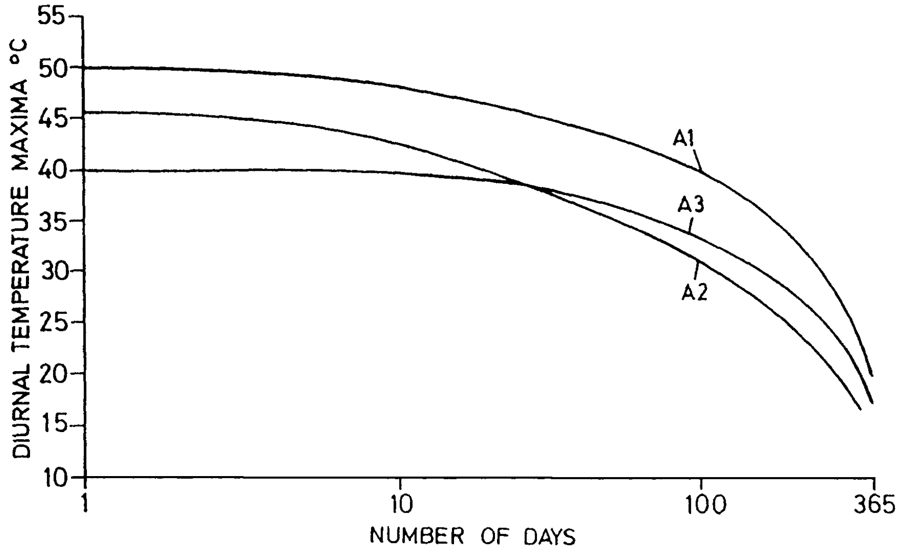
4 Solar radiation may be considered negligible for the diurnal cycles quoted for categories C0 to C3 and there is none for category C4.

TABLE 11
ADDITIONAL NOTES ON ENVIRONMENTAL CATEGORIES

General Notes on 'B' Categories	
B1	The meteorological conditions are derived from those recorded in Singapore. As direct solar radiation is negligible, the same set of values is given for storage conditions. Trials should be based on 7 days of saturation at 24°C, and the temperature and humidity cycles of the remaining 358 days.
B2	Meteorological conditions are derived from the Gulf of Mexico coastal stations and subsequently confirmed by observation in other tropical areas. Although higher temperatures and humidities are known to occur, they rarely do so simultaneously. The storage temperatures are defined as equal to those of the A2 storage condition to take into account the relatively high ambient air temperatures and direct solar radiation which can occur when clear skies prevail.
B3	Meteorological conditions are derived from Dharan and other hot, humid stations. Other notes as for B2 above, but with A1 substituted for A2.

General Notes on 'C' Categories	
C0	Meteorological conditions are derived from the coldest 5 - 10% of the European weather stations.
C1	Meteorological conditions are based on the coldest period of the year in North Dakota, USA and Southern Alberta, Canada.
C2	Meteorological conditions are based on several of the colder locations in Canada.
C3	As the coldest days are really long nights, the temperature is constant throughout the 24 hours. The storage cycle is the same as the meteorological conditions as there is sufficient time for temperature equilibrium to be established.
C4	As for the C3 case.

General Notes on 'M' Categories	
M2	Although higher temperatures and humidities are known to occur, they rarely do so simultaneously.
M3	The storage condition is the same as for the meteorological condition because in these conditions of low radiation there is sufficient time for temperature equilibrium to be established.



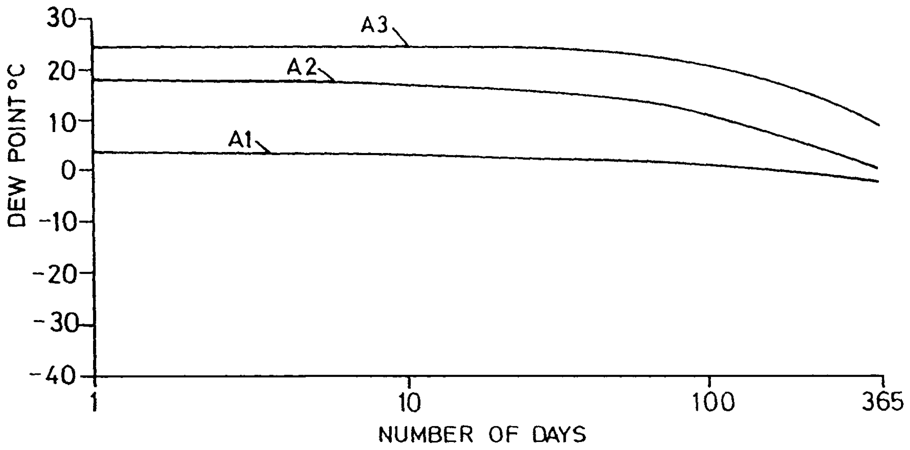


Figure 1

The number of days of the year on which, on average, a given temperature is just attained or exceeded, together with the corresponding dew points, for the A1, A2 and A3 meteorological conditions. The corresponding diurnal temperature cycle is obtained from Table 7.

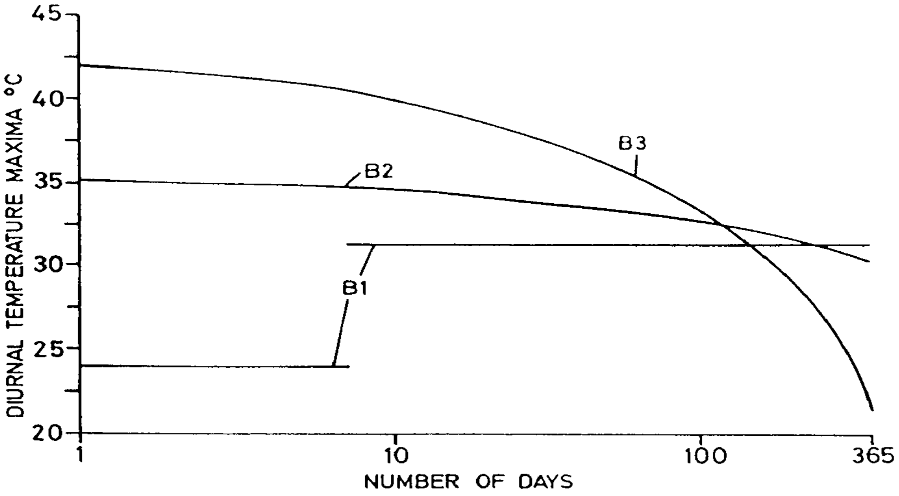


Figure 2

The number of days of the year on which, on average, a given temperature is just attained or exceeded, for the B1, B2 and B3 meteorological conditions. The associated diurnal temperature cycles and corresponding dew points or relative humidities are obtained from Table 8.

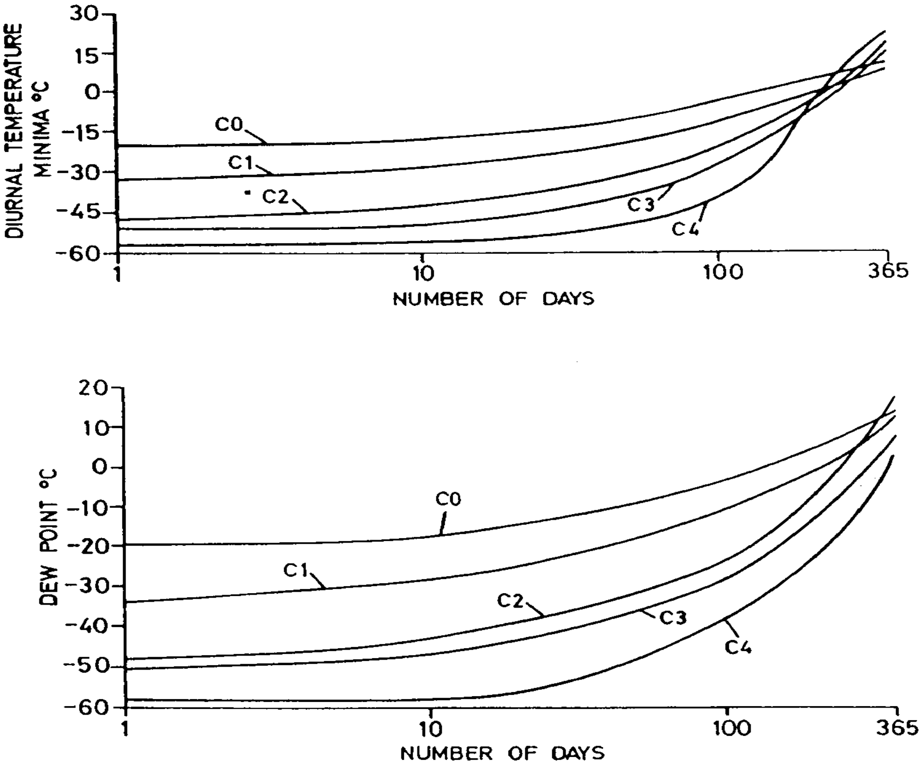


Figure 3

The number of days of the year on which, on average, a given minimum temperature is not exceeded, together with the corresponding dew points, for the C0, C1, C2, C3 and C4 meteorological conditions. The associated diurnal temperature cycle is obtained from Table 10.

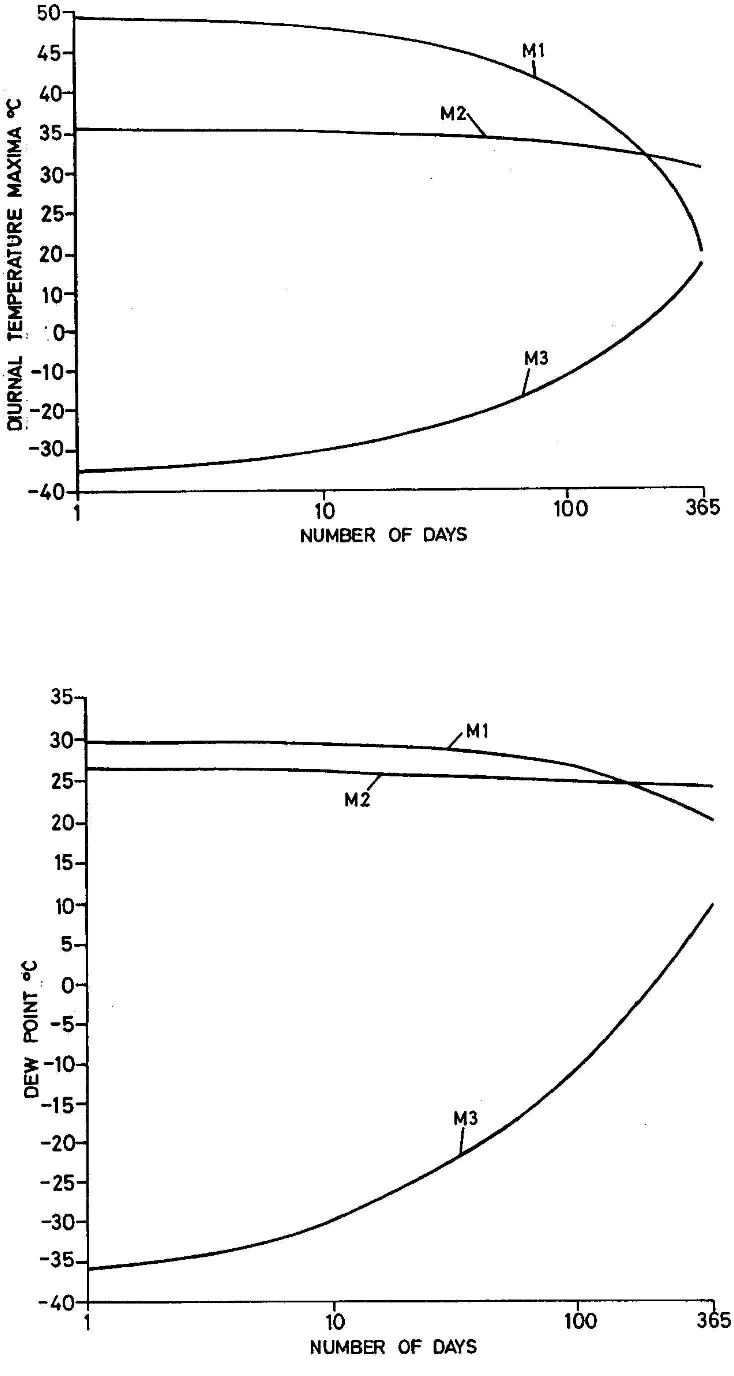


Figure 4

The number of days of the year on which, on average, a given temperature is just attained or exceeded or in the case of Category M3 a given minimum temperature is not exceeded, together with the corresponding dew points, for the M1, M2 and M3 meteorological conditions. The associated diurnal temperature cycles are obtained from Table 9.

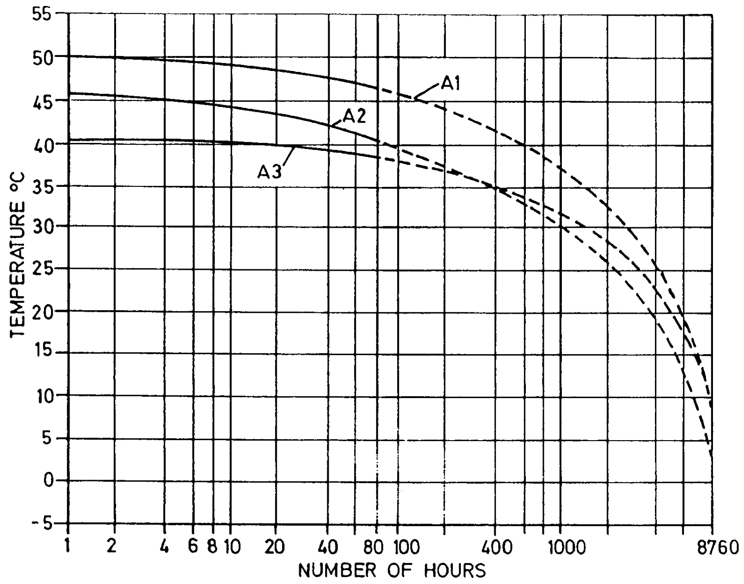


Figure 5

The number of hours in each year for which the air temperature just reaches or goes above a given value in the A1, A2 and A3 meteorological conditions. Computed from the information supplied at Figure 1 and Table 7.

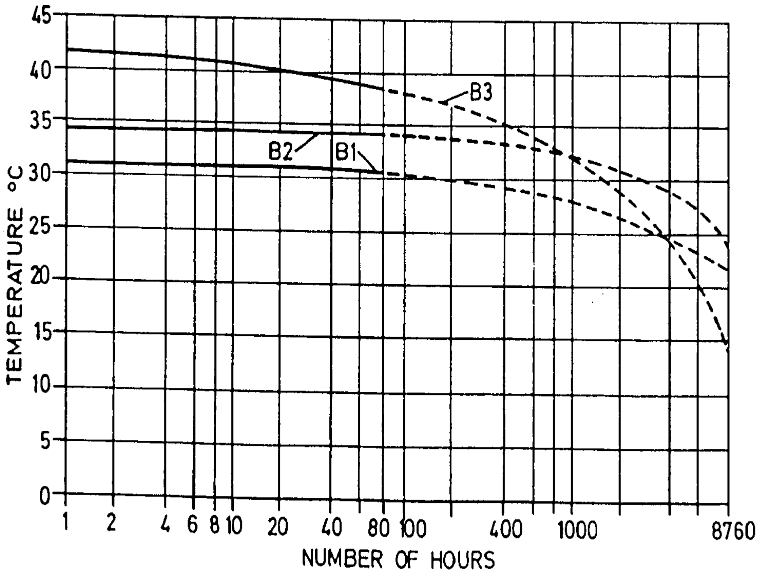


Figure 6

The number of hours in each year for which the air temperature just reaches or goes above a given value in the B1, B2 and B3 meteorological conditions. Computed from the information supplied at Figure 2 and Table 8.

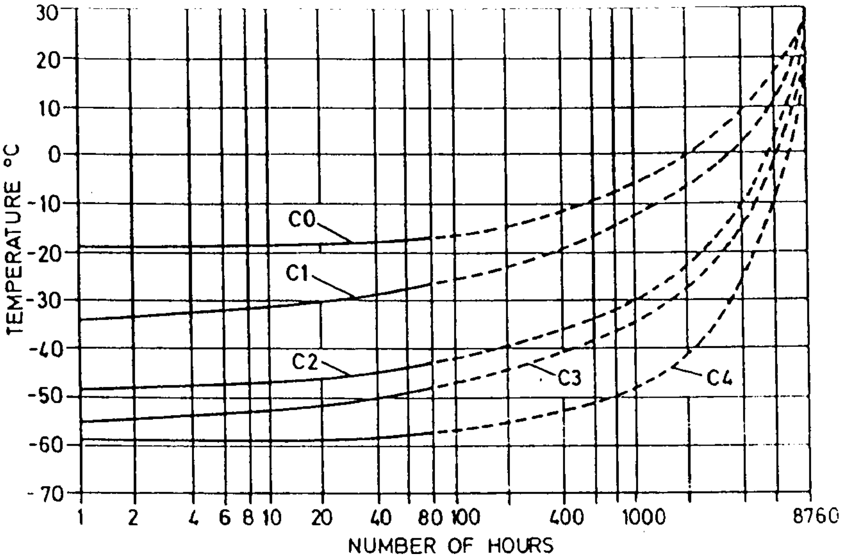


Figure 7

The number of hours in each year for which the air temperature just reaches or goes below a given value in the C0, C1, C2, C3 and C4 meteorological conditions. Computed from the information supplied at Figure 3 and Table 10.

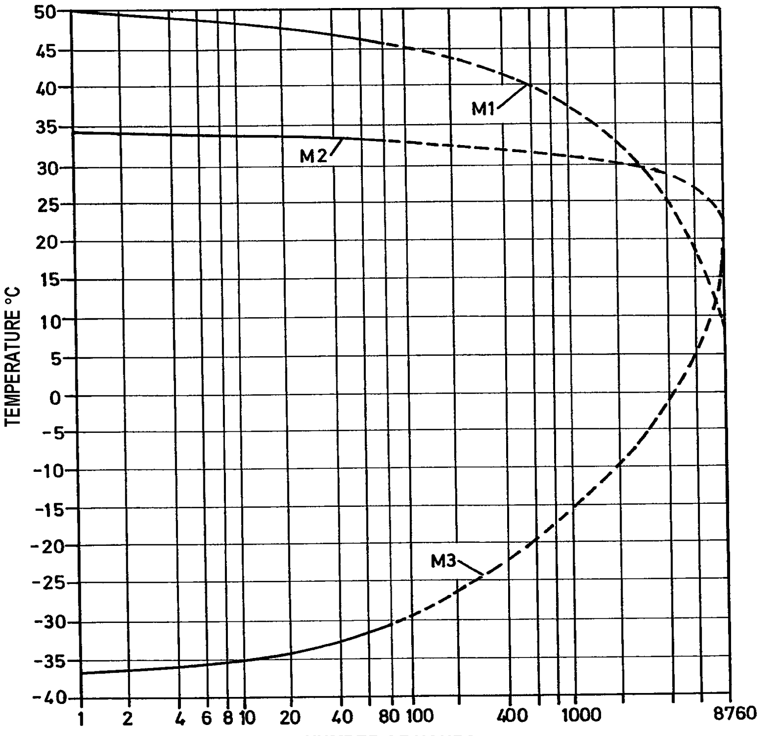


Figure 8

The number of hours in each year for which the air temperature just reaches or goes above a given value, or in the case of Category M3 a minimum temperature is not exceeded, in the M1, M2 and M3 meteorological conditions. Computed from the information supplied at Figure 4 and Table 9.

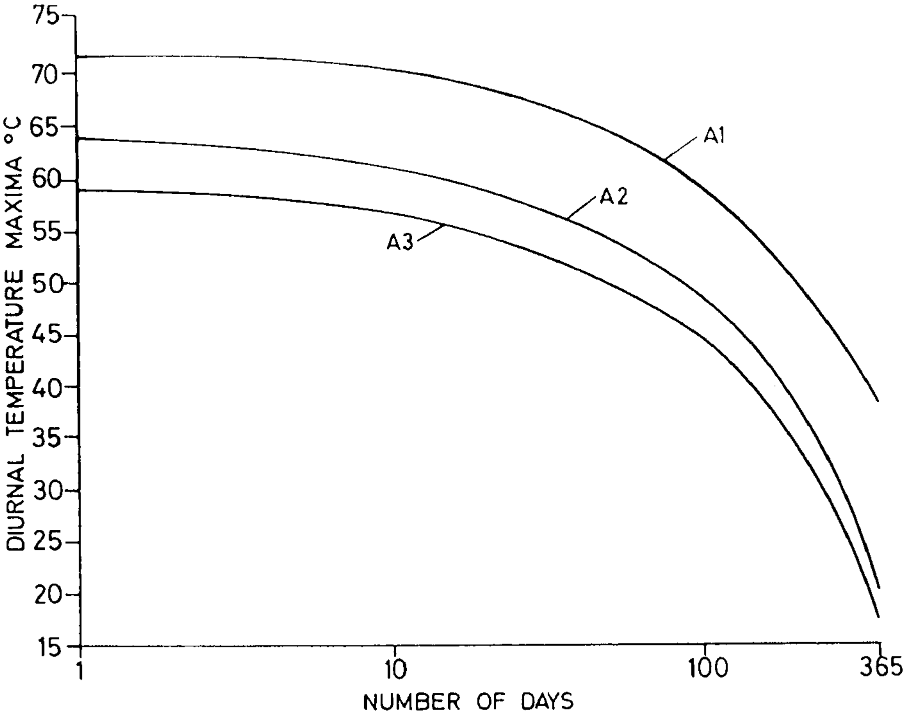


Figure 9

Distribution of the maxima of the diurnal temperature cycles for the year, for the A1, A2 and A3 storage conditions. The associated diurnal temperature cycle is obtained from Table 7.

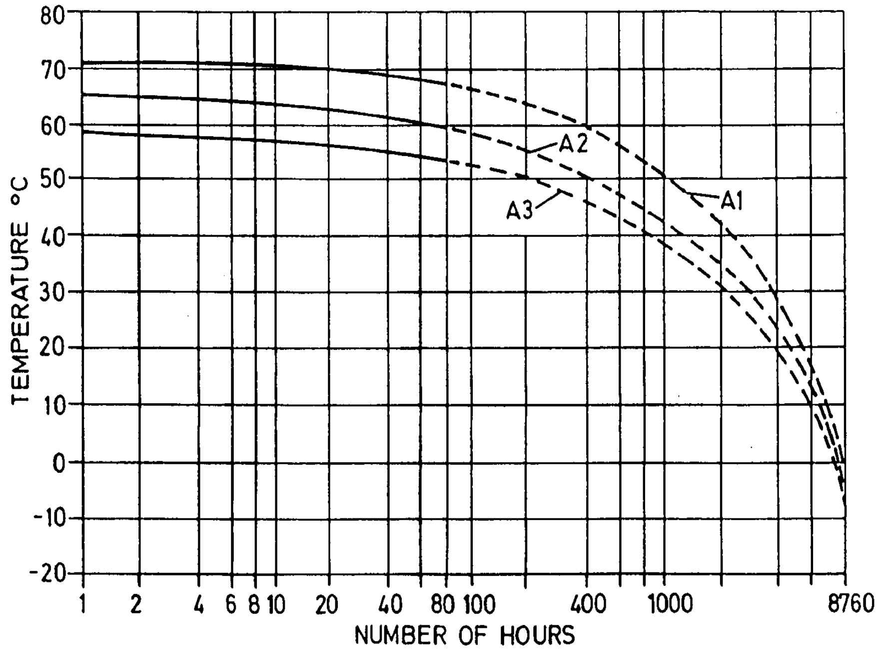


Figure 10

Number of hours in each year for which the air temperature just reaches or goes below a given value in the A1, A2 and A3 meteorological conditions. Computed from the information supplied at Figure 9 and Table 7.

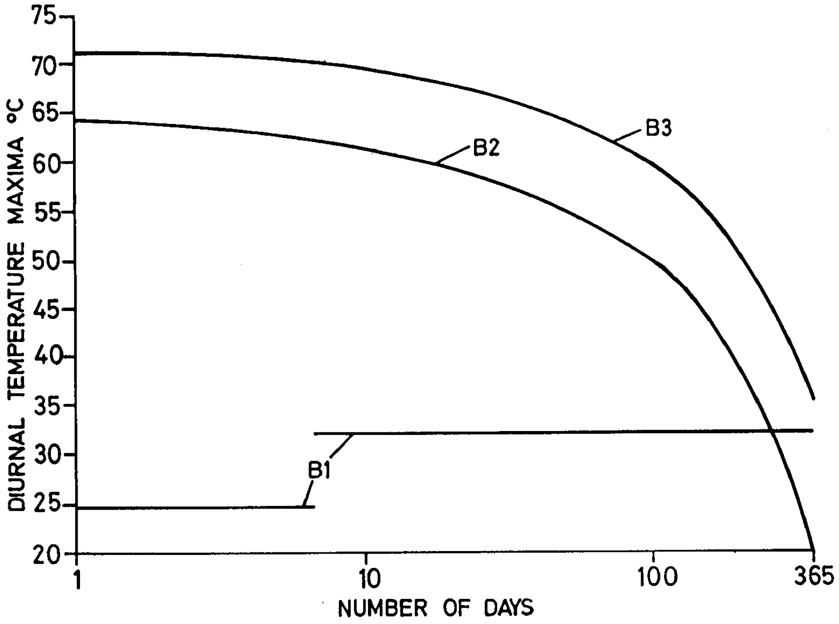


Figure 11

Distribution of the maxima of the diurnal temperature cycles for the year, for the B1, B2 and B3 storage conditions. The associated diurnal temperature cycles are obtained from Table 8.

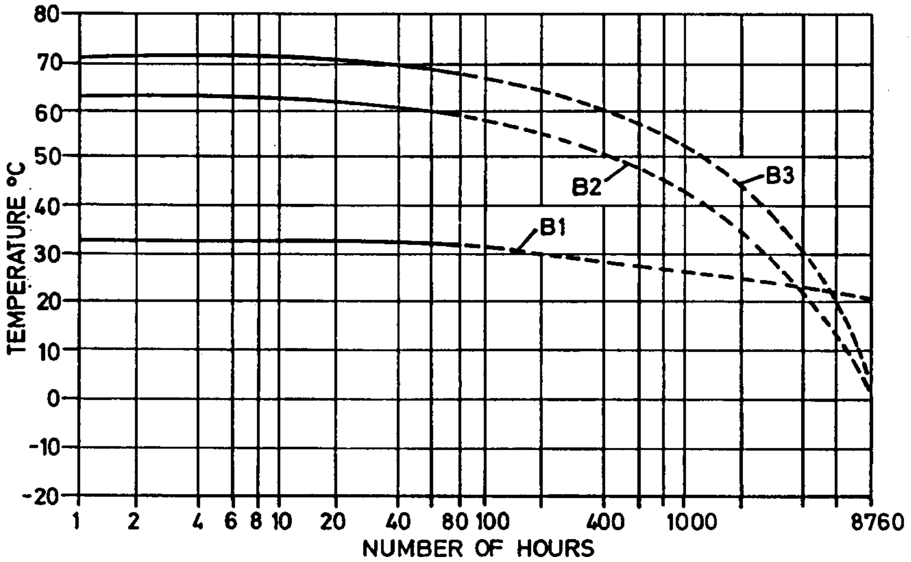


Figure 12

Number of hours in each year for which the air temperature just reaches or goes above a given value in the B1, B2 and B3 storage conditions. Computed from the information supplied at Figure 11 and Table 8.

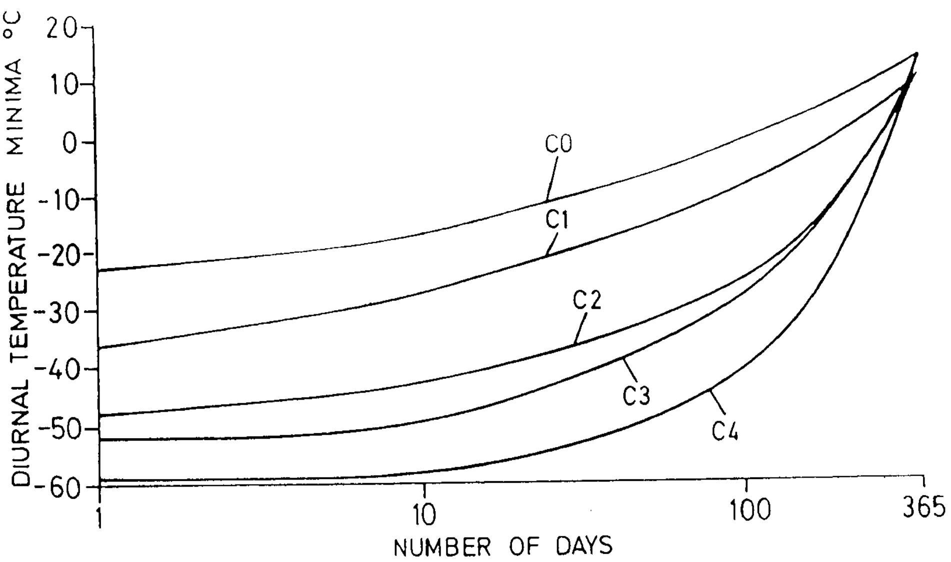


Figure 13

Distribution of the minima of the diurnal temperature cycles for the year, for the C0, C1, C2, C3 and C4 storage conditions. The associated diurnal temperature cycles are obtained from Table 10.

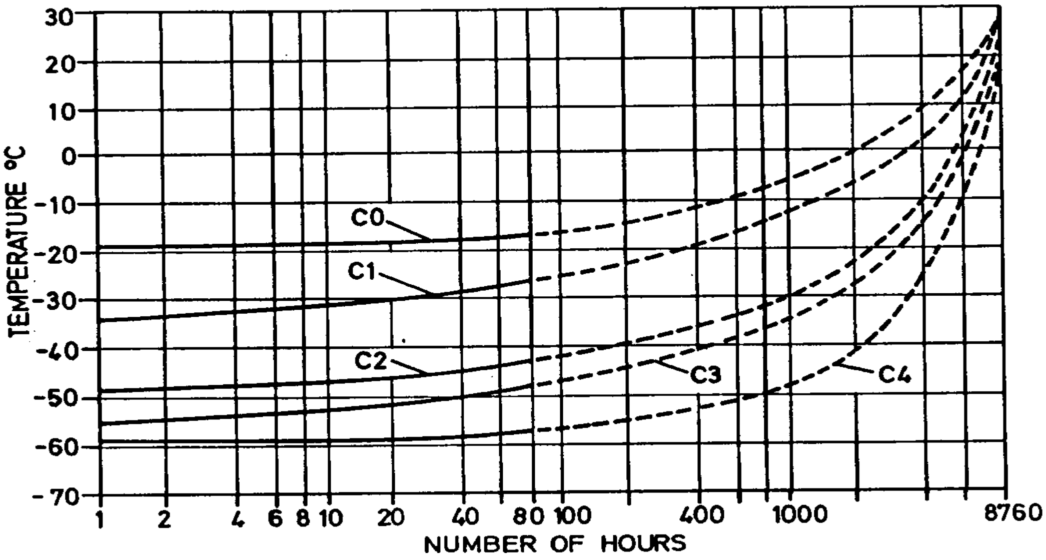


Figure 14

Number of hours in each year for which the air temperature just reaches or goes below a given value in the C0, C1, C2, C3 and C4 storage conditions. Computed from the information supplied at Figure 13 and Table 10.

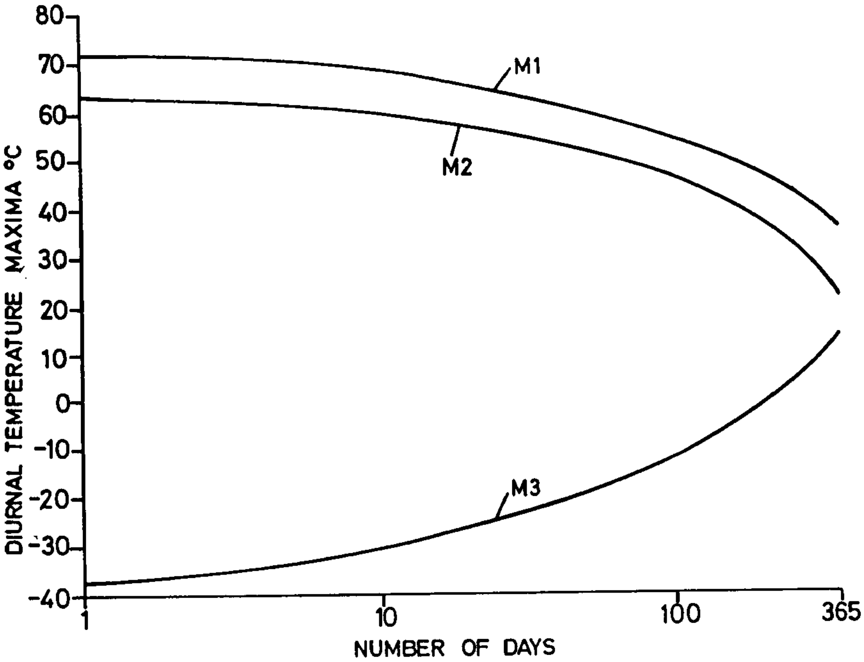


Figure 15

Distribution of the maxima or minima of the diurnal temperature cycles for the year, for the M1, M2 and M3 storage conditions. The associated diurnal temperature cycles are obtained from Table 9.

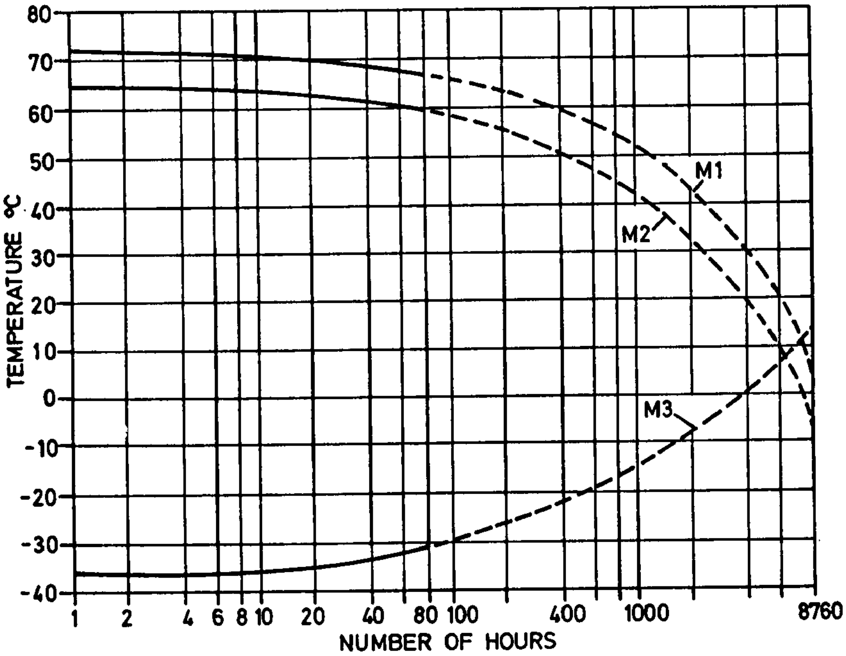


Figure 16

Number of hours in each year for which the air temperature just reaches or goes above, or in the case of Category M3 does not exceed a minimum given value in the M1, M2 and M3 storage conditions. Computed from information supplied at Figure 15 and Table 9.

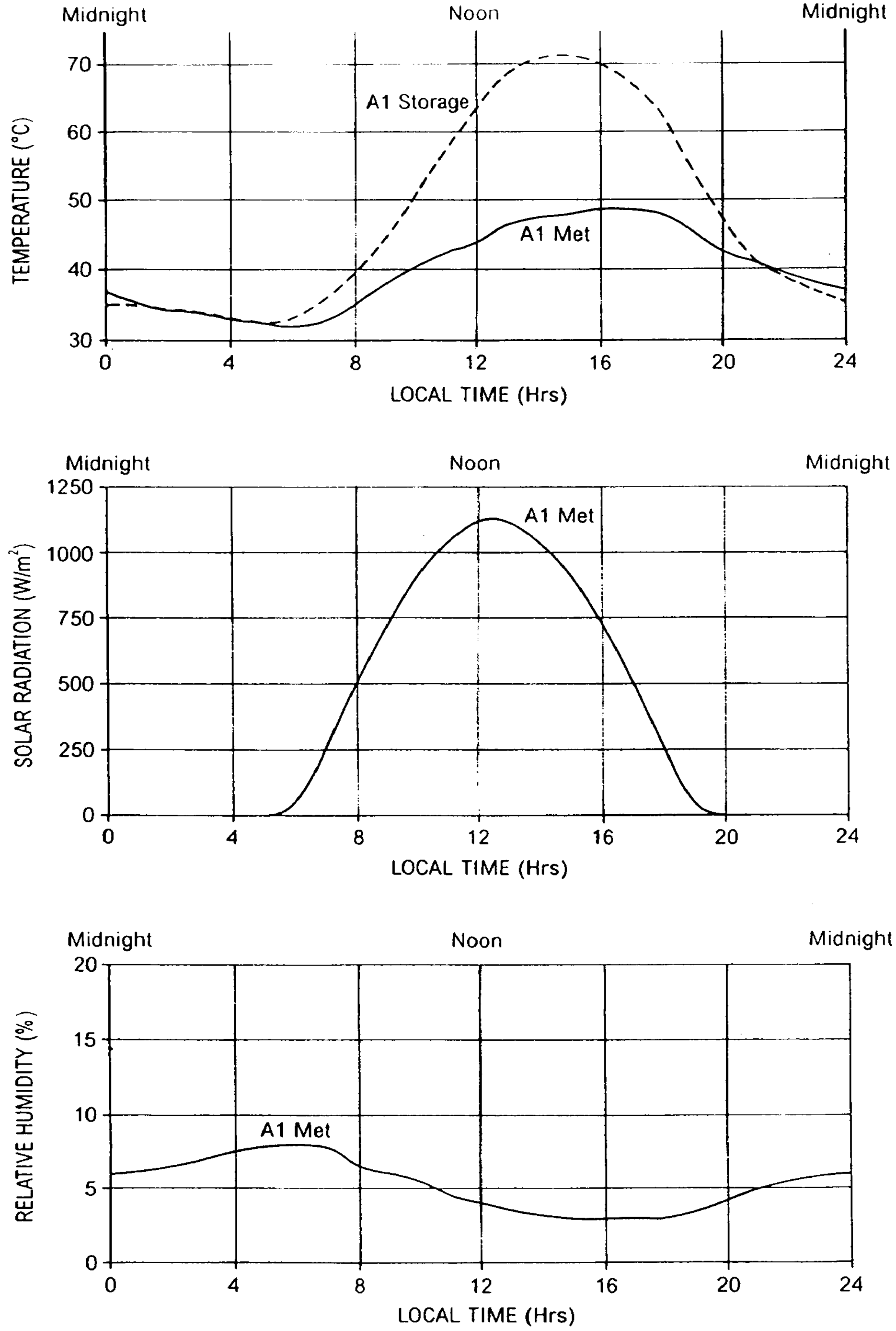


Figure 17 Diurnal Cycles for Climatic Category A1

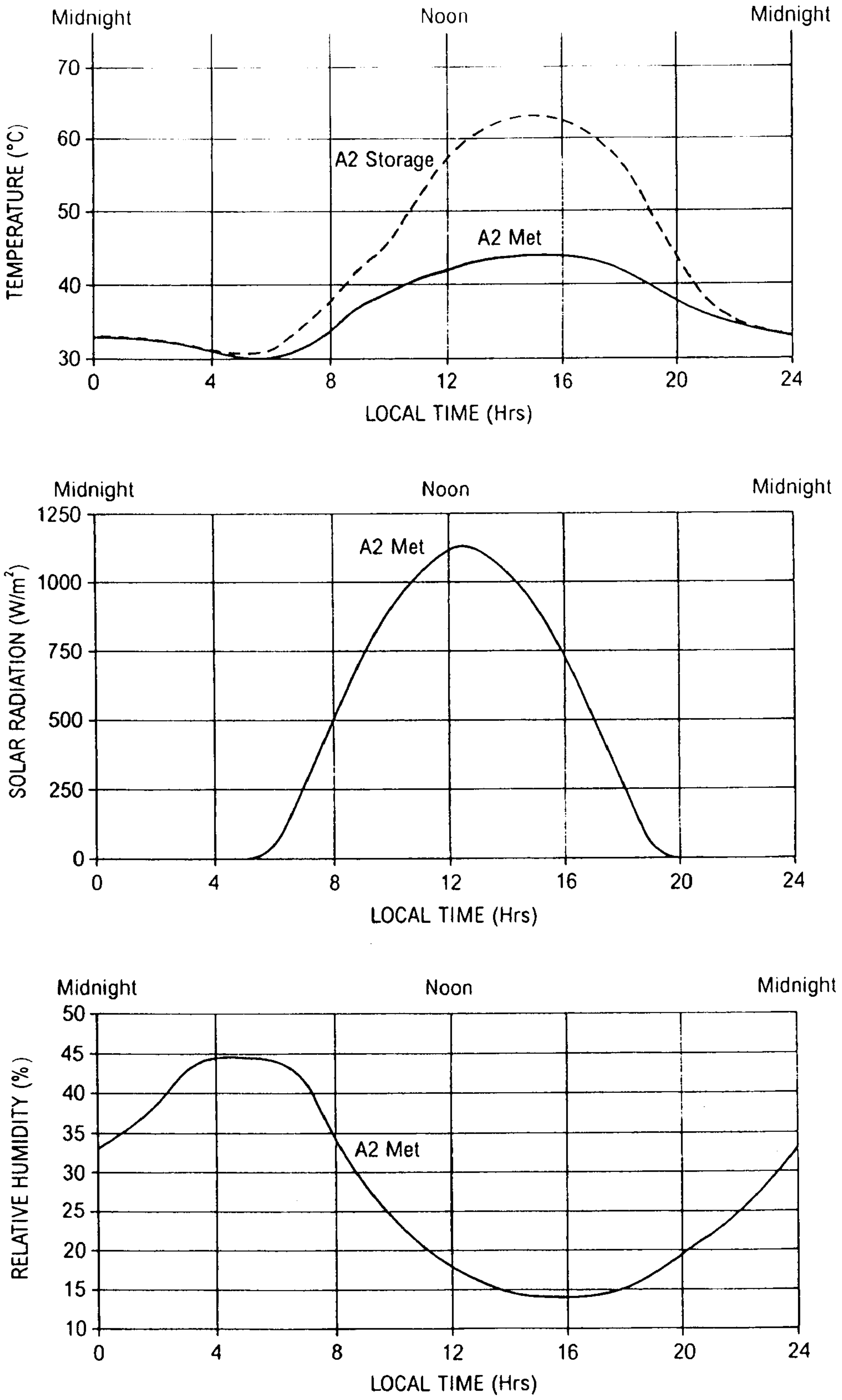


Figure 18 Diurnal Cycles for Climatic Category A2

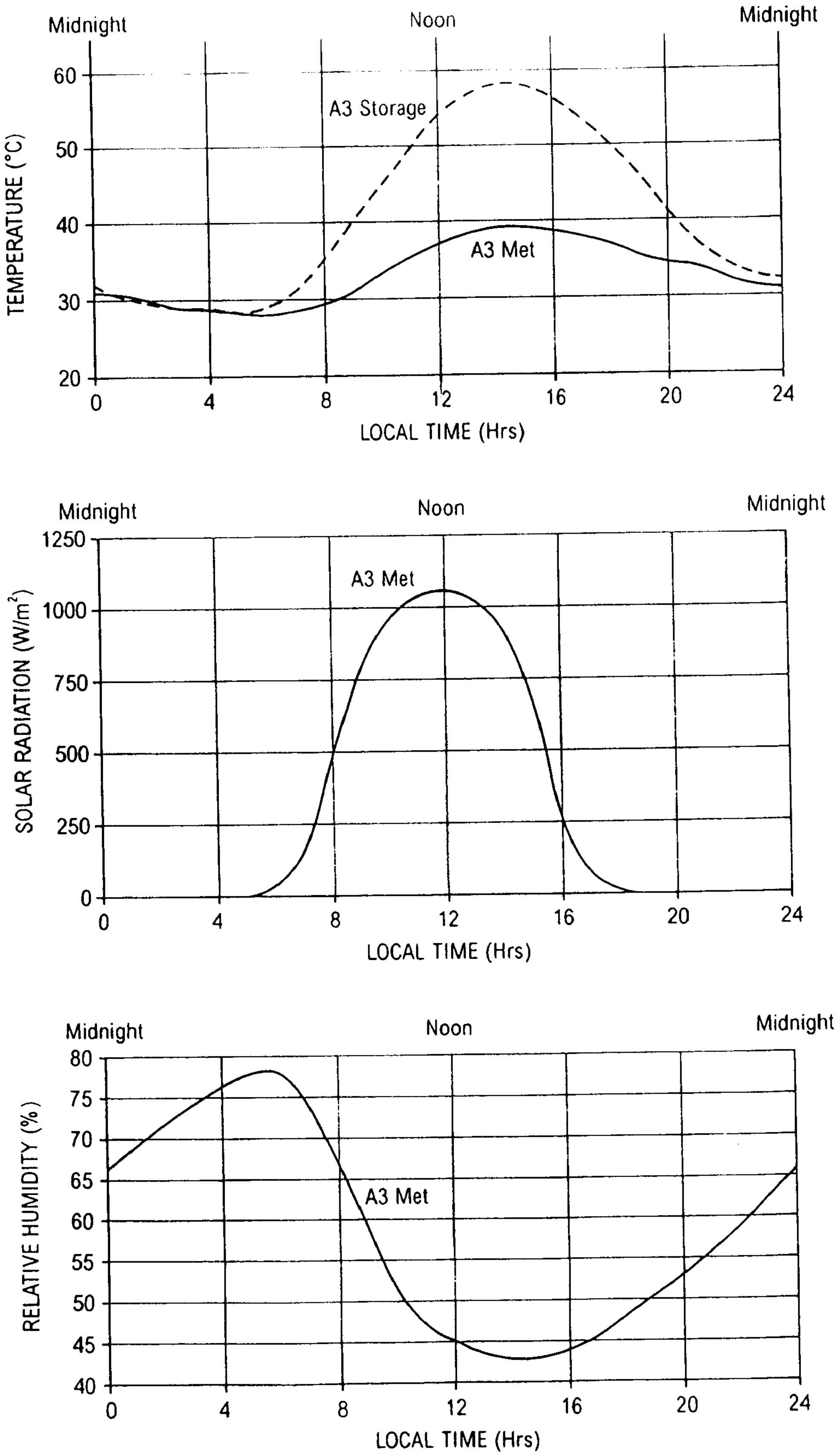
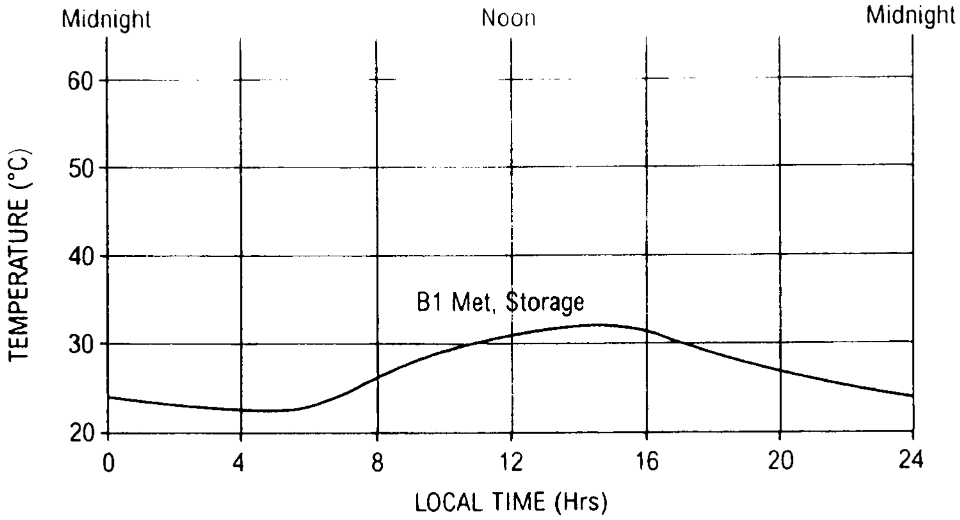


Figure 19 Diurnal Cycles for Climatic Category A3



Solar radiation for Zone B1
can be considered negligible

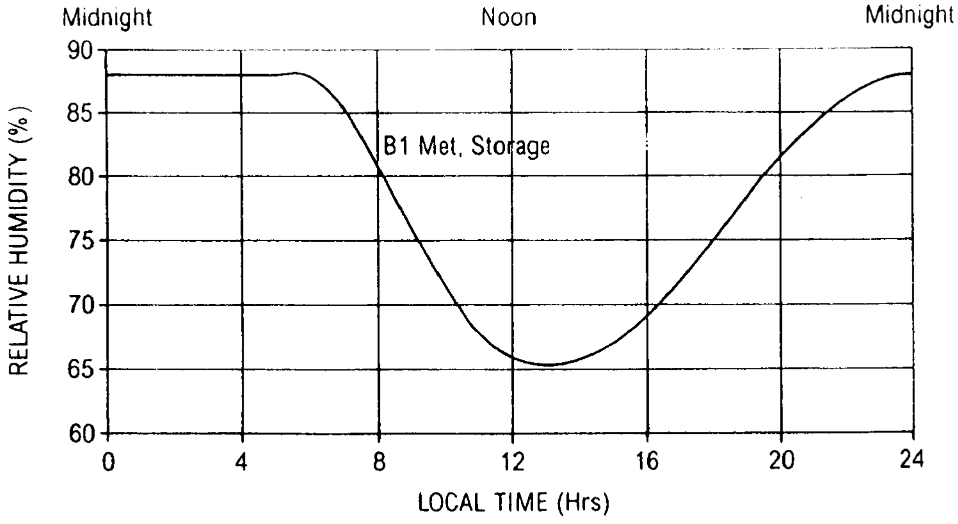


Figure 20 Diurnal Cycles for Climatic Category B1

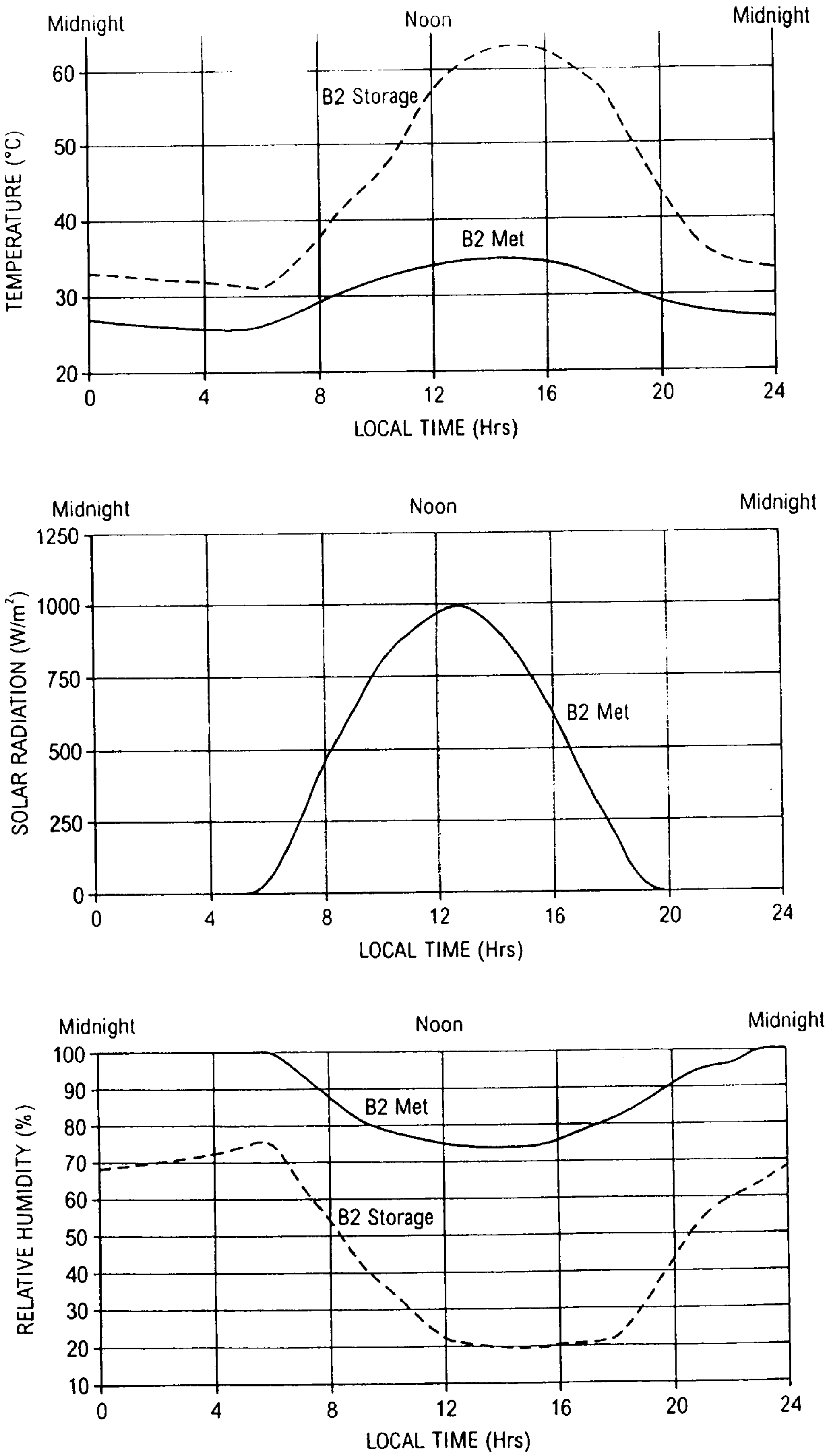


Figure 21 Diurnal Cycles for Climatic Category B2

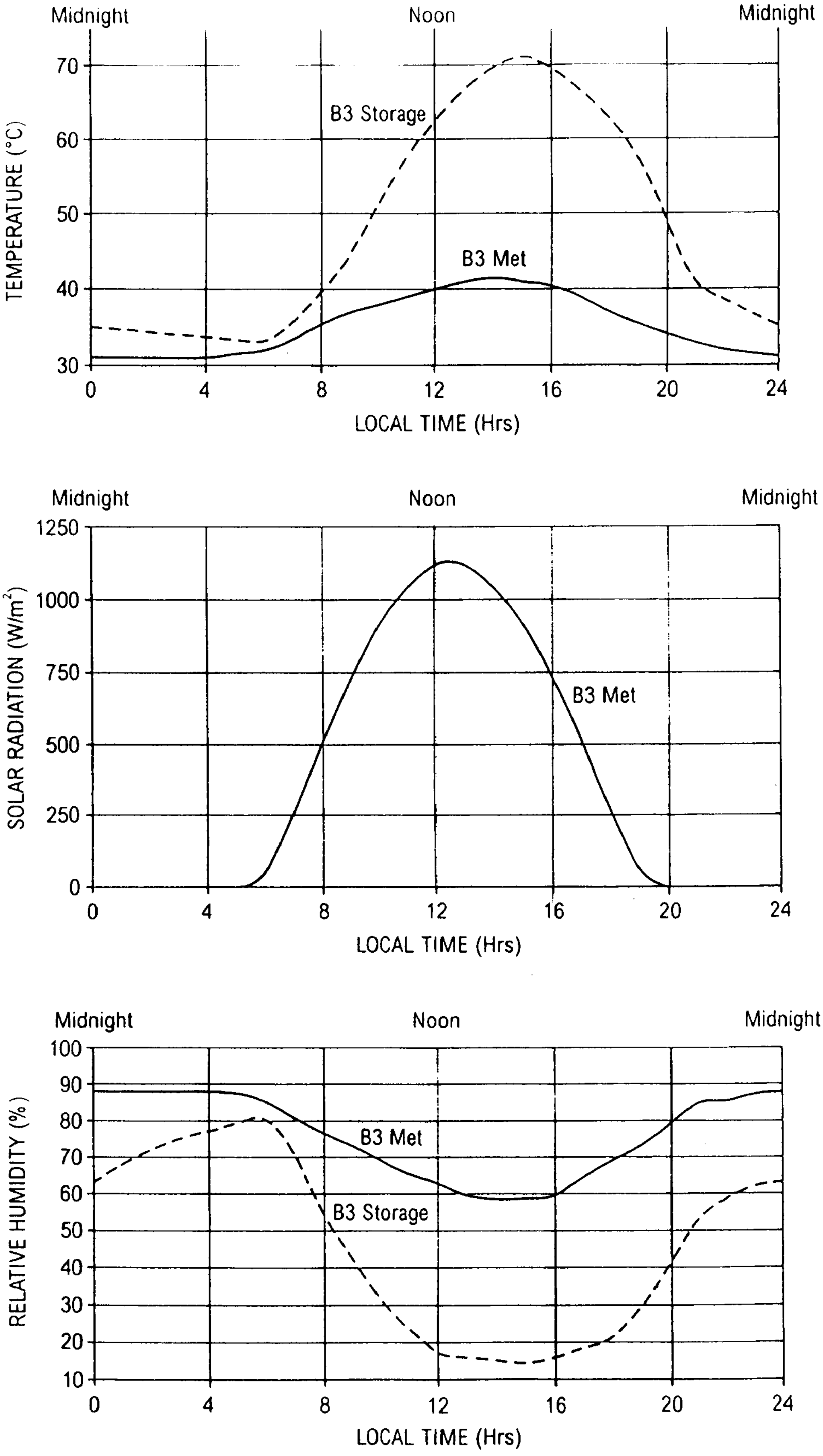


Figure 22 Diurnal Cycles for Climatic Category B3

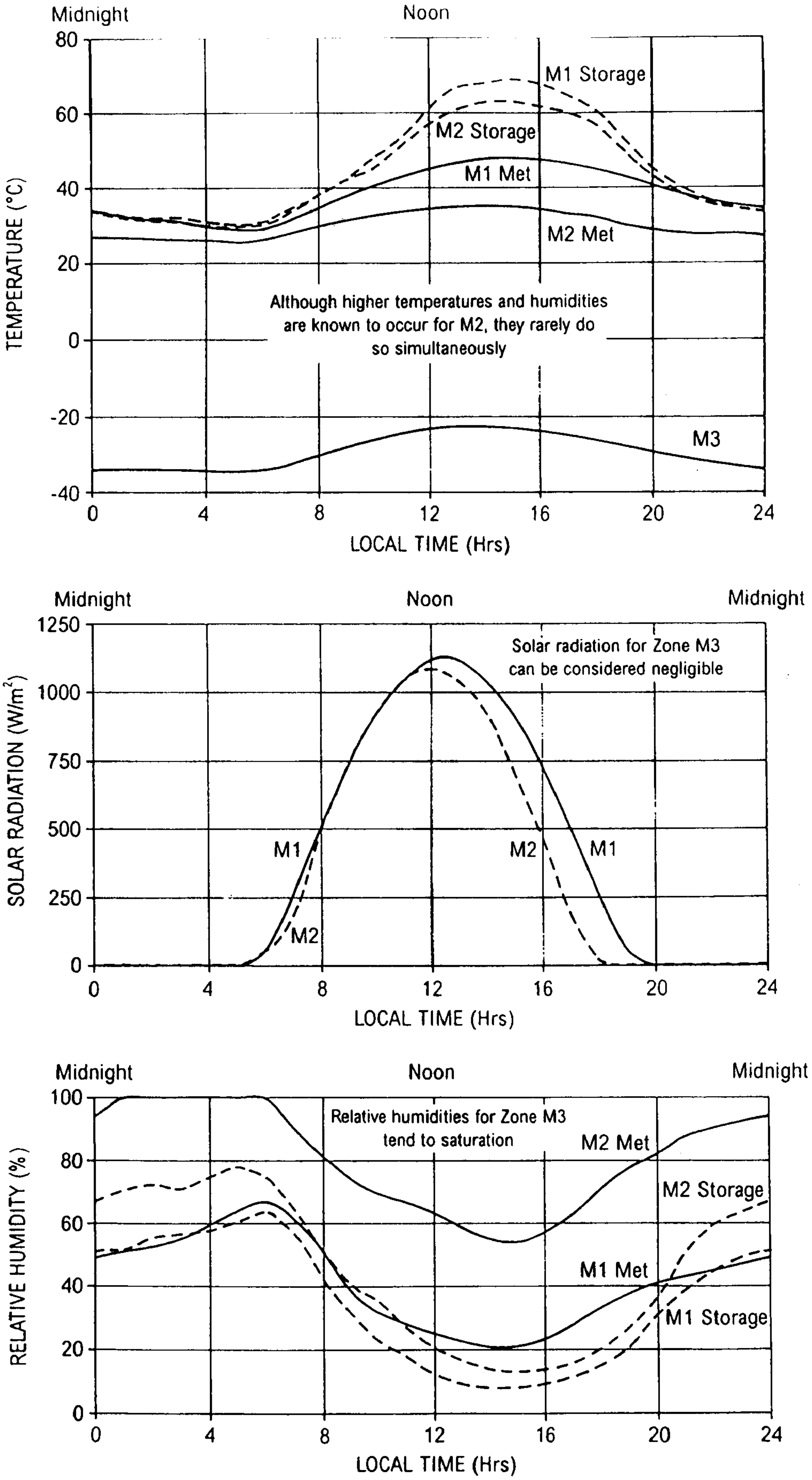
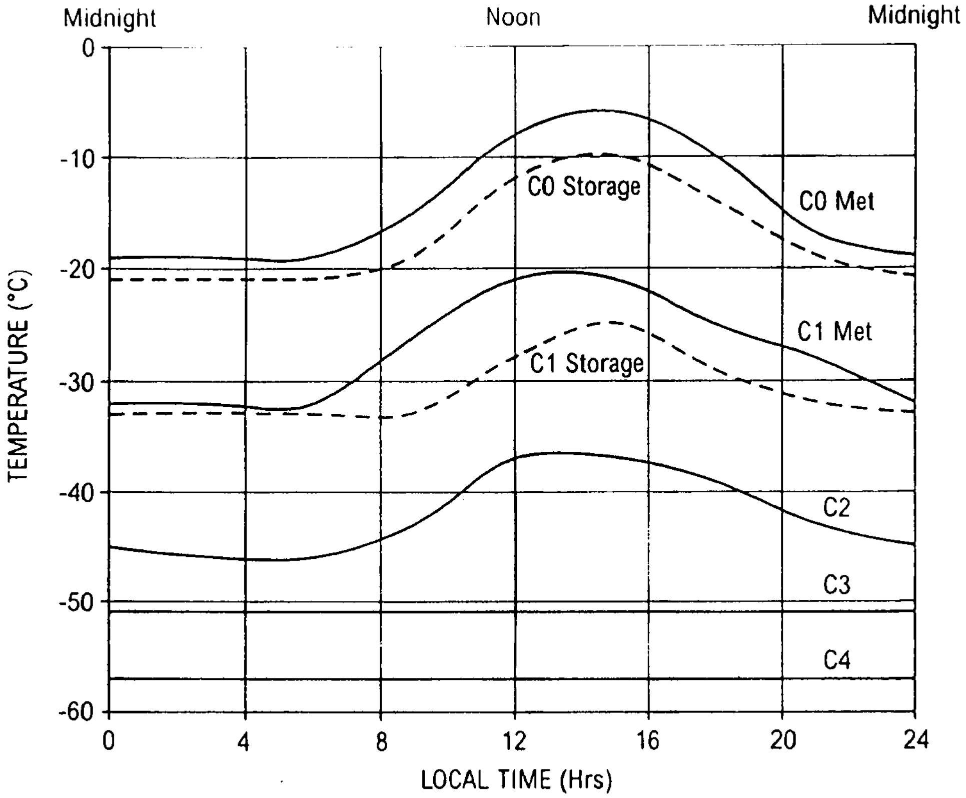


Figure 23 Diurnal Cycles for Climatic Categories M1, M2 & M3



Solar radiation can be considered
negligible for Zones C0 to C3
and zero for C4

C0, C1, C2, C3, & C4 tend to saturation

Figure 24 Diurnal Cycles for Climatic Categories C0, C1, C2, C3 & C4

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CHAPTER 2-01
TEMPERATURE

1 INTRODUCTION

1.1 This chapter considers natural, free air temperatures and the temperature of surface sea-water. Air temperatures inside buildings or confined spaces and inside equipments are covered in Part 5.

1.2 The temperature of the air varies at different times and from place to place. The variation of temperature with change of height is especially important, and changes can be quite significant in the first few metres above ground. Reported temperatures are usually those measured at a standard height and the World Meteorological Organisation has recommended a standard height of 1.25 to 2 metres.

1.3 In this chapter attention will be concentrated on temperatures at the standard height. Apart from the large temperature gradients (positive and negative) occurring near the ground, temperature usually decreases with height above sea level and, where necessary, correction should be made for this effect. The correction factor is equal to -0.5°C per 100 metres and may be used for stations up to 2500 metres above sea level. It is a linear approximation to the two stage profile (constant temperature then decrease) of paragraph 5.2.1 in Chapter 1-02.

1.4 Temperatures in the upper air are discussed briefly at the end of the chapter. The upper air, in this context, is considered to be free air above the immediate effects of any land or sea surface.

2 DISTRIBUTION OF TEMPERATURE

2.1 Distribution of mean temperature

2.1.1 Figure 1 presents the distribution of average annual temperature, reduced to sea level, over the world. Features worthy of note include:

(a) The wide belt of uniformly high temperatures between latitudes 20°N and 20°S.

(b) Isotherms in the Southern Hemisphere running almost due W-E over the oceans.

(c) Low temperatures over the eastern parts of Asia and North America where the extremely cold winters have more effect than the comparatively warm summers.

(d) The warm area between Iceland and Scandinavia, where the North Atlantic Drift flows towards the Arctic Ocean.

2.2 Standard deviation of temperature

2.2.1 Temperatures measured routinely are generally found to conform well with normal distribution, over the greater part of the temperature range. Thus, knowing the long-term mean value, Figure 1, and the standard deviation, Figure 2, it is possible to estimate the probability of occurrence of any given temperature. An example is given below:

LONDON (HEATHROW)

Given temperature 20°C
Mean annual temperature 10.1°C
Standard deviation 6.1°C
Departure of given temperatures from mean = 9.9°C
Number of standard deviations = 9.9/6.1 = 1.622 standard deviations

Reference to Figure 3 shows that 1.622 on the x-axis corresponds to 5.23% probability on the y-axis. So the probability of occurrence of 20°C or higher at Heathrow is 5%. This procedure is described more fully in many standard works of statistics.

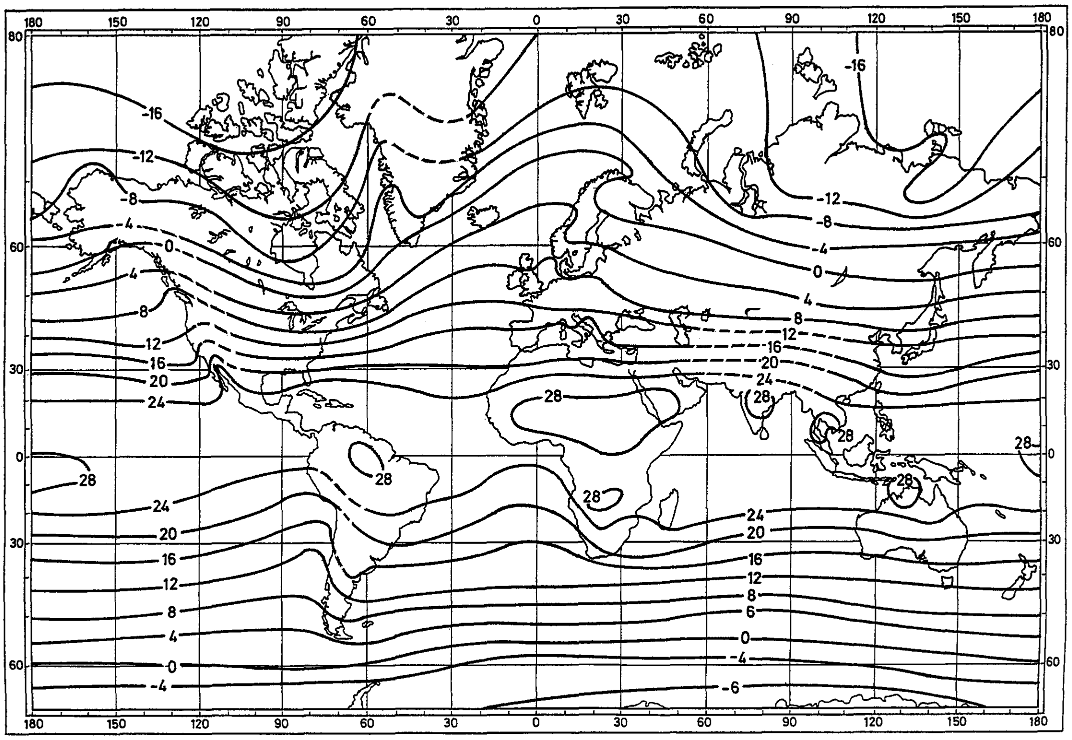

Figure 1. Average annual temperature (MSL) °C

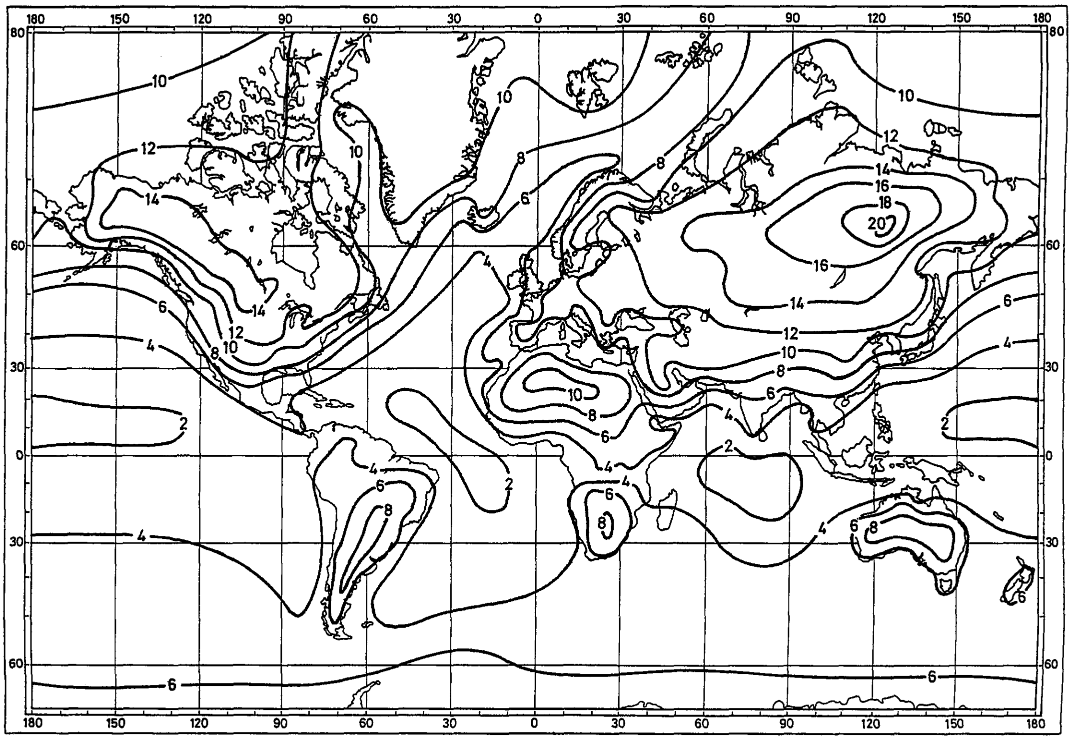

Figure 2. Standard deviation of temperature °C

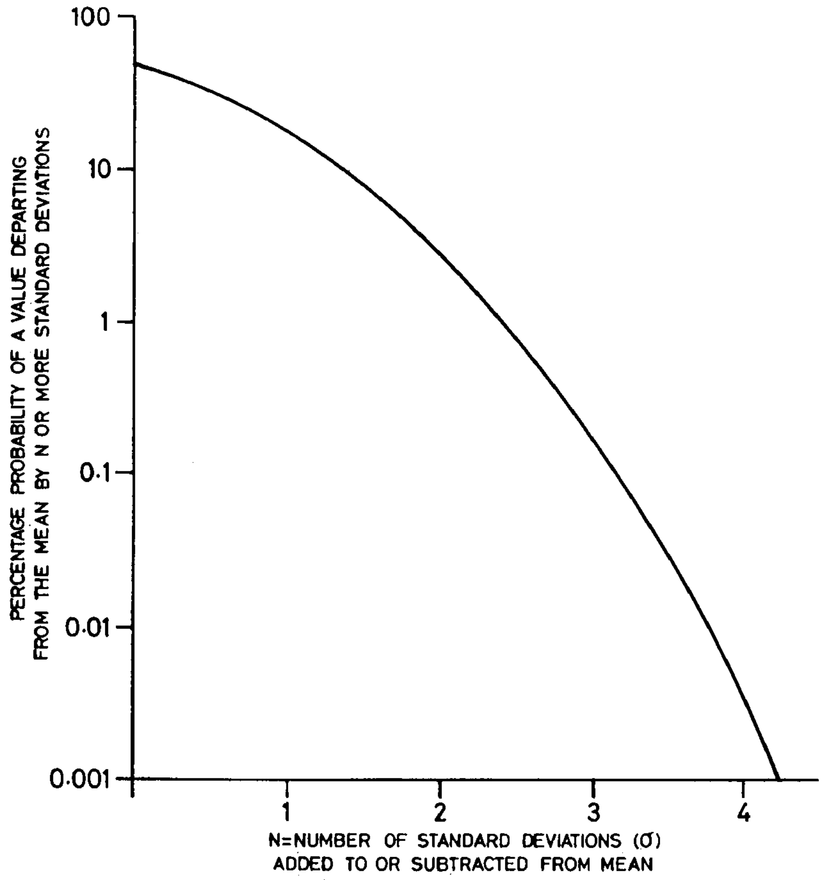

Figure 3. Relationships between probability of occurrence and standard deviation

2.2.2 The probability of occurrence of a temperature of 0°C or below has been determined by the method illustrated by the example above, and the results are depicted in Figure 4.

2.2.3 Near the extremes of the distribution, there are appreciable differences between the actual and normal distributions, especially in certain climates. These differences usually occur where large seasonal ranges of temperature are experienced, for example the interior of continents in the Northern Hemisphere away from equatorial regions.

2.2.4 Table 1 presents some examples of the differences between actual and normal distributions, for a number of stations representative of different climatic regions. It may be noted that the calculated upper two-percentile, that is the temperature not exceeded during 98% of the time, is generally 1 or 2°C above the observed value; whilst the calculated lower two-percentile, that is the temperature exceeded during 98% of the time, is usually somewhat nearer the actual value.

2.2.5 In some parts of the world, the differences between actual and normal distribution may be larger than shown in Table 1, especially where that standard deviation of temperature is itself large. Figures 5 and 6 give examples of temperature distributions for Europe and the World, using a probability plot where a normal distribution results in a straight line. It is recommended that the Meteorological Office be consulted when information is required for a specific area.

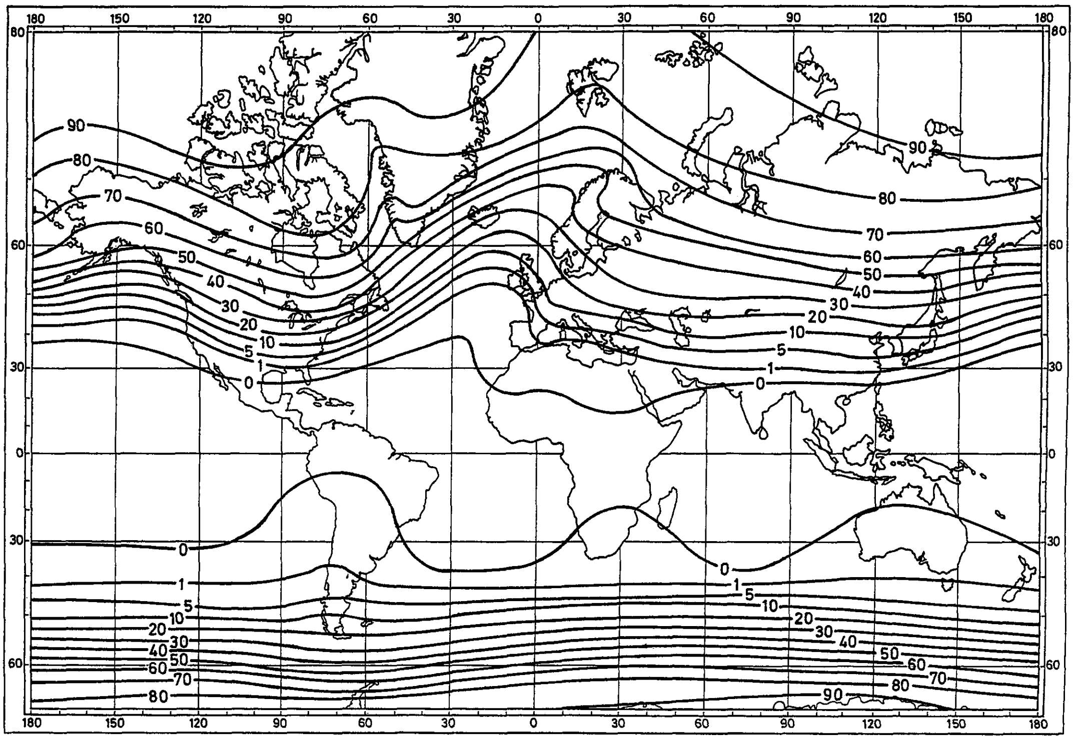

Figure 4. Percentage probability of occurrence of a temperature of 0°C or below (MSL)

TABLE 1
SOME EXAMPLES OF TEMPERATURE DIFFERENCES OUTSIDE NORMAL DISTRIBUTION

Station	Gan	Singapore	Aden	London	Gander	Montreal	Moscow
Height above MSL (metres)	2	16	3	25	147	57	154
Mean annual temperature (°C)	27.6	27.1	28.7	10.1	4.4	6.7	4.4
Standard deviation (°C)	1.6	2.3	3.4	6.1	9.5	12.5	11.5
Normal distribution							
Upper 2 percentile °C	31	32	35.5	22.5	23.5	31.5	28
Upper 1 percentile °C	31.5	32.5	35.6	24.5	26	35	31.5
Upper 0.05 percentile °C	33	34.5	40	30	35.5	47	42.5
Actual distribution from sample							
Upper 2 percentile °C	31	32.5	36	22.5	23	28	26.5
Upper 1 percentile °C	31.5	33	36.5	24	25	29.5	28
Upper 0.05 percentile °C	32.5	34.5	38.5	29.5	30	33	34
Normal distribution							
Lower 2 percentile °C	24.5	22.5	21.5	-2.5	-15.5	-20	-19
Lower 1 percentile °C	24	21.5	20.5	-4	-18	-23	-22.5
Lower 0.05 percentile °C	22.5	19.5	17.5	-10	-27.5	-35	-33.5
Actual distribution from sample							
Lower 2 percentile °C	23.5	23	21.5	-2.5	-20	-19	
Lower 0.05 percentile °C	22	21	17.5	-8.5	-28	-33.5	

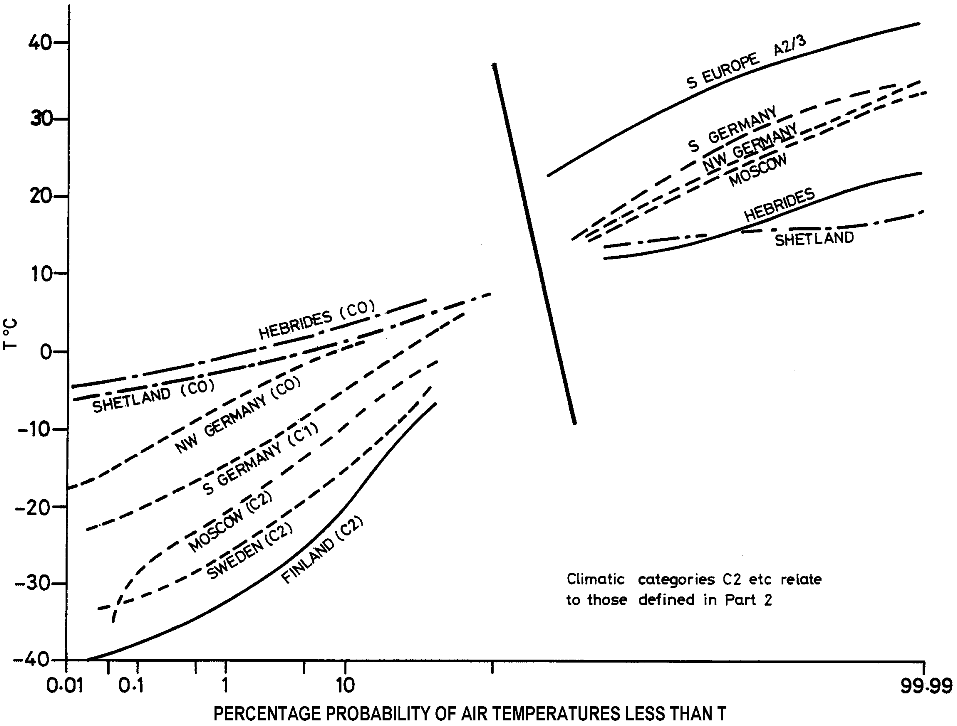

Figure 5. Temperature probability - Europe

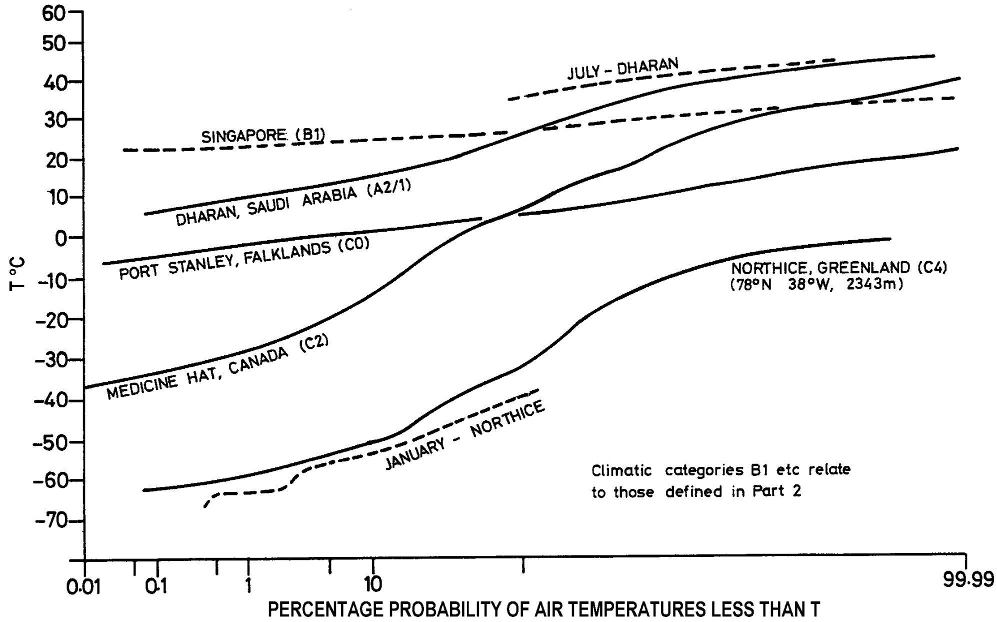

Figure 6. Temperature probability - Global

2.3 Extremes of temperature

2.3.1 Figures 7 and 8 show isotherms of the absolute maximum and minimum temperatures experienced, based mainly on records covering a period of 50 years.

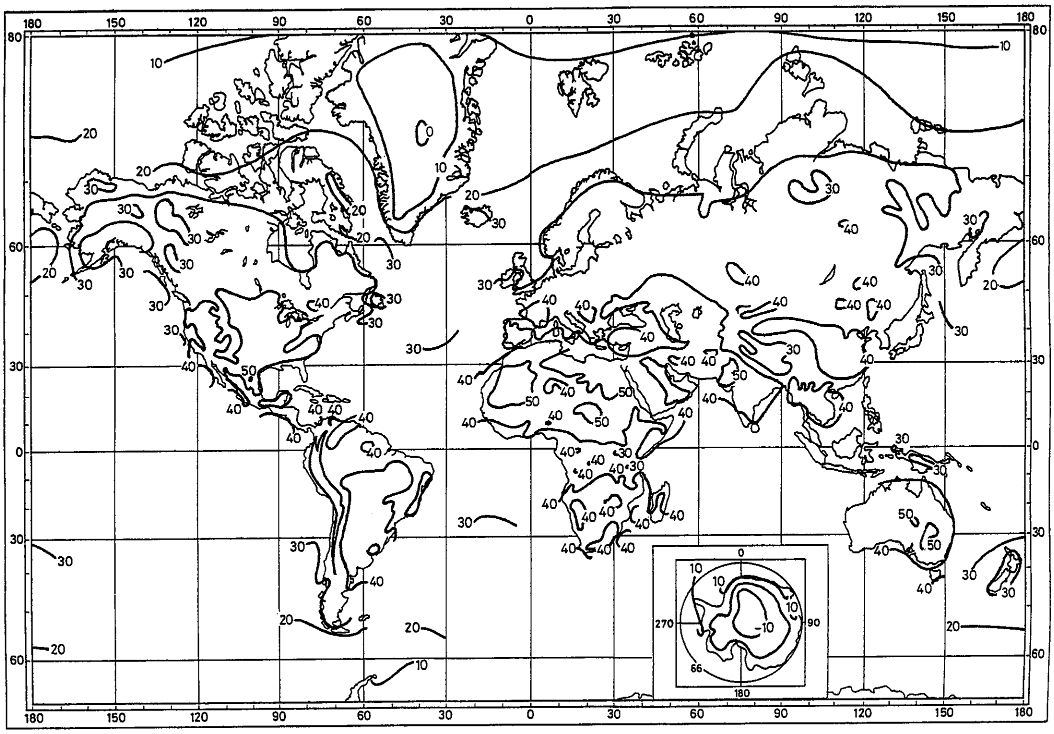

Figure 7. Absolute maximum temperatures recorded over a period of 50 years in 0°C

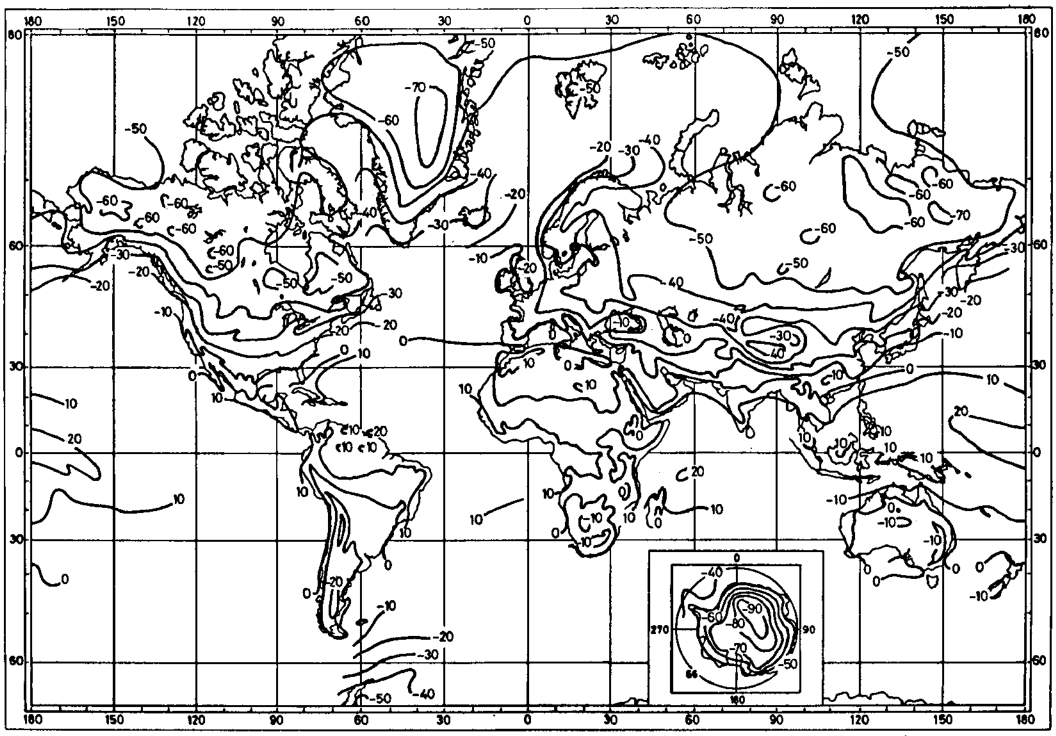

Figure 8. Absolute minimum temperatures recorded over a period of 50 years in °C

3 DIURNAL VARIATION OF TEMPERATURE

3.1 Main influence

3.1.1 If a sufficiently large number of days are considered, the occasional irregular changes of temperature during a 24 hour day are usually averaged out, leaving a fairly regular variation of temperature throughout the 24 hours. This regular change of temperature in the course of the average day is known as 'diurnal variation'.

3.1.2 The main factors controlling this variation in the lowest few metres above the ground are short-wave solar radiation, long-wave terrestrial radiation, nature of the ground surface, including proximity of the sea, and horizontal transfer of heat by wind. The usual result is a temperature maximum in mid-afternoon and a minimum just before sunrise. Cloud cover reduces both incoming and outgoing radiation, so that the largest diurnal variations of temperature can be expected under clear skies. The variation is greatest when the wind is calm or light; though a wind may cause temperature changes if it brings in air from warmer or cooler regions.

3.1.3 After strong radiative nocturnal cooling and little or no wind, a temperature inversion may be present in which the air temperature may increase up to an altitude of several hundred metres. An increase of wind which breaks down such an inversion, may cause a marked rise of temperature. Increases of 20°C over a period of two to three hours have been reported from high latitudes in winter.

3.2 Land-sea differences

3.2.1 The large thermal capacity of the sea restricts the variation of sea-surface temperatures between day and night to less than 1°C, and in calm conditions the air temperature near to the sea-surface is equally steady. Even with appreciable wind, the diurnal variation in the temperature over land is often large, particularly in the interior of continents when the sun has an appreciable elevation, averaging nearly 20°C in a few areas in some seasons.

3.2.2 The extent to which the sea will moderate the diurnal variation of a coastal region, will depend mainly on wind direction; with winds off the sea a marked reduction in the diurnal temperature range can be expected, but this moderating influence will be almost completely absent when the wind blows from the land.

3.3 Latitude differences

3.3.1 In polar regions during the winter, the sun remains continuously below the horizon and the diurnal range is practically nil. Temperature variations are controlled mainly by air-mass changes, cloud and wind, and both maximum and minimum temperatures may occur at any time in the 24 hours. During summer, most of the solar energy is used in melting the ice and the maximum temperature seldom exceeds 0°C by much.

3.3.2 In middle latitudes, the daily temperature pattern shows the effects of transient weather disturbances, such as depressions, wind-direction shifts and air-mass changes, as well as the regular diurnal variation. The effect of these transient disturbances usually decreases towards the equator; and, in the tropics, the diurnal range seldom exceeds 6°C and is fairly constant from day to day.

3.4 To illustrate the diurnal variation of temperature under differing climatic conditions Table 2 gives mean temperatures at two-hourly intervals, for the four mid-season months, at a selection of stations.

TABLE 2
MEAN TWO-HOURLY TEMPERATURES (°C) IN MID-SEASON MONTH (LOCAL TIME)

Station		00	02	04	06	08	10	12	14	16	18	20	22
GAN - 00° 41´ S 73° 09´ E 2 metres EQUATORIAL ISLAND Local time - GMT plus 5	Jan	26½	26½	26	26½	27½	28½	28½	29	28½	28½	27	26½
	Apr	27	27	26½	27	28½	29½	29½	30	28½	28½	27½	27
	Jul	26½	26½	26	26½	27½	28½	29	29	28	28	27	26½
	Oct	26	26	26	26½	27½	28	28½	28½	27½	27	26½	26½
CHANGI SINGAPORE 01° 22´ N 103° 59´ E 16 metres EQUATORIAL Local time - GMT plus 7	Jan	24½	24½	24	24	25½	27½	29	29	28	26½	25½	25
	Apr	26	26	25½	25½	27½	29½	30½	30	29	28	27	26½
	Jul	26½	26	26	25½	27½	29	30	29½	29	27½	27	26½
	Oct	26	25½	25	25	27	29½	30	29½	29	27	26½	26
MANAOS 03° 08´ S 60° 01´ W EQUATORIAL RAIN FOREST Local time - GMT minus 4	Jan	26	25	24½	24	25	27½	30	31	30½	29½	27½	26½
	Apr	26	25	24½	24½	25½	28	30	30½	30½	29½	28	26½
	Jul	25	24½	24	23½	25	28	31	31½	31	30	27½	26
	Oct	26½	26	25½	25	26½	30	32½	33	32½	31½	29	27½
WADI HALFA 21° 50´ N 31° 18´ E 160 metres HOT DRY DESERT Local time - GMT plus 2	Jan	12½	11½	10	8½	11	16	20½	23½	23½	21½	18	14½
	Apr	23	21½	20	19½	23	28	32½	34½	34½	33	29	25
	Jul	29	27	25½	26	30	35½	38½	40½	40½	39	35½	31½
	Oct	25½	24	22½	21½	25	30	34	36½	36	33½	30	27½
BUENOS AIRES 34° 35´ S 58° 29´ W 27 metres PRAIRIE STEPPE (S Hemisphere) Local time - GMT minus 4	Jan	19½	19	17½	18½	20½	24	27	29	28½	26½	23½	21½
	Apr	13½	13	12½	12	14	17	20½	22	21½	19½	17	15
	Jul	8	7½	7	6½	7½	9½	12	13½	13½	11½	10	8½
	Oct	12½	11½	10½	10	12½	15	18½	20	19½	17½	15½	13½
PERTH 31° 57´ S 115° 49´ E 59 metres MEDITERRANEAN TYPE (S Hemisphere) Local time - GMT plus 7½	Jan	20	19½	18½	18½	21	24½	26½	27	26	24½	22	21
	Apr	17	16	15½	15	16½	20½	23	24	23	20½	19	18
	Jul	11	10½	10	9½	10½	13½	15½	16	15½	14	13	12
	Oct	14½	14	13	13½	16	19	20½	20½	20	17½	16	15½
LONDON (Heathrow) Airport 51° 29´ N 00° 27´ W 25 metres TEMPERATE MARITIME Local time - GMT	Jan	3	3	3	3	3	3½	5	5½	5	4	3½	3½
	Apr	7	6½	6	6	7½	10	11½	12	12	11	9½	8
	Jul	15	14	13	13½	15½	18	19½	20	20½	19½	18	16
	Oct	10½	10	9½	9½	10	12	14	15	14½	12½	11½	11
KEFLAVIK 63° 59´ N 22° 35´ W 51 metres SUB-POLAR MARITIME Local time - GMT - minus 1½	Jan	-½	-½	-½	-½	-½	-½	-½	-½	-½	-½	-½	-½
	Apr	4	4	3½	3½	4	5	5½	6	6	6	5	4½
	Jul	9½	9	9	9½	10	11	11½	12	12	12	11½	10½
	Oct	4	4½	4½	4½	4½	4½	5½	6	5½	5	5	4½
WARSAW 52° 10´ N 20° 58´E 124 metres SEMI-CONTINENTAL Local time - GMT plus 1½	Jan	-3	-3	-3½	-4	-3	-2	-1	-1	-1½	-2	-2½	-2½
	Apr	5	4½	4	4	5	7	9	10½	10	9	7½	6
	Jul	17	16	15	16	18	20	22	23	23	22	20	18
	Oct	7	6½	6½	6	7	8½	11	11½	11	10	9	7½
CHURCHILL 58° 45´ N 94° 05´ W 35 metres SUB-POLAR CONTINENTAL Local time - GMT minus 6	Jan	-30½	-31	-31½	-32	-32½	-29	-25½	-23½	-24½	-26½	-28½	-30
	Apr	-13½	-13½	-14½	-14½	-13½	-10	-6½	-4½	5	-7	-10	-12
	Jul	8	7½	6½	7	9	12½	15½	16½	16	14	11½	9
	Oct	-4½	-5	-5½	-6	-5	-3	-½	½	½	-1	-2½	-4

4 LARGE CHANGES OF TEMPERATURE IN SHORT PERIODS (12 hours or less)

4.1 Conditions favourable for rapid changes

4.1.1 In addition to the large diurnal changes discussed above, rapid changes of temperature may occur in much shorter periods of time, under the following conditions:

(a) When a wind from the land is replaced by one from the sea, or vice-versa. The largest effects are likely when a wind from a hot land mass is replaced by one from a much cooler sea.

(b) When a change of air-mass occurs, as with the passage of a well-marked front.

(c) When air is forced to descend in the lee of a mountain range, producing warm winds. Examples include the 'Fohn' winds of the Alps, the 'Berg' wind of the west coast of South Africa and the 'Chinook' which blows down the eastern slopes of the Rocky Mountains.

(d) In hot weather, heavy showers and thunderstorms may cause rapid falls in temperature, owing to the cooling effect of the rain or hail and evaporation from the wet ground.

4.2 Regional differences

4.2.1 In general, the largest changes of air temperature in a short period, excluding special localities mentioned below, are likely to occur in the Arctic or Antarctic, in the high latitudes of Northern Hemisphere continents, and in the interior of land masses in the sub-tropics. In temperate latitudes, especially with a maritime climate, the maximum changes are usually smaller. The largest changes usually occur when an inversion of temperature, set up during the night, is destroyed by wind and/or solar heating.

4.2.2 In the Arctic or Antarctic in winter, when there is no sunshine, wind is the only factor; but in lower latitudes both wind and solar radiation play a part. In general, in high latitudes, the largest changes occur in the winter half year; in lower latitudes there is some preference for the warm dry seasons; but large changes may occur at any time of the year, depending on locality.

4.3 Estimates of maximum temperature change in 24 hours

4.3.1 Rough estimates, excluding special localities, are as follows:-

(a) High latitudes - 30°C (perhaps 35°C in some localities).

(b) Middle latitudes away from the sea, and low latitudes with pronounced dry season - 25°C (30°C in some localities).

(c) Middle latitudes near the sea - About 20°C (25°C in some localities).

(d) Low latitudes with no dry season - 15°C or less.

4.3.2 The wide variation within latitude bands prevents greater detail being given, for specific locations the Meteorological Office should be consulted.

4.4 Examples of rapid temperature changes

4.4.1 The most rapid temperature changes are usually due to a combination of the factors listed above; for example, when a change of air-mass reinforces a mountain effect, as occurs when a Chinook wind (in North America) is suddenly replaced by an Arctic air-stream.

4.4.2 Table 3 lists some examples of extreme changes of air temperature, associated with the onset or cessation of some very localised winds. Although the examples are for specific localities, it is stressed the Fohn winds are likely in the lee of many mountain barriers. The combination of air-mass changes, with change of wind from the off-land to off-sea, can also produce extreme effects; falls of 15 to 20°C in an hour have occurred during the onset of a 'Southerly Burster' in South Australia.

TABLE 3
EXAMPLES OF EXTREME CHANGES OF AIR TEMPERATURE

TEMPERATURE RISES	
NORTH AND SOUTH DAKOTA, MONTANA, ALBERTA	
Granville	46°C in 12 hours
Calgary	19°C in 30 minutes
Claresholm	22°C in 20 minutes
Havre	24°C in 15 minutes
Kipp	19°C in 7 minutes
Spearfish	27°C in 2 minutes (This was a very exceptional case)
GRAHAM LAND (ANTARCTIC)	18°C in 1½ hours
SOUTH GEORGIA (SOUTH ATLANTIC)	12°C in 15 minutes
WEST COAST OF SOUTH AFRICA	
Port Nolloth	18°C in 30 minutes
TEMPERATURE FALLS	
MONTANA, SOUTH DAKOTA	
Browning	56°C in 24 hours
Fairfield	47°C in 12 hours
Rapid City	34°C in 2 hours
Spearfish	32°C in 27 minutes
Rapid City	26°C in 15 minutes
WEST COAST OF SOUTH AFRICA	
Port Nolloth	19°C in 5 minutes

5 UPPER AIR TEMPERATURES (Free Air)

5.1 General

5.1.1 In this context, upper air is considered to be free air above the immediate effects of any land or sea surface beneath or adjacent to it. Above the surface layers, the air temperature usually decreases with increasing height, through the lowest several kilometres. Any increase with height which may occur, is called an 'inversion' of the normal environmental lapse rate.

5.1.2 When unsaturated air rises or falls, it cools or warms at a rate known as the dry adiabatic lapse rate (9.8°C/km). Rising air, however, cools at the dry adiabatic rate only until it reaches its dew point (or frost point), after which liberation of the latent heat of condensation keeps the lapse rate below the dry adiabatic and constitutes the saturated adiabatic lapse rate. This saturated lapse rate varies rapidly with temperature and slowly with pressure. In general, the actual environmental lapse rate is between the dry and saturated rates and is mostly near 1.98°C/k.ft.

5.1.3 This decrease of temperature stops abruptly, or falls to a very low value at a surface known as the tropopause. The height of the tropopause varies with latitude, season and weather situation, but in general it is lowest (8 - 10 km) in the Arctic and Antarctic in winter, and highest (16 - 18 km) in the tropics. The region below the tropopause is known as the troposphere and the region above is known as the stratosphere. In the stratosphere temperatures usually increase with height, slowly at first, then more rapidly to about 50 km, where the average temperature is near 0°C. This surface of maximum temperature near 50 km is known as the stratopause, and above this there is a region of decreasing temperature, the mesosphere, which ends at the mesopause at 80 to 90 km where the lowest temperatures, about -90°C, are found. Above the mesopause lies the thermosphere, the upper boundary of which is not defined.

5.2 The Standard Atmosphere

5.2.1 A hypothetical atmosphere, corresponding approximately to the average state of the real atmosphere, has been adopted internationally. This hypothetical atmosphere known as the ISO Standard Atmosphere is used to define the pressure and temperature at all heights.

5.2.2 The main parameters of this standard are: mean sea level pressure 1013.25 hPa, mean sea level temperature 15°C, temperature lapse rate 6.5°C/km up to 11 km, where the temperature is -56.5°C, and an isothermal lower stratosphere between 11 and 20 km, followed by a slow rise of temperature up to the stratopause. Chapter 10-01 gives details of the pressure, temperature and height values up to 50 km, in the ISO Standard Atmosphere.

5.3 Departures from the Standard Atmosphere

5.3.1 Apart from the differences at any one place caused by day-to-day changes of air-mass, there are also systematic seasonal and latitudinal changes. Figure 9 shows the average vertical distribution of temperatures for January and July from the Equator to 75°N.

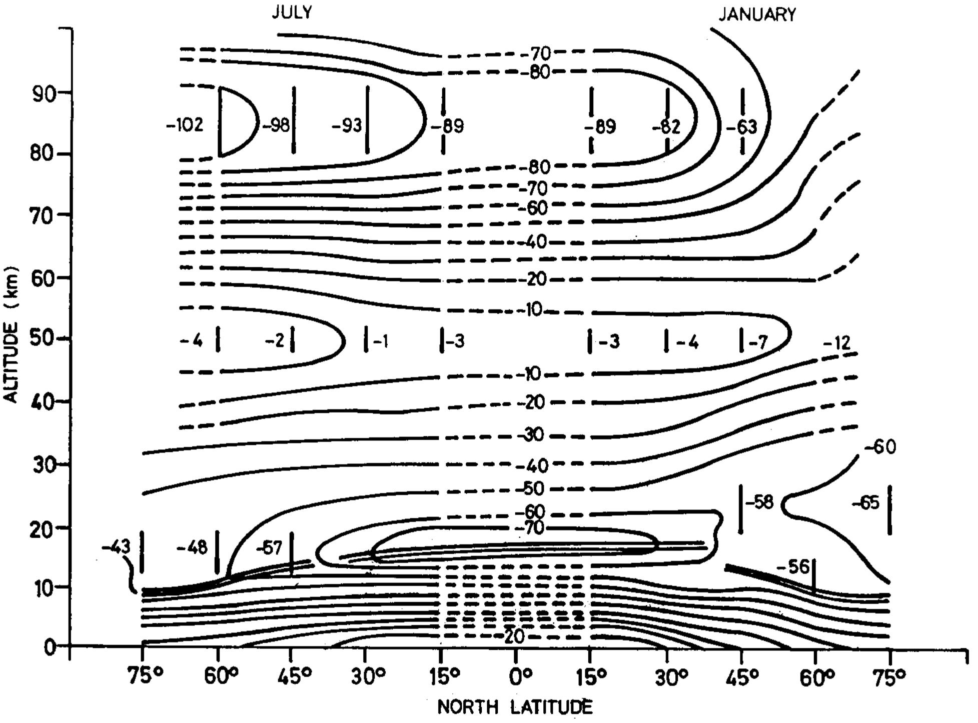

Figure 9. Latitudinal cross-section of temperature (°C) up to 100 km in January and July

6 TEMPERATURE OF SURFACE SEA-WATER

6.1 Items of materiel which might be floated on or immersed in sea-water world-wide may experience temperatures from 36 to -2°C. Sea-water of average salinity freezes at -2°C.

6.2 The upper value is the surface sea-water temperature which is exceeded for only 7.4 hours (1%) of the month of the year in which sea temperatures are at their highest. Similarly, the lower value is the surface sea-water temperature which is exceeded for all but 7.4 hours (1%) of the month of the year in which sea temperatures are at their lowest.

6.3 The highest and lowest surface sea-water temperatures ever reliably recorded are 38°C and -6°C respectively.

7 FURTHER READING

Met O 538, 'Handbook of Statistical Methods in Meteorology'	C E P Brooks and N Carruthers
WMO No 117 TP 52, 'Climatological Normals (CLINO) for the CLIMAT and CLIMAT SHIP Stations for the Period 1931 - 1960 World Meteorological Organization Geneva 1971	-
WMO-No 847, 'Climatological Normals (CLINO) for the period 1961-1990' World Meteorological Organisation, Geneva, 1996	

Met O 617, 'Tables of Temperature, Humidity, Precipitation and Sunshine for the World'. London, HMSO, 1971	-
Met O 488, 'Climatological Atlas of the British Isles'. London, HMSO, 1952	-
Met O GM 101, 'Upper Air Temperatures over the World'. London, HMSO, 1958	N Goldie, J G Moore and E E Austin
'Unusual Extremes and Diurnal Cycles of Desert Heat US Air Force Environmental Research Papers No 323 Air Force Cambridge Research Laboratories, 1970	Irving I Gringorten and Norman Sissenwine
'Duration and Unusual Extremes of Cold' US Air Force, Environmental Research Papers No 326 Air Force Cambridge Research Laboratories, 1970	Irving I Gringorten
'Atmospheric Temperature, Density and Pressure: Chapter 15, 1983 Revision, Handbook of Geophysics and Space Environments' Hanscom AFB,Mass.,Air Force Geophysics Laboratory, Environmental Research Papers No 840, 1983	A E Cole et al
'US Standard Atmosphere' Washington, NOAA, NASA, USAF, 1976	-
WMO No 8 'Guide to Meteorological Instruments and Methods of Observation' Fifth Edition, World Meteorological Organization, Geneva, 1983	-
'Die Mittleren Jahrlichen und Absoluten Extremtemperaturen der Erde Berlin, Freien Universitat, Institut Fur Meteorologie und Geophysik, Meteorolgische Abhandlungen Band VIII Heft 3 und Beiheft, 1960	G Hoffman
'Air Temperature and its Variability' London Meteorological Office, IDM No 96, 1964	L Dodds and F E Dinsdale
ISO 2533 - 1975, 'Standard Atmosphere'	-
'Handbook of Geophysics and Space Environments' McGraw Hill Book Co Inc, 1965	-

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CHAPTER 2-02
THE EFFECTS OF TEMPERATURE

1 GENERAL INTRODUCTION

1.1 All materials exhibit changes in properties with increasing or decreasing temperature. Changes in the basic properties of materials, such as loss of mechanical strength and variation in characteristics of electrical components, can be allowed for at the design stage by adopting suitable criteria to prevent malfunction or failure of systems within the anticipated environmental temperature extremes. Allowance must also be made for effects of temperature cycling, diurnal and otherwise.

1.2 This chapter is principally concerned with indicating the salient changes in properties with changes in temperature, and the temperature limitations of typical materials and components. Where examples are given, these are intended as illustrations and must not be regarded as comprehensive. This chapter deals with the effects of both natural and induced temperature changes.

1.3 The quantity of published literature and data on the subject is too vast to enable the coverage here to be comprehensive, and some of the information included in the chapter is necessarily of a generalized nature. Where information or data on specific materials or components is required, the appropriate manufacturers' literature or relevant specifications should be consulted.

2 GENERAL VARIATIONS IN THE PROPERTIES OF MATERIALS WITH TEMPERATURE

2.1 Mechanical properties

2.1.1 The structure of many materials, for example metals and ceramics, is substantially crystalline. The mechanical behaviour of such materials at both high and low temperatures may be ascribed to the presence of imperfections in their lattice structure, known as dislocations.

2.1.2 Mechanical strength generally decreases at higher temperatures, owing to the thermal agitation of constituent atoms and the increased ease of movement of dislocations under stress. At low temperatures, the force that must be applied to the dislocations to enable them to move through the structure of the material increases, because of the fall off in thermal agitation of atoms. This produces an increase in yield and ultimate tensile strengths.

2.1.3 In general, elasticity is not as temperature dependent, since the movement of dislocations is not the dominant factor.

2.1.4 The structure of high strength polymers is very complex. Consequently, individual types of polymer show characteristic behaviour with change in temperature.

2.2 Thermal properties

2.2.1 Thermal conductivity varies widely among different types of material and depends markedly on temperature, purity and the physical state of the material. For pure metals conductivity decreases with rising temperature, while for alloys it tends to increase. The thermal conductivity of non-metallic solids may either increase or decrease with temperature.

2.2.2 The emissivities of most polished metal surfaces are low, but increase with rising temperature. For example, infra-red emissivities of the order of 0.04 at 0°C increase to about 0.06 at 25°C. At temperatures below about 200°C most non-metallic surfaces, whatever their colour, have emissivities of approximately 0.9. Above this temperature the emissivities of light coloured surfaces usually decrease.

2.2.3 The coefficient of linear expansion of most materials increases with temperature.

2.3 Electrical conductivity

2.3.1 The electrical conductivity of non-metals increases rapidly with temperature, owing to the increase in the density of conduction electrons as the temperature is raised. The electrical conductivity of metals decreases with rising temperature; for pure metals, conductivity is inversely proportional to the absolute temperature, up to approximately the melting point.

2.4 Chemical reactivity

2.4.1 In general, chemical reactivity increases rapidly with temperature. For example, the rate of most reactions involving water doubles with every 100°C rise in temperature.

2.5 Effects of temperature cycling

2.5.1 The temperature environment is normally subject to diurnal cycling. Temperature cycling often enhances the effects of temperature changes and may lead to early mechanical fatigue, to relief of stresses in solid propellants, and to a permanent shift in value of the properties of electronic components.

2.5.2 Attention is drawn later to the effects of oxide scale, which may flake off exposing a fresh surface for oxidation. Similarly the protective properties of finishes such as paints and varnishes may be reduced by crazing. Mention is made later of the possibility of strain hardening. All these factors are affected by temperature cycling.

2.5.3 There is, in general, insufficient evidence to give quantitative guidance, but the effects of temperature cycling are often most pronounced during the first few cycles, and therefore, from the point of view of stability, it is often advantageous to submit components or equipment to an initial cycling procedure in advance of the main tests.

3 METALS

3.1 Effect of temperature on mechanical properties

3.1.1 The yield stress, ultimate stress, and the modulus of elasticity fall with increasing temperature.

3.1.2 While some metals become more ductile as the temperature increases, precipitation of carbides and intermetallic compounds in certain alloys causes a loss of ductility. Metals usually show a reduction in ductility at low temperature, although the factors controlling resistance to brittle fracture are not well understood. The basic physical structure of a metal is, however, a guide to the effect of decreasing temperature; for example the ductilities of metals with face-centred cubic structures are comparatively unchanged at low temperatures. References 1 & 2 provide further information.

3.1.3 Metals are subject to creep, that is they will continually deform under a constant stress that can be considerably below the yield stress. This subject is dealt with in Reference 1. The rate of deformation or creep increases with temperature and stress, and can be significant at temperatures well below the melting point. Creep properties are specified by the creep strength, the stress which causes a certain deformation in a fixed time, and the creep-rupture strength, the stress which causes rupture in a specified time.

3.1.4 The resistance of metals to mechanical fatigue falls with increasing temperature.

3.2 Mechanical properties of some metals at high temperatures

3.2.1 Aluminium alloys

(a) The higher strength aluminium alloys derive their strength from a precipitation hardening treatment (ageing) at temperatures in the range 130°C to 180°C. Strength decreases when the metal is heated above the ageing temperature.

(b) Further information and data on the properties of aluminium alloys are contained in References 6 - 9.

(c) Sintered aluminium products (SAP), consisting essentially of an unalloyed aluminium containing a very finely dispersed aluminium oxide phase, are superior to any wrought alloy in the temperature range of 225°C to 375°C. The yield stress of SAP is approximately 138 N/mm^2 at 375°C. However, poor fabrication properties make it unsuitable as a material for major structures. The properties of SAP are discussed in References 3 & 4.

(d) The variation of ultimate stress and 0.1% proof stress, with temperature, of a widely used aluminium alloy RR58 is shown in Figure 1.

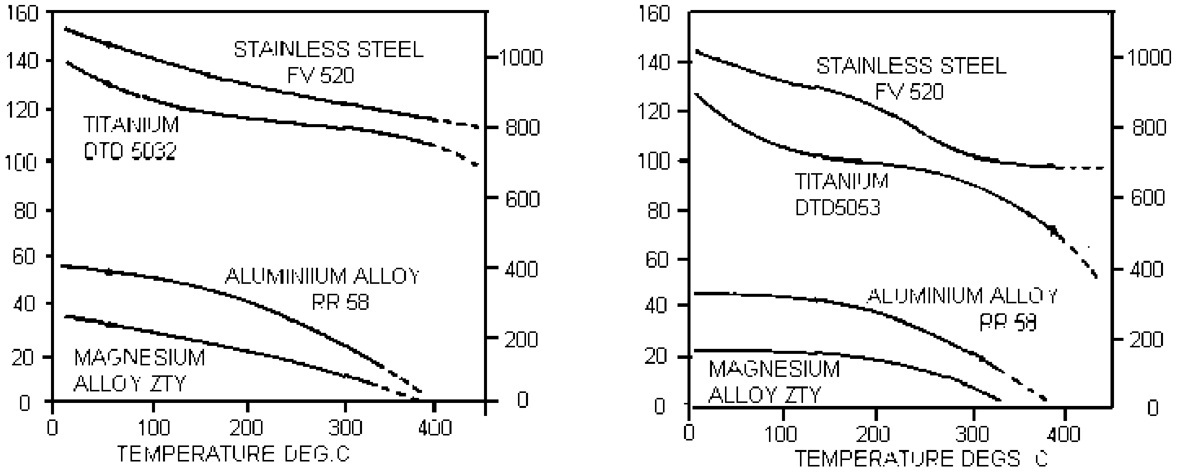

Figure 1. Variation with temperature, of ultimate stress and 0.1% proof stress of some alloys

3.2.2 Magnesium alloys

(a) Modern alloys containing additions of the rare earth metals zirconium and thorium, retain a significant proportion of their room temperature strength up to 300°C. In general, magnesium alloys have comparatively poor creep properties.

(b) The effect of temperature on the ultimate stress and 0.1% proof stress of magnesium alloy ZTY is illustrated in Figure 1. For additional information and data on the properties of magnesium alloys, References 5, 6, 8, 10 & 11 should be consulted.

3.2.3 Steels

(a) Steels or other high temperature alloys must be employed at temperatures in excess of 250-300°C because aluminium and magnesium alloys show a rapid loss in strength.

(b) Mild steel can maintain a long term stress of approximately 172 N/mm^2 at 400°C. The high temperature properties can be considerably improved by heat treatments and the inclusion of alloying elements.

(c) The main group of high temperature steels comprise the 'stainless' materials containing between about 10% to 18% chromium with various additions of nickel, molybdenum, manganese, vanadium and silicon.

(d) At temperatures up to 350°C, martensitic stainless steel based on a 12% chromium composition, provide the highest strength properties of the stainless group. A typical material (FV 448) has an ultimate stress in excess of 1034 N/mm^2 at 200°C. Although possessing inferior strength properties at lower temperatures, up to approximately 350°C austenitic and semi-austenitic steels find application in the temperature ranges 500°C to 900°C.

(e) The best alloys are capable of withstanding short term stresses in the region of 186 N/mm^2 at 750°C.

(f) The variation of ultimate stress and 0.1% proof stress of a semi-austenitic, precipitation hardened, stainless steel (FV 520) with temperature, is shown is Figure 1.

(g) References 6, 12 & 13 contain information and data on the high temperature properties of steel.

3.2.4 Titanium alloys

(a) In spite of the high melting point of titanium, alloys of the metal show a rapid decrease in strength between 550°C and 650°C. Alloys show a plastic strain of approximately 0.5% in 1000 hours, when stressed at 480 to 550 N/mm^2 at 400°C.

(b) The effect of temperature on the ultimate stress and 0.1% proof stress of a titanium alloy (DTD5053) is illustrated in Figure 1. Further information and data on the properties of titanium alloys is contained in References 6, 14 and 15.

3.2.5 Nickel and cobalt base alloys

(a) High temperature alloys based on nickel and cobalt are used in applications where resistance to deformation and failure is required at temperatures above 650°C. Nickel rich alloys such as Nimonic 80 and Inconel X can withstand short term stresses of the order of 186 N/mm^2 at 900°C.

(b) The 100 hour creep rupture strengths of typical nickel and cobalt base alloys are compared in Table 1. More information on the behaviour of nickel and cobalt base alloys at higher temperatures is contained in References 6 and 16.

TABLE 1

TYPICAL 100 HOUR CREEP RUPTURE STRESSES FOR NICKEL AND COBALT BASE ALLOYS

Stresses to produce rupture in 100 h (N/mm^2)					
Temperature °C	650	700	750	800	850
Nickel-base Nimonic 80A	556	405	276	181	-
Cobalt-base G32	-	346	263	209	165

3.3 Mechanical properties of some metals at low temperatures

3.3.1 Aluminium alloys

(a) Aluminium alloys have face-centred cubic structures, and usually retain their toughness and ductility at very low temperatures. In general, alloys show an increase of between 40% and 100% in ultimate tensile strength and 10% in the modulus of elasticity, over the temperature range +25°C to -253°C.

(b) Alloys containing greater than 5% of magnesium or zinc may suffer a loss of toughness, or embrittle at temperatures between -75°C and -175°C. The effect of low temperature on the ultimate tensile strength and percentage elongation of aluminium alloy 7079 (Billet stock, 3% Mg, 4.7% Zn, 0.5% Cu) is illustrated in Figure 2. The characteristics were measured at fixed temperatures of 20K, 77K, 195K and 300K and any interpolation between these values is inadvisable without reference to the source data. Further information is given in References 17 and 18.

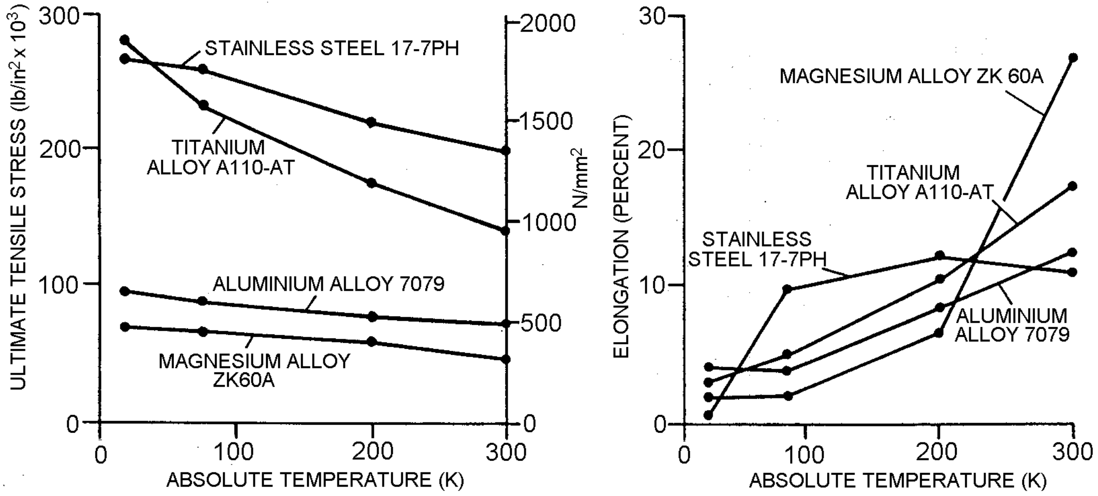

Figure 2. Variation in ultimate tensile stress, and elongation, of some alloys between 300 K and 20 K

3.3.2 Magnesium alloys

(a) Although the strength properties of magnesium alloys increase at low temperatures, the majority of alloys exhibit a loss in toughness and ductility between -75°C and -200°C. The variation in ultimate strength and percentage elongation of magnesium alloy ZK60A (Bar stock, 5.4% Zn, 0.5% Zr) at low temperatures, is shown in Figure 2; further information is given in Reference 18.

3.3.3 Steels

(a) Carbon steels, cast irons and low and medium alloy steels possess a body-centred cubic structure, and over the temperature range +25°C to -225°C, strength properties increase by about 20%. The modulus of elasticity also increases by about 20%, and at the transition temperature there is a large decrease in ductility and toughness. Further information is detailed in Reference 22.

(b) The transition temperature may vary from above room temperature to as low as -125°C, dependent upon a large number of variables affecting the microstructure of the metal. These variables include impurities, alloy and melting and processing procedures.

(c) High alloy ferretic and martensitic steels are affected by low temperatures in much the same way as carbon and low alloy steels, and undergo a ductile to brittle transition in the temperature range +25°C to -125°C.

(d) Many stainless steels retain a face-centred cubic structure at temperatures of +25°C and below, and the effects of low temperature on these metals is a large increase in strength properties with little change in ductility and toughness. Other stainless steels undergo a transformation from face-centred cubic to body-centred cubic, and large decreases in toughness and ductility may occur.

(e) The effect of low temperature on the ultimate tensile strength and percentage elongation of stainless steel 17 - 7PH (sheet material, precipitation hardening, 0.08% C, 7.0% Cr, 0.3% Mo, 1.0% A1), is illustrated in Figure 2.

3.3.4 Titanium alloys

(a) The behaviour of titanium alloys at low temperatures depends on the alloying elements, and the solid solutions and inter-metallic compounds that are found as a result of the alloying. Using aluminium as the principal alloying element can increase the strength of titanium alloys considerably, over the temperature range +25°C -253°C.

(b) The ductility of these alloys is generally reduced below about -196°C. An alloy containing 6% aluminium and 4% vanadium remains ductile and tough down to -253°C. The variation in ultimate tensile strength and percentage elongation at low temperature, of titanium alloy A110-AT (sheet material, annealed, 5.0% Al, 3.0% Sn) is shown in Figure 2, and Reference 22 provides further information.

3.3.5 Nickel and cobalt base alloys

(a) Nickel alloys and cobalt alloys containing greater than about 10% nickel possess face-centred cubic structures down to -255°C. These alloys show increases in strength properties of up to 100%, with little or no change in ductility or toughness from +25°C to minus 255°C.

3.3.6 Further information on the properties of metals at low temperatures is contained in References 19 to 22. Reference 18 contains an extensive bibliography on the subject.

3.4 High temperature corrosion

3.4.1 General

(a) Corrosive processes relying on the presence of moisture as detailed in Chapter 8-02, for example electro-chemical attack, are accelerated by an increase in temperature. Above 100°C however, when the presence of liquid water is unusual, 'high temperature' or 'dry' corrosion occurs.

(b) High temperature corrosion involves a chemical reaction between the metal and corrosion gases and usually results in surface oxidation of the metal (scaling), it may include additional reactions with active components of the corrosive media. Some metals also possess the ability to absorb certain gases at higher temperatures, which can produce a deterioration in their mechanical properties.

(c) In many applications the main corrosive gas is atmospheric oxygen; but other corrosive gases or contaminants may often be present, such as sulphur containing gases, vanadium ash produced from crude or residual mineral oils, lead occurring as a deposit in internal combustion engines burning leaded petrol and oxidising gases that may be present in the combustion products of liquid fuelled rockets. Data is given in Table 2 illustrating the oxidising effect of various gases on some metals at different temperatures.

TABLE 2

OXIDATION EFFECT OF VARIOUS GASES ON METALS AND ALLOY STEELS (EXPRESSED AS WEIGHT GAIN, mg/dm²)

Test Material	O_2			H_2O			$C0_2$			SO_2			complex* Gas
	700°C	800°C	900°C	700°C	800°C	900°C	700°C	800°C	900°C	700°C	800°C	900°C	900°C
Iron	5100	6000	12400	6200	8500	5800	5900	7200	11300	3500	7900	40000	11400
Nickel	100	100	300	30	40	100	40	90	400	9200	36600	8400	500
Chromium	50	100	200	10	40	100	30	30	100	20	40	300	200
Mild Steel	1000	3000	8300	400	2200	7500	1000	3700	7500	1000	4200	17700	8000
37% Ni Steel	400	1000	1400	300	1300	3600	300	1000	2500	2000	14100	19900	3000
8% Cr, 3% Si Steel	30	200	200	30	50	90	20	20	40	50	100	500	100
13% Cr Steel	20	200	300	50	60	1500	80	90	1600	40	100	1000	1800
19% Cr Steel	60	70	200	20	60	200	20	80	300	50	50	80	100
18% Cr, 8% Ni Steel	100	100	300	20	50	600	40	100	300	100	200	200	300

*Composition: 73%N_2, 12% $C0_2$, 10% H_20, 5% 0_2 and 0.05% $S0_2$.

3.4.2 Scaling

(a) Chemical attack from the surrounding atmosphere on a metal at high temperature causes corrosion, with a gradual wasting away of the metal. This corrosion produces a surface scale, with a rate of growth dependent upon the adherence and continuity of the scale and on its ability to inhibit diffusion of the corrosive gases.

(b) In practice, breakdown in the continuity of the scale may be caused by:

(i) Thermal cycling, producing thermal stresses between the scale and the underlying metal owing to their differing coefficients of expansion, so that pieces of the scale ultimately flake away.

(ii) The metal being subjected to a progressive deformation such as creep or fatigue, the mechanical properties of the metal and scale may then differ sufficiently for the scale to crack.

(iii) Reaction of the scale with any contaminants that form molten products at the service temperature. Vanadium containing ash produces a reaction of this kind when the service temperature is above 650°C which is the melting point of vanadium oxide. Reference 23 provides more detailed information.

3.4.3 Solution of gases

(a) Although steels dissolve hydrogen and nitrogen at high temperatures, the phenomenon is of little importance over the temperature range in which they are normally used.

(b) Serious effects stemming from the solution of gases are confined to the newer metals. Titanium and zirconium for example, dissolve oxygen at service temperatures, causing a notable increase in creep resistance accompanied by embrittlement. The solution of hydrogen in titanium alloys at high temperatures has an adverse effect on both creep resistance and ductility. Further information is available in Reference 23.

3.4.4 Resistance to high temperature corrosion

(a) The principal alloying elements used in metals to achieve resistance to corrosion at higher temperatures are chromium, aluminium and silicon. Almost all protective scales formed on these alloys contain a high proportion of chromium oxide, and sometimes smaller amounts of aluminium oxide and silica.

(b) Table 2 indicates the importance of chromium in reducing the high temperature oxidation of alloy steels.

3.5 Exposure time and maximum service temperature

3.5.1 The effect of temperature on the structural properties of metals is related to the time exposure at the service temperature. The length of exposure time at higher temperatures due for example to kinetic heating, may range from seconds for a missile structure, to hundreds of hours for an aircraft. Thus creep, for example, may have little significance in the behaviour of missile structures, but may be an important factor in the stressing of aircraft structures. Estimates of the maximum service temperatures of several families of structural alloys, as related to the service time, are given in Figure 3.

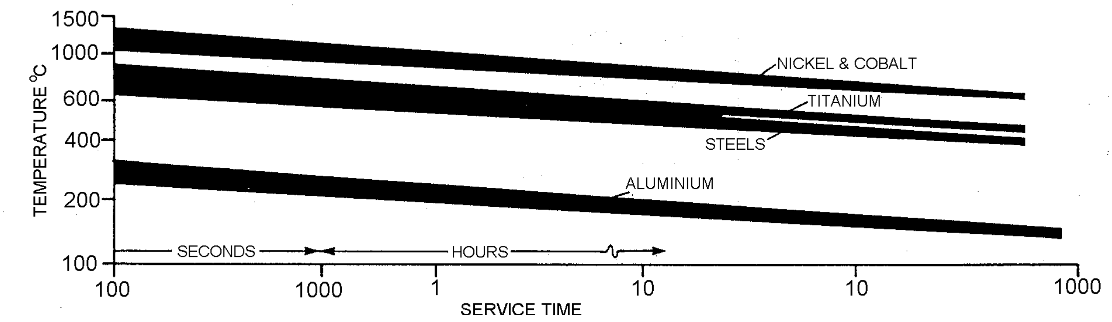

Figure 3. Estimated maximum service temperatures for several families of alloys, as related to service time.

4 POLYMERIC MATERIALS (PLASTICS, RUBBERS, FIBRES, SURFACE COATINGS AND ADHESIVES)

4.1 General

4.1.1 Many polymeric materials undergo losses in physical, mechanical, optical or electrical properties when exposed to heat. The losses may be permanent, following thermo-chemical reactions with the heat environment, or the result of reversible physical changes.

4.2 Thermo-chemical reactions with the natural environment

4.2.1 If sufficient thermal energy is introduced, an irreversible chemical reaction may occur between the polymer and components of the natural environment, for example water vapour and oxygen. The reaction rates will accelerate with increasing temperatures. Further information is available in References 24 and 25.

4.2.2 The chemical reaction of water with polymers is limited to materials containing hydrolysable groups, see Chapter 4-02.

4.2.3 Thermal oxidation is similar to the photo-oxidation of polymers inasmuch as it results in a modification of the molecular structure. However, thermal degradation will tend to occur throughout the polymer while photo-chemical reactions will be initially restricted to the illuminated surface areas. The degradation of polymers caused by photo-chemical reactions stimulated by solar radiation is discussed in Chapter 3-02.

4.3 Reversible physical changes with temperature

4.3.1 The physical properties of a polymer at a given temperature will depend on its chemical nature. The normal state of a polymer at room temperature may be one of flexibility combined with high extensibility and elasticity, for example the rubbers, or one of rigidity and relatively low extensibility, for example the thermoplastics and thermosets. Further information is available in Reference 31.

4.3.2 Polymers that are rubbery at normal temperatures soften and show increased flexibility as the temperature is raised, but at low temperatures they may stiffen and ultimately become brittle. The temperature at which rubbers and certain tough plastics become too brittle to pass a specified mechanical test is known as the 'brittle point'.

4.3.3 Heating a thermoplastic polymer may cause it to lose its crystallinity or hard amorphous condition and become rubbery, further heating continues to soften it until it may be categorized as a viscous fluid. Highly cross-linked polymers such as thermosets do not soften to a truly fluid condition, but some do soften sufficiently at higher temperatures to permit them to be bent into simple shapes. Cooling a thermoplastic or thermosetting polymer has little effect, except to harden it and increase its brittleness.

4.4 Gross effect of temperature

4.4.1 Polymers exposed to heat are thus subject to two effects:

(a) A time dependent slow 'thermal ageing' of a chemical nature.

(b) Immediate physical changes, due solely to temperature.

4.4.2 In determining the behaviour of a polymeric material at the working temperature, over a known lifetime, it is usually necessary to consider the gross effect of temperature, that is, the thermal ageing and the immediate physical changes acting simultaneously. However, the maximum short term service temperature is generally governed by the immediate physical effects of temperature.

4.5 Properties and temperature limitations of some polymeric materials

4.5.1 The mechanical properties of some commonly used materials vary with temperature, and it is important to know their temperature limitations. It must also be borne in mind that equipment is often required to survive, without damage, a temperature lower than the operating temperature.

4.5.2 In assessing the temperature performance of a polymeric material the overall composition, form and application must be taken into account. Examples of composition are the inclusion of reinforcement, fillers anti-oxidants or pigments. Form may be moulding, film, foam or fibre. Application can be structural, electrical or surface coating etc. A detailed review of the properties of polymeric materials on this basis is beyond the scope of this Standard. Such information can however, be obtained from References 26 to 34 and from the suppliers. The information obtained should include guidance as to which of the changes in properties are permanent.

4.5.3 Plastics

(a) The strength properties of plastics decline at higher temperatures. A heat resistant phenolic/asbestos laminate (Durestos RA7) shows a 50% to 60% strength reduction after 2000 hours at 200°C. Low temperature effects are not so marked, but in general the elongation and impact strength of thermoplastic materials are reduced with decrease in temperature.

(b) The maximum long term service temperature of some plastics is given in Table 3. Certain structural reinforced plastics are capable of short term service at much higher temperatures. For example, asbestos reinforced phenolics can give short term service of the order of seconds at 1000°C. Reference 35 should be consulted for further information.

TABLE 3

MAXIMUM LONG TERM SERVICE TEMPERATURE OF SOME PLASTICS

Plastic	Maximum long term service temperature (°C)
Cellulose Acetate-Butyrate	55
Cellulose Nitrate	55
Polymethyl Methacrylate	55
Laminated Polyesters	60-100
Polyvinyl Chloride	60-120
Polystyrene	80
Urea-Formaldehyde	80
Polyethylene	90
Epoxy	110-180
Phenol-Formaldehyde	120
Polycarbonate	135
Nylon	140
Acetal and Alkyds	150
Polypropylene	150
Silicone	150-260
PCTFE	200
Phenol-Formaldehyde (Mineral filled, heat resistant)	200
PTFE	230-300

4.5.4 Rubbers

(a) At higher temperatures, rubbers soften and show a reduction in significant mechanical properties such as tensile strength and elongation. The tensile strength of a high temperature synthetic rubber (Viton A) was reduced by approximately 50% and the elongation at break by 10%, after 16 hours at 315°C. Table 4 gives the maximum long term service temperature of some rubbers.

(b) At low temperatures the tensile strength of rubbers tends to increase, while the elongation and impact strength is markedly reduced. Natural rubber and some synthetics such as polysulphides, Viton, Hypalon and Butyl generally have unsatisfactory mechanical properties, owing to extreme brittleness at temperatures below -55°C. However, certain silicones and fluorosilicones can be used as low as -85°C. References 35 and 36 should be consulted for further information.

TABLE 4

MAXIMUM LONG TERM SERVICE TEMPERATURES OF SOME RUBBERS

Rubber	Maximum long term service temperature (°C)
Natural Rubber	70
Synthetic Polyisoprene	70
SBR (23% styrene)	100
Polysulphide	100
Hypalon	125
NBR (30% nitrile)	125
Polyurethane and Neoprene	125
Acrylic Ester	150
Butyl	150
Fluoro-Silicone and Silicone	200
Kel-f Elastomer or Viton	200
Poly FBA	200

4.5.5 Paints and surface coatings

(a) The principal effects of heat on paints and coatings are discolouration and loss of mechanical properties as evidenced by peeling and cracking. In general, stoving finishes are used for high temperature applications if practical, as they usually possess higher heat resistance than the air drying formulations.

(b) The approximate long term maximum service temperatures of some paint types are given in Table 5. Also listed in the table are service temperatures for coatings used in the protection of primary structures, such as radomes, from the effects of rain erosion.

(c) The embrittlement of paint films and coatings by low temperatures can render them more susceptible to damage by impact.

TABLE 5

MAXIMUM LONG TERM SERVICE TEMPERATURES OF SOME PAINTS AND COATINGS

Paint type	Maximum long term service temperature (°C)*
Nitrocellulose and Alkyds	100-120
Acrylic, Epoxies and Polyurethane	150
Polyvinyl Butyral (primer)	150
Silicones	200
Coating type	
Neoprene	80
Polyurethane	100-120
Methoxy Methyl Nylon	130-140

* The temperatures quoted represent the upper limit of mechanical stability although discolouration may occur at much lower temperatures.

4.5.6 Fibres

(a) Fibres soften and undergo a reduction in their tensile strength with increasing temperature. A heat resistant type (Nylon 66, Type 242) retains approximately 50% of its tensile strength after 60 days at 150°C, or 10 days at 175°C. Reference 30 should be consulted for further information.

(b) Probably the most commonly used types for high temperature applications are the polyamides (Nylon 66 or HT1) and the polyesters (Terylene and Dacron). Suggested continuous service temperature ranges are -195°C to +150°C for polyamide, and -250°C to +150°C for Polyester. Reference 36 provides further information.

(c) An aromatic polyamide fibre possesses substantially improved resistance to high temperatures over other organic polymer fibres. It retains 50% of its tensile strength after 500 hours at 250°C. The tested strength becomes zero at 400°C, compared with 240°C to 250°C for Nylon 66 and Terylene.

4.5.7 Adhesives

(a) Adhesives soften and show losses in bond strength at higher temperatures. All structural adhesives suffer from loss of bond strength at temperatures in excess of 120°C, but several types can be used at temperatures up to about 250°C. Table 6 indicates the maximum service temperatures of some adhesives. References 27 and 36 provide further information.

TABLE 6

MAXIMUM SERVICE TEMPERATURES OF SOME ADHESIVES

Adhesive	Maximum service temperature (°C)
Neoprene	60 (6 months)
Phenolic-Vinyl	60 (Long term service)
Polyurethanes	95*
Phenolic-Nitrile	120-150*
Unmodified Epoxy	150 (Medium term service)
Epoxy-Polysulphide	150-175*
Silicones	250*
Unmodified Phenolic (Ray Bond R84015)	340*
Epoxy Phenolic (Shell Epon 422J)	370*

* Service time not specified.

(b) At very low temperatures, near the boiling point of nitrogen (-196°C), even the most cold-resistant types become brittle and have reduced impact strength, reduced resistance to vibration and reduced tensile-compressive fatigue life.

5 MISCELLANEOUS MATERIALS

5.1 Ceramics

5.1.1 Insulants

(a) The electrical properties of ceramic insulants are strongly influenced by the amount and composition of the glass produced during the firing of the material. The glass content makes a comparatively large contribution to the dielectric loss and electrical conductivity of the ceramic, especially at higher temperatures. Reference 37 provides further information.

(b) Ceramics containing an alkaline glass, for example porcelain, vitreous and porous cordierite and normal steatite, have rather high power factors and poor resistivity/temperature characteristics whilst those containing mainly alkaline earth glasses, for example low loss steatite, forsterite ceramics, zircon and alumina porcelain are relatively good from these points of view. Certain practically glass-free materials, for example sintered oxides of aluminium, beryllium, thorium and zirconium, have particularly good power factors and high resistivities at higher temperatures.

(c) The volume resistivity/temperature characteristics of electrical porcelain, low loss steatite and sintered alumina are given in Figure 4.

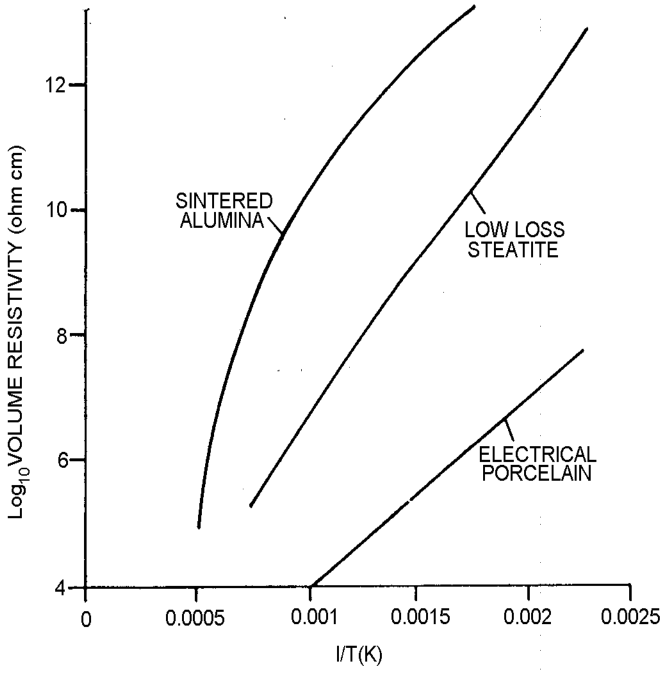

Figure 4. Volume resistivity/temperature characteristics of ceramic insulating materials

5.1.2 Dielectrics

(a) Ceramic dielectric materials are almost entirely crystaline, and the dielectric properties vary with the dielectric properties vary with the mixture of materials.

(b) Materials based in titanium oxide have a dielectric constant of approximately 100, with a negative temperature coefficient of the order of -800 x 10^{-6} per °C.

(c) Low temperature coefficient dielectrics are produced from magnesium titanate or mixtures of titanates and oxides, which have dielectric constants of between 12 and 40 and temperature coefficients ranging from +100 to -100 x 10^{-6} per °C depending on the mixture.

(d) High permittivity materials, such as the modified barium titanates, have dielectric constants between 1000 and 7000, but the dielectric properties are more temperature dependent then the previously mentioned materials.

5.1.3 Structural ceramics and coatings

(a) Ceramic materials can be used at considerably high temperatures than most metals. However, their use in structural applications at high temperatures is restricted by their susceptibility to thermal and mechanical shock. The melting points of some refractory ceramics are given in Table 7.

(b) In respect of thermal shock, the oxides are inferior to the nitrides, carbrides, borides and silicides. The oxides are of course stable to high temperature oxidation. The silicides, and to a lesser extent the borides, are fairly stable, but the suplhides and carbides are poor in this respect. Information and data of the behaviour of structural ceramics are contained in References 38,39 and 40.

TABLE 7

APPROXIMATE MELTING POINTS OF SOME CERAMIC MATERIALS

Material	Approximate melting point (°C)
Molybdenum Silicide	2030
Aluminium Oxide	2050
Aluminium Nitride	2220
Silicon Carbide	2400
Zirconium Oxide	2700
Boron Nirtride	3000
Zirconium Diboride	3000
Thorium Oxide	3050

5.2 Glass

5.2.1 The effect of temperature on the optical properties of glass is small. The temperature coefficient (per °C) of the refractive index ranges from -3×10^{-6} for crown glass, up to 9×10^{-6} for heavy flint glass. For silica glass this represents an increase in the refractive index, at a wavelength of 0.5016 µm, of from 1.4617 at -160°C to 1.4772 at +1000°C.

5.2.2 The volume resistivity and dielectric strength of glass decrease with an increase in temperature, while the dielectric losses increase. The temperature dependence of the electrical properties increases with the content of alkali metal oxides.

5.2.3 Most types of glass have optimum strength properties around 150°C, above this figure strength decreases almost linearly with temperature. Glass may be characterised as a brittle solid and therefore is susceptible to thermal shock. Most window and structural glasses are designed to withstand an abrupt change of temperature of approximately 70°C. Where high resistance to thermal shock is required, glass having a low coefficient of expansion should be used, for example borosilicate.

5.2.4 Information and data on the effects of temperature on glass are given in References 41, 42 and 43.

5.3 Wood

5.3.1 Within the naturally occurring extremes of hot and cold, the properties of wood are not usually directly affected by changes in temperature. However, the physical properties of wood are very dependent on moisture content, and inasmuch as temperature determines the prevailing relative humidity it may be considered as exerting an indirect influence. Reference 44 provides further information.

5.3.2 Long exposure of wood to temperatures greater than approximately 80°C results in a gradual loss of strength, the rate of loss increasing with rising temperature. At these temperatures there is also a risk of spontaneous combustion.

5.4 Paper

5.4.1 The loss factor, dielectric constant, and to a lesser degree the dielectric strength of paper varies with temperature. This temperature dependence is evidenced by the considerable variation in the electrical properties of paper capacitors. The mechanical properties of most papers, used for electrical purposes deteriorate in air at temperatures in excess of 80°C. Reference 42 provides further information.

5.4.2 'Book' papers discolour and become brittle when exposed to moderate heat over a long period.

5.5 Magnetic materials

5.5.1 General

(a) The term 'magnetic materials' in this context, refers to ferromagnetic metals. These include iron, and metals having similar magnetic properties to iron such as nickel and cobalt and their alloys.

(b) The greatest changes in magnetic properties with temperature occur just below the Curie point, or near temperatures at which there are changes in the structure of the material. The Curie point may be defined as the temperature at which a ferromagnetic material loses all its distinguishing magnetic properties and behaves as a paramagnetic material.

(c) The Curie points of some high permeability materials are given in Table 8. Suppliers of high permeability nickel iron alloys, and of ferrites, should be consulted concerning the Curie point of the material concerned, as this will depend considerably on composition.

(d) Although the Curie point represents the theoretical limiting temperature for operation of ferromagnetic materials, the maximum service temperature is often considerably lower. For further information, Reference 45 should be consulted.

TABLE 8

CURIE POINTS OF SOME HIGH PERMEABILITY MATERIALS

Type of material	Curie point (°C)
Nickel Zinc Ferrite	130
79% Nickel Iron	200
Nickel	360
79% Ni-Fe with 4% Molybdenum	460
50% Nickel Iron	500
4% Silicon Iron	690
25% Co 45% Ni 30% Fe (Perminvar)	715
Grain-orientated 3% Silicon Iron	740
Iron (up to 0.2% impurities)	770
Mild Steel (0.2% C)	770
50% Cobalt Iron	980
Cobalt	1120

5.5.2 Magnetic core materials

(a) With magnetic core materials, including silicon irons, aluminium irons, nickel irons, vanadium-cobalt-irons and cobalt-nickel-irons, increasing temperatures generally cause a decrease in the saturation flux density, remanent flux density and coercive force.

(b) The changes in permeability are dependent on the magnetizing force. For example, at high field strengths the permeability decreases with increasing temperature, while at low field strengths the permeability increases to a maximum just below the Curie points and then decreases rapidly as the Curie points are exceeded. Most materials show significant irreversible changes as a result of exposure to high temperatures of the order of 500°C and subsequent cooling to room temperature.

(c) Cobalt-iron alloys are core materials with high Curie points and in the range -60°C to +500°C the changes in their magnetic properties are relatively small. Further information is available in References 51 and 62.

5.5.3 Permanent magnet material

(a) Changes in permanent magnets because of heating can be grouped as follows:

  (i) Metallurgical changes, which affect the hysteresis loop and hence remain even after remagnetization.

  (ii) Irreversible magnetization changes, which remain on cooling to room temperature but which can be reversed by remagnetization.

  (iii) Reversible changes, which disappear on cooling to room temperature without remagnetization.

(b) Metallurgical and irreversible magnetization changes in certain materials can be almost eliminated over a wide temperature range, for example up to 500°C in the case of iron-aluminium-nickel alloy, by suitable heat treatment. Reference 47 provides further information.

5.6 Lubricants

5.6.1 Oils and greases

(a) The lubrication efficiency of oils and greases at high temperatures is impaired by evaporation, oxidation and the lowering of their viscosity. Oils and greases also tend to migrate at low temperatures but special additives are available to inhibit this. Data on the temperature/viscosity characteristics and performance of lubricating oils are contained in Reference 48.

5.6.2 Solid lubricants

(a) Solid lubricants have a wider service temperature range than oils and greases, but unlike oil lubricants they cannot be used to dissipate frictional heat. The most commonly used solid lubricants are molybdenum disulphide and graphite.

(b) The maximum service temperature of molybdenum disulphide in air is limited by decomposition to molybdenum trioxide, an abrasive oxide, which occurs at about 400°C. In practice, the service temperature depends on the form in which it is applied, for example as a powder, bonded coating, or dispersion. When applied as a powder, molybdenum disulphide has a service temperature range of -185°C to +400°C.

(c) Graphite begins to oxidize in air at approximately 460°C but little seems to be known of its high temperature lubricative properties. However, to lubricate effectively graphite requires the presence of a film of absorbed moisture, and it is doubtful whether this film could be maintained for any length of time at high temperatures.

(d) Further information is available in References 49, 50 and 51.

6 ELECTRONIC CONPONENTS

6.1 General

6.1.1 Some general information can be given on temperature stability and maximum operating temperatures of representative types of electronic components. However, the coverage is by no means exhaustive and detailed information should be sought from the manufacturer's literature or the relevant specifications.

6.1.2 Designers must take into account the combined effects of temperature which may lead to a cumulative effect, affecting system performance. On the other hand, it is sometimes possible to improve stability by off-setting a positive temperature coefficient component with one having a negative coefficient, for example inductors and capacitors in filter circuits, or matched pairs of capacitors.

6.2 Resistors

6.2.1 Fixed resistors may be broadly considered as general purpose or high stability. General-purpose resistors are usually of carbon composition in the form of rod or film, while high stability resistors include wire-wound, metal or metal oxide film types. Reference 52 provides further information.

6.2.2 Carbon composition types are seriously affected by ambient temperatures over 100°C, mainly by changes in the structure of the binder used in the resistor mixture. High stability resistors can be used at higher temperatures, for example, special metal and metal-oxide types can operate at surface temperatures between 500°C and 600°C.

6.2.3 The approximate maximum temperature coefficients and maximum surface temperature of different classes of resistor are given in Table 9.

TABLE 9

APPROXIMATE MAXIMUM OPERATIONAL SURFACE TEMPERATURES AND TEMPERATURE COEFFICIENTS OF RESISTOR TYPES

Resistor type	Approximate max temperature coeff (x 10^{-6}/°C) over temp range indicated	Approximate max operational surface temperature (°C)
Carbon composition	-1200 to +1200 (+20°C to +70°C):	110
Cracked carbon	-200 to -1000 (+20°C to +70°C)	150
Wirewound (general purpose)	+200 (+20°C to +130°C)	130 (lacquered types)
Wirewound (high stability)	+5 (+20°C to +130°C)	320 (vitreous enamelled types)
Metal film	+600 (-40°C to +150°C)	200
Oxide film	-500 to +500 (-40°C to +300°C)	300

6.2.4 Suppliers should be consulted for details of the temperature coefficient related to resistance value and operating temperature. In some instances resistors of controlled coefficient can be provided, for example metal film resistors with coefficients less than 50 x 10^{-6}.

6.2.5 Prolonged storage of carbon composition and cracked-carbon resistors at very low temperature (-65°C) can result in large temporary increases in resistance, of approximately 20% for carbon composition and 5% for cracked carbon.

6.3 Capacitors

6.3.1 The temperature characteristics of a capacitor depend largely on the dielectric employed. Table 10 gives the approximate operating range and temperature coefficients of capacitors of representative types, classified according to their dielectric materials.

6.3.2 Other properties such as power factor, leakage current and dc working voltage, and the ability to remain sealed may also be temperature dependent.

TABLE 10

APPROXIMATE OPERATING TEMPERATURE RANGE AND TEMPERATURE COEFFICIENTS OF CAPACITOR TYPES

Capacitor type	Approximate operating temperature range °C	Approximate temperature coefficient (x 10^{-6}/°C)
Paper	-40 to +85	+100 to +200
Mica	-40 to +85	-100 to +100
Ceramic (based on Titania)	-55 to +100	*
PTFE	-55 to +200	-200
Polyethylene Terephthalate	-55 to +125	+
Polystyrene	-40 to +80	-200
Polycarbonate	-55 to +125	+50
Aluminium foil electrolytic	-25 to +70	/
Tantalum electrolytic	-55 to +125	$

* Dependent on composition

\+ Approximately -4% and +10% capacitance change, at lower and upper limits of temperature range respectively.

/ Approximately -20% and +15% capacitance change, at lower and upper limits of temperature range respectively.

$ Approximately -8% and +10% capacitance change, at lower and upper limits of temperature range respectively.

6.3.3 Some types, for example PTFE and polycarbonate, are available in matched pairs for small tolerance and low temperature coefficient (down to 10 x 10^{-6}/°C).

6.4 Semiconductor devices

6.4.1 The absolute upper operational temperature limit of transistors is governed by the maximum permitted junction temperature, but in many applications a lower limit may have to be accepted, owing to changes in other temperature sensitive characteristics. Germanium devices are limited to maximum junction temperatures of between 60°C and 90°C, compared with 150°C to 200°C for silicon.

6.4.2 The majority of transistors and diodes may be operated down to -55°C.

6.4.3 The upper temperature limit of the majority of integrated circuits is 125°C. Manufacturers should be consulted on temperature characteristics.

6.5 Miscellaneous components

6.5.1 Table 11 lists the approximate maximum operating temperature of some miscellaneous electrical components. The figures quoted refer to a reasonably long life. Many of the components can operate at significantly higher temperatures if a shorter life is accepted.

TABLE 11

APPROXIMATE MAXIMUM OPERATING TEMPERATURE OF SOME MISCELLANEOUS ELECTRICAL COMPONENTS

Component type	Temp °C	Remarks
1 Variable resistors		
(a) Wire-wound ceramic formers	150-200	High wattage, open type, toroidal wound, unsealed
(b) Carbon composition, zero dissipation	115	Spindle seal temperature limited to 70°C for neoprene seal. (See 'Spindle seals')
(c) Cermet, zero dissipation	175	Glass and metal film, linear trimmer type. Thermoset plastic cases possibly supporting combustion.
2 Transformers and Chokes		
(a) High temperature	250	Transformers have been developed to work at 500°C (limited life)
(b) Normal types	110	
3 Relays - Ceramic and glass insulation	150	
4 Plugs and Sockets - Ceramic insulation	300	
5 Switches		
(a) Ceramic base	150-180	Rotary type - mechanical binding of spindle governs temperature limit
(b) Toggle switch	100-115	
6 Sleeving		
(a) PVC	85	
(b) High temperature PVC	100	
(c) Glass fibre	250	
(d) PTFE	250	
7 Cables - Mineral insulation	250	
8 Spindle seals		
(a) Neoprene rubber	70	
(b) Silicone	100	

7 THERMAL STRESS

7.1 General

7.1.1 Structures or components of weapon systems can be adversely affected by temperature induced stresses, unless suitable design criteria have been adopted.

7.1.2 Thermal stresses may be induced as a result of:

(a) Temperature gradients produced in a structure by transient heating.

(b) Changes in temperature of materials in structural contact having different coefficients of thermal expansion.

(c) External restraints preventing expansion.

7.1.3 The stresses due to (a) and (b) are generally superimposed, but it is important to remember that stresses produced by temperature gradients can exist in a structure made of the same material throughout.

7.2 Thermal stress modulus

7.2.1 The thermal stress modulus is the product of the modulus of elasticity and the coefficient of thermal expansion of the material. It is a useful parameter for estimating the thermal stresses induced in a structure.

7.2.2 The thermal stress moduli of some structural alloys at 200°C are given in Table 12, and Reference 55 provides further information.

TABLE 12

THERMAL STRESS MODULI OF SOME STRUCTURAL ALLOYS

Material	Thermal stress modulus at 200°C (N/mm² °C)
Titanium alloys	1.02
Magnesium alloys	1.08
Aluminium alloys	1.51
Alloy steels	2.41
Nimonics	2.78

7.3 Stresses due to differences in the coefficient of thermal expansion

7.3.1 In a structure built from materials having different coefficients of expansion, a comparison of the thermal stresses induced between structural elements is provided by the differences in thermal stress moduli.

7.3.2 From the data given in Table 12, it can be seen that Titanium and Nimonic alloys in structural contact would experience thermal stresses approximately four times as severe as alloys of magnesium and aluminium in a similar thermal environment. This assumes a uniform temperature distribution; however, in practice the problem of thermal stresses is complicated by the existence of thermal gradients in the structure and the addition of stresses due to applied loads.

7.4 The distinction between thermal stresses and applied stresses

7.4.1 When dealing with stresses in the inelastic range, it is particularly important to appreciate that the temperature change results directly in element strain and only indirectly affects element loads (or stresses). Applied loads however, directly affect the element loads (or stresses) and only indirectly affect the element strains.

7.4.2 The distinction is purely academic if the total element loads lie within the linear elastic range. At the yield point however, an increase of about 1.3 on the applied load is likely to fail a stable structure, whereas the strain would have to be increased by about 10 to produce ultimate failure in most aircraft structure materials. A temperature change is therefore unlikely to produce ultimate failure of a stable structure, unless it is accompanied by severe degradation of mechanical strength.

7.5 Stresses due to temperature gradients

7.5.1 Temperature gradients are the product of transient heating, occurring, for example, in a missile structure during periods of acceleration. In these circumstances a large temperature differential may exist between the skin and the inside of the structure. The thermal stress between, say, the skin and a supporting web of the same material will be proportional to the temperature difference and the thermal stress modulus.

7.5.2 Temperature gradients and in general, thermal stresses, will be reduced by use of materials having high thermal diffusivities, that is, the product of specific heat and density. The thermal conductivity, specific heat, density and thermal diffusivity of some structural alloys are compared in Table 13; Reference 54 provides further details.

7.5.3 Consideration must be given to the finite time needed for heat to penetrate a structure, and to possible internal effects of 'delayed action'.

TABLE 13

THERMAL PROPERTIES OF SOME STRUCTURAL ALLOYS

Material	Thermal Conductivity (W/cm °C)	Specific heat (J/g °C)	Density (g/cm³)	Thermal diffusivity (cm²/s)
Titanium alloys	0.17	0.544	4.5	0.07
Magnesium alloys	1.26	1.026	1.8	0.68
Aluminium alloys	1.47	0.963	2.7	0.56
Alloy steels	0.25	0.461	7.8	0.07
Nimonics	0.13	0.461	8.3	0.03

7.6 Thermal shock

7.6.1 If the temperature gradient and the associated thermal stresses are produced very quickly, the effect on the material may be different than for a slow rate, even though the resultant stress level may be the same in both cases. Rapid application of stress may embrittle some materials and cause failure at a much lower strain than under steady conditions.

7.6.2 Brittle and ductile materials react differently to thermal stress. Since the thermal stress arises from strain due to temperature expansion, brittle materials, which can endure very little strain before rupture, may fail under thermal shock. Ductile materials, which can undergo large strains before rupture, can usually absorb the thermal shock. However, ductile materials may fatigue under repeated application of the shock.

7.6.3 For brittle materials such as ceramics, the ratio $\frac{\sigma}{E\alpha}$ has been suggested as a measure of thermal shock resistance,

where σ = rupture strength
E = modulus of elasticity
α = coefficient of thermal expansion

Thus thermal shock resistance is inversely proportional to the coefficient of thermal expansion, and directly proportional to the strain $\frac{\sigma}{E}$ the materials can withstand before rupture.

7.6.4 A high thermal conductivity will tend to reduce thermal shock, but the degree of its influence depends on the operating conditions. Table 14 lists the approximate ratio $\frac{\sigma}{E\alpha}$ and thermal conductivity of some ceramics and cermets, and further details are found in Reference 61.

TABLE 14

PHYSICAL PROPERTIES RELATING TO THERMAL SHOCK RESISTANCE OF SOME CERAMICS AND CERMETS

Material	Coefficient of thermal expansion (per °C)	Strength at rupture (N/mm^2)	Modulus of elasticity E at 20 °C (kN/mm^2)	Thermal conductivity (W/cm °C)	$\frac{\sigma}{E\alpha}$
Silica	0.5 x 10^{-6} (20 - 1000°C)	131.0 (1000°c)	72.4	0.017 (100°C) 0.050 (1000°C)	3600
Silicon Nitride	2.5 x 10^{-6} (20 - 1000°C)	110.3 (1200°C)	62.1	0.015 (20°C)	710
Titanium Carbide Cermet	5.6 x 10^{-6} (20 - 1000°C)	896.3 (1000°C)	344.7	0.293 (20°C)	460
Self-bonded Silicon Carbide	3.9 x 10^{-6} (25 - 1400°C)	206.8 (1200°C)	468.8	0.502 (100°C) 0.042 (1000°C)	110
Chrome-Alumina Cermet	8.9 x 10^{-6} (20 - 1000°C)	137.9 (1000°C)	258.6	0.335 (100°C) 0.209 (1000°C)	60
Sintered Alumina	8.6 x 10^{-6} (20 - 1000°C)	151.7 (1000°C)	365.4	0.289 (100°C) 0.059 (1000°C)	48

7.6.5 Thermal shock conditions may produce dynamic effects through vibration of the structure, in which case inertia terms must be included in the thermal stress equations.

7.7 Inelastic thermal stress and fatigue

7.7.1 It is possible that temperature cycling will produce in a member the condition of fully plastic in tension followed by fully plastic in compression, on each cycle. The alternate plasticity of the member will probably lead to strain hardening and failure after a few hundred cycles.

7.8 Thermal buckling

7.8.1 Thermal stresses induced in structures by temperature differences must cancel within the structure. Thus the thermal stress distribution must contain compressive stresses, and there is a possibility of buckling. If an element buckles, the high bending strains induced very much reduce the overall total strain required to produce ultimate failure.

7.8.2 This effective reduction is highly dependent upon the geometry of the element, the buckling mode and the buckling stress level, but usually the result is that the ultimate overall thermal strain is less than double that required to initiate buckling. However, it should be noted that there is often still an appreciable margin between the buckling and ultimate thermal loads, so that thermal buckling is generally not so serious as buckling under applied loads.

7.8.3 Since thermal stresses are proportional to the product of elastic modulus (E) and temperature coefficient, and as the buckling criteria are also proportional to E, it is clear that thermal buckling is primarily dependent upon temperature coefficient.

7.9 Aerothermoelasticity

7.9.1 The interaction of aerodynamic heating with aeroelastic phenomena has meant that a range of possibly coupled effects need to be considered. Typical aerothermoelastic problem areas are:

(a) Non-linear aeroelastic effects due to the reduction of torsional and flexural stiffness under heating conditions.

(b) Chordwise curling of the leading edge of low aspect ratio wings. The possibility may arise of chordwise divergence being affected by the thermal curvatures due to heating, which itself might be modified by the chordwise bending.

(c) Influence of thermal stresses on body bending and static aeroelasticity.

(d) Influence of thermal stresses on panel flutter.

(e) Effect of leading edge ablation on wing flutter characteristics.

8 OPERATION OF COMPLEX SYSTEMS

8.1 General

8.1.1 The materials and components used in complex weapon systems may be affected by temperature in many ways. The following specific temperature effects have been included as a guide. References 55 and 56 provide further information.

8.2 Mechanical, hydraulic and pneumatic systems

8.2.1 The accuracy of delicate controls, such as gyros, accelerometers and inertial platforms, is dependent upon close temperature tolerances since dimensional changes may cause a shift in the centre of gravity.

8.2.2 Different coefficients of expansion may reduce mechanical clearances causing binding or seizure at high or low temperatures, resulting in increased wear of rubbing parts or complete malfunctioning of equipment.

8.2.3 Increased temperatures may lower the viscosity of hydraulic fluids and greases sufficiently to cause leakage problems.

8.2.4 An increase in the viscosity of oils and hardening of greases may cause difficulty in the starting of rotating machinery and the operation of hydraulic systems.

8.2.5 The ingress of moisture, and subsequent freezing, in pneumatic systems can clog metering orifices and lines.

8.3 Electrical and electronic systems

8.3.1 High temperatures may cause decomposition and dielectric failure of capacitors, resistors and insulating materials, and instability and shifts in values and parameters of components. High temperatures can cause deterioration of most types of electro-chemical batteries, other than certain primary, reserve types.

8.3.2 At low temperatures, critical electronic systems require more time for warm up to temperature stability. The outputs of electrochemical batteries, other than thermal batteries, may fall off excessively.

8.4 Propulsion

8.4.1 Decomposition of liquid rocket propellants is excessive during storage in tropical or desert areas. For example nitric acid decomposes within 2 months at approximately 70°C.

8.4.2 The vapour pressure of liquid propellants builds up with increasing temperature. Increased vapour pressure may be sufficient to cause vapour locks in propellant lines or cooling passages and cavitation in pumps.

8.4.3 Liquid propellant metering equipment is usually sensitive to high temperature.

8.4.4 Solid propellant rockets usually have a higher burning rate at high temperatures, resulting in a somewhat higher thrust of shorter duration. At low temperatures solid propellant rockets usually have a decreased burning rate, resulting in lower thrusts over a longer burning time.

8.4.5 If solid propellant rockets are exposed to direct sunshine the temperature rise in the charge will be greater over the insulated area, thus causing uneven burning and possibly erratic operation.

8.4.6 Differing coefficients of expansion can cause the bond between solid rocket propellant charges and the combustion chamber wall to crack, which will result in uneven burning and possibly an explosion.

8.4.7 Liquid propellant rocket engines are more difficult to start and operate at low temperatures, owing to greater ignition lags, susceptibility to combustion instability, viscosity of fluids and sluggish operation of propellant flow controls.

8.4.8 Moisture in propellant lines or absorbed by the fluid, may freeze, causing valves to stick, or filters, valves and orifices to clog.

8.5 Structure

8.5.1 High skin temperatures resulting from aerodynamic heating lower the strength properties of structural metals and plastics.

8.5.2 Low temperatures cause an increase in brittleness of some metals and structural plastics, resulting in a lowering of their ability to withstand impact.

8.6 Observations

8.6.1 The successful operation of equipments at temperature extremes depends on:

(a) Correct selection of materials and components.

(b) Allowance at the design stage for any shift in significant properties or parameters with temperature.

(c) The achievement of a satisfactory heat balance.

(d) Pre-service proving of systems at the anticipated environmental temperatures.

9 HUMAN TOLERANCE OF TEMPERATURE EXTREMES

9.1 The humidity/temperature limits of human physical activity are outlined in Chapter 4-02. Further information is available in Reference 58.

9.2 Figure 5 shows experimentally determined ranges of thermal tolerance for resting men without protection and also protected with the best clothing for each zone of heat or cold. The environments used in establishing the curves were all characterized by low air movements of less than 30 m/min, and approximately equal air and wall temperatures.

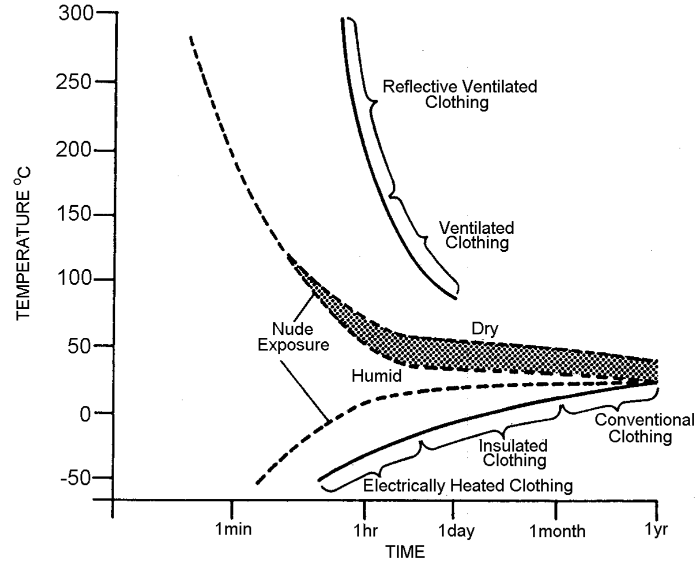

Figure 5. Ranges of human thermal tolerance

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CHAPTER 3-01
SOLAR RADIATION

1 INTRODUCTION

1.1 This chapter discusses the solar radiation received at the earth's surface under both clear and cloudy skies.

1.2 Radiation from the sun provides virtually all the energy for the natural processes which take place in the oceans, on land and in the atmosphere. High speed particles emitted by the sun represents only a very small part of the total energy, and hence for most practical purposes solar radiation can be regarded as electromagnetic.

1.3 The spectrum of the sun's radiation extends from radio wavelengths to beyond the ultra-violet. However the major part of the energy lies in the ultra-violet, visible and near infra-red bands, with 98% between the wavelength of 0.2 and 3 micrometres. All solar radiation causes heating when absorbed.

2 SOLAR RADIATION OUTSIDE THE EARTH'S ATMOSPHERE

2.1 The Solar Constant is defined as the amount of radiant solar energy which falls in unit time upon unit area of a plane; the plane being positioned just outside the atmosphere, normal to the sun's rays and at the mean earth-sun distance. The most recent measurements give a value of 1370 W/m^2 for the solar constant with a probable error of ±10 W/m^2; but the figure used in this chapter is the previously accepted value of 1360 W/m^2.

2.2 Variations in the earth's solar distance and solar elevation angle

2.2.1 The orbit of the earth about the sun is an ellipse with the centre of the sun at one focus, and with the mean earth-sun distance being about 149.4 x 10^6 km. This elliptical orbit has only a small eccentricity, resulting in a maximum deviation of ±1.67% between perihelion (4 January) when the earth is closest to the sun, and aphelion (5 July) when it is furthest away. Since the radiation intensity varies as the square of the distance, the actual energy received on a surface normal to the sun's rays can be 2.8% higher or lower than the solar constant, and therefore varies between 1400 W/m^2 at perihelion to 1320 W/m^2 at aphelion.

2.2.2 The intensity of radiation received at any instant, on a horizontal surface just outside the atmosphere, is proportional to the sine of the solar elevation angle, this may be derived from the equation:

$$\sin a = \sin \Theta \sin d + \cos \Theta \cos d \cos h$$

Where
a = Solar elevation angle required
Θ = Latitude of station
d = Solar declination
h = Hour angle of the sun (its angular distance from the observer's meridian).

2.2.3 The total amount of radiation received in a day on a horizontal surface just outside the atmosphere will depend on latitude and time of year. Figure 1 shows the total energy in W/m^2 received, averaged over 24 hours; the shaded areas represent arctic and antarctic winter nights. To obtain the energy received per unit area between sunrise and sunset in MJ/m^2, multiply the figures shown by 0.0864.

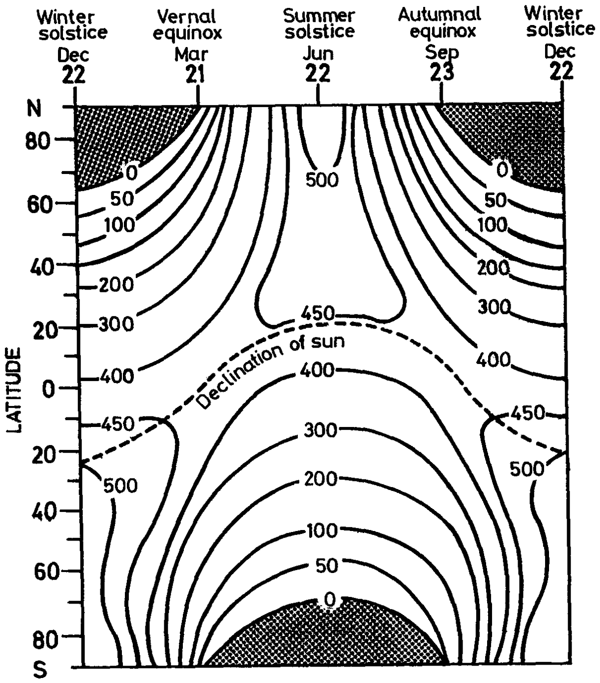


Figure 1. **Daily total of solar radiation received on a horizontal surface just outside the atmosphere, expressed in W/m^2 averaged over the 24 hours**

3 INTENSITY OF RADIATION RECEIVED AT THE EARTH'S SURFACE

3.1 Factors affecting the total radiation

3.1.1 The intensity of radiation received depends not only on the solar constant, the earth-sun distance and the solar elevation angle, but also on:

(a) The extent to which the direct radiation is attenuated by the atmosphere.

(b) The amount of scattered radiation received from the sky.

3.2 Optical air mass

3.2.1 The atmospheric path length through which the radiation must pass before reaching the earth's surface may be expressed in terms of the 'optical air mass' or simply air mass. This is taken as unity when the sun is in the zenith (solar elevation = 90°). At other times the air mass is approximately equal to the cosecant of the solar elevation, provided this angle is not less than about 12°. These values of air mass are based on atmospheric pressure of 1013.25 hPa; to derive the appropriate air mass for any other pressure it is necessary to multiply by the ratio of actual to standard pressure.

3.3 Attenuation of direct radiation

3.3.1 In passing through the earth's atmosphere the direct radiation is partially absorbed by water vapour in the infra-red band and by ozone in the ultra-violet band. It is also attenuated as a result of scattering by molecules of nitrogen, oxygen and other atmospheric gases. However, as the amount of scattering is inversely proportional to the fourth power of the wavelength (Rayleigh's Law) only the shorter wave lengths are scattered appreciably. Some scattering and absorption is also caused by dust, but because the aerosol particles are often much larger than the wavelength of the solar radiation, Rayleigh's Law does not apply. Specialist literature should be consulted if more detailed information is required.

3.3.2 Any appreciable cloud between the sun and the observer will reduce direct radiation to zero, thinner cloud having proportionately less effect. On days of broken cloud with strong winds at cloud level, the intensity of direct radiation may vary between nil and its maximum value within a few seconds.

3.3.3 Figure 2 shows the variation with latitude and season of the direct solar radiation received on a horizontal plane at the earth's surface, with cloudless skies and an atmospheric transmittancy of 0.7 at an air mass of 1.0. Atmospheric transmittancy T of a medium of thickness r can be defined as $T = \tau^r$, where τ is the transmittivity. Transmittivity is the fraction of radiation intensity incident on a medium which remains in the beam after passing through unit thickness of the medium.

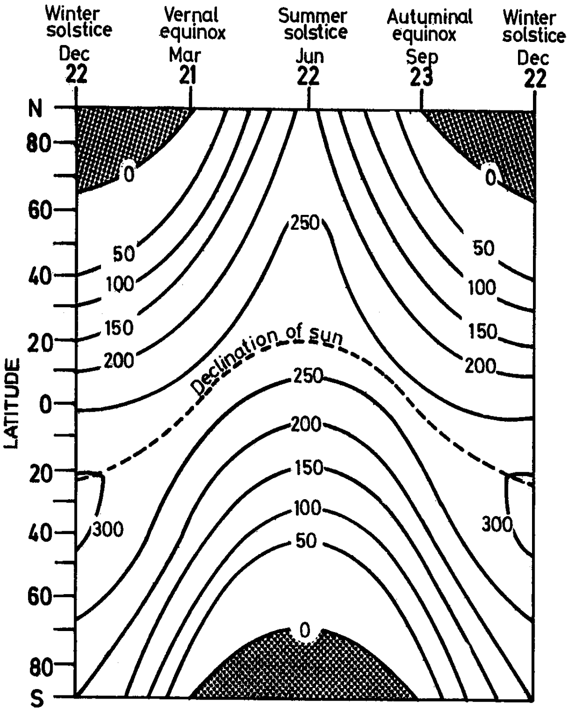


Figure 2. Daily total of direct solar radiation received at the Earth's surface, expressed in W/m^2 averaged over the 24 hours.

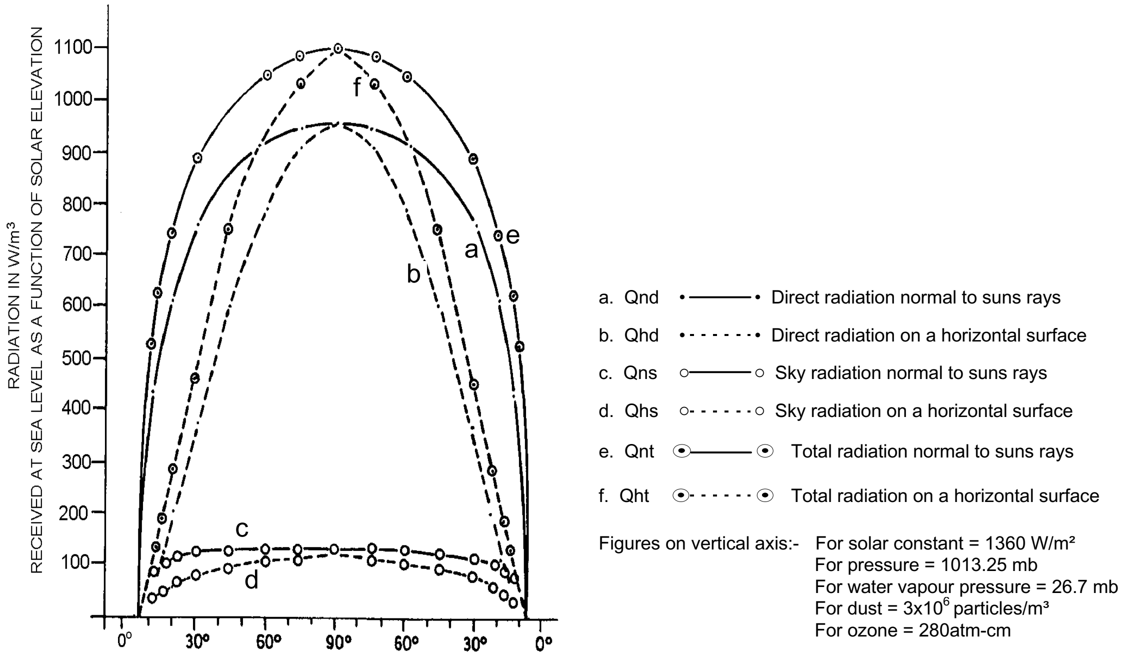
3.4 Diffuse radiation from the sky

3.4.1 Part of the direct radiation scattered in the atmosphere by gas molecules reaches the earth's surface as diffuse sky radiation. But since only the shorter wavelengths suffer appreciable scattering in this way, the contribution of sky radiation is much greater in this part of the spectrum, accounting for the blue colour of the sky. In the ultra-violet band it may often exceed the direct radiation.

3.4.2 It can be seen from Figure 3 that sky radiation is relatively constant between sunrise and sunset, and as a result accounts for approximately 1/8th of total radiation at noon, when direct radiation is at its highest. However, shortly after sunrise and approaching sunset, when direct radiation levels are very low, sky radiation will be the predominant factor.

3.4.3 Similarly, a portion of the direct radiation scattered by dust is also directed downwards. The more scattering of this type, the more the sky appears luminous and bright in colour. Scattering by dust particles is generally more important than scattering by gas (air) molecules. The proportion of sky radiation at noon varies from about 1/10th with a clean atmosphere to about 1/4 when the concentration of aerosols is high, for example over the UK.

3.4.4 Although the direct radiation is reduced when the sky is cloudy the presence of cloud also causes scattering and reflections. As a result the diffuse component increases with increasing cloudiness until the sky is a little over three-quarters covered, after which it starts to decrease as absorption becomes the dominant factor. The amount of absorption is related to cloud thickness, so that on days when the sky is covered by thick cloud not only is the direct radiation cut off but the diffuse component is considerably reduced.



Figures on vertical axis:- For solar constant = 1360 W/m²
For pressure = 1013.25 mb
For water vapour pressure = 26.7 mb
For dust = $3x10^6$ particles/m³
For ozone = 280atm-cm

Figure 3 Radiation received at sea level as a function of solar elevation

3.4.5 On days of broken cloud there may be short periods when the direct component is unobstructed, and reflection from the surrounding clouds yields a higher than normal value for the diffuse component. During such periods the total radiation received may exceed the maximum which is theoretically possible under clear skies.

3.5 Total radiation received at the earth's surface

3.5.1 Table 1 and Figure 3 show the direct, diffuse and total radiation which will be received on a normal and a horizontal surface as the solar elevation varies during a day with no clouds and little aerosol, for a total maximum intensity of 1100 W/m^2.

TABLE 1
DIRECT, SKY AND TOTAL SOLAR RADIATION ON THE NORMAL AND HORIZONTAL PLANES AS A FUNCTION OF SOLAR ELEVATION

Air mass	Solar elevation	Direct radiation W/m^2		Sky radiation W/m^2		Total radiation W/m^2	
		Qnd	Qhd	Qns	Qhs	Qnt	Qht
1	90°	960	960	140	140	1000	1100
1.04	75°	950	920	140	130	1090	1050
1.15	60°	920	790	140	120	1060	910
1.41	45°	840	600	130	110	970	750
2	30°	760	380	130	90	890	470
3	19°30'	620	210	120	70	740	290
4	13°30'	520	130	110	60	630	190
5	11°30'	440	90	100	50	540	140

3.5.2 Figure 4 shows the daily total of a direct and diffuse radiation received at the earth's surface as a function of season and latitude, assuming an atmosphere which transmits 0.7 of the direct radiation, at an air mass of 1.

3.6 Variation with altitude

3.6.1 If factors such as location, date, time and absence of cloud do not vary, the intensity of radiation increases with altitude owing to the reduced depth of the attenuating atmosphere. Total radiation intensity averages about 10% more at 1000 m above mean sea level and 20-25% more at 3000 m, compared with that expected at sea level. At higher altitudes the rate of increase is slower, reaching a maximum of about 30% at the 'top' of the atmosphere. Radiation at wavelengths filtered by the atmosphere become increasingly significant at high altitude.

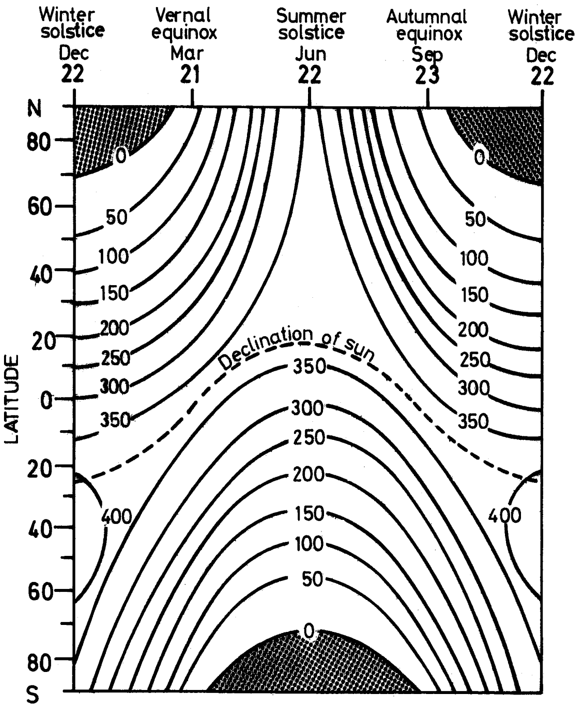


Figure 4. Daily total of direct and diffuse solar radiation received on the Earth's surface expressed in W/m^2 averaged over the 24 hours.

4 SPECTRAL ENERGY DISTRIBUTION

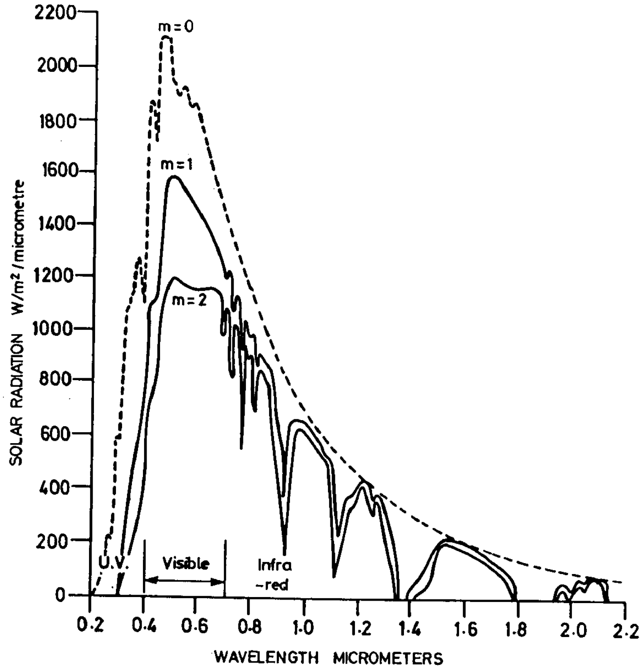
4.1 Table 2 provides information on the spectral energy distribution of direct radiation on a surface normal to the sun's rays, expressed as a percentage of total radiation, for air mass readings from 0 to 5. Energy received on a horizontal surface will be in the same proportion but its actual magnitude will depend on the solar elevation.

TABLE 2
VARIATIONS IN PROPORTIONS OF SOLAR RADIANT ENERGY IN ULTRA-VIOLET, VISIBLE, AND INFRA-RED BANDS WITH INCREASING AIR MASS

Wavelength(micrometres)		Air mass					
		0	1.0	2.0	3.0	4.0	5.0
Ultra-violet	0 -0.29	0.79%	-	-	-	-	-
	0.29-0.40	8.23%	4.3%	2.7%	1.6%	1.1%	0.6%
Visible	0.40-0.70	40.04%	45.3%	44.3%	42.6%	40.4%	38.1%
Infra-red	0.70-1.10	28.13%	33.3%	36.1%	38.4%	40.3%	42.2%
	1.10-1.90	16.24%	15.7%	15.7%	16.2%	16.9%	17.7%
	1.90-	6.57%	1.4%	1.2%	1.2%	1.3%	1.4%
W/m^2 normal to the sun's rays		1375	970	770	625	525	445

4.2 From Table 2 it can be seen that for an air mass of 1, about 50% of the direct radiation is infra-red, 45% is visible, and less than 5% ultra-violet. As the air mass increases, the proportion of infra-red rises, because although attentuation takes place throughout the spectrum it is greater at shorter wavelengths.

4.3 Figure 5 shows spectral energy distribution for air mass 0 (outside the atmosphere), 1 (at the earth's surface, solar elevation = 90°) and 2 (at the earth's surface, solar elevation = 30°).



Parameters when m = 1:

Solar constant ....= 1360 W/m^2
Total pressure ....= 1013.25hPa
Water vapour pressure ....= 26.7 hPa
Dust ....= 3x10^8 particles/m^3
Ozone ....= 280 m atm-cm

Figure 5. Spectral energy distribution of direct solar radiation on a surface normal to the sun's rays

5 SEASONAL VARIATION AT THE SURFACE

5.1 Figures 6 to 18 are world maps showing the average monthly and annual solar radiation in W/m^2. To obtain the energy received per unit area between sunrise and sunset (in MJ/m^2) multiply the figures shown by 0.0864. A comparison of Figures 6 to 18 with Figure 4 indicates the fraction of the maximum possible solar radiation without any cloud, actually received in any particular place and month.

5.2 The '0' line, when it appears in Figures 6 to 18, represents the latitude above which the sun remains below the horizon throughout that month. These charts show average conditions and are not restricted to measurements on clear days; the effect of cloud is very marked. The areas with broken lines (or isopleths) on these maps are high ground, where it is not possible to give reliable figures.

5.3 It is possible for the extreme values of solar radiation and temperature to occur on the same day, but experience shows that the probability of these extremes occurring simultaneously is very low. However, where equipment temperatures are critical, such as where explosives are involved, it may be necessary to evaluate this combination of conditions in detail and the Meteorological Office should be consulted for this information.

6 SOLAR RADIATION REFLECTED AT THE EARTH'S SURFACE

6.1 The fraction of the total solar radiation reflected by a particular kind of surface is called the albedo. Typical values are 0.8 for fresh snow, 0.5 for old snow, 0.4 for light-coloured dry sandy soil, 0.25 for most field crops, 0.2 for grass, 0.15 for forests and less than 0.1 for water (though larger values, due to reflection, can occur at low solar elevations). The reflection from some surfaces is strongly dependent on wavelength. The reflected radiation has to be taken into account when calculating the amount of radiation absorbed by equipment, especially over light-coloured surfaces such as deserts and snowfields.

7 FURTHER READING

Smithsonian Meteorological Tables - 6th Revised Edition, pp. 411-447, Smithsonian Institute, Washington, 1968.	
'Atlas of the Heat Balance of the Earth' Moscow, USSR, 1963.	M I Budyko
'An Introduction to Atmospheric Physics' Academic Press, 1963.	R G Fleagle and J A Businger
'Handbook of Meteorological Instruments' Vol. 6, Met 0, 919f, London HMSO 2nd Edition, 1982,.	
'An Introduction to Solar Radiation' Academic Press, 1983.	M Iqbal

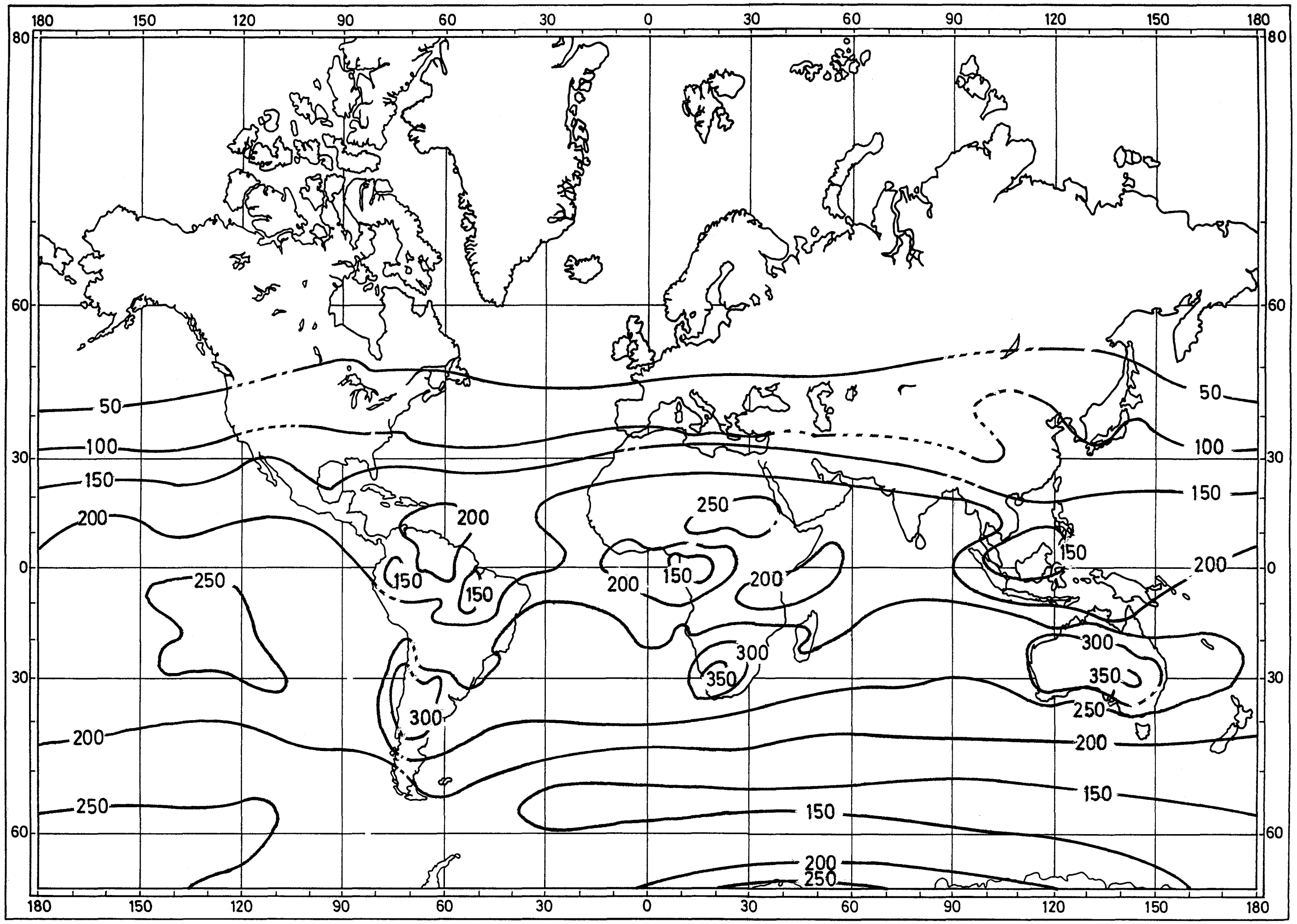


Figure 6. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - January

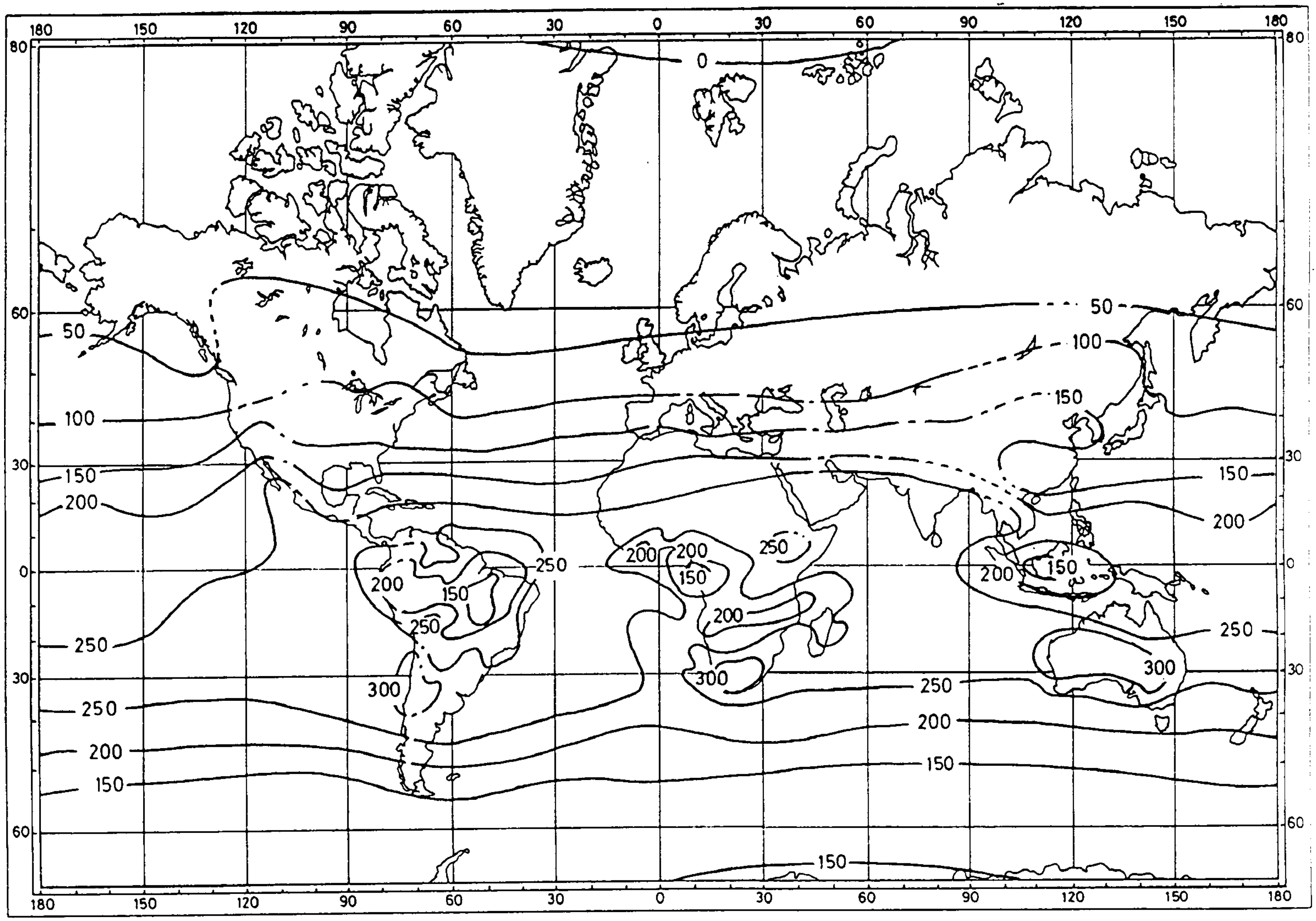


Figure 7. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - February

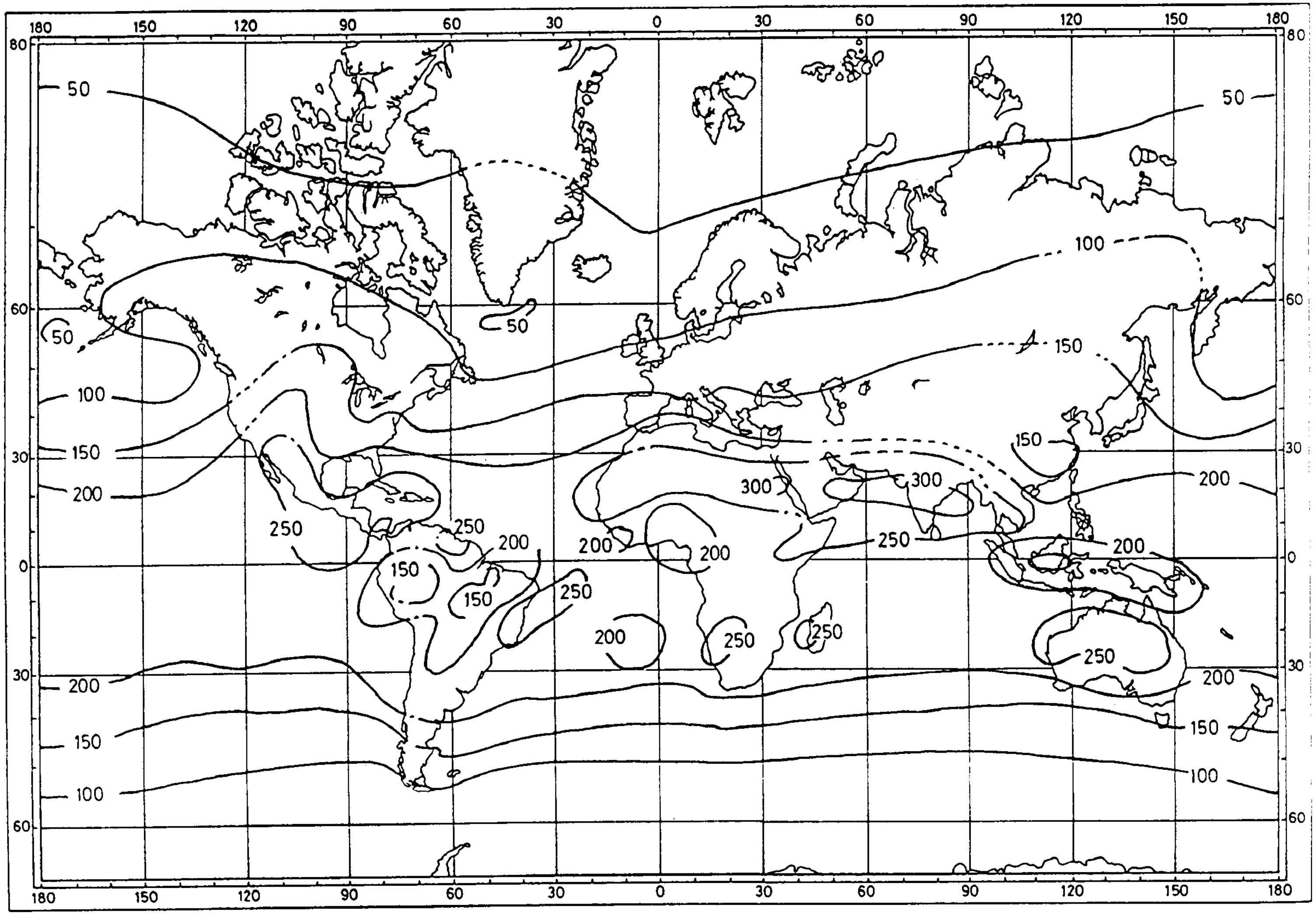


Figure 8. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - March

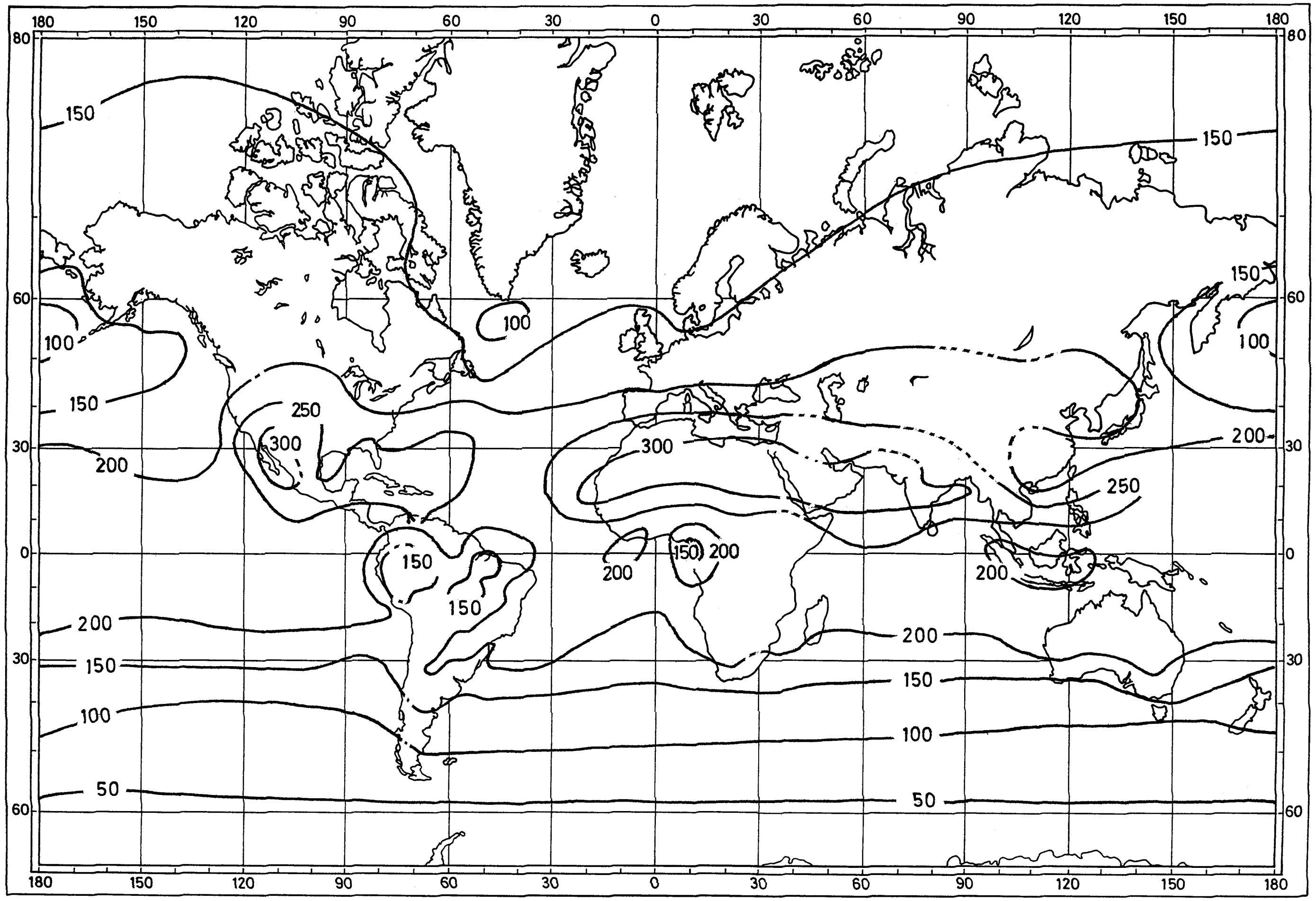


Figure 9. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - April

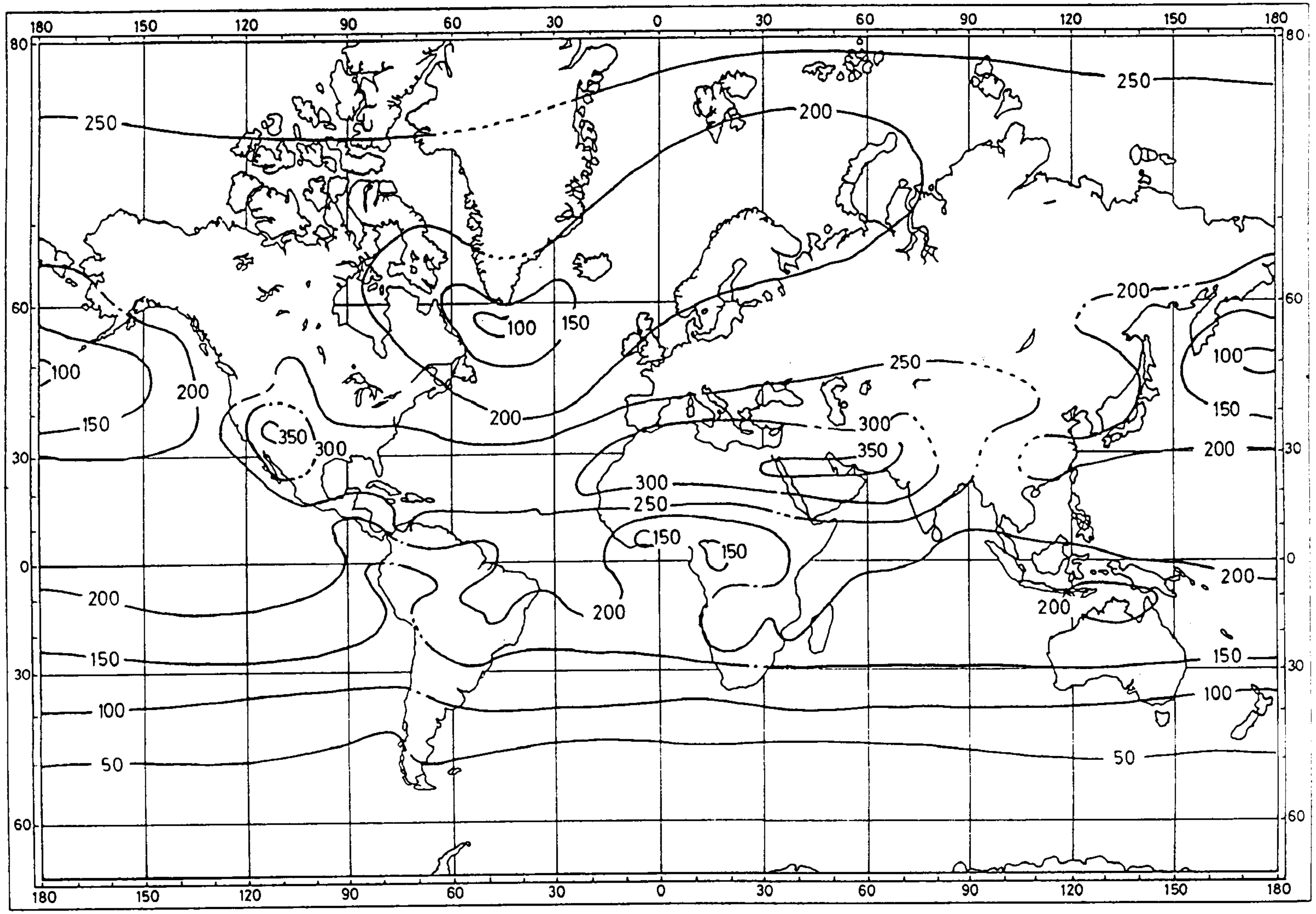


Figure 10. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - May

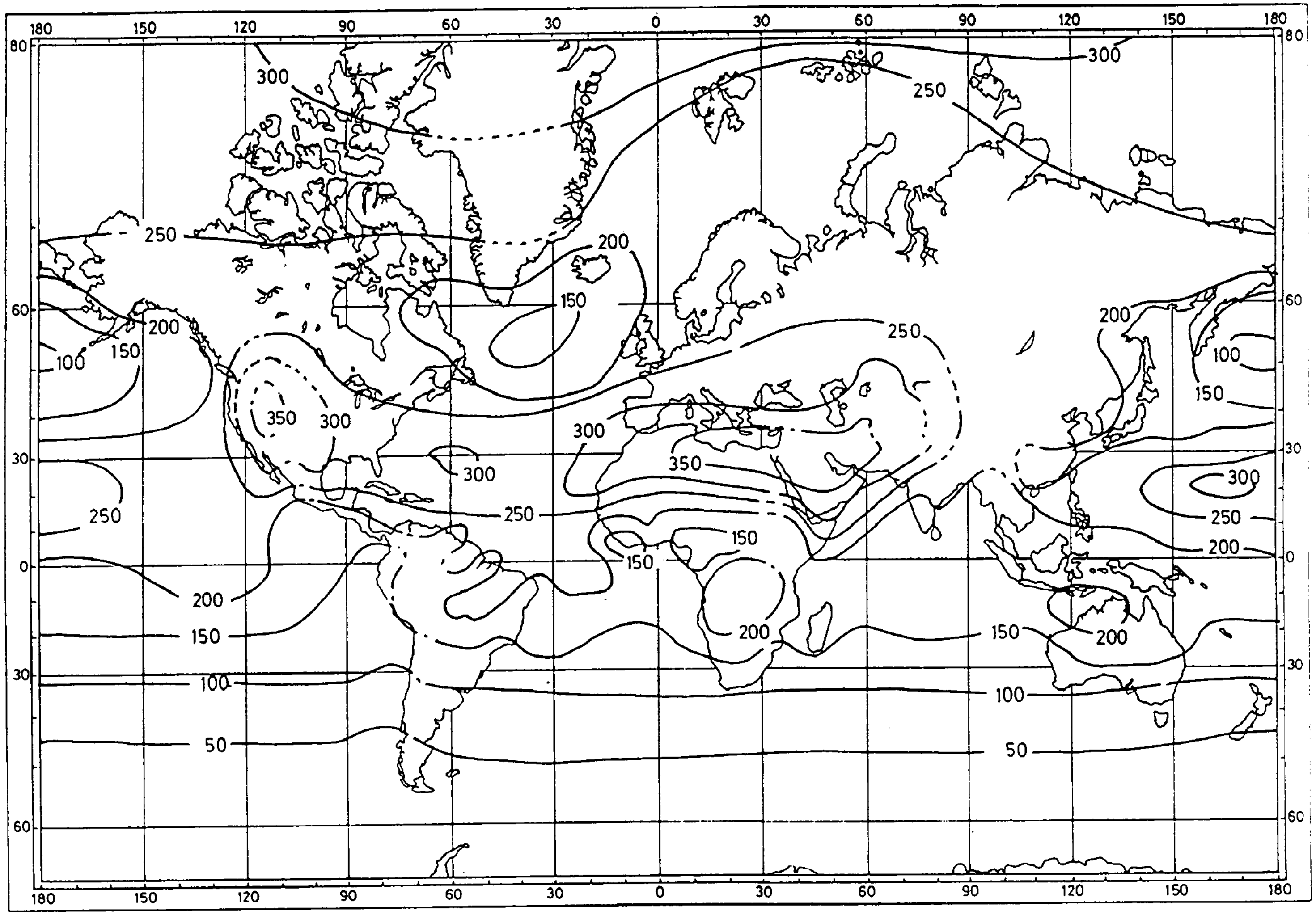


Figure 11. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - June

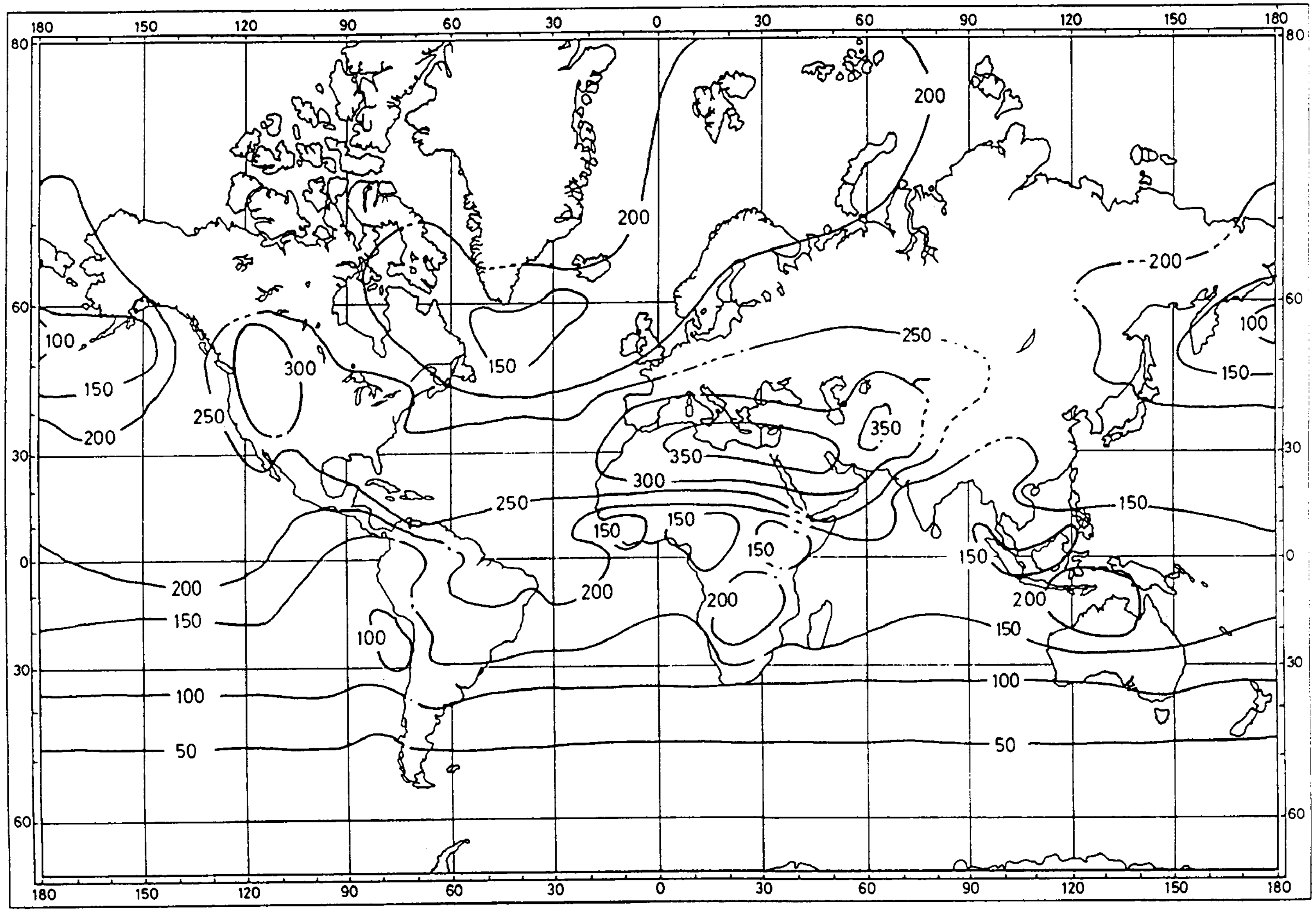


Figure 12. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - July

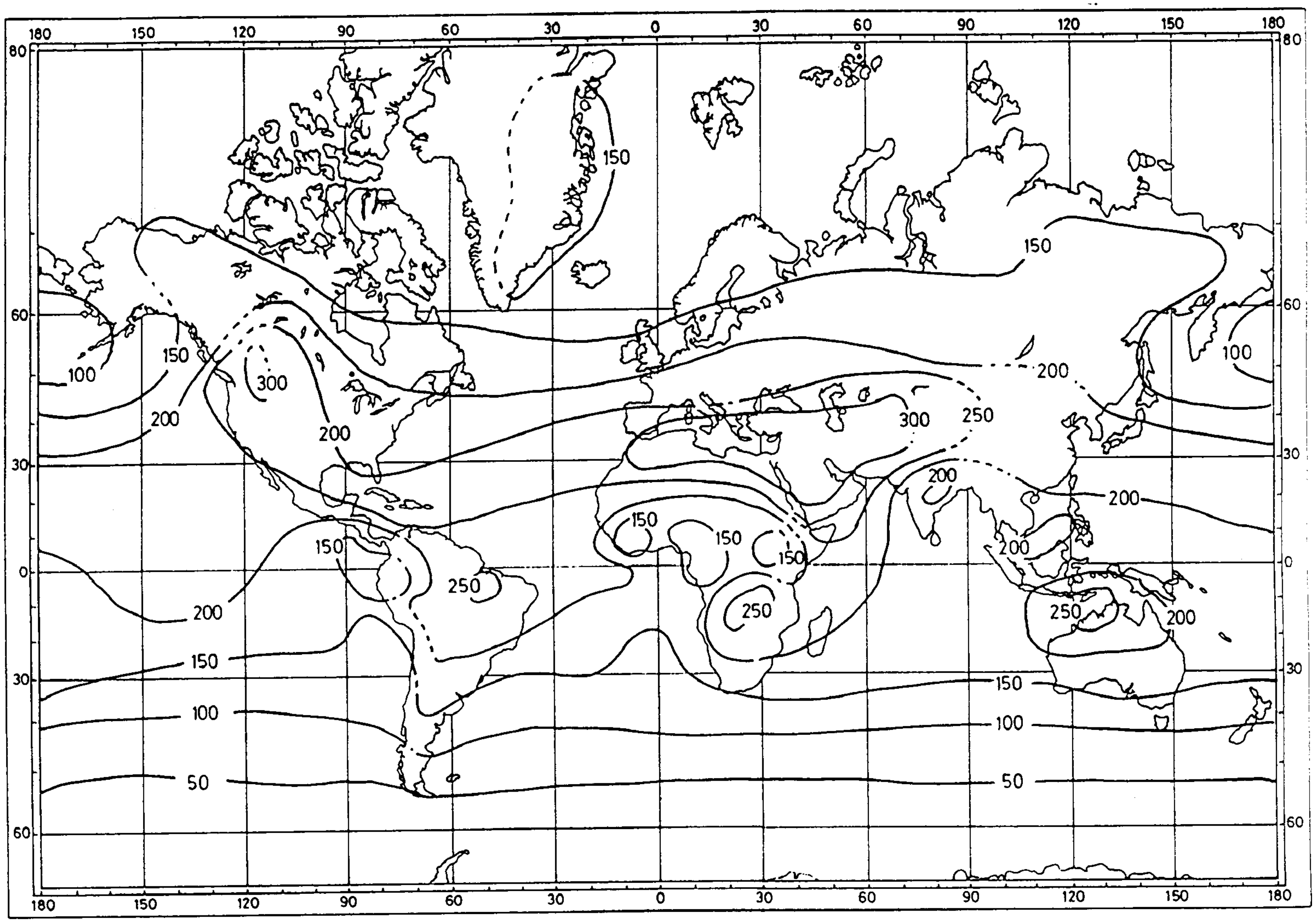


Figure 13. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - August

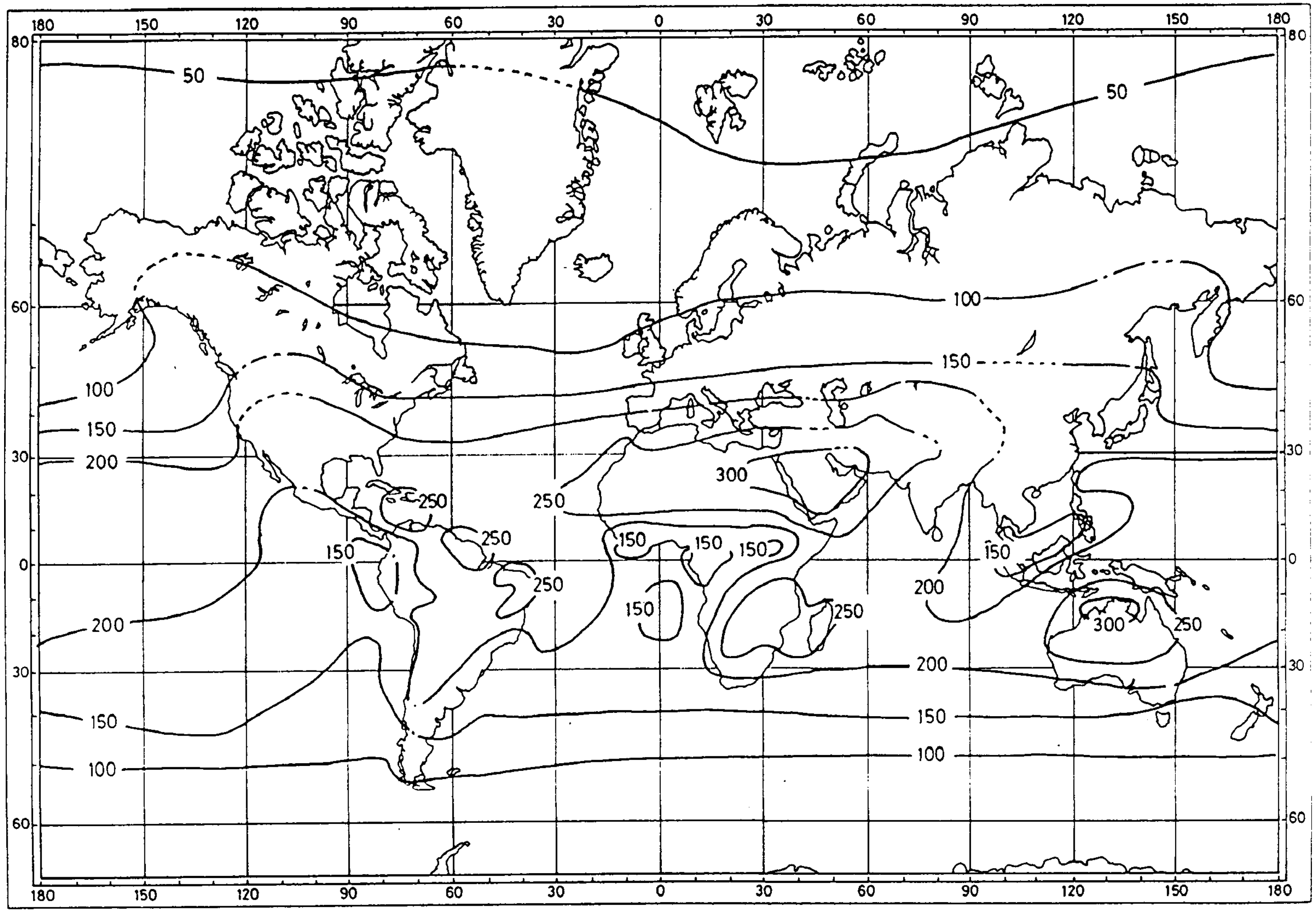


Figure 14. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - September

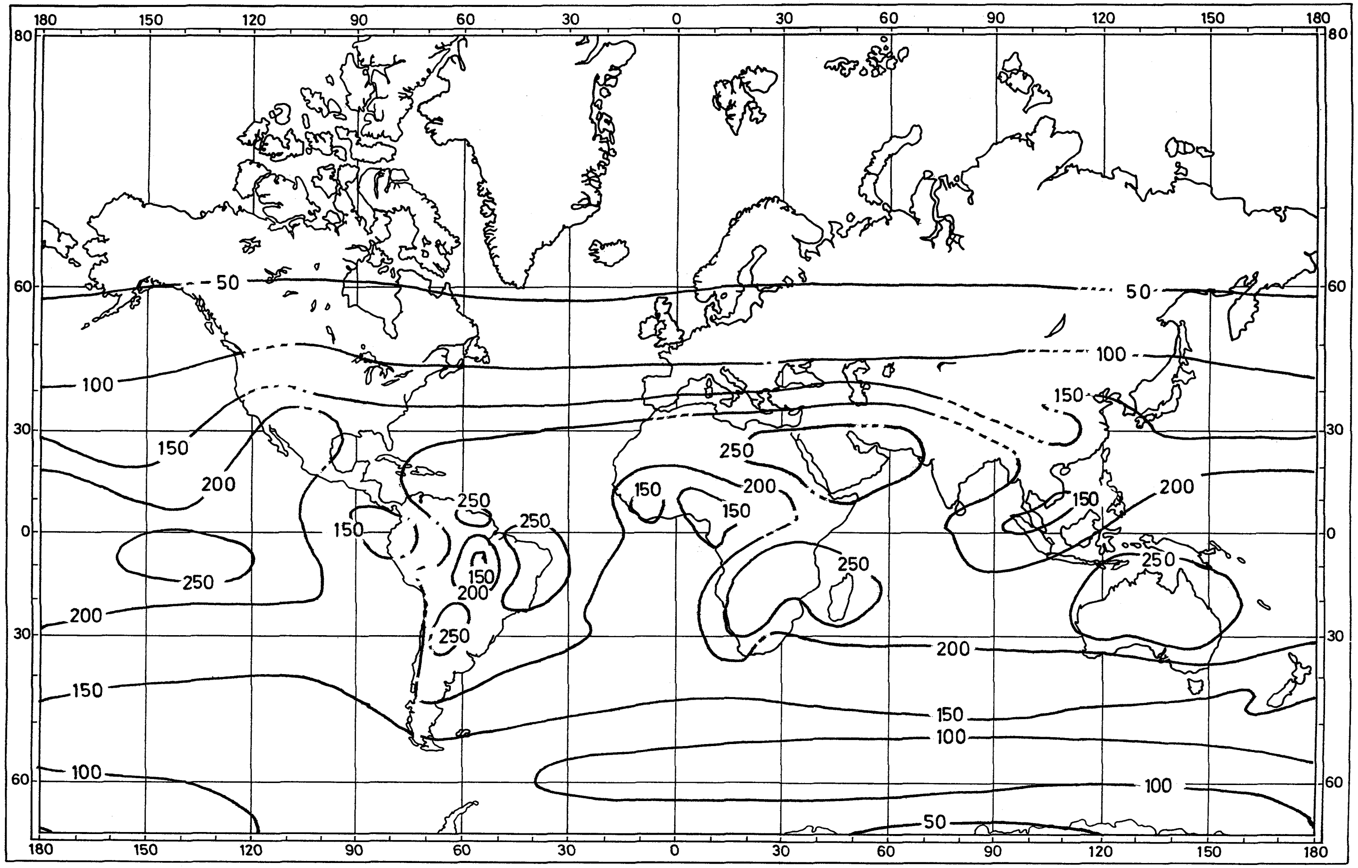


Figure 15. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - October

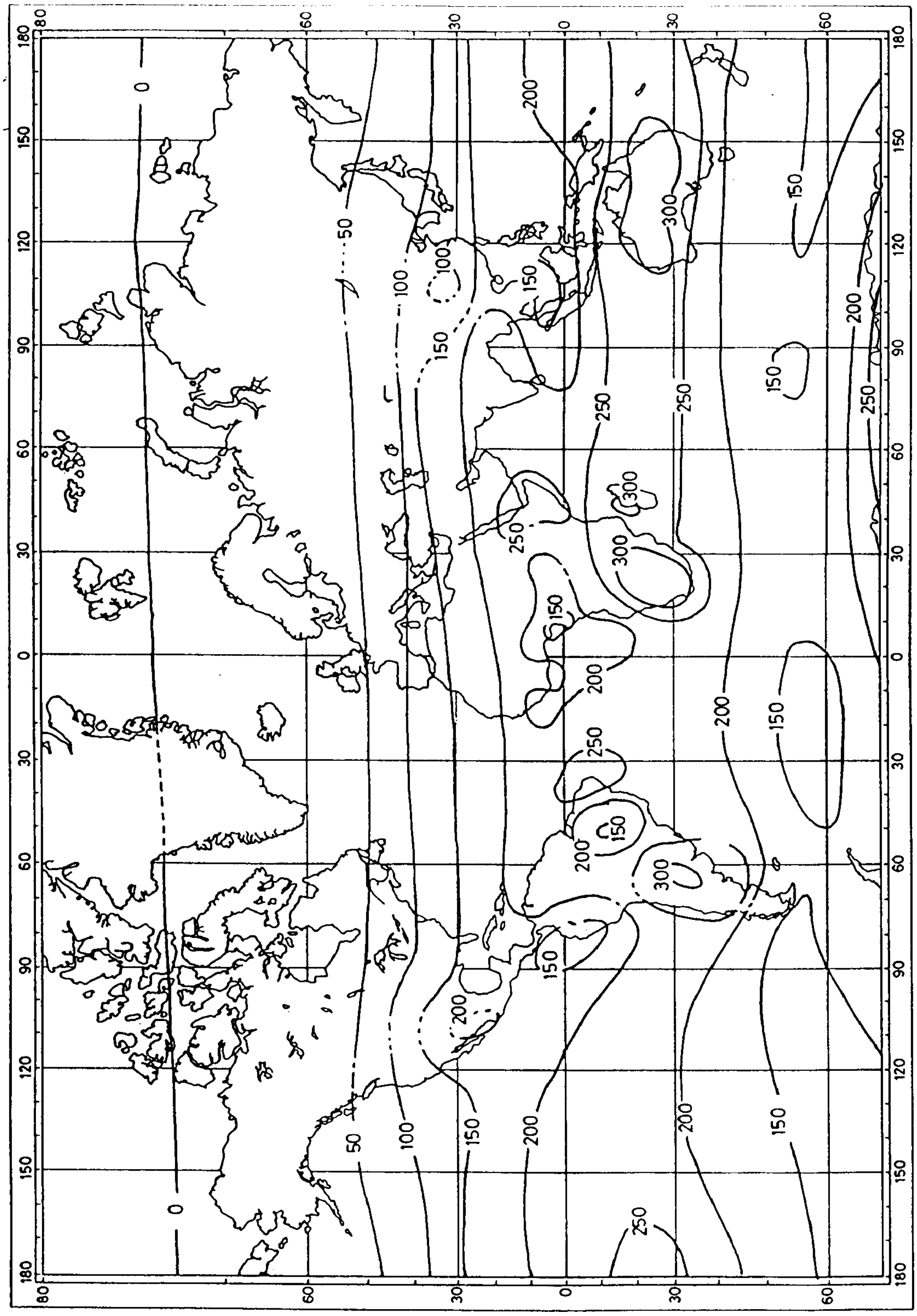


Figure 16. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - November

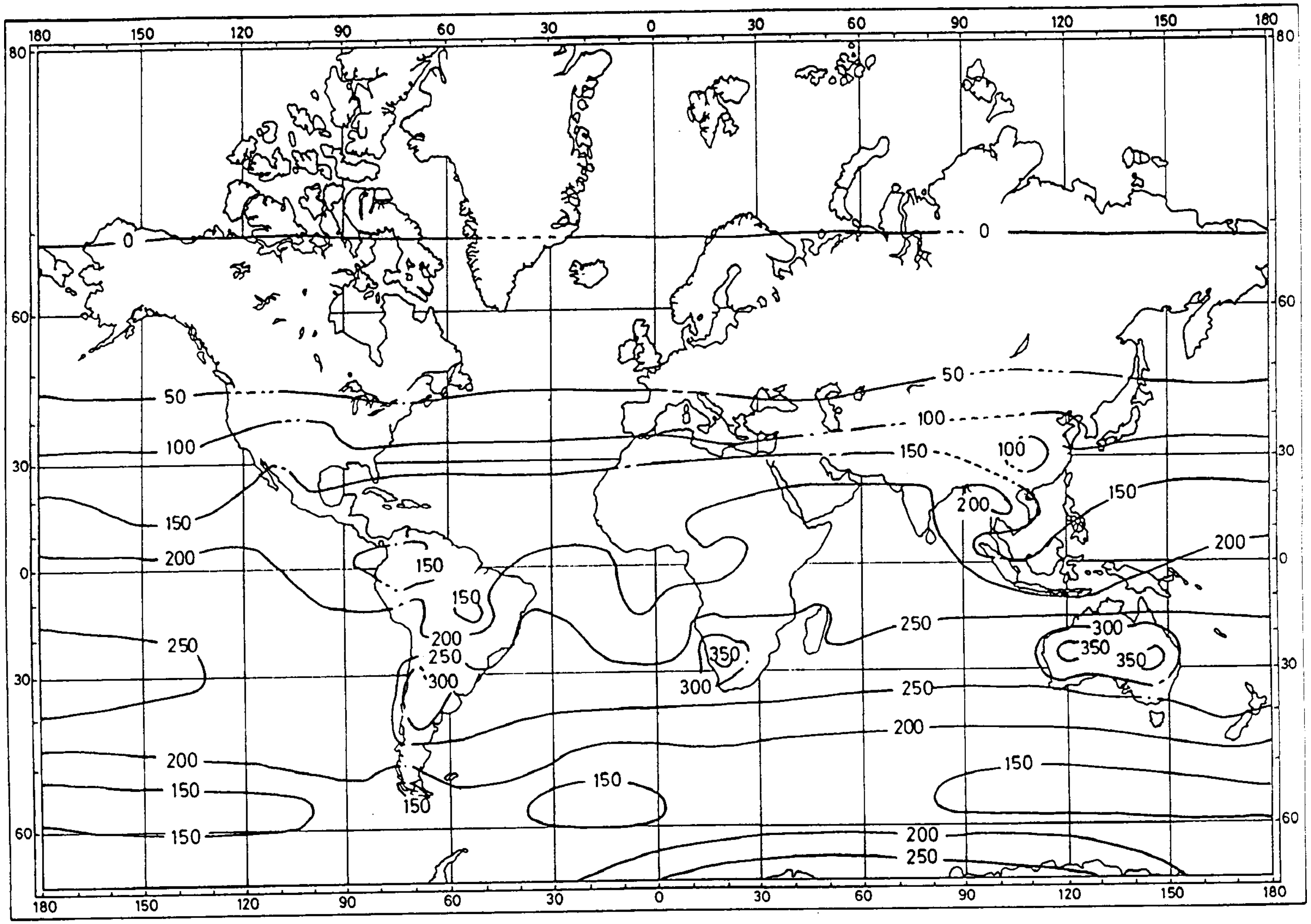


Figure 17. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - December

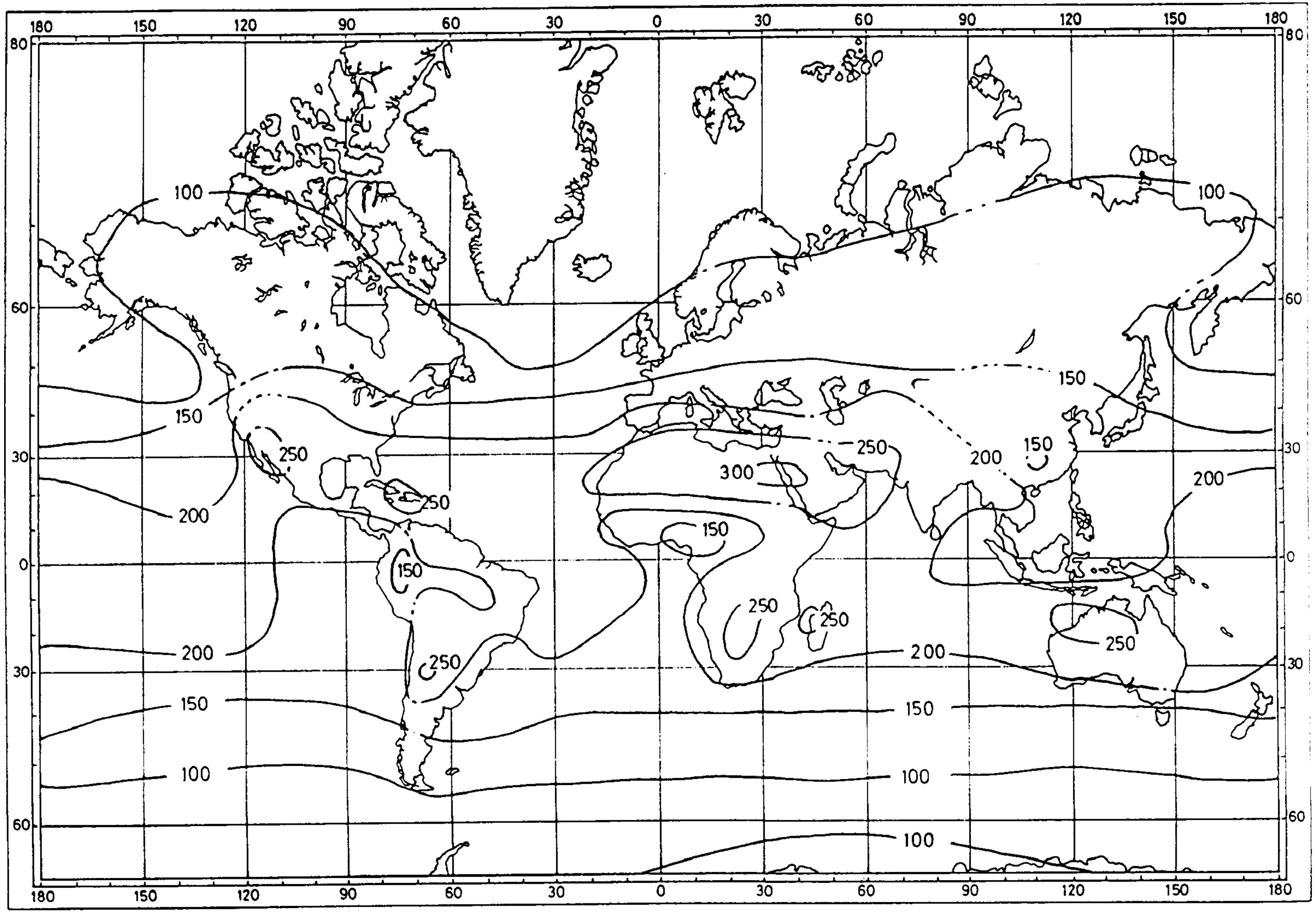


Figure 18. Mean intensity of global solar radiation on a horizontal plane at the surface of the earth (W/m^2 averaged over the 24 hours) - Year

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CHAPTER 3-02
THE EFFECTS OF SOLAR RADIATION

1 INTRODUCTION

1.1 The chemical reactions brought about by solar radiation, either acting alone or in the presence of other agents such as moisture or oxygen, cause widespread damage to materials and equipment. These reactions are known as actinic degradation.

1.2 The materials most subject to actinic degradation are organic compounds belonging to a class called polymers. Polymers are basically materials with very large molecules each one of which is made up of a simpler unit, called the monomer, repeated end to end. The materials may be natural or synthetic and include plastics, rubbers, textile fibres and surface coatings.

1.3 The effects of solar radiation referred to in this chapter, relate to a terrestial environment in which atmospheric oxygen is always present. In such an environment materials are not subject to irradiation by wavelengths shorter than 0.29 micrometres (μm), owing to the absorption of the far ultra-violet by ozone in the upper atmosphere. The polymers, however, are now being used extensively in space technology and in such applications may be liable to irradiation by the complete solar spectrum in space vacuum. These differing exposure conditions, which are not dealt with here, will affect the severity and rate of actinic degradation.

1.4 On the subject of actinic degradation, it should be noted that the terms 'solar radiation' and 'sunlight' are generally regarded as synonymous; and the terms, when used in the context of this chapter, may be regarded as such.

2 SOLAR RADIATION AND PHOTO-CHEMICAL REACTIONS

2.1 Before chemical reactions can proceed, the molecules must be supplied with a minimal amount of energy known as the activation energy. In photo-chemical reactions the activation energy is gained by the absorption of radiant energy. Irradiation will thus cause a reaction if the following conditions are fulfilled:

(a) The radiations contain component frequencies that are absorbed by the reacting system.

(b) The quanta of the absorbed frequencies possess sufficient energy to activate the molecules.

2.2 A knowledge of radiation energies, plus information on the activation energies of chemical reactions, will indicate those wavebands of solar radiation most likely to initiate damaging photo-chemical processes.

2.3 In relating activation and radiation energies, it is convenient to use the unit of radiation called the einstein. The einstein is the energy absorbed when each molecule of a gram molecule absorbs 1 quantum of radiation. A gram molecule of a molecular substance contains 6.023×10^{23} molecules.

2.4 The energy of a quantum is related to the radiation wavelength by the formula:

$$E = \frac{hc}{\lambda}$$

where:
E is the energy per quantum in joules
h is Plank's constant = 6.62×10^{-34} joule seconds
λ is the wavelength of the radiation in micrometres
c is the velocity of light = 3×10^{14} μm/s

2.5 The energy per einstein can thus be computed by multiplying the quantum energy by Avogadro's Number. Table 1 lists the energy present in various types of radiation, in joules per quantum and joules per einstein.

TABLE 1

ENERGY IN VARIOUS TYPES OF RADIATION

Description	Wavelength	Energy Per Quantum (Joules)	Calories per Einstein	Joules Per Einstein
X-rays	0.0001	1.986×10^{-15}	2.84×10^{8}	1.196×10^{9}
Ultra - Violet	0.1 0.2 0.3	1.986×10^{-18} 9.93×10^{-19} 6.62×10^{-19}	284500 142300 94840	1.196×10^{6} 5.981×10^{5} 3.987×10^{5}
Visible (violet)	0.4	4.965×10^{-19}	71120	2.99×10^{5}
Visible (blue-green)	0.5	3.972×10^{-19}	57000	2.392×10^{5}
Visible (orange)	0.6	3.31×10^{-19}	47400	1.99×10^{5}
Visible (red)	0.7 0.8	2.837×10^{-19} 2.483×10^{-19}	40600 35500	1.709×10^{5} 1.495×10^{5}
Near infra-red	1.0	1.986×10^{-19}	28450	1.196×10^{5}
Infra-red	3.0 10.0	6.62×10^{-20} 1.986×10^{-20}	9483 2845	3.987×10^{4} 1.196×10^{4}
Far infra-red	100.0	1.986×10^{-21}	284	1.196×10^{3}

2.6 Most chemical reactions require energies of between 25000 and 100000 calories per gram molecule for activation. This implies that usually only absorbed radiations possessing energies in excess of 25000 calories per einstein will initiate photo-chemical reactions. When considering the deterioration of materials caused by solar radiation it can be seen from Table 1 that the higher frequency components in the blue-green and ultra-violet bands are the most significant.

3 PLASTICS

3.1 General

3.1.1 Plastics may be conveniently divided into two groups: the thermoplastics which are softened by heat, and the thermosets that are permanently hardened by heat. The two groups are further differentiated by their distinctive molecular structures, the predominantly linear or chain like structure of the thermoplastics contrasting with the highly cross-linked structure of the thermosets.

3.1.2 The effect of solar radiation in the presence of air on most unprotected plastics is to produce a photo-chemical reaction, usually involving oxidation, which results in a modification of the molecular structure. Fortunately, ultra-violet absorbers are available which, when mixed with the plastic, are capable of retarding actinic degradation. However, if photo-chemical reaction occurs, the effects may appear as a loss of strength, or as embrittlement, crazing, cracking and discolouration, loss of electrical properties.

3.1.3 Owing to the attenuation of solar radiation by absorption in the material, the volume undergoing actinic degradation will be limited. Therefore, the structural strengths of plastic components having volumes much greater than the proportion undergoing photo-chemical change may not be seriously affected. However, plastics in the form of thin sheets and coatings may have their properties more seriously impaired.

3.2 Thermoplastics

3.2.1 Photo-chemical reactions occurring in the thermoplastics may result in chain scission, cross-linking or side group modification of the molecular structure. Such reactions produce crazing and embrittlement in unprotected polyethylene, polypropylene and the cellulose esters, while in unprotected polyvinylchloride (PVC) it leads to hardening and discolouration. The effects of sunlight on a variety of thermoplastics are given in Table 2. The wavelengths of maximum sensitivity for some thermoplastics are given in Table 3, where it can be seen that the ultra-violet wavelengths are the most damaging.

TABLE 2

EFFECT OF SUNLIGHT ON THERMOPLASTICS

Thermoplastics	Effect of sunlight
Acetal	Chalks slightly
Acrylonitrile Butadiene-Styrene Terpolymers and blends	None to yellows slightly
Cellulose Acetate Butyrate moulding	Slight
Cellulose Acetate Butyrate sheet	No visible change
Cellulose Acetate, High Acetal	Slight
Cellulose Acetate moulding	Slight
Cellulose Acetate sheet	No visible change
Cellulose Nitrate (Pyrroxylin)	Discolours, becomes brittle
Cellulose Propionate moulding compound	Slight
Chlorinated Polyether	Slight loss in surface ductility
Ethyl Cellulose moulding compounds and sheets	Slight when properly stabilized
Ethylene-Ethyl Acrylate Co-polymer	Very slight yellowing
Ethylene Vinyl Acetate Co-polymer	Very slight yellowing
FEP Fluorocarbon	None
Impact Acrylic moulding compound	Slight strength loss
Methyl Methacrylate	None
MMA/Alpha Methylstyrene Co-polymer	None
MMA Styrene Co-polymer	None
Nylon moulding compound	Discolours slightly
Phenoxy	Slight discolour and embrittlement
PCTFE	None
Polycarbonate	Slight colour change and embrittlement
Polyethylene	Unprotected material crazes rapidly. Requires carbon black for complete protection
Polypropylene	Unprotected material crazes, protected grades are available
Polystyrene moulding compound and sheet (unfilled	Yellows slightly
(impact resistant	Some strength loss
Polyvinylidene Fluoride	Slight bleaching on long exposure
cold moulded and inorganic compounds cold moulded refractory (inorganic)	None
inorganic moulded plastics and glass-bonded mica	None
PTFE	None
Styrene-Acrylonitrile Co-polymer	Yellows slightly
Vinyl Butyral moulding compounds	Slight
Vinyl Chloride and Vinyl Chloride- Acetate	Slight
Vinyl Formal moulding compound	Slight
Vinylidene Chloride moulding compounds	Slight

TABLE 3

WAVELENGTHS OF MAXIMUM SENSITIVITY

Thermoplastic	Wavelength (μm) of maximum sensitivity
Polyethylene	0.300
Polystyrene	0.318
Polypropylene (non-heat-stabilized)	0.310
Polyvinylchloride (PVC)	0.310
Polyvinylchloride (copolymer with vinyl acetate)	0.322 and 0.364

3.3 Thermosets

3.3.1 Thermoset plastics have highly interconnected molecular structures, and occasional chain scission or cross-linking, caused by photo-chemical reactions, does not usually affect their mechanical properties. Therefore the most conspicuous effects of sunlight on the thermosets are surface changes, following side group modification of the molecular structure. Such changes may include discolouration and alteration in the surface insulation resistance or moisture absorption properties. Details of the effect of sunlight on various thermosets are given in Table 4.

TABLE 4

EFFECT OF SUNLIGHT ON THERMOSETS

Thermosets	Effect of sunlight
Allyl cast resins	Yellows slightly
Casein moulding compound and sheet	Colours may fade
Cast Liquid Urethane	Slight yellowing
Diallyl Phthalate moulding compounds	None
Epoxy cast resins	None
Epoxy moulding compounds	Slight
Flexibilized Epoxy casting resins	None
Furan moulding compounds	None
Melamine-Formaldehyde moulding compounds	Slight colour change
Phenolic cast resin (asbestos filler)	Darkens slightly
Phenolic cast resin (mineral filler)	Darkens
Phenolic cast resin (no filler)	Colours may fade
Phenol-formaldehyde and Pheno-Furfal moulding compounds	General darkening
Polyacrylic Ester moulding material	None
Polyester and Alkyd moulding materials and compounds	None to slight
Polyester cast resin (rigid)	Yellows slightly
Silicone cast resins	None
Silicone moulding compounds	None to slight
Urea-Formaldehyde moulding compound	Pastel colours grey

3.3.2 The high energy radiations of wavelengths in the ultra-violet band are the most damaging to thermosets. The wavelengths of maximum sensitivity for polyesters of various formulations has been reported as 0.325 μm.

3.3.3 The resin impregnate used in the formation of laminated plastics is of the thermoset type, and so the effects of sunlight on this class of plastics are generally restricted to surface phenomena. The effects of sunlight on a variety of laminated plastics are listed in Table 5.

TABLE 5

EFFECT OF SUNLIGHT ON LAMINATED PLASTICS

Laminated plastic		Effect of sunlight
Diallyl Phthalate	glass fibre base or cotton fabric base	None
	glass fabric or matt base	Negligible
	paper or cotton base	Slight darkening
Polyester	paper or cotton base	Slight darkening
Vulcanized Fibre		Slight
Teflon	glass non woven fibre base, or ceramic non woven fibre base, or glass fabric base	None
Silicone	glass fabric base, or asbestos fabric base	None
Lignin	laminated, or continuous glass filament base	Slight
Epoxy	glass fabric base or cellulose paper base	Slight colour change
Melamine-Formaldehyde	cellulose or asbestos paper base, or cotton, asbestos or glass fabric base	Slight colour change
Phenol-Formaldehyde	cellulose paper, cotton, nylon, glass, asbestos fabric, cotton web, asbestos paper, or wood base	Lowers surface resistance and general darkening

3.4 Ultra-violet absorbers

3.4.1 The absorber protects the plastic by absorbing the ultra-violet energy and dissipating it as heat. Ideally, the absorber should have an absorption efficiency many times greater than that of the plastic in the part of the ultra-violet spectrum to which the plastic is most sensitive.

3.4.2 Colourless or near colourless ultra-violet absorbers, based on benzotriazole or benzophenone, are in common use. For maximum efficiency they should be completely dispersed in the material.

3.4.3 As an example of the effectiveness of absorbers, 0.25% of 2-hydroxy-3-methoxybenzophenone has been found to retard the yellowing of clear polyester resin by a factor of ten.

4 NATURAL AND SYNTHETIC RUBBERS

4.1 General

4.1.1 Rubbers are polymeric materials in which the molecules are long, flexible and joined by a few cross-links, and randomly coiled. Only when the rubber is under stress do the molecules tend to align in rows, following the direction of the stress. On removal of the stress, the inter-molecular forces cause the rubber to revert to its original configuration.

4.1.2 The degradation of natural rubber, and some of the synthetic rubbers, follows the pattern of the thermoplastics.

4.2 Natural rubber

4.2.1 The rapid oxidation and perishing of natural unvulcanized rubber makes it unsuitable as an engineering material. For this reason, the term 'natural rubber' used in this chapter means natural rubber in its vulcanized state.

4.2.2 Photo-oxidation of natural rubber, during exposure to sunlight, may result in simultaneous cross-linking and chain scission in the molecular structure. Excessive cross-linking is characterized by the formation of a random network of fine cracks on the surface. The term 'light cracking' has been proposed for this type of degradation. It should not, however, be confused with 'exposure' or 'ozone cracking` which is discussed later.

4.2.3 Chain scission can result in a reduction of the elongation of the rubber. In controlled exposure tests, 'light cracking' of 2 mm thick latex-rubber vulcanizate sheets occurred after six weeks exposure to sunlight, while after six months exposure the tensile strength of the sample was reduced by over 50%.

4.2.4 The deleterious effects of sunlight on natural rubber can be counterbalanced to a certain extent by the inclusion of protective substances; for example, loading the rubber with carbon black which acts as a light screen. Investigations have shown that latex-rubber vulcanizates containing nickel dibutyldithiocarbonate (NBC) as a protective agent, suffered a loss of tensile strength of 18-30%, following 12 months exposure to sunlight, compared with 85% for unprotected samples.

4.3 Synthetic rubbers

4.3.1 Synthetic rubbers are not chemically identical to natural rubbers, but do possess rubber-like physical qualities due to their molecular structure. The value of synthetic rubbers, however, is in their particular properties, such as superior resistance to swelling in oil or to decomposition by heat or sunlight. Table 6 illustrates the comparative resistance of natural and synthetic rubbers to sunlight.

TABLE 6

COMPARATIVE RESISTANCE OF NATURAL AND SYNTHETIC RUBBERS TO SUNLIGHT

Rubber	Comparative resistance to sunlight
Natural	Low
Butadiene-Styrene (SBR)	Low
Butyl (GR-I)	High
Polychloroprene (Neoprene)	High
Nitrile (Buna N)	Medium
Polysulphide (Thiokol)	Medium
Silicones	High
Chlorosulphonated Polyethylene(Hypalon)	High
Acrylate	High
Polyesters (Polyurethane)	High
Fluorinated	High

4.3.2 In the photo-oxidation of neoprene, SBR and the nitrile rubbers, cross-linking in the molecular structure is usually the dominant reaction. This results in surface 'light cracking', with loss of extensibility and increase in hardness, although the tensile strength is not usually affected and may actually increase.

4.3.3 As with natural rubber, the resistance of synthetic rubbers to actinic degradation can be increased by the inclusion in the rubber of protective agents.

5 TEXTILES

5.1 General

5.1.1 Solar radiation is generally agreed to be the most active climatic component responsible for the deterioration of exposed textiles. The effect of irradiation may appear as a loss of tensile strength or elasticity, or by discolouration of the fibre.

5.1.2 Of all exposure conditions, the presence or absence of oxygen appears to be the most important in determining the effect of solar radiation.

5.1.3 Whether the surface of the fibre is lustrous or dull will affect its capacity for absorbing solar radiation. For example, bright nylon will tend to reflect sunlight and for this reason is more resistant to actinic degradation than dull nylon. Similarly, the most lustrous cotton (Egyptian) is more resistant than the other cottons. Coarse yarns are more resistant than fine, since in the former the outer layers protect the inner ones from irradiation.

5.1.4 It should be noted that the rate of the photo-chemical action is affected by certain dye stuffs, sizing, weighting, other specialized finishing materials, fungicides, traces of acids, alkalis, salts, soaps, and oils.

5.2 Natural fibres

5.2.1 Natural textile fibres may be cellulosic such as cotton, ramie, jute or linen; or belong to a class of proteins, called keratins, having animal sources - for example wool and silk.

5.2.2 Information illustrating the actinic deterioration of various textile fibres is given in Table 7.

TABLE 7

PHOTO-DEGRADATION OF TEXTILE FIBRES

Fibres as undyed yarn	Exposure for reduction to half of initial tensile strength***
Silk, degummed	2.9
Silk, raw	3.8
Nylon, delustred**	4.0
Cotton, bleached	8.8
Viscose rayon, bright*	8.8
Wool, bleached	11.8
Cellulose acetate	13.8

*** Experimental results for a set of samples exposed in air, at an angle of 45° behind a south window 6 miles south of Manchester. (The units of exposure are average summer months.)

** Resistance increases two to threefold in the absence of delustrant such as titanium dioxide pigment.

* Resistance much decreased at high humidity and in the presence of delustrant.

5.2.3 The action of sunlight on cellulose, in the presence of oxygen, is usually regarded as one which leads to the formation of oxycellulose, although there are indications that sunlight alone can rupture or weaken the glycosidic linkages within the cellulose molecule. It has been suggested that weakening of the glycosidic linkages prepares the way for oxygen to attack cellulose; thus cotton and linen textiles that have been exposed to solar radiation will continue to deteriorate when shielded from sunlight, due to a continuation of the oxidative process. It is generally believed that the ultra-violet wavelengths below 0.364 µm are the most destructive to cellulose.

5.2.4 Solar radiation produces primary and secondary reactions on wool, the initial effect being an activation of the disulphide group. This is followed by an emission of hydrogen sulphide, which is oxidized to sulphuric acid when the wool is irradiated in air.

5.2.5 Silk appears to be the most light sensitive of the fibres, the degree of photo-chemical destruction depending upon the pH value at which the exposure is made.

5.2.6 The gross effect of irradiation on the natural fibres is a loss of tensile strength and a tendency of the white cellulosic fibres to yellow.

5.2.7 In evaluating the natural fibres, wool is regarded as the most resistant to solar radiation, followed in decreasing order of resistance by cotton, jute and silk. Ramie and linen are similar to cotton in their resistance to actinic degradation.

5.3 Semi-synthetics

5.3.1 Semi-synthetic fibres may be considered as those fibres built up from a particular constituent, such as cellulose, protein or glass.

5.3.2 The effect of sunlight on cellulose acetate (Celanese), viscose and cuprammonium rayons is a loss of tensile strength but very little discolouration. Dull viscose rayon has been reported as being twice as light sensitive as bright viscose rayon or cotton.

5.3.3 The regenerated protein fibre 'Aralac` is similar to wool in its resistance, while 'Vicara' is slowly weakened by sunlight.

5.3.4 The effect of sunlight on viscose rayon and cellulose acetate is illustrated by the data given in Table 7.

5.3.5 Glass fibre is considered to be stable to the action of sunlight.

5.4 Synthetics

5.4.1 Synthetics are those fibres built up from basic chemical elements. Many of the plastics discussed above appear as synthetic textile fibres, and are subject to similar actinic degradation.

5.4.2 The polyamides (Nylon, Perlon, Igamid) show some discolouration and loss of strength on prolonged exposure to sunlight. The resistance of nylon to actinic deterioration depends on its type and also whether the fibre is bright or delustred.

5.4.3 Some sources claim that polyethelene terephthalate fibres (Terylene, Dacron) are exceptionally resistant to photo-chemical weakening, while others suggest that these fibres are more subject to actinic degradation than either cotton or viscose rayon.

5.4.4 Unplasticised polyvinyl chloride fibres (Rhofibre, Rhovyi, Thermayvl), polyvinyl alcohol fibres (Vinylon, Kanebiyan), and polyacrylonitrile fibres (Acrilan, Orlon, Redon) are practically unaffected by sunlight.

5.4.5 Fibres of the copolymers vinyl chloride - acrylontrile (Dynel, Vinyon N), and vinyl chloride - vinyl acetate (Vinyon, Vinyon HH) darken somewhat after prolonged irradiation.

5.4.6 Slight darkening and slight loss of tensile strength of polyvinylidene chloride fibres (Saran) occurs after prolonged exposure to sunlight.

5.4.7 Research has revealed methods of protecting synthetic fibres from the effects of sunlight by the incorporation in the fibre of certain bensophenone derivatives and manganese salts. The fibres most responsive to treatment are the polyamides, acrylics and polyester types.

6 SURFACE COATINGS, DYESTUFFS AND PAPER

6.1 Surface coatings

6.1.1 Organic surface coatings, such as paint, varnish, enamel and lacquer are subject to actinic degradation which may be indicated by discolouration, darkening, cracking or a loss of adhesion to the substrate. Solar radiations below 0.4 μm are generally regarded as the most damaging to such coatings.

6.1.2 A surface coating may be considered to consist of two components, the vehicle or binder which is usually wholly organic and the pigment which may be either organic or inorganic. Both of these components are liable to photo-chemical degradation. The organic pigments such as magnesium carbonate and zirconium oxide, that are good reflectors of ultra-violet, can protect light sensitive vehicles such as linseed oil.

6.1.3 Research into the development of thermal control coatings for space craft has produced a new class of paints, employing inorganic vehicles, that are inherently more stable to the effects of solar radiation than commercially available organic coatings.

6.2 Dyestuffs

6.2.1 Modification of the structure of the dye molecule following photo-chemical reactions initiated by sunlight will eventually cause fading or colour change of many dyestuffs. The rate of fading depends on a number of factors such as temperature, humidity, spectral distribution and the nature of the dyed fibre.

6.3 Paper

6.3.1 All papers are subject to damage by sunlight in varying degrees. Paper, like cotton and linen, has a dominant cellulosic component, and its photo-chemical degradation presents similar problems. Information on the action of sunlight on cellulose is given in this chapter.

6.3.2 Actinic degradation of paper is evidenced by yellowing, bleaching, whitening, embrittlement and loss of tensile strength. The resistance of paper to sunlight is dependent on the source of the material used in its manufacture. That manufactured from new rag is the most resistant, followed by refined sulphite, old rag, soda sulphite and newsprint. The presence of other substances, such as resin, glue, alum, iron or lignin, influence the effect of sunlight.

7 OZONE

7.1 General

7.1.1 Measurements of variations in the ultra-violet intensity with altitude suggest that ozone is formed by the action of solar energy of wavelength less than 0.2 μm on atmospheric oxygen, although the details of the photo-chemical reaction are not fully understood.

7.1.2 Ozone is also produced from oxygen in the vicinity of any artificial source radiating significant amounts of ultra-violet energy, the efficiency of the reaction increasing as the wavelength becomes shorter.

7.1.3 The concentration of ozone at the earth's surface is very low, ranging from 0 to 10 parts per 10^8, but even at these concentrations it represents a serious hazard to unsaturated polymeric materials such as the rubbers.

7.1.4 Information on the distribution of ozone in the atmosphere and the seasonal variations is contained in Reference 1.

7.2 Effect of ozone on rubber

7.2.1 When rubber is not under strain, attack by ozone appears to be negligible. If, however, the rubber is under strain, attack by ozone produces a form of deterioration known as 'exposure' or 'ozone cracking'. This is characterized by the formation of deep fissures running perpendicular to the direction of strain.

7.2.2 Natural rubber, butadiene-styrene (SBR) and the nitrile rubbers have been found to be the most sensitive to ozone cracking but the saturated rubbers, such as chlorosulphonated polyethylene (Hypalon), silicones and some of the polysulphides are not subject to attack.

7.2.3 The most effective method for protecting rubber compounds from ozone is by the incorporation of a small percentage of wax in the material.

8 THERMAL EFFECTS OF SOLAR RADIATION

8.1 General

8.1.1 The temperatures given in climatic charts are 'shade' temperatures. A shade temperature is the temperature of the air indicated by a thermometer sheltered from precipitation, from the direct rays of the sun and from heat radiation from the ground and neighbouring objects, and around which air circulates freely. A standard shelter, such as the Stevenson Screen, is intended to satisfy these conditions. A statistical method of estimating the probability of occurrence of any given temperature is presented in Chapter 2-01.

8.1.2 The temperature of objects subject to direct radiation may be very much higher than the prevailing shade temperature. The temperature is dependent upon the intensity of the solar radiation, the nature of the surface, particularly its colour, heat capacity and conductivity, the nature of the surroundings and the loss of heat by conduction to the air. Charts and data on solar radiation intensities are contained in Chapter 2-01.

8.1.3 As an example of the high temperatures reached by objects exposed to solar radiation, skin temperatures of 100°C have been recorded on guided missiles during ground phase operations, at maximum air temperatures of 52°C.

8.2 Solar absorptivity and low temperature emissivity

8.2.1 The absorptivity (α) of a surface is that fraction of the incident radiation which is absorbed. In general, the efficiency of most materials in this regard is dependent on the spectral composition and source of radiation.

8.2.2 As the largest proportion of the solar heat energy is contained in the visible (0.4 - 0.7 µm) and near visible infra-red (0.7 - 1.1 µm) regions, the absorptivity and reflectivity ($1-\alpha$) are greatly influenced by the surface colour. However, the response of materials to long wave infra-red depends on factors such as molecular composition and density of surface.

8.2.3 Emissivity (e) is the ratio of the rate of loss of heat, per unit area of surface at a given temperature, to the rate of loss of heat of a black body at the same temperature.

8.2.4 It has been stated that the amount by which the temperature of a surface exposed to solar radiation exceeds the shade temperature is proportional to:

$$\frac{\alpha C}{e}$$

where α = the solar absorptivity
e = low temperature emissivity (eg at 100°C)
C = convection heat loss

8.3 Observations of surface temperature of irradiated objects.

8.3.1 Figure 1 gives an estimate of the distribution of the maximum temperatures which would be reached in an average year, by non-conducting surfaces exposed to the sun.

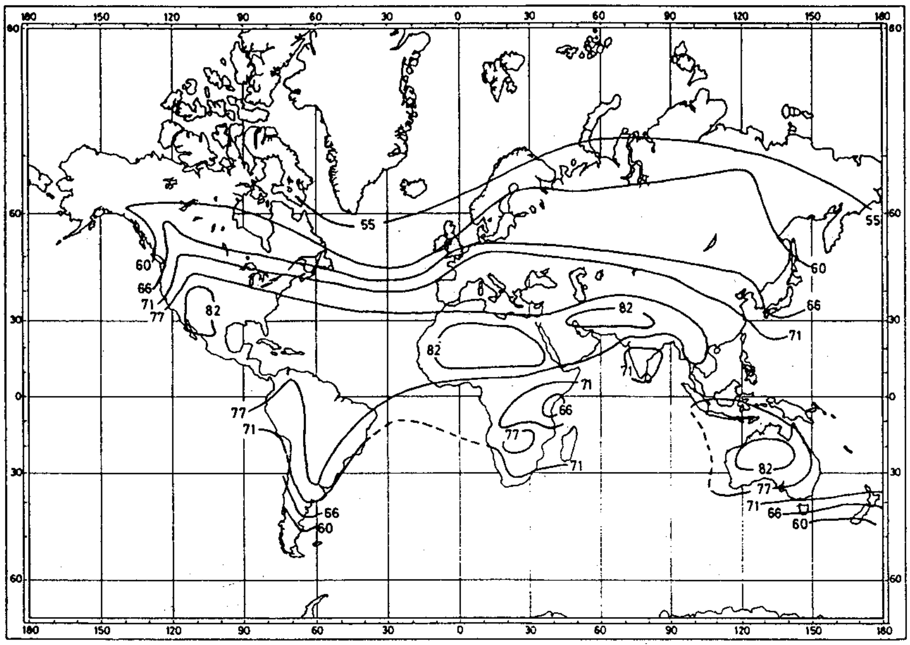

Figure 1. Estimated distribution of max temperatures (°C) of non-conducting surfaces exposed horizontally to the sun.

8.3.2 Table 8 presents the results of several observations of the temperature of objects exposed to the sun. In general, they support the estimates of Figure 1 although several of the recordings are considerably higher.

TABLE 8

OBSERVATIONS OF SURFACE TEMPERATURES OF OBJECTS EXPOSED TO THE SUN

Surface or object	Temp°C	Exposure site	Lat °
Aircraft wing	102	Tucson, Arizona, USA	32N
Aircraft wing	90	Alice Springs, NT Aust	24S
Paint exposure panels	85	Coral Gables, Florida, USA	26N*
Black bituminous roof (27° slope)	84.5	Melbourne, Aust	38S
Aircraft wing	82	Madison, Wis, USA	43N
Aircraft wing	80	Cairns, Aust	17S
Black bituminous roof	74.5	Central Texas, USA	32N*
Painted metal-topped box (interior temp.)	72	Watford, England	52N
Aircraft wing	70	Princes Risborough, England	52N
Painted galv. iron roof	67	South Africa	26S*
Blackened steel plate	67	Middleton, Ohio, USA	40N

* Estimated Latitude

8.4 Effect of colour

8.4.1 The results of experiments on the effect of colour on the temperature of bodies exposed to solar radiation are given in Table 9. These results show that black and dark objects reach higher temperatures than light coloured objects. In the table the difference between the temperature of a black object and the corresponding shade temperature is expressed as 100, and the excess of a coloured object over the shade maximum as a percentage of this.

TABLE 9

TEMPERATURE OF DIFFERENT COLOURS AS PERCENTAGES OF 'BLACK'

Colour	Cloth	Painted tins		Steel rail	Soil		Mean
	Khartoum	Halfa	Kasauli	Panama	Poona		
					Jan	May	
Black, °C	84.3	70.8	58.0	53.9	53	64.4	
	%	%	%	%	%	%	%
Black	100	100	100	100	100	100	100
Dark Brown	89	-		-	-	-	89
Brown	-	88		-	-	-	88
Cement wash	-	85		-	-	-	85
Green	-	79	90	90	-	-	85
Plain metal	-	73	-	-	-	-	73
Grey, ash colour	-	79	-	-	70	76	75
Khaki	76	72	-	-	69	78	74
Red	-	69	-	66	77	-	73
Pale blue	72	-	-	-	-	-	72
Straw	-	54	-	-	-	-	54
Cream	-	49	-	-	-	-	49
White	42	40	54	58	42	40	46
Shade max. °C	42	42	34	31	31	30	37

8.4.2 In a series of tests to compare the solar heat absorbed by mild steel plates coated with various commercial finishes, the greatest heat reflection was obtained by a prime coating of red lead, followed by two coats of white undercoat and finished with two coats of white high quality enamel.

8.5 Effects of temperature

8.5.1 The effects on plastics, rubbers, textiles, paper, surface coatings and dye stuffs are due to photo-chemical reactions activated by the absorption of solar radiation. Irradiation may, however, raise the temperature of materials to a critical level above which non-reversible chemical changes take place. Such temperatures may also have other effects such as volume changes, loss of rigidity and damage to the finish of mechanical components. Although solar radiation can be deemed an agent of such deterioration these effects may also be regarded as temperature effects and as such are described in Chapter 2-01.

9 GENERAL OBSERVATIONS

9.1 Selection of suitable materials, for use in the manufacture of equipments liable to prolonged exposure to solar radiation, may be aided by the information contained in References 2, 3, 4, 5, and 6.

9.2 The sunlight resistance of a particular material may be increased, when applicable, by:

(a) Deposition of light screen or reflector on the surface of the material.

(b) Incorporation in the material of ultra-violet absorbers or light protecting agents.

9.3 Surface heating due to incident radiation may be reduced by use of suitable light coloured coatings and adoption of highly polished surface finishes. Sunlight shields are also used, either as permanent or temporary protection. When shields are fitted, the most efficient system has been found to be one where an air space exists between the shield and the object.

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CHAPTER 4-01
HUMIDITY

1 INTRODUCTION

1.1 The term 'humidity' refers to the water vapour content of the air. Several parameters have been used to describe it, and it is necessary to carefully define the terms used. Definitions of the terms most commonly used are given below.

1.2 Although there is a small dependence on pressure, the maximum concentration of water which can remain in vapour form is generally dependent only on temperature. Below 0°C, an additional factor is the solid or liquid state of the water present.

1.3 This chapter is mainly concerned with humidity near the ground, however, variations of humidity with altitude changes are dealt with briefly. In addition the phenomenon of local condensation and the attendant drip hazards are described.

2 DEFINITIONS

2.1 Vapour concentration

2.1.1 Vapour concentration (alternatively, vapour density or absolute humidity) is defined as the mass of water vapour in unit volume of the mixture of dry air and water vapour; it is usually expressed in g/m^3, and is normally of the order of 10 g/m^3.

2.1.2 Vapour concentration is inversely proportional to the absolute temperature of the mixture, and it decreases from its saturation value as the temperature increases above the dew point (see 2.6).

2.2 Humidity mixing ratio

2.2.1 The mixing ratio is the ratio of the mass of water vapour to the mass of dry air with which the water vapour is associated. It is usually expressed in grams per kilogram (g/kg), and is normally of the order of 10g/kg.

2.3 Vapour pressure

2.3.1 Vapour pressure is that part of the total atmospheric pressure which is exerted by water vapour.

2.4 Relative humidity

2.4.1 Relative humidity is the ratio of the actual vapour pressure to the saturated vapour pressure, with respect to water at the same temperature and pressure.

2.5 Specific humidity

2.5.1 Specific humidity is the ratio of the mass of water vapour to the total mass of moist air in which it is contained.

2.6 Dew point

2.6.1 The dew point is the temperature to which the air must be cooled in order that it shall be saturated with respect to water at its existing pressure.

2.7 These common terms are inter-related, and, as shown by the nomogram in Figure 1, knowledge of one of the terms will enable the others to be derived.

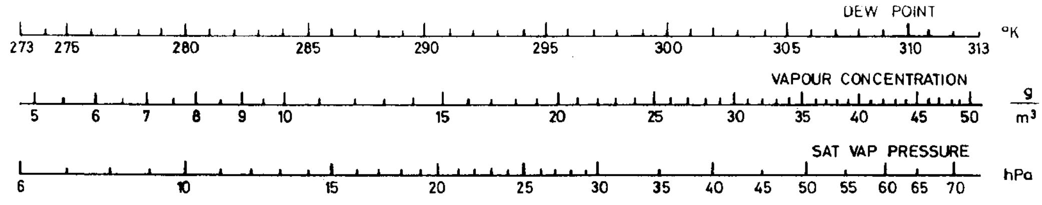


Figure 1. Nomogram relating dew point, saturation vapour pressure and vapour concentration at saturation.

2.8 The saturated vapour pressure is the maximum vapour pressure possible at a particular air temperature, but the actual amount of water vapour present at any time is a complex function of several variables, so that although theoretically a cubic metre could hold some 100 grams of water vapour at 55°C (about the highest recorded natural temperature), the highest recorded water vapour content at any temperature is only about 34 g/m^3.

3 FACTORS AFFECTING HUMIDITY

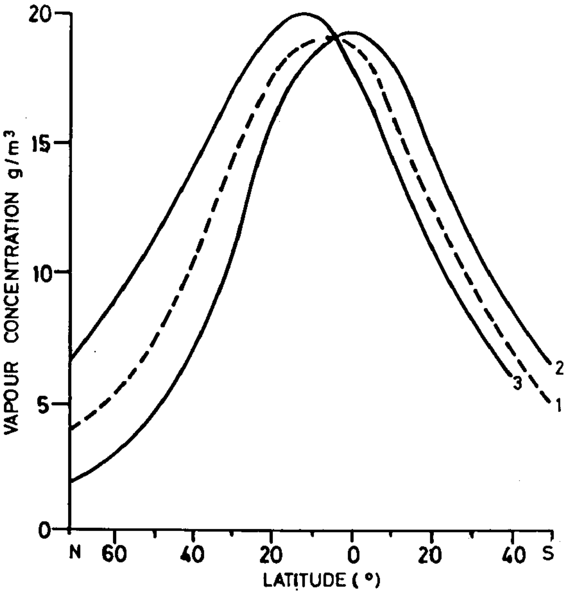
3.1 General

3.1.1 The water vapour content of the atmosphere varies according to time of day, season of the year and geographical location, and depends also on local characteristics such as the nature of vegetation and the moisture state of the soil. Changes of humidity arise from local evaporation or condensation, and from temperature changes of moist or drier air, caused by the wind.

3.1.2 Since the saturated vapour pressure rises with temperature, a given relative humidity at a high temperature implies a higher vapour pressure, vapour concentration, and dew point, than does the same relative humidity at a low temperature.

3.2 Effects of latitude and season

3.2.1 Figure 2 indicates the average distribution of vapour concentration with latitude, for the summer and winter months. This clearly shows the seasonal shift in distribution of water-vapour content, the greatest amounts being present during the summer in each hemisphere, although the land/sea distribution modifies this latitude effect.



1. Annual average
2. Average of December, January and February
3. Average of June, July and August

Figure 2. Average vapour concentration in various geographical latitudes

3.3 Diurnal changes

3.3.1 Figures 3 to 10 show the diurnal variation of temperature, vapour concentration and vapour pressure, for several stations in selected months. Figure 11 illustrates the annual variation of vapour concentration for four selected stations. The stations are representative of polar, temperate, tropical and desert regions. Local factors can cause considerable variation from the general pattern, and these figures include such local peculiarities.

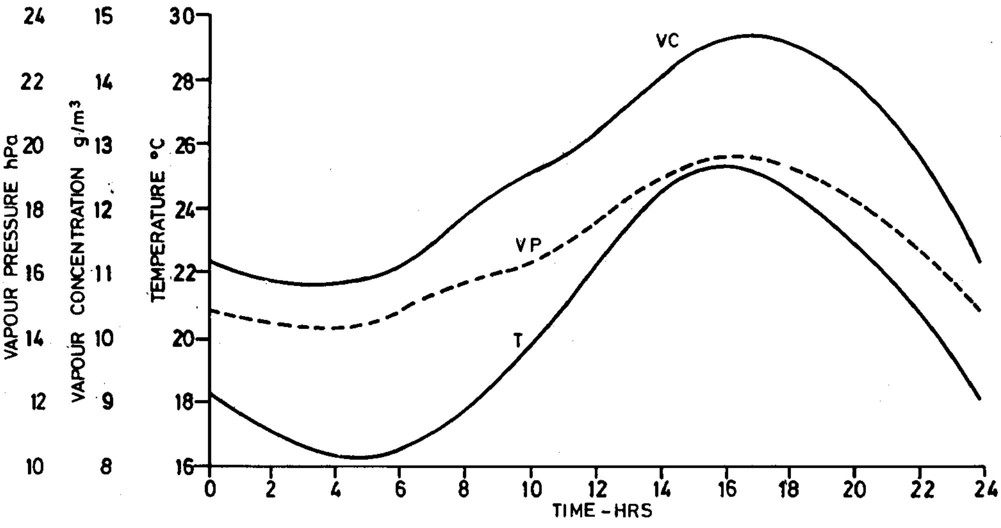


Figure 3. Toronto, daily cycle (summer)

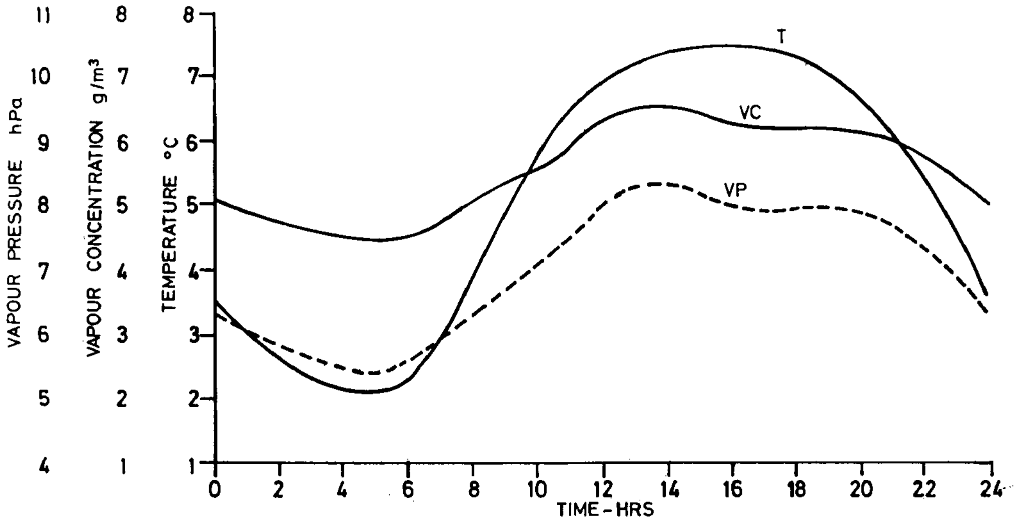


Figure 4. Thule, daily cycle (summer)

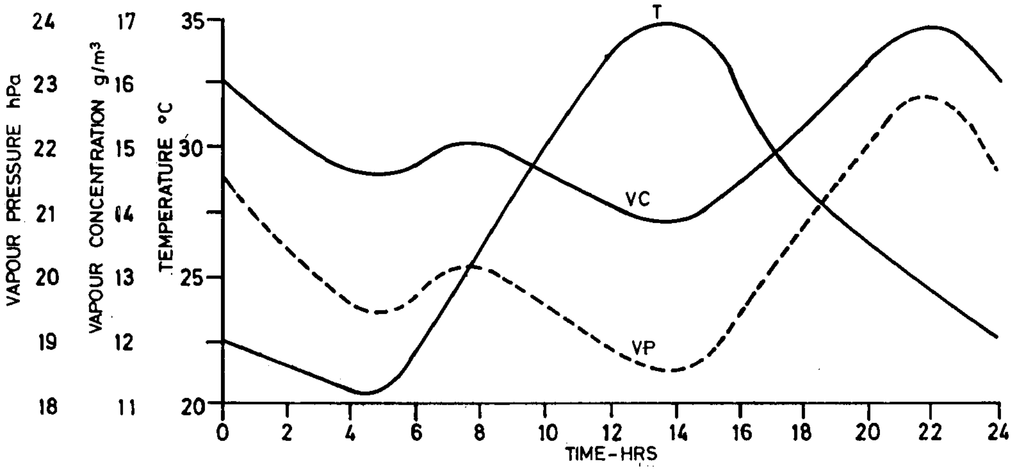


Figure 5. Tripoli (Libya) daily cycle (July)

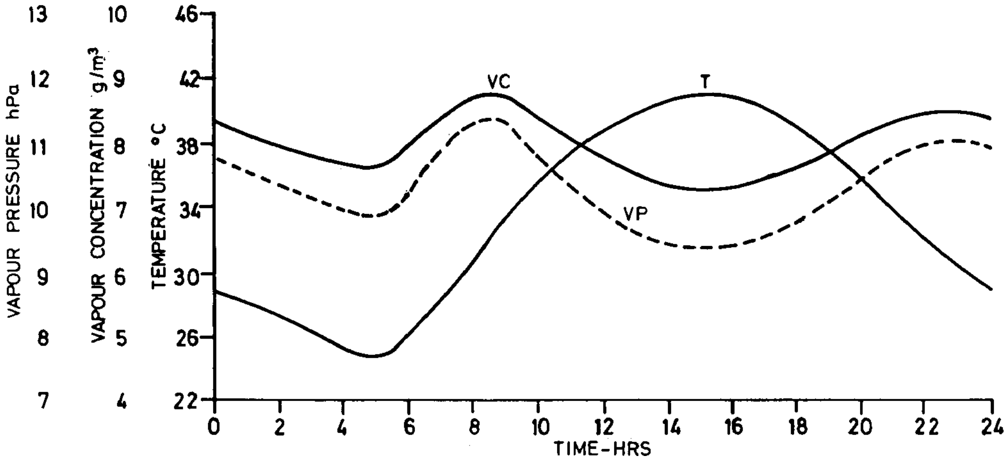


Figure 6. Wadi Halfa, daily cycle (July)

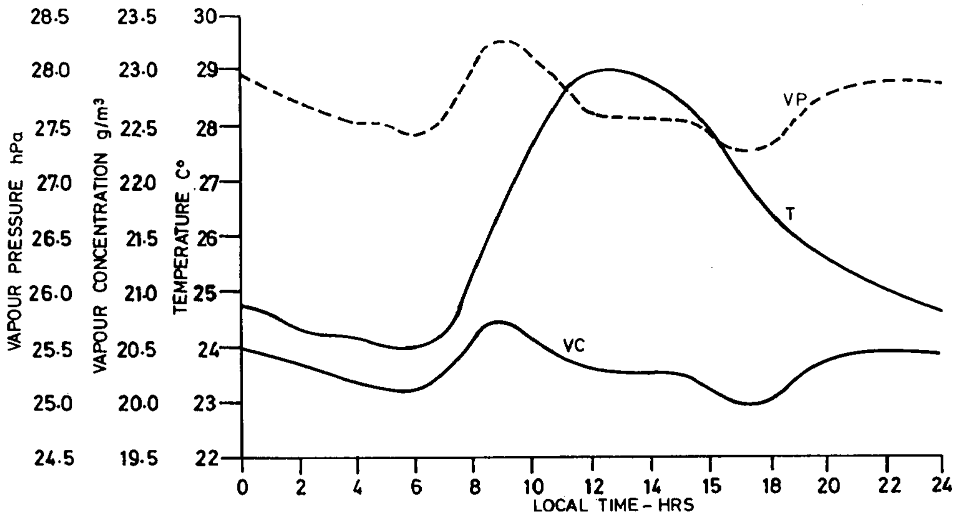


Figure 7. Singapore, daily cycle (January)

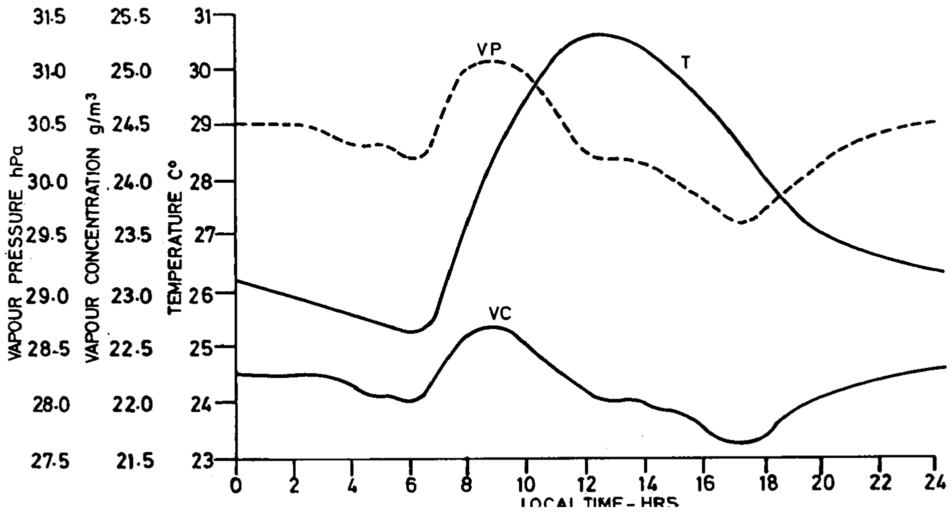


Figure 8. Singapore, daily cycle (April)

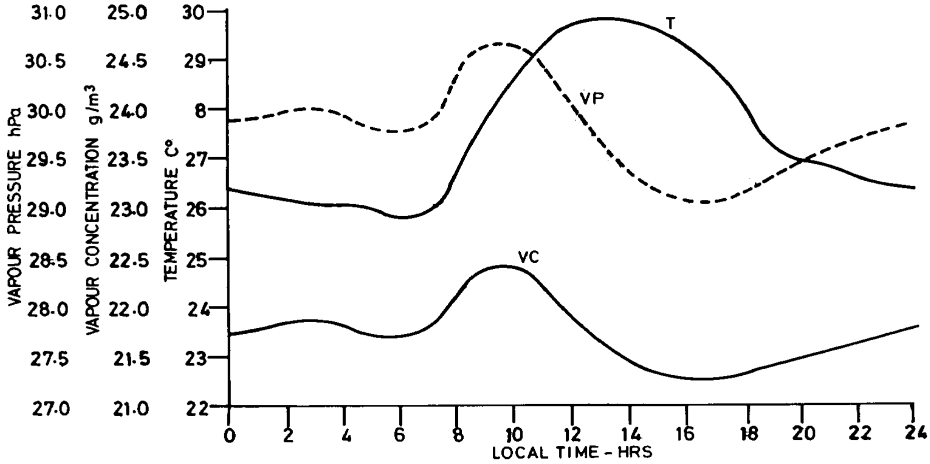


Figure 9. Singapore, daily cycle (July)

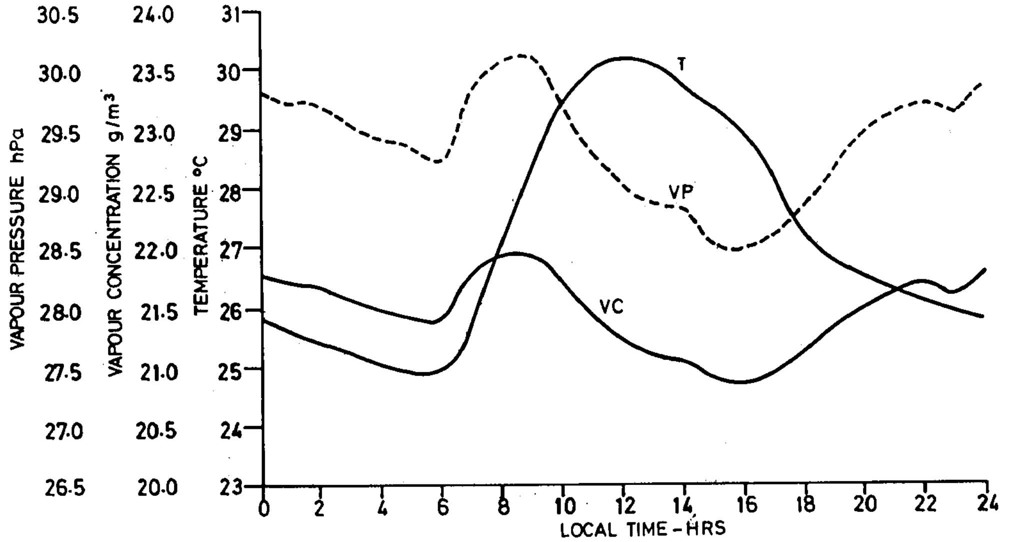


Figure 10. Singapore, daily cycle (October)

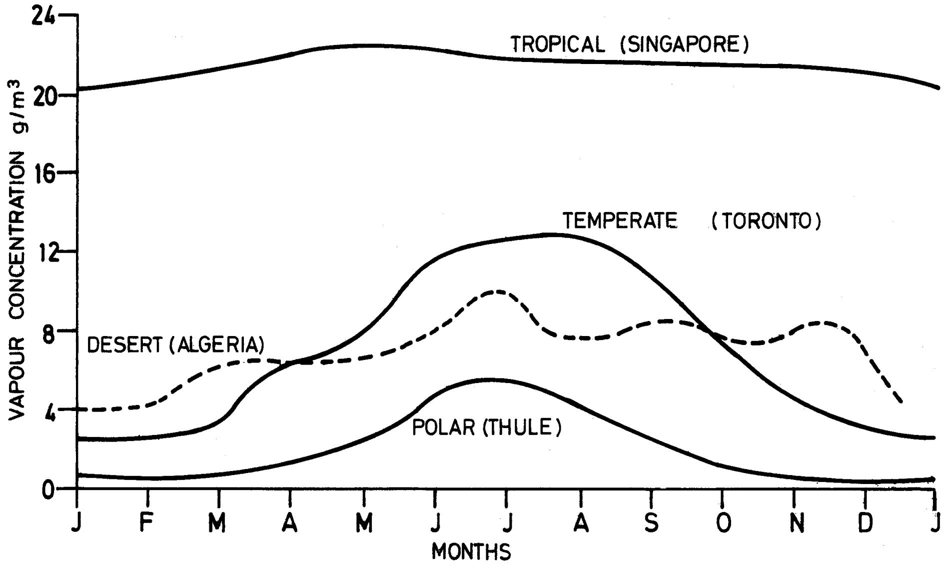


Figure 11. Yearly mean vapour concentration

3.3.2 Two main patterns can be identified from the curves in Figures 3 to 11:

(a) The first is indicative of most temperate regions, plus some polar regions in summer, where the soil and vegetation, or the sea surface, provide ample moisture without excessive convective losses. In consequence the diurnal cycle of vapour concentration, vapour pressure and dew point is similar to that of temperature, having a minimum around dawn and a maximum in the early afternoon. However, the amplitude of the dew point cycle is generally only a fraction of that of the air temperature cycle.

(b) The second is typical of most desert regions, where moisture is in short supply and convection is well developed. In these circumstances the daily cycle shows:

(i) A slight increase of vapour pressure after sunrise, as dew is evaporated.

(ii) A steady decrease of vapour pressure from mid-morning to mid-afternoon, as convection spreads the moisture through a deeper layer of the atmosphere.

(iii) A rise of vapour pressure towards sunset as convection dies down.

(iv) A slow decrease of vapour pressure from late evening until sunrise, as the lowest layers cool and moisture is deposited as dew.

3.3.3 The first pattern is illustrated by Toronto and Thule, and the second by Tripoli and Wadi Halfa, but in most places local factors such as sea breezes and nocturnal winds cause considerable variations; Singapore illustrates a pattern which has been modified in this way. Variations on individual days will be even more complex owing to precipitation, cloud and sunshine, air-mass changes, and subsidence, that is the slow downward movement of air over a large area.

3.3.4 Relative humidity has a marked systematic diurnal variation opposite in phase to that of temperature, that is, it shows a daily minimum in the afternoon and a maximum around dawn. There is also a month-to-month variation of mean relative humidity, especially in the afternoon, again of opposite phase to that of the temperature, but this variation is less well-marked than the diurnal one.

3.3.5 The greatest changes in relative humidity are noted in places where the greatest temperature changes occur between day and night, namely, in mountains and in arid tropical regions. Falls of relative humidity from 100% to 10% during the day have been reported from Pangerango, Java (3032 m above sea level), whilst a rise from 2% to 88% in two hours has occurred at Alexandria (32 m above sea level), when the temperature fell by 17°C. At Kew the relative humidity fell from 73% to 16% in about eight hours on 10 July 1934.

4 EXTREMES OF HUMIDITY

4.1 High humidity

4.1.1 The vapour pressure can never exceed the saturated vapour pressure at the temperature of the source of evaporation; this sets an upper limit, not only to the vapour pressure itself, but also to the dew point and vapour concentration. The source of moisture is usually the sea, and as the warmest sea, the Persian Gulf, seldom has surface temperatures higher than 32°C, this represents the upper limit for the dew point, corresponding to a vapour pressure of about 48 hPa and vapour concentration of about 34 g/m^3.

4.1.2 Only in special local situations, such as a shower falling on heated ground, are higher values reached, and then only for a short time. In Table 1 it may be noted that at Bahrain in the Persian Gulf the vapour concentration has reached this theoretical maximum, the relative humidity being only 3% below saturation, but that maximum humidities from all other stations are lower.

TABLE 1
HIGH VAPOUR CONCENTRATION WITH ASSOCIATED TEMPERATURE

Station	Maximum vapour concentration g/m;	Temperature °C	Relative humidity %
Bahrain	34	33	97
Aden	30	34	77
Karachi	29	32	85
Hong Kong	27	32	80
Darwin	27	32	80
Gan	26	31	81
Akrotiri	26	32	78
Cairo	20	32	59
Boscombe Down	18	29	64

4.1.3 Complete saturation (100% relative humidity) becomes progressively less common above 20°C and is virtually unknown above 30°C, Figure 12 gives a selection of maximum temperature/humidity records which illustrates this fact; it also shows that above about 44°C there is a sudden drop in vapour concentration, temperatures higher than this being reached only in dry desert regions.

4.1.4 Examples of highest recorded humidities, at temperatures of 45°C and above, are given for a selection of stations in Table 2.

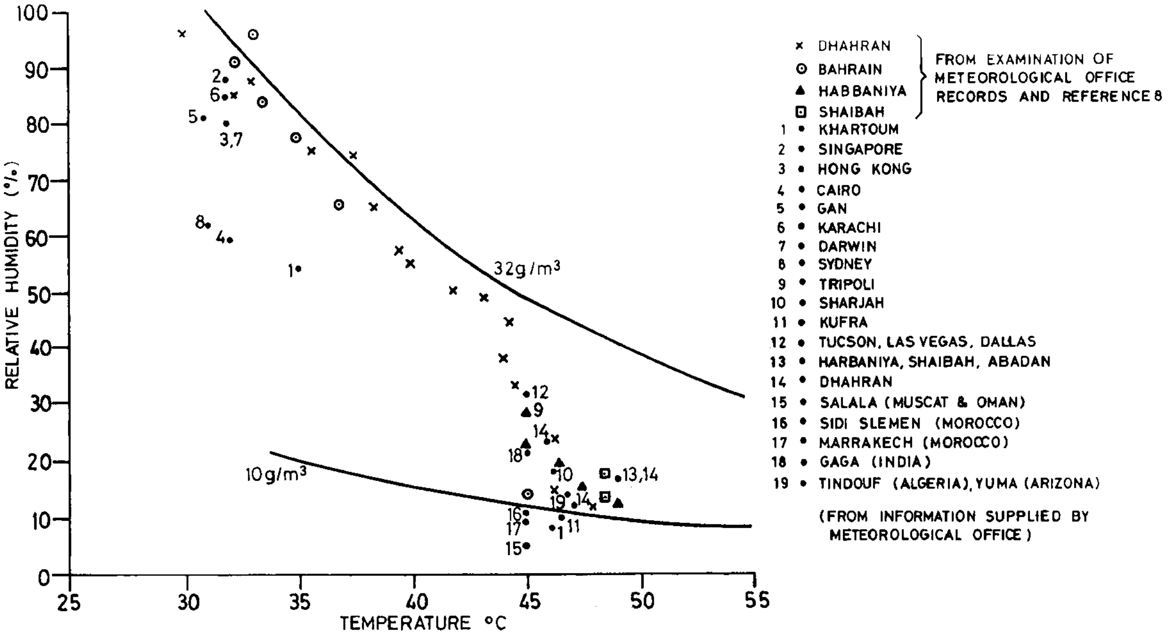


Figure 12. Maximum relative humidity values recorded for given temperatures compared with vapour concentration curves.

TABLE 2

TEMPERATURES OF 45°C AND ABOVE WITH MAX HUMIDITIES RECORDED UP TO 1966

Station	Maximum temperature °C	Associated Vapour concentration (g/m³)	Relative humidity %
Abadan (Iran)	49	15	17
Habbaniya (Iraq)	49	13	17
Shaibah (Iraq)	49	12	17
El Golea (Algeria)	48	9	11
Tripoli (Libya)	48	8	12
Dhahran (Saudi Arabia)	47	11	13
Kufra (Libya)	47	8	12
Tinouf (Algeria)	47	8	11
Yuma (Arizona, USA)	47	8	16
Allahabad (India)	46	12	8
Khartoum (Sudan)	46	6	18
Sharjah (Arabia)	46	12	14
Bahrain (Persian Gulf)	45	9	15
Hermosillo (Mexico)	45	13	22
Gaga (India)	45	15	10
Marrakech (Morocco)	45	7	14
New Delhi (India)	45	10	6
Salalah (Muscat and Oman)	45	5	11
Sidi Sleman (Morocco)	45	8	

4.1.5 High temperature and high relative humidity occurring together can cause rapid deterioration in certain materials and equipment; it is also an unpleasant and enervating condition for man. Figures 13 to 15 give percentages of time throughout the year when both temperature and humidity are above specified limits; these maps show that such conditions are confined almost entirely between latitudes 40°N and 40°S, and that the belt of maximum frequency lies along, or just south of, the equator.

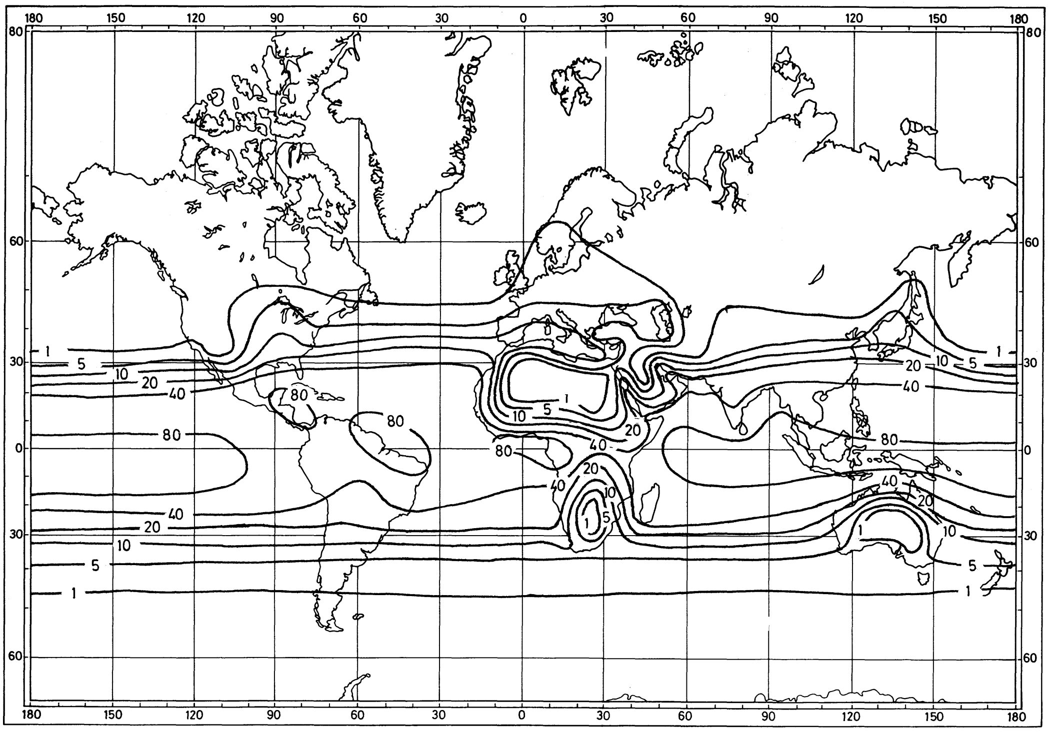


Figure 13. Estimated percentage of time when temperature is greater than 20°C and relative humidity greater than 70%

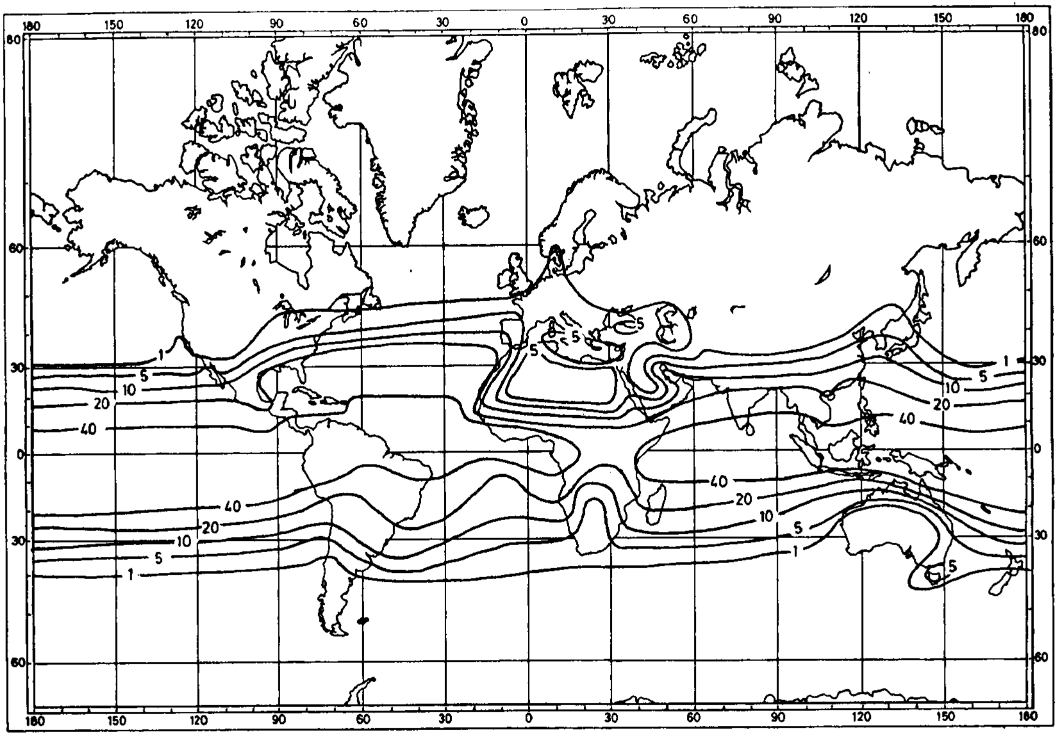


Figure 14. Estimated percentage of time when temperature is greater than 20°C and relative humidity greater than 80%

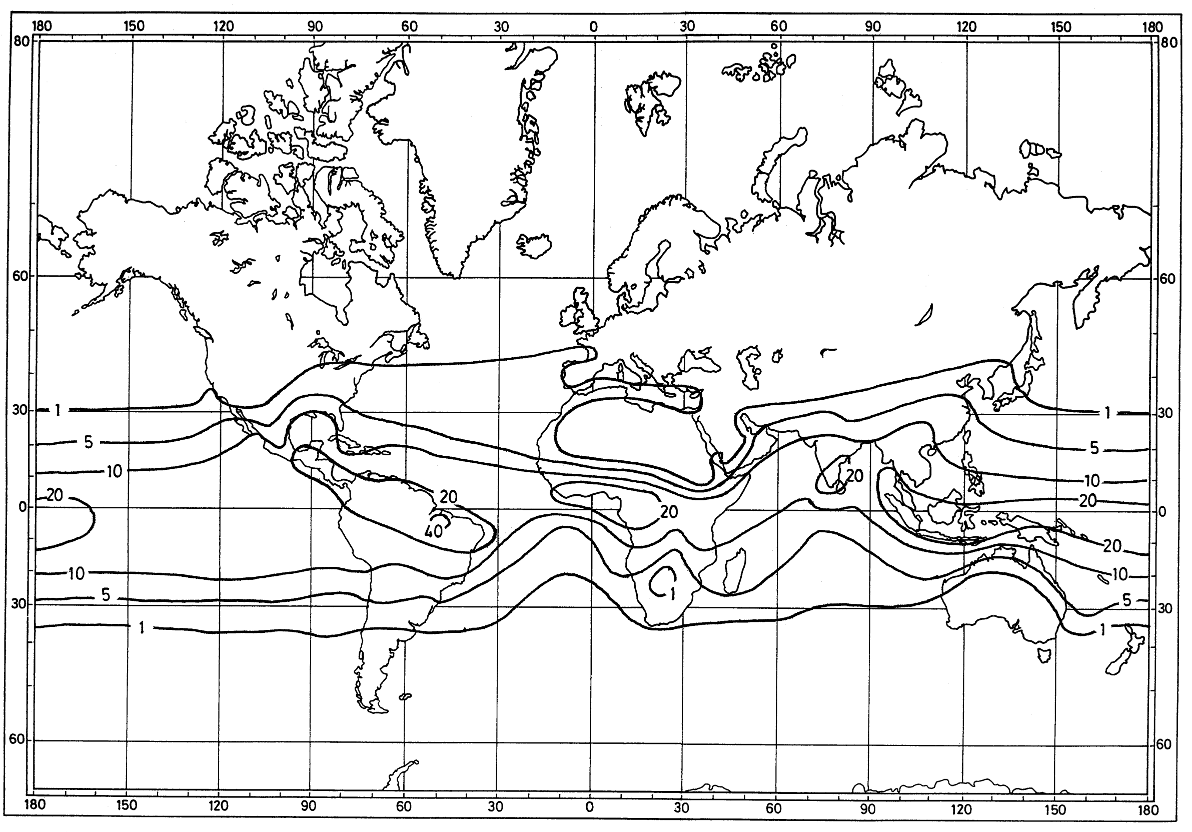


Figure 15. Estimated percentage of time when temperature is greater than 20°C and relative humidity greater than 90%

4.1.6 Singapore (Changi) is representative of a very humid, equatorial region; hourly statistics have been extracted, for the years 1958-70, of those occasions when a temperature in excess of 25°C occurred with a relative humidity greater than 90%. Figures for four representative months, of the percentage frequency of occurrence of the 25°C temperature/90% humidity combination, plotted against the time of day are given in Table 3. Figure 16 presents the same information in graphical form

TABLE 3
PERCENTAGE FREQUENCY OF OCCURRENCE OF TEMPERATURE GREATER THAN 25°C AND RELATIVE HUMIDITY GREATER THAN 90%, CHANGI 1958-70

Month		Frequency of occurrence %											
	Time(hr)	0	0100	0200	0300	0400	0500	0600	0700	0800	0900	1000	1100
Jan		20.3	24.6	20.3	15.7	13.2	10.7	9.2	15.6	11.9	4.2	3.2	2.0
Apr		46.9	54.9	59.5	59.2	63.6	64.4	63.3	61.8	12.6	2.8	2.3	2.3
Jul		19.9	21.3	26.6	28.8	24.3	27.3	32.3	31.5	11.4	5.2	2.2	3.0
Oct		36.7	44.4	46.7	43.9	38.7	36.0	34.0	49.9	9.4	4.0	3.0	1.7
	Time(hr)	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300
Jan		3.2	4.5	5.2	3.2	4.7	5.5	6.9	5.2	8.4	10.4	13.6	18.1
Apr		1.5	5.9	5.9	6.2	5.6	7.7	10.0	13.6	17.2	23.1	31.3	39.2
Jul		3.5	4.2	2.7	3.7	4.7	4.0	5.2	7.7	7.9	10.4	13.6	16.9
Oct		1.7	2.5	2.0	3.0	4.5	6.0	6.0	9.2	12.3	17.9	25.3	29.2

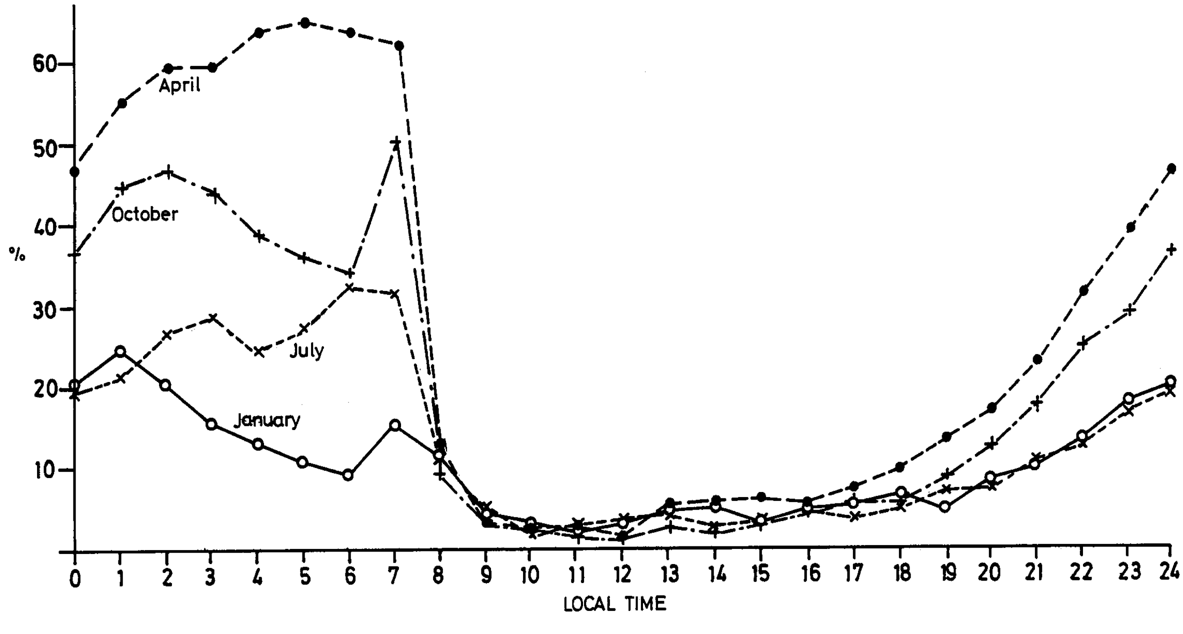


Figure 16. Changi: percentage frequency of occurrence of temperature greater than 25°C and relative humidity greater than 90%, 1958-70

4.1.7 Figure 17 shows the number of times and the total hours in a year that the 25°C temperature/90% humidity combination occurs for a given length of time.

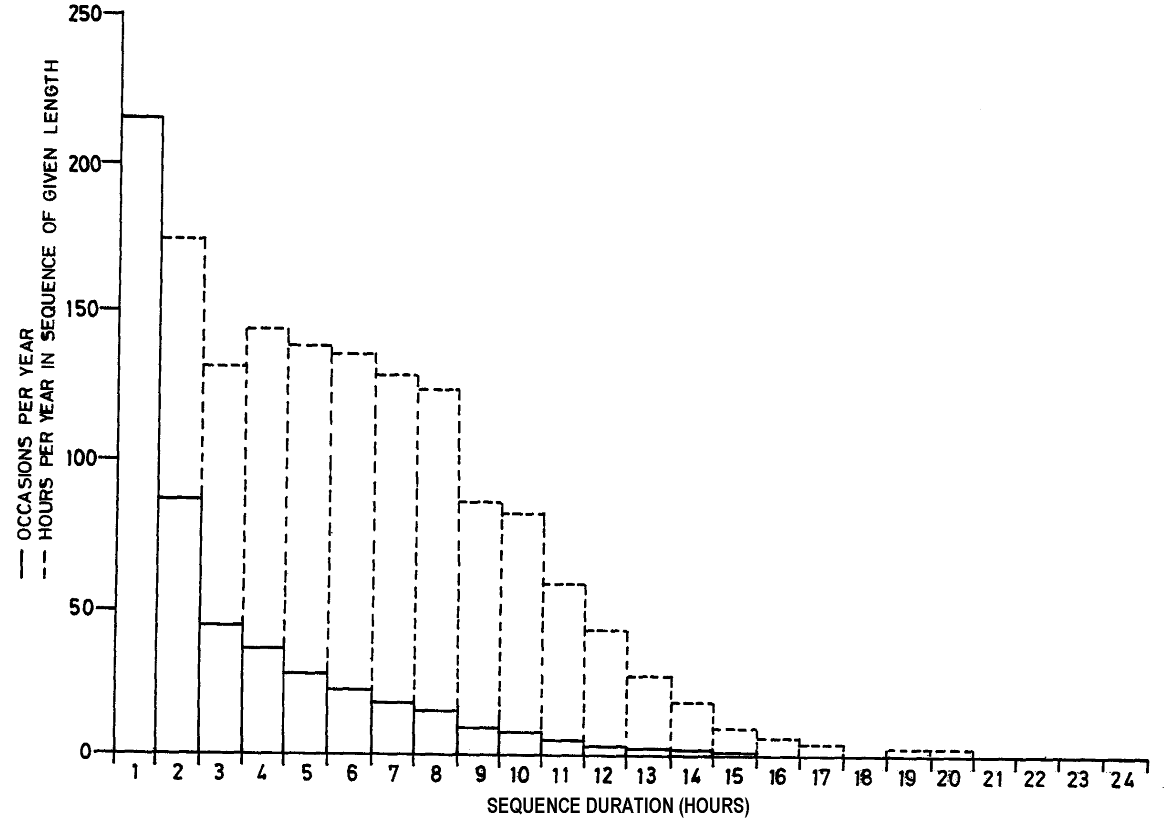


Figure 17. Changi: frequencies of durations of temperature greater than 25°C and relative humidity greater than 90%, recorded in the period 1958-70

4.2 Low humidity

4.2.1 In deserts, and in steppe and savanna regions, the dry season, high temperatures and low relative humidities usually occur together, with the latter frequently falling below 30%. Among extremely low relative humidities on record, are a monthly average of 20% in the Californian Desert, and a period at Alexandria in 1901 when it remained continuously below 15% for 46 hours. In these regions the maximum temperature of early afternoon coincides with the time of lowest vapour pressure; extremely low relative humidities may be reached, as for example 2% at Alexandria during the 46 hours mentioned above.

4.2.2 The most extreme example of low humidity comes, however, from Europe. On 10th February 1927 the continent was covered by a cloudless subsiding high pressure area, with warm air aloft over the Baltic and Alps; at 0300 hrs on this day two places near Donnersberg in Germany reported a relative humidity of 5%. Low humidities of around 5% have been experienced more recently on some Scottish mountain tops.

5 CHANGES OF HUMIDITY WITH HEIGHT

5.1 Within the troposphere, water vapour content usually decreases with height, and most observations have shown the lower stratosphere to be very dry. In general it seems that the mixing ratio decreases with altitude, to a minimum value at several kilometres above the tropopause; after which it increases up to a level of at least 32 km. In middle latitudes, the mixing ratio varies from near 6 g/kg at the surface, to about 0.02 g/kg at the tropopause, and then to a minimum of below 0.01 g/kg at about 15 km, followed by a very slow rise.

6 DRIP HAZARDS

6.1 When moist air comes into contact with materiel having a surface temperature below the dew point of the ambient air, condensation occurs. If, as a result sufficient water accumulates on the surface of the materiel, it will tend to form globules, which, on reaching a sufficient size, will run down gradients or drip from overhanging surfaces. Condensation will be most pronounced where the surface materials are good thermal conductors, such as metals or glass. In cold climates, a further hazard could arise from expansion of drips upon freezing.

6.2 In addition, unsealed items having an internal atmosphere may draw in air when subjected to cooling. Where the moisture content of the air is sufficient, condensation will occur within the item and the resulting water may not be completely expelled on a subsequent rise in temperature. Repeated cycles of this environment could cause progressive increase of liquid water inside the item. Again, freezing constitutes a further hazard in these circumstances.

7 REFERENCES AND OTHER SOURCES OF INFORMATION

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CHAPTER 4-02
THE EFFECTS OF HUMIDITY

1 INTRODUCTION

1.1 The moisture content of materials is dependent both upon their hygroscopic characteristics and the humidity of the environment. All materials tend towards an equilibrium, where the partial pressure of the absorbed or adsorbed water vapour contained in or on the material, balances the partial pressure of the water vapour in the surrounding air. Under the right conditions, moisture vapour from the air can condense onto the surface of materials as liquid water.

1.2 Moisture is not always harmful to materials and may be essential to the useful properties of some, for example wood and paper. However moisture is a major physical and chemical agent of deterioration.

1.3 The physical effects of moisture can be seen in the shrinking and swelling of wood, paper, hydrophilic plastics and textile fibres, as water is desorbed and absorbed with changing humidity. Moisture also acts chemically, as in the corrosion of metals, and the deterioration of some organic materials.

1.4 Moisture may stimulate attack by other agents; wood, for example, having a moisture content of less than 20% is not generally attacked by fungi. Further information is given in Reference 1. Moisture may also act in conjunction with other atmospheric components in degradative processes, such as in the formation of conducting surface films on insulators.

1.5 Changes caused by moisture in the electrical and mechanical properties of materials may affect the function of equipment of which they form a part. Generally, the more severe the moisture conditions, the more rapid the degradative effect.

2 MOISTURE PICK-UP BY MATERIALS

2.1 General

2.1.1 The ability of a material, in contact with water vapour, to pick up moisture depends on its sorptive characteristics. The term `sorption` covers the two processes of moisture pick up, that is adsorption and absorption. Absorbent materials may be further defined by specifying their permeability to water vapour.

2.1.2 Liquid condensation of ambient water vapour will occur at the surface of materials, if the relative humidity reaches 100% at the point of condensation. However, there are circumstances in which condensation can occur when the relative humidity of the air is below saturation and the circumstances under which this can occur are described later.

2.2 Sorptive characteristics

2.2.1 Adsorption is defined as the taking up of one substance at the surface of another. Almost all materials when exposed to water vapour will adsorb one or more molecular layers of water depending on the water vapour pressure and the nature of the material.

2.2.2 Absorption is the term for the penetration of a substance into the body of another.

2.2.3 Water vapour can enter the body of certain materials, such as plastics and rubbers, by diffusion through spaces in the molecular structure.

2.2.4 Permeability may be defined as the rate of diffusion of gas or water vapour under a pressure gradient through a porous material. It is expressed, for thin material, as the rate per unit area and for thicker materials, as the rate per unit cube.

2.3 Condensation of water vapour

2.3.1 Condensation of water vapour from the air can take place at relative humidities below 100%, in the following circumstances:

(a) Condensation can occur in pores or crevices of molecular dimensions. For example condensation from the air, at 80% RH and 2ºC, will occur in pores less than 0.01 micrometres (μm) diameter.

(b) All water soluble substances will absorb moisture from a humid environment. The water vapour pressure, Ps, in equilibrium with its saturated solutions is less than the normal saturated vapour pressure, Pa. If the relative humidity of the air is more than one hundred times the ratio of water vapour pressure to the saturated vapour pressure, water will condense and dissolve the soluble material. If the supply of water vapour in the air is unlimited, the solution will be further diluted by condensation until the water vapour pressures of the solution and the air balance. This phenomenon is associated with the corrosion of metals, where soluble dust particles may dissolve and form corrosive electrolytes at relative humidities less than 100%.

2.3.2 Further information on the condensation of water vapour is given in Reference 2.

2.4 Sorptive processes in metals, alloys and organic polymers

2.4.1 Metallic materials, in a medium in which humidity is below saturation level, become covered with a layer of adsorbed moisture. The layer thickens with increasing vapour pressure, but is never more than a few molecules deep. As mentioned earlier, condensation of water vapour can occur in any pores or crevices of molecular dimensions, at humidities less than saturation.

2.4.2 The absorption of water vapour in the organic polymers proceeds by diffusion through spaces in the molecular structure. The molecular configuration of the polymer, therefore, exerts a considerable influence on the absorptive characteristics.

2.4.3 The permeability to water vapour of polymers having linear configurations, for example cellulosics, is comparatively high. Thermosets, such as the phenolics, have highly cross linked structures, so the diffusion path is long and erratic; therefore the permeability of most thermosets is low.

2.4.4 Linearity of structure is not the only factor affecting permeability. Of the other criteria, the absorptivity of the constituents of the polymer is important. Polymers containing absorbent groups, for example polyamides, polyacrylonitrile and cellulose derivatives, almost always exhibit high permeability.

2.4.5 As a general rule the water retention capability of polymers is related to their permeability; polymers with low permeabilities to water vapour have low water retention, although the converse of this is not always true.

2.5 Measurement of sorptive characteristics

2.5.1 The measurement of sorptive properties is defined in several British Standard specifications. Such specifications include measurement of the water absorption and permeability of plastics and rubbers, and the moisture regain and water retention of fibres.

2.5.2 Water absorption is measured by immersing a test piece of specified dimensions in water for a specified time. The weight of water absorbed is expressed as a percentage of the initial dry weight of the sample. The test piece is usually disc or slab shaped, 3 mm or 10 mm thick, according to the specification followed. For detailed information on methods of testing of certain materials, References 3, 4 and 5 should be consulted. Table 1 gives the approximate order of water absorption for some common plastics and rubbers, where the % water absorption figures refer to 24 hours immersion from dry.

$$\% \text{ Water absorption} = \frac{\text{Weight of sample - wet}}{\text{Weight of sample - dry}} \times 100\%$$

2.5.3 The Permeability of plastics and rubbers is a measure of the ability of water vapour to diffuse through the substance. The amount of gas or water vapour Q, passing in time t, through a barrier of area a, with a pressure (or relative humidity) difference dp across the thickness b, may be defined as:

$$Q = P\frac{at}{b}dp \quad \text{(Fick's Law)}$$

where P is a proportionality constant.

TABLE 1

WATER ABSORPTION OF PLASTICS AND RUBBERS

Material	Approximate % water absorption
Polyisobutylene	0 – 0.5
Butyl rubber	
Polyethelene	
Polytetrafluoroethylene	
Polytrifluorochloroethylene	
Polysulphide rubbers (depends on compounding)	
Coumarone-Indene resins	
Polystyrene	
Isomerized rubber	0.02
Vulcanized rubber - Ebonite (best grade)	0.06
Polyvinylchloride (unplasticized)	about 0.1
Vinyl Chloride-Vinyl Acetate co-polymers	
Polyvinylidene Chloride	
Polyesters (cross linking type)	
Epoxy resins	
Anilene-Formaldehyde resin Melamine-Formaldehyde resin unfilled or mineral filled	
Polymethyl Methacrylate	0.2 – 0.5
Phenol-Formaldehyde resins unfilled or mineral filled	
Polyvinylchloride (plasticized)	
Silicone resins	0.05 - 0.5
Polyesters (most alkyds, including fibre forming type)	about 0.2
Rubber (unvulcanized, soft) Benzylcellulose	about 0.5 - 1.0
Rubber (some vulcanized samples, depending on compounding and cure)	0.2 - 3.0
Cellulose Triacetate	Up to about 1.0
Polyvinyl Formal	
Melamine-Formaldehyde resins(Cellulose filled)	
Cellulose Acetobutyrate	about 1.5
Ethylcellulose (Plastics grade)	
Polyamides (Nylon) Polymethyl Acrylate	
Cellulose Nitrate (plasticized sheet)	1.0 - 3.0
Butadiene-Styrene copolymers (maximum)	about 2.0
Polyacrylonitrile	
Urea-Formaldehyde resins (cellulose filled)	
Butadiene-Acrylonitrile copolymers (maximum)	about 3.0

TABLE 1 (contd)

WATER ABSORPTION OF PLASTICS AND RUBBERS

Material	Approximate % water absorption
Polyvinyl Acetate	about 5.0
Phenol-Formaldehyde resins (cellulose filled)	1.0 - 10.0
Regenerated Proteins (Formalized Casein)	7.0 - 14.0
Zein Plastics	about 10
Polyvinyl Alcohol	Soluble
Low molecular weight condensates of, Urea-Melamine- and Phenol-Formaldehyde resins	

2.5.4 Table 2 illustrates the comparative permeability of common plastic and rubbers, but where available the permeability is included. Reference 6 should be consulted for further information. In these cases dp is a percentage relative humidity difference (100% to 0%). No generally accepted method of measuring permeability exists, but some British Standard specifications covering the testing of materials include measurement of permeability.

TABLE 2

PERMEABILITY OF PLASTICS AND RUBBERS TO WATER VAPOUR

Material	Permeability where known **	Approx order of permeability *
Regenerated Cellulose, moisture proofed		extremely low (very highly Impermeable)
Rubber Hydrochloride		
Chlorinated rubber		
Polysulphide rubbers		
Polyethylene		
Polytetrafluoroethylene		
Polyvinyl Chloride		
Polyvinylidene Chloride		
Phenol-Formaldehyde resins		
Silicone resins		
Rubber vulcanized, hard (Ebonite)		highly impermeable
Gutta-percha		
Isomerized rubber		
Polychloroprene, vulcanized		
Polyisobutylene and Butyl rubber		
Polyacrylonitrile		
Rubber, vulcanized, soft	some 80	highly or moderately impermeable
Polystyrene	30	
Polyvinyl Butyral	Butvar 60	
Vinyl Chloride-Vinyl Acetate Copolymers	10	
Polymethyl Methacrylate	40	
Cellulose Nitrate, Commercial sheets	200	moderately impermeable
Cellulose Triacetate	700	
Cellulose Acetate-Butyrate	500	
Ethylcellulose, Plastics grade	700	
Benzylcellulose	200	
Polyesters and Polyamides	100	
Rubber, 'vulcanized, soft	some 100	
Polyvinyl Acetate	300	
Urea-Formaldehyde resins	500	
Cellulose Acetate, commercial sheets	1000	fairly permeable
Regenerated Cellulose		permeable
Polyvinyl Alcohol		"

* The range (from extremely low, up to permeable) represents a difference of at least 100 fold in transmission.

** Permeabilities are expressed in (gm cm /sq cm /hour) x 10^9 per percentage relative humidity difference.

2.5.5 The moisture regain represents the equilibrium value for the absorption of water that occurs when dry fibres are exposed to an atmosphere of specified humidity, at a specified temperature. The increase in weight is expressed as a percentage with respect to the dry weight of the sample. Table 3 shows the range of absorption moisture regain of common fibres, at 65% RH and 25°C.

TABLE 3

MOISTURE REGAIN OF COMMON FIBRES AT 65% RH AND 25°C

Fibres	Moisture Regain %
Polyethylene	under 0.1
Polystyrene	
Polyvinylidene Chloride	
Polyvinyl Chloride (unplasticized)	about 0.1
Vinyl Chloride - Vinyl Acetate Copolymer(Vinyon HH)	
Glass (Surface Adsorption)	
Vinyl Chloride - Acrylonitrile Copolymer	under 0.5
(Dynel, Vinyon N)	0.35
Rubber Hydrochloride (Pliofilm, Thin Films)	under 0.5
Polyester fibres (Terylene)	0.45
Asbestos	about 0.5
Rubber, unvulcanized or vulcanized, soft (filament or thin sheet)	
Nylon 11	1.05
Nylon 610	1.7
Polyurethane (Perlon U)	1.2
Polyacrylonitrile	between 1 & 2
Nylon 6 (Perlon L)	3.8
Nylon 66	4.2
Polyvinyl Alcohol formalized	4.5
Cotton	between 6 & 8
Cellulose Acetate	6
Cotton, Mercerized	8.5
Flax	9
Sunn Hemp	between 8 & 9
Hemp and Manila Hemp	10
Jute	10.5
Silk, degummed	10
Regenerated vegetable proteins (Ardil, Vicara)	about 10
Regenerated Cellulose	about 10
Viscose Rayon	11.5 - 14
Wool	about 14
Regenerated Casein	12.5
Calcium Alginate	between 20 & 30

3 CORROSION OF METALS AND ALLOYS

3.1 General

3.1.1 Nearly all metallic materials, apart from the noblest metals, such as gold, become covered with an invisible film of oxide when exposed to pure, dry air. In most instances the imperviousness of the film inhibits further oxidation. The thickness and character of oxide films are described in Chapter 8-02.

3.1.2 Apart from such forms of dry oxidation, atmospheric corrosion usually requires the presence of moisture and soluble impurities, which may be inherent in the material or contained in the atmosphere. The solutions thus formed provide electrolytes for the electro-chemical reaction of the corrosive process. (See Chapter 8-02.) Visible wetting of the surface is not required, an invisible adsorbed film of moisture being sufficient to support electro-chemical corrosion.

3.1.3 For several metals there is a critical relative humidity, above which a sharp rise in the rate of corrosion, will occur.

3.2 Critical relative humidity

3.2.1 Studies of the atmospheric corrosion of metals have demonstrated the existence of critical relative humidities below which corrosion was negligible. It has been found that corrosion of iron, in pure air, was small even at a sustained relative humidity of 100%. However, in the presence of traces of sulphur dioxide at approximately 50% RH, the primary critical humidity, there was a marked increase in corrosion as measured by weight increments of the samples.

3.2.2 At about 80% RH, the second critical humidity, the rate of corrosion increased sharply. This second critical humidity is believed to mark the point at which water held in the capillaries of the iron hydroxide becomes free to take part in the corrosive process.

3.2.3 Other critical relative humidities for various metals have been identified and these are shown in Table 4.

TABLE 4

CRITICAL RELATIVE HUMIDITY FOR VARIOUS METALS

Metal	Atmosphere	Critical RH %
Aluminium	polluted	80
Nickel	by	70
Mild Steel	sulphur	60-75
Copper	dioxide	63
Zinc	pure air	70
Magnesium	"	90

3.2.4 It should be emphasized that above the critical humidity most metals are corroded to an extent that is dependent upon the degree of atmospheric pollution, either gaseous, for example sulphur dioxide, or solid, for example ammonium sulphate. It follows that at high relative humidities the controlling factor is provided by the degree of purity of the atmosphere. References 7 and 8 provide further information.

3.3 The effect of water droplets

3.3.1 Condensation conditions can result in the formation of water droplets. This phenomenon can cause intensive localized corrosion at the centre of the metal-droplet interface. Oxygen diffuses rapidly through the thin layer of solution at the water line, producing a 'differential aeration cell', and rapid attack on areas of metal where the oxygen concentration is lower.

3.4 Exposure tests

3.4.1 Outdoor exposure tests on metal samples have been extensively undertaken for many years, in order to determine the corrosivity of the locality and to indicate the method, extent and frequency of the protective treatment required.

3.4.2 In general, such investigations have confirmed the results of laboratory experiments on the corrosion of ferrous metals, that above the critical humidity, iron is corroded to an extent dependent upon the degree of atmospheric pollution. As an example of the influence of humidity and pollution some results showing the rates of corrosion at different exposure stations are given in Table 5.

TABLE 5

INFLUENCE OF RELATIVE HUMIDITY AND POLLUTION ON THE ATMOSPHERIC CORROSION OF STEEL

Corrosion rate μm/year	Station	Average annual relative humidity	Atmospheric pollution	
			SO_3	Cl
2.5	Khartoum	30	slight	Nil
7.5	Delhi	55	slight	Nil
51	Llanwrtyd Wells	80	slight	appreciable
127	Sheffield	85	heavy	pronounced
25.4	Apapa, Nigeria	80	slight	appreciable
610	Lighthouse Beach, Lagos, Nigeria	85	slight	heavy

3.4.3 At a fixed level of atmospheric pollution, the most significant factor affecting the corrosion of an exposed metal surface is probably the proportion of time during which the relative humidity exceeds the critical value. and not the average relative humidity.

3.4.4 Figure 1 illustrates the relationship between the corrosion rate of mild steel and relative humidity obtained during exposure tests at Kanpur, India.

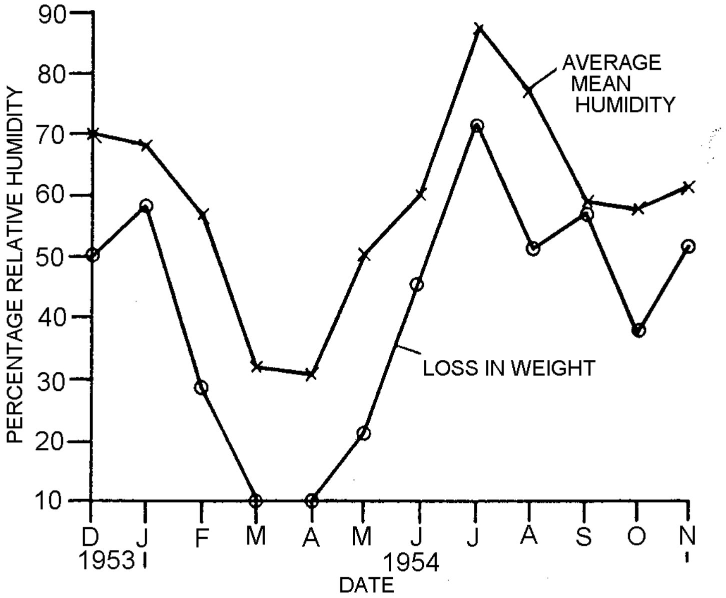

Figure 1 Relationship between the corrosion rate of mild steel and humidity, at Kanpur, India

3.4.5 Although the corrosion rate was high when the average mean humidity, that is the average of the mean daily relative humidity taken over the month, was greater than the critical value of 70%, the results indicate that corrosion was still significant during most of the remaining months. This may be explained by moisture in the form of dew, inducing corrosion during these months. Table 6 gives associated information on the amount of dew and number of dew days in different months. Dew days are defined as days on which more than one cubic centimetre of dew was collected.

TABLE 6

AMOUNT OF DEW AND NUMBER OF DEW DAYS IN DIFFERENT MONTHS AT KANPUR, INDIA

Month	Number of dew days	Amount of dew in cm^3 on 100 cm^2 area
December, 1953	9	24.6
January, 1954	6	14.7
February, 1954	6	8.1
March-August, 1954	NIL	NIL
September, 1954	6	17.4
October, 1954	12	20.7
November, 1954	18	28.2

4 PLASTICS

4.1 General

4.1.1 As mentioned earlier, the absorptive characteristics of a plastic depend on its chemical nature and structure. The degree of water absorptivity of a plastic may, however, be decisively influenced by the filler used (compare phenol-formaldehyde resin, cellulose filled and unfilled, as listed in Table 1) and by the presence of microscopic air cavities between the filler and the resin.

4.1.2 The mechanical and electrical properties, and the dimensions of a plastic component may be affected by the absorption and desorption of moisture especially if the plastic contains hydrolysable groups.

4.2 Chemical reaction with water

4.2.1 The chemical reaction of water with plastics is limited to materials which contain hydrolysable groups, such as esters, amides, nitriles, acetals and certain types of ketones. As an example of such a reaction, it has been shown that the -CN groups of acrylonitrile polymers will hydrolyse to -C00H, liberating ammonia (NH_3).

4.2.2 Hydrolysis may be accelerated by an increase in temperature, and catalysed by the acidity, or alkalinity of the surroundings. Polyamides are examples of plastics affected by acidity, and polyesters are examples affected by alkilinity.

4.3 Effect of chemical reaction with water

4.3.1 If the hydrolysable groups are links in the skeletal chain of the polymer, the result of hydrolysis may be serious because it constitutes scission of the primary chain, and hence affects the mechanical strength of the plastic. Plastics subject to this form of chain scission include the polyesters, polyamides, cellulose esters and ethers.

4.3.2 When the vulnerable groups are side groups of a polymer chain, composed exclusively of carbon to carbon bonds, their hydrolysis may affect properties of the plastic, such as dielectric constant, power factor, insulation resistance and water absorption; but, in general, the mechanical properties are unaffected. Examples of plastics in which only the side group is affected are polyvinyl acetate and polyvinyl nitrile.

4.4 Evaluation of plastics

4.4.1 It has been suggested that the resistance of plastics to the effects of moisture may be judged by reference to their water absorbing capacity, that is, plastics with high water absorption will have their properties more seriously impaired by moisture. Complicating factors, such as the possibility of hydrolysis and the catalytic action of moisture in other weathering processes, would seem to throw doubt on the reliability of such a method of evaluation.

4.4.2 In general, however, a plastic having good dimensional stability and constant electrical properties under conditions of high and fluctuating humidity, will have low water absorption. Examples include polytetrafluoroethylene (PTFE), polystyrene, polyethylene, polymethyl methacrylate (Perspex) and polyvinyl carbazole.

4.4.3 An indication of the resistance of a plastic to a humid environment may be obtained from consideration of data obtained from exposure stations and/or laboratory experiments.

4.4.4 The effects on the properties of a plastic exposed at a particular station will be the result of the interplay of several climatic factors, for example temperature, solar radiation, humidity and rainfall. The sites, however, are usually situated where a particular component of weather is dominant.

4.4.5 Tropical exposure tests on plastics have been conducted, and a number of reports published in Reference 9. A 'jungle undergrowth' site chosen for these tests is described as warm humid and shady, and so the deterioration that occurs could be attributed to temperature and moisture. However, as such an environment is conducive to microbiological attack, and many of the samples showed evidence of microbiological contamination, it would seem impossible to separate the effects due to moisture and micro-organisms.

4.4.6 The results of exposure tests carried out in different climates, and on a large number of plastics have indicated that moisture has a deleterious effect on products containing cellulosic filler, for example formo-urea cellulose woodflour filled phenolic, whose mechanical and electrical properties are seriously affected.

4.4.7 Laboratory experiments usually require the exposure of a sample to constant or cyclic damp-heat conditions or immersion in water, and involve the measurement of changes occurring in a particular property. Although artificial tests of this type cannot accurately predict reaction to the natural environment, they are useful for obtaining quick indications of the relative resistance of different materials.

4.4.8 Figures 2 and 3, and Table 7 illustrate the effect of absorbed moisture on the properties of various plastics. Reference 10 contains information on the variation of mechanical and electrical properties of many types of plastics when exposed to a number of different damp heat conditions.

4.5 Electrical surface tracking

4.5.1 Table 7 indicates that the specific surface resistance and specific volume resistance of the plastics tested changed on the absorption of moisture. The presence of a conducting electrolyte on the surface of a plastic under voltage stress can, however, cause a more serious progressive electrical failure known as surface tracking. The role of moisture in the process is to dissolve any impurities that may be present in or on the material thus providing the conducting electrolyte.

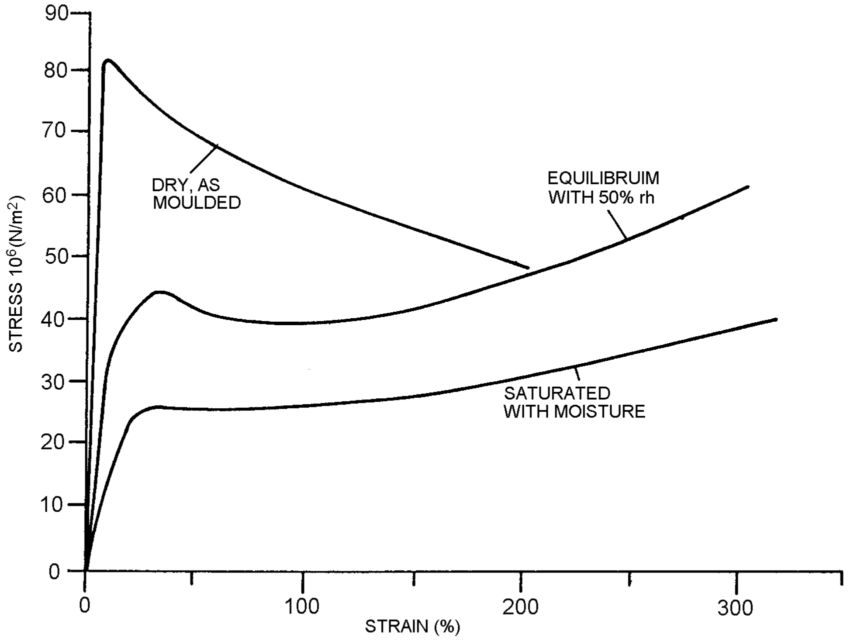

Figure 2. Tensile stress vs strain of Nylon 6. Effect of moisture content at 23°C

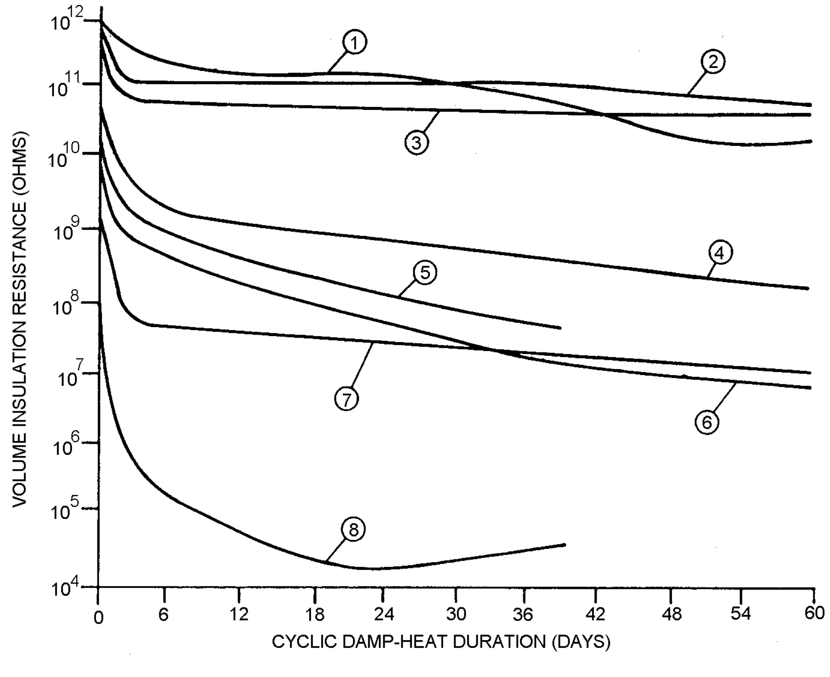

Figure 3. Volume insulation resistance of Novolak (a Phenol-Formaldehyde resin) mouldings, with various fillers, exposed to cyclic damp heat.

Key to fillers:

(1)	Crushed mica	(2)	Crushed low alkali glass and feldspar
(3)	No filler	(4)	Low alkali glass and crushed mica
(5)	Textile fibres	(6)	Woodflour
(7)	Asbestos and crushed mica	(8)	Textile cuttings.

TABLE 7

CHANGES IN THE ELECTRICAL AND MECHANICAL PROPERTIES OF SOME PLASTICS, DURING PROLONGED ABSORPTION OF WATER AT 20°C

			Electrical properties ***				Mechanical properties		
Sample*	Measuring point **	Weight/ gm	Specific surface resistance ohm	Specific volume resistance ohm/cm	Tangent of the angle of dielectric loss at 50Hz	Dielectric permiti-vity at 50 Hz	Impact strength kgf.cm/ cm^2	Cross breaking strength Kgf/mm^2	Brinell hard-ness gf/mm^2
1 Co-polymer MSN	A	36.9086	2.7×10^{16}	8.6×10^{15}	0.015	3.6	815	12.4	18.0
	D	37.1722	4.0×10^{12}	4.3×10^{13}	0.018	3.7	1.227	10.4	19.8
2 Polyamide 68	A	18.2875	1.05×10^{15}	1.2×10^{15}	0.021	3.6	90.2	668	14.4
	B	18.3607	8.9×10^{14}	8.0×10^{14}	0.041	3.6	89.8	530	11.7
	C	18.6009	6.2×10^{12}	1.1×10^{12}	0.080	3.7	73.2	458	10.2
	D	18.7022	4.7×10^{12}	4.7×10^{11}	0.019	2.1	67.4	402	5.72
3 Moulding powder based on an organic hardener and novolak phenolformaldehyde resin in the proportion 30:70	A	43.8983	2.2×10^{14}	1.6×10^{15}	0.026	5.4	-	-	-
	D	44.2591	4.5×10^{13}	3.4×10^{13}	0.029	5.5	-	-	-
	E	44.0104	1.8×10^{13}	7.0×10^{13}	0.027	5.6	-	-	-
4 Moulding powder based on an organic hardener and novolak phenolformaldehyde resin in the proportion 40:60	A	45.7677	1.2×10^{15}	1.5×10^{15}	0.028	5.7	-	-	-
	D	46.2078	2.7×10^{13}	1.3×10^{13}	0.026	5.9	-	-	-
	E	45.9382	1.0×10^{15}	3.6×10^{13}	0.029	5.6	-	-	-
5 FKP-1	A	40.0175	2.9×10^{12}	5.0×10^{11}	0.291	17.1	12.8	655	20.7
	C	41.2320	3.7×10^{8}	4.3×10^{8}	****	****	11.19	611.6	22.9
	E	40.1818	3.9×10^{12}	7.2×10^{11}	0.337	23.8	-	-	-
6 KMS-9	A	49.7309	2.1×10^{14}	1.3×10^{14}	0.0063	5.2	-	-	-
	C	49.9892	2.4×10^{9}	1.0×10^{9}	0.081	****	-	-	-
	E	48.1326	2.0×10^{13}	9.9×10^{13}	0.019	4.5	-	-	-
7 AG-4V	A	32.2714	2.8×10^{13}	5.4×10^{12}	0.025	6.6	64.7	2.152	46.6
	D	32.4213	3.8×10^{10}	1.6×10^{11}	0.026	6.2	47.14	1.561	37.3
	E	31.9372	1.3×10^{14}	3.8×10^{13}	0.021	6.3	-	-	-
8 Plastic based on polyester resin with glass fibre filler	A	49.4692	4.5×10^{13}	2.1×10^{14}	0.018	4.8	-	-	-
	C	50.5845	1.6×10^{9}	5.5×10^{8}	****	****	-	-	-
	E	49.3276	2.7×10^{13}	6.2×10^{13}	0.029	4.9	-	-	-

*	MSN	Terpolymer of methylmethacrylate, styrene and acrylonitrile.
	FKP-1	Moulding powders based on phenol-formaldehyde novolak resin plus rubber and fillers; for high impact-strength mouldings.
	KMS-9	Moulding material based on silicone resin with glass fibre filler; for heat resistant dielectric parts.
	AG-4V	Glass fibre mat reinforced moulding material based on phenol- formaldehyde resin.

** The values were determined: A on samples dried to constant weight in delivery condition (before testing), B,C and D after immersion in water for 1, 21 and 56 days respectively, E after the conclusion of the action of water on samples dried to constant weight.

*** The specific surface resistance is the resistance between two opposite edges of a surface film which is one centimetre square. The specific volume resistance is the resistance between opposite faces of a cube having a volume of one cubic centimetre.

**** It was impossible to measure the value as a result of the high conductivity of the sample.

4.5.2 Surface tracking is evidenced by a mass of branched and sometimes interconnected carbonized channels on the surface of the insulant caused by scintillation, i.e. tiny surface arcs.

4.5.3 Table 8 gives a list of unfilled polymers, tabulated in increasing order of surface tracking resistance.

TABLE 8

TRACKING RESISTANCE OF UNFILLED POLYMERS UNDER MOIST CONDITIONS

Material	Hours*
Polyester, Chlorinated	0.4
Epoxy Resin	0.4
Polycarbonate Resin	0.4
Polyamide (FM-3001)	0.4
Polyvinyl Chloride	0.5
Polystyrene	0.9
Epoxy, Modified	1.2
Polyester, Acrylic Modified	8
Butyl Rubber	11
Polyethylene	15 - 40
Methyl Methacrylate	90
Polyoxymethylene	95
Polypropylene	182
Polytetrafluoroethylene	172

*The number of hours before surface tracking occurs in the test piece.

4.5.4 The incorporation in the polymer of large amounts of hydrated fillers has resulted in compositions based on many types of epoxy and polyester resins which are very resistant to surface tracking. References 11 and 12 provide further information.

5 RUBBERS

5.1 General

5.1.1 Moisture is considerably less damaging than ozone, heat, oxygen and sunlight, as an agent of deterioration of natural and synthetic rubbers. In fact it is considered that the high humidity conditions in the tropics have no adverse effects on rubber mouldings and that, on the contrary, such conditions constitute an effective screen to the highly actinic solar radiation.

5.2 Chemical reaction with water

5.2.1 The chemical reaction of the rubbers with water is limited to those containing hydrolysable groups, for example polyesters, as part of their original composition or that have been formed by oxidation.

5.2.2 Hydrolysis, occurring in the rubbers in common use, would seem to have serious effects only on the polyester rubbers, for example polyurethane, Chemigum SL, Vulcollan and Vulcaprene, where it is in part responsible for chain scission in the skeletal chain. The hydrolysis of the polyester rubbers is catalysed by the acidity or alkalinity of the surroundings and by high temperature.

5.3 Electrical properties

5.3.1 Where conditions of high humidity alternate with dry periods, there would appear to be no great danger of permanent modification of the volume resistance or dielectric properties of rubbers. However, if high humidity and temperature are permanent climatic features, the diffusion of water into rubber components may substantially impair the electrical properties.

5.3.2 Moisture can accentuate the deterioration of electrical properties initiated by other climatic factors. As an example, the hydrogen sulphide produced by exposure of hard rubber to solar radiation may dissolve in absorbed moisture and form a conductive surface film, thus reducing the insulation resistance of the material.

5.3.3 The phenomenon of electrical surface tracking also occurs with rubbers. The tracking resistance of butyl rubber and some polyester rubbers may be improved by the addition of large amounts of hydrated fillers, for example $Al_20_3.3H_20$.

5.4 Evaluation of rubbers

5.4.1 Table 9 gives the comparative resistance to water of natural and some synthetic rubbers. Although in this table polysulphide and silicone rubbers are attributed a 'medium' resistance to water, Reference 6 contains the following qualifications with respect to their resistance:

(a) For Polysulphide rubbers, water absorption is very low and permeability to water vapour exceptionally low. Their very low permeability to gases and vapours make them suitable for gas proof diaphragms and the lining of storage tanks.

(b) High water repellance is a characteristic of all organo-silicon oxide polymers. They have a resistivity of 10^{14} ohm cm, a figure that is maintained even at high humidity.

TABLE 9

COMPARATIVE RESISTANCE OF NATURAL AND SYNTHETIC RUBBERS TO WATER

Rubber	Comparative resistance to water
Natural	High
Butadiene-Styrene (SBR)	Medium to high
Butyl (GR-I)	Fairly high to high
Polychloroprene (Neoprene)	Medium
Nitrile (Buna N)	Medium
Polysulphide (Thickol)	Medium
Silicone	Medium
Chlorosulphonated Polyethylene(Hypalon)	High
Acrylate	Medium
Polyesters (Polyurethane)	Fairly low
Fluorinated	High

6 GLASS

6.1 General

6.1.1 The exposure of glass to high humidities can cause deterioration in its electrical and optical properties. Impairment of the electrical properties of glass may be due to the presence of an adsorbed moisture film, or the result of an actual chemical reaction between the glass and water; degradation of the optical qualities being a consequence of this reaction.

6.2 The action of water on glass

6.2.1 Although glass is soluble in water at ordinary temperatures, to a certain extent the amount of decomposition which occurs is extremely small. A typical figure for corrosion rate would be below 5.7 µm per year for an ordinary soda-lime-silica glass.

6.2.2 In the three main groups of glass, namely, 'soft' - soda-lime-silica, 'hard' - borosilicate, and neutral glasses of intermediate composition, the most mobile ions are those of sodium. If an adsorbed moisture film is present, an exchange of sodium ions and hydrogen ions from the water will take place. This results in the formation of a solution of sodium hydroxide which in turn, can attack the silica network.

6.2.3 When the amount of water at the surface is considerable, rather than just an adsorbed layer, dilution of the sodium hydroxide formed can allow the ion exchange to continue until eventually a layer of 'silicon-rich' glass some hundredths of micrometres thick may develop at the surface. This layer will possess different optical properties from the main body of the glass.

6.3 Effect on electrical properties

6.3.1 The specific volume resistance and dielectric properties of glass are relatively unaffected by high humidities. However, the surface insulation resistance of the material may be lowered, in the first instance by the adsorbed film of moisture, and then further by contamination of the surface by the decomposition products of the reaction between glass and water.

6.4 Effect on optical properties

6.4.1 Alkali extracted from the glass by the action of absorbed water may eventually form a visible film of solid matter. In some types of glass the film may be removed by washing, but in others the action of the alkali may permanently etch the surface. The etching of the surface will be aggravated by the presence of any other acid or alkaline contaminants.

6.4.2 The rate of fogging depends on the composition of the glass but it has been reported that visible dimming of even the most stable types occurred after one month's exposure in a tropical warehouse during the rainy season.

6.4.3 Where highly polished specimens of five commercial glasses were exposed to humid conditions, it was found that the degree of visible attack increased with the level of the relative humidity. However, there was no correlation between losses in the transmission of the specimens and their visual appearance. Some samples even showed an improvement in transmission characteristics following exposure.

6.4.4 In spite of this evidence high relative humidities should be assumed to be harmful to the optical qualities of glass, either directly or by fostering microbiological attack. References 1 and 13, and Chapter 10-02 provide further information.

7 ORGANIC COATINGS (PAINT, VARNISH, ENAMEL AND LAQUER)

7.1 General

7.1.1 Moisture in the form of water vapour or liquid is a major weathering factor in the breakdown of organic coatings. The relative importance of sunlight and moisture as deteriorating agents has yet to be established, however, their importance probably varies with location. In tropical and subtropical regions moisture plays a prominent part but is of little consequence in desert localities. There is evidence, however, that where the two climatic components combine, the photo-chemical decomposition of paint is accelerated by the presence of moisture in the form of rain, dew, or water vapour.

7.1.2 The action of water on organic coatings will be determined by properties such as the chemical composition, permeability, thickness and continuity of the coating, and the nature of the substrate.

7.2 Effect of composition

7.2.1 Although organic coatings consist of many components, a useful simplification is to consider their structure as comprising a 'vehicle' which imparts the film forming characteristics and carries the 'pigment'.

7.2.2 Water is capable of softening some vehicles, such as straight or long-oil (paints and varnishes) and cellulosic (lacquers) types. Other vehicles are affected in varying degrees; but in general, resins containing active hydroxyl (OH) and acid (C00H) groups are more susceptible to moisture. If soluble pigments are included in a paint formula, they may cause blistering by absorbing moisture.

7.3 Diffusion and effect of substrate

7.3.1 An organic coating can be considered as a semi-permeable membrane, and so moisture may penetrate the film by diffusion processes and eventually reach the substrate. On reaching the substrate the effect may be to destroy adhesion and cause blisters. If the substrate is a metal, the formation of corrosion products will accelerate the breakdown of the coating.

7.3.2 When the function of a coating is primarily to exclude moisture from the substrate, it should have low permeability and be applied as thickly as possible.

7.4 Moisture resistant coatings

7.4.1 When properly used in vehicles, tung and dehydrated castor oils, resins such as phenolics, melamines, vinyl co-polymers of high vinyl chloride content, and vinylidene chloride and its co-polymers, all impart improved water resistance to paints. Combinations of alkyd resins with amine derivatives, and alkyds modified with phenol and the better oils, have good moisture resistance, but as a class alkyds are considered inferior to phenolics and vinyls.

7.4.2 Measurements of the insulation resistance of coils impregnated with silicone varnishes, following cyclic damp-heat tests, would seem to indicate that these insulating varnishes are resistant to moisture.

7.4.3 References 1 and 10 contain further information.

8 TEXTILES

8.1 General

8.1.1 Textile fibres may be divided into two main groups, namely, natural and man-made fibres.

8.1.2 Fibres with high moisture regain figures usually suffer a loss of tensile strength and extensibility on the absorption of water, although cotton is an exception. In addition, such fibres will swell to a considerable degree when exposed to a humid atmosphere.

8.2 Natural fibres

8.2.1 Natural fibres may be further sub-divided into two groups according to their origin, i.e. vegetable or animal fibres.

8.2.2 Within the range of vegetable fibres, jute is unusually hygroscopic and can absorb up to 23% of its own weight in moisture, under conditions of high humidity. Flax and cotton are both strongly absorbent, but have the peculiarity of increasing in strength when saturated with water. It has been suggested that the presence of water vapour accelerates the photo-chemical degradation of cellulose, the basic component of vegetable fibres.

8.2.3 Among the animal fibres, wool and silk both swell and lose tensile strength on the absorption of moisture. Wool absorbs water more readily than other common fibres, with the exception of calcium alginate. There are indications that moisture is catalytic in the deterioration of wool caused by solar radiation.

8.3 Man-made fibres

8.3.1 Man-made fibres may be conveniently divided into two sub-groups, semi-synthetics and synthetics. In the semi-synthetics the fibre forming material is of natural origin, while the synthetics are built up from basic chemical elements.

(a) Of the semi-synthetics, viscose rayon absorbs twice as much water vapour from the air as cotton, and will lose up to 50% of its tensile strength when wet. Cuprammonium rayon has similar characteristics. Cellulose acetate does not absorb as much water as the rayons, or lose strength so markedly. The casein fibres readily absorb water, the fibres becoming swollen and soft, losing much of their strength.

(b) Many of the plastics appear as synthetic fibres, for example polyamides and polyesters, and the general comments regarding plastics, made earlier in this chapter, will be applicable. The synthetic fibres absorb less water than natural fibres, and their properties are not so seriously affected by conditions of high humidity. Table 10 summarises information derived from References 6 and 14, on the effect of moisture on the common synthetic fibres.

TABLE 10

EFFECT OF MOISTURE ON COMMON SYNTHETIC FIBRES

Fibre	Effect of moisture
Polyamides (Nylon, Perlon)	Absorb less water than most natural fibres; tensile strength and elongation relatively unaffected.
Polyesters (Terylene, Dacron)	Moisture absorbency lower than the polyamides; mechanical properties practically unaffected by water.
Polyacrylonitrile (Acrilan, Orlon, Courtelle)	Absorb less water than polyamides although suffers some loss in strength when wet.
Unplasticized PVC (Rhovyl, Rhofibre)	Noted for very low water absorption and stability of mechanical properties when wet.
Co-polymers vinylchloride - acrylonitrile (Dynel, Vinyon N)	Absorb very little moisture. Moisture has a negligible effect on the tensile properties and does not cause swelling.
Co-polymers vinylchloride - Vinyl acetate (Vinyon)	Similar in resistance to moisture as vinylchloride-acrylonitrile copolymers but are more affected by heat, and begin to lose properties at around 50 °C.
Polyvinylidene chloride(Saran)	Practically non-absorbent, water has no effect on tensile strength nor does it cause swelling.

9 MISCELLANEOUS MATERIALS

9.1 Paper

9.1.1 Ordinary unimpregnated paper loses its structural strength when wet, owing to softening of the gelatinous binder used to hold the fibres together.

9.1.2 Even if the paper is not 'wetted', high relative humidites can accentuate the deterioration of paper caused by other agents such as acid gases and micro-organisms.

9.1.3 'Wet strength' papers are produced by the addition of certain resins that reinforce the binding between the fibres. Such papers maintain their mechanical properties even when soaked with water.

9.1.4 Paper is almost always impregnated when used for electrical insulation. The impregnate slows down the rate of moisture pick up by the paper, thus tending to stabilize its electrical properties when exposed to fairly rapid fluctuations of relative humidity.

9.2 Wood

9.2.1 The physical properties of wood are very dependent on its moisture content, and a change in moisture level may result in loss of strength, rigidity, dimensional changes, warping and alteration in electrical properties, etc. To minimise such changes, wood should be dried to a moisture content appropriate for its particular use and situation prior to fabrication. When this cannot be done, trouble can be avoided to some degree by the design of the structure or product, but seldom by treatment or coatings.

9.3 Inorganic insulating materials

9.3.1 In glazed ceramic materials, the sorption of moisture is generally restricted to a monomolecular layer adsorbed at the surface. If the material is unglazed, capillary condensation of water vapour may take place in pores of molecular dimensions. For this reason the effect of moisture on the surface insulation resistance is more marked on unglazed than glazed ceramic insulators.

9.3.2 Pure sheet mica has low moisture pick up and therefore maintains its good electrical properties under conditions of high humidity. Mica is normally used, however, in laminated insulation systems in which layers of mica alternate with layers of binder (sizing varnish) and carriers (paper or fabric). In such fabrications, the hygroscopicity of the binder and carrier largely determine the effect of moisture on the insulant.

9.3.3 Asbestos is a composite inorganic material consisting of mineral fibres of various length. The moisture pick up of asbestos is comparatively high and unimpregnated asbestos is seldom used for insulation purposes. Even impregnated asbestos does not exhibit particularly stable electrical properties under humid conditions, but in spite of this, is used in some applications, because of its excellent thermal resistance.

9.4 Electrical insulating oils

9.4.1 Mineral oils consisting of various blends of liquid naphthenic, aromatic and aliphatic hydrocarbons are used as liquid insulants and coolants in electrical engineering. All such oils rapidly absorb moisture from the atmosphere, the rate being substantially higher in low viscosity oils. As an example of the effect of humidity, the dielectric strength of a transformer oil exposed to 80% RH for seven days fell to approximately 25% of its original value. The impairment of the electrical properties by moisture becomes much more marked if the oil is polluted.

10 LOW HUMIDITY

10.1 The deterioration of materials described earlier was due to the taking up of atmospheric moisture. However, for many materials there is an optimum moisture content for the maintenance of useful properties.

10.2 A 'dry' environment will cause moisture to be desorbed until an equilibrium is reached with the prevailing low relative humidity, causing materials to become excessively dry. Most organic materials when 'dried-out' suffer volume changes and embrittlement to various degrees. Special mention should be made of the loss of extensibility of cellulosic fibres, in which absorbed water acts as a plasticiser, the cracking and shrinking of timber, the stiffening of leather and embrittlement of paper.

10.3 Desorption of moisture from insulants results in a marked improvement in their electrical characteristics. In precision equipment where electrical parameters are required to be constant, such variations may impair operation.

10.4 The performance of dynamo-electric machines can be adversely affected by low humidity, because the sliding of graphite brushes on commutators and slip rings depends on the presence of a very thin layer of water for lubrication. Breakdown of the lubrication film results in excessive friction and increased electrical losses, with consequent rapid brush wear and possible temperature rise of the machine. To combat this effect various solid lubricants such as barium fluoride, molybdenum disulphide and PTFE can be incorporated in the brushes.

11 EFFECT ON EQUIPMENT SYSTEMS

11.1 In the construction of an equipment system, a wide variety of materials will generally be employed. When exposed to a humid environment, the individual materials, unless protected, will be subject to the forms of deterioration discussed in the preceding paragraphs. Such deterioration may degrade the function of specific components, and therefore the performance of the system.

11.2 Component deterioration attributable wholly or in part to moisture includes:

(a) Corrosion of plugs, connectors, control knobs, chassis and valve pins.

(b) Failure of relays, resistors, power transformers and paper dielectric capacitors.

(c) Fungus growth on cotton sleeving and laminated bakelite insulation.

(d) Alteration of the electrical constants of tuned circuits, with resulting loss in sensitivity or range of signal equipment.

12 ARTIFICIALLY INDUCED HUMID ENVIRONMENT

12.1 Both high and low humidities can occur as induced states, brought about by working or storage conditions. Circumstances often occur when the natural climatic environment combines with the conditions of storage or transport, to create conditions more severe than the external ambient. Under operational conditions storage facilities might be very crude and in a badly ventilated storage shelter in the tropical sun, both temperature and humidity may exceed that of the outside atmosphere.

12.2 The natural diurnal temperature cycle will lead to 'breathing' of partially sealed equipment. A fall in temperature causes a reduction of pressure inside the equipment, and moist air is drawn in. If there are hygroscopic materials present these will absorb moisture, and if the equipment is badly ventilated, this will not be completely expelled when the temperature rises and the air flow is reversed. When the temperature cycle is repeated more moist air is drawn in, and more moisture is absorbed leading to a progressive increase in the moisture content of the hygroscopic material.

12.3 Condensation of this 'inhaled' moist air will occur if the temperature falls to the dew-point, thus even in the absence of hygroscopic materials moisture can accumulate inside partially sealed enclosures.

12.4 Artificially induced humidity in partially sealed equipment can, as the result of 'breathing', exceed 32 g/m^3, and relative humidities up to 100% are possible at temperatures above 31°C.

12.5 The relative humidity inside completely sealed containers is subject to variation with temperature. Thus, with equipment sealed in ground ambient conditions, condensation may occur on the inner surfaces when it is cooled by being taken to high altitude. Even at ground level the changes of internal relative humidity can be considerable and desiccants may be necessary to contain the relative humidity swing within acceptable limits.

13 HUMIDITY/TEMPERATURE LIMITS OF HUMAN PHYSICAL ACTIVITY

13.1 The difficulty of working in damp heat conditions, and the loss of efficiency, is well known. The wet-bulb temperature may be used to indicate the amount of cooling possible, through evaporation of the moisture on the human body surface; thus it can be considered as an element related to human comfort.

13.2 Hard physical work, even in light clothing, becomes very difficult when the wet-bulb temperature rises above 29°C and practically impossible above 32°C. Light work is possible up to a wet-bulb temperature of 31°C in still air, or 34°C in a moderate breeze. 26°C has been taken as the limit for fair skinned people in the open, but experience during the Second World War has shown this limit to be too low. For half-naked men the limit can be raised by one or two degrees. Figure 4 outlines the comfort and danger zones of the humidity and temperature field.

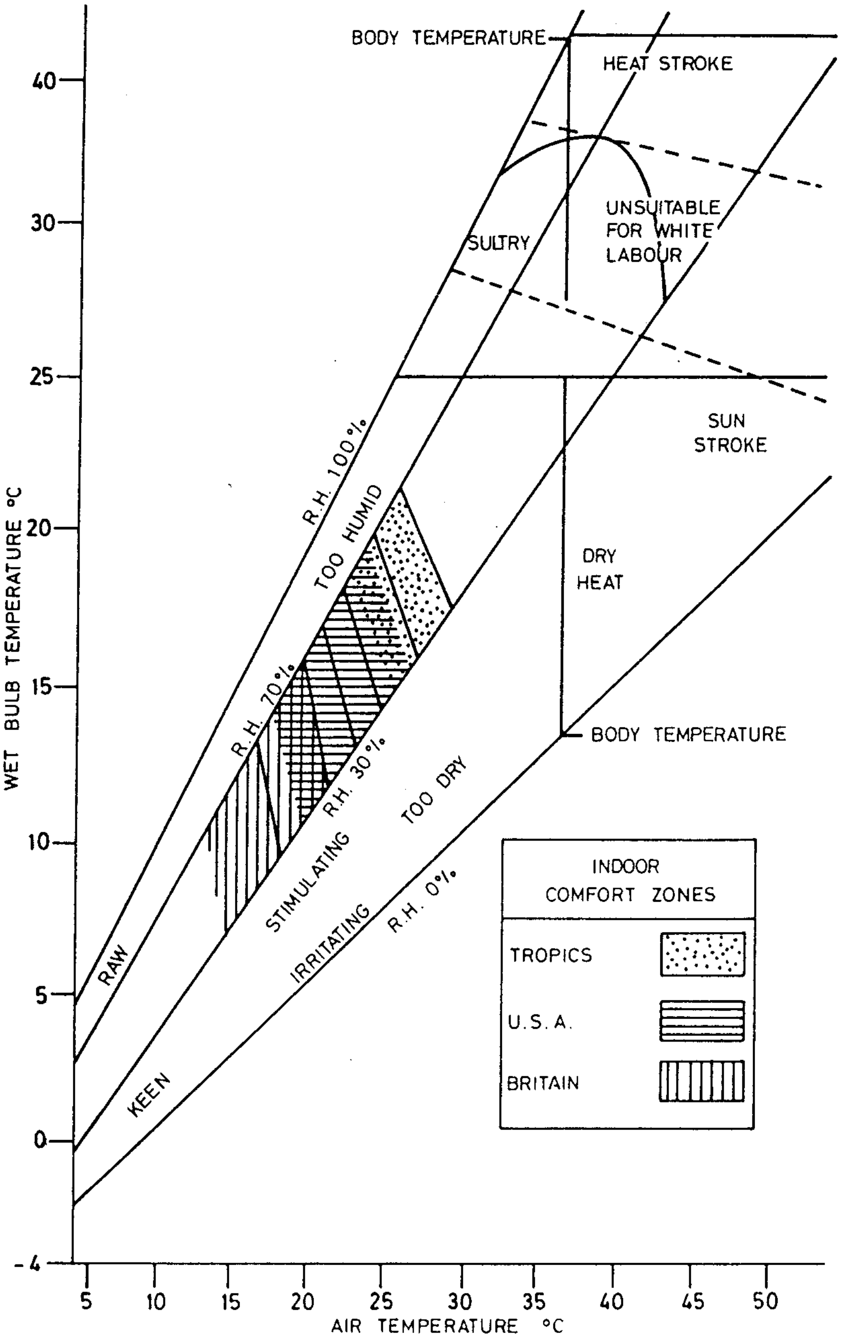

Figure 4. Comfort and danger zones

14 GENERAL OBSERVATIONS

14.1 Moisture effects on equipment systems can be combatted by:

(a) Use of resistant materials, for example insulating materials having minimum moisture sorption and water vapour permeability.

(b) Impregnation or coating of components with moisture repellant varnishes.

(c) Potting components in suitable resins.

(d) Encasing assemblies or individual components in a hermetically sealed container. The internal pressure may range from a high vacuum to a pressure above atmospheric. Where a sealed design is not possible, then well ventilated equipment compartments should be used. This may include the incorporation of heaters or dessicants to lower the relative humidity of the compartment.

14.2 For methods of limiting corrosion, Chapter 8-02 should be consulted. Protection against spoilage due to micro-organisms is dealt with in Chapter 11-02.

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CHAPTER 5-01
WIND

1 GENERAL

1.1 Wind is the horizontal movement of air, relative to the earth's surface. Wind exists because of the pressure differences from place to place caused by the inequalities of air mass. The direction of the wind is from regions of high pressure to regions of lower pressure. This movement is also influenced by the earth's rotation and topographical features.

1.2 Wind is subject to fluctuations on a variety of scales, with periods ranging from a fraction of a second to several minutes. Fluctuations about the mean speed comprise the gustiness of the wind. Large variations can occur between places a short distance apart, and it is not possible to indicate all the special problems which arise. This chapter attempts to provides data relating to mean winds and gustiness.

1.3 It must be noted, however, that the available data are relatively sparse, being based on a limited number of recording stations. It is recommended that the Meteorological Office should be consulted for advice on any particular locality.

1.4 It should also be noted that this chapter deals mainly with winds in the lowest 600 metres or so of the atmosphere; that is, the layer in which the influence of the earth's surface friction on air motion is appreciable.

1.5 Above about 600 metres the wind becomes modified by factors other than surface friction, and winds at altitudes of several kilometres may bear little resemblance to those within the first few hundred metres above the surface. Some data on the upper winds over the world is contained in References 1 and 2. However, at these higher altitudes, jet streams are only one feature of the winds, and the Meteorological Office should be consulted for advice on winds at high altitude, for specific cases.

2 MEAN WIND SPEED

2.1 Variation of wind speed with height.

2.1.1 In the lowest levels of the atmosphere friction with the earth's surface is the dominant feature so that in general the mean windspeed increases with increasing height above ground up to about 600 metres, above which the variation becomes primarily dependent on factors other than friction. Since the measured wind depends on height above ground all values given have been reduced to their equivalents at the World Meteorological Organisation (WMO) standard height of 10 m.

2.1.2 To derive speeds at other altitudes, provided the wind is moderately strong, the relationship $V_H/V_{10} = (H/10)^{\alpha}$ is generally found to apply, where V_H and V_{10} are the mean wind speeds at H and 10 metres above ground respectively. The Factor α varies from about 0.1 to 0.4, according to the terrain. For general use, a value of 0.17 is usually adopted; although, to be accurate, this is only appropriate to undulating country with few trees or obstructions. This value of α does not apply at low levels over built-up areas, where the increase in mean wind speed for the first 30 metres or so above roof top level is relatively much greater. But the wind speed variation in the 30 to 200 metres layer above towns conforms to a value of 0.2 for α, which is not much different from that for open country at the same height.

2.1.3 A good indication of the average wind speed at about 600 metres altitude during the winter and summer seasons may be obtained from the atmospheric pressure maps in Figures 1 and 2, bearing in mind that:

(a) At this altitude the direction of the wind is parallel to the isobars, with the low pressure on the left in the northern hemisphere, and on the right in the southern hemisphere.

(b) Wind speed is inversely proportional to the distance between isobars; that is, the closer the isobars the stronger the wind

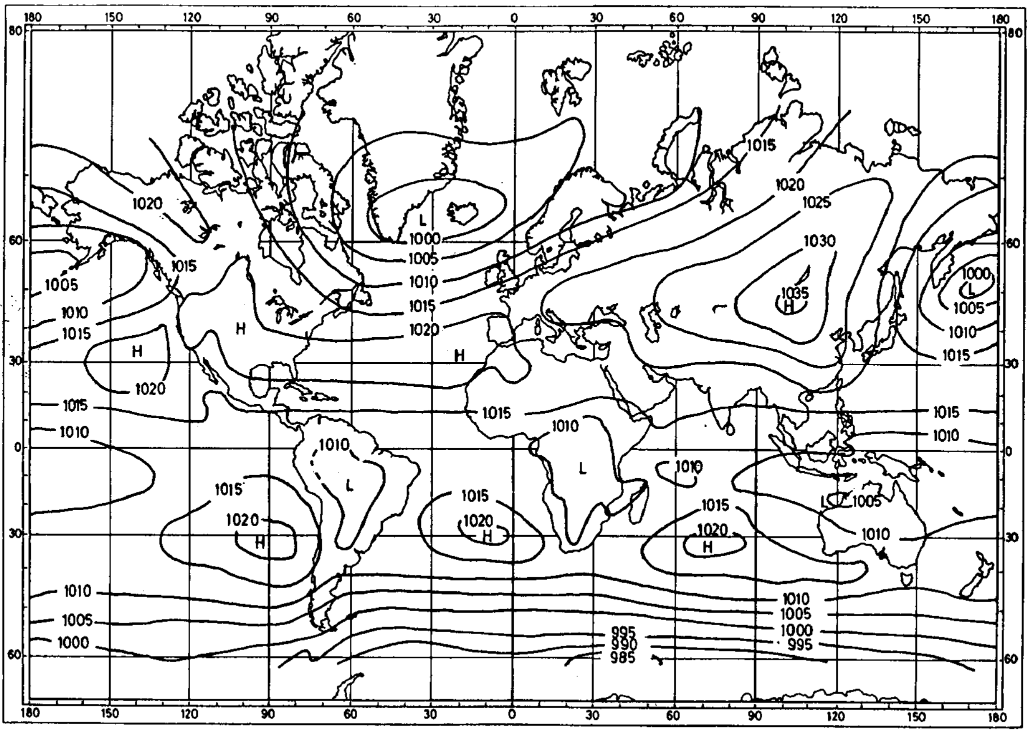

Figure 1. Average atmospheric pressure (hPa) at mean sea level in January

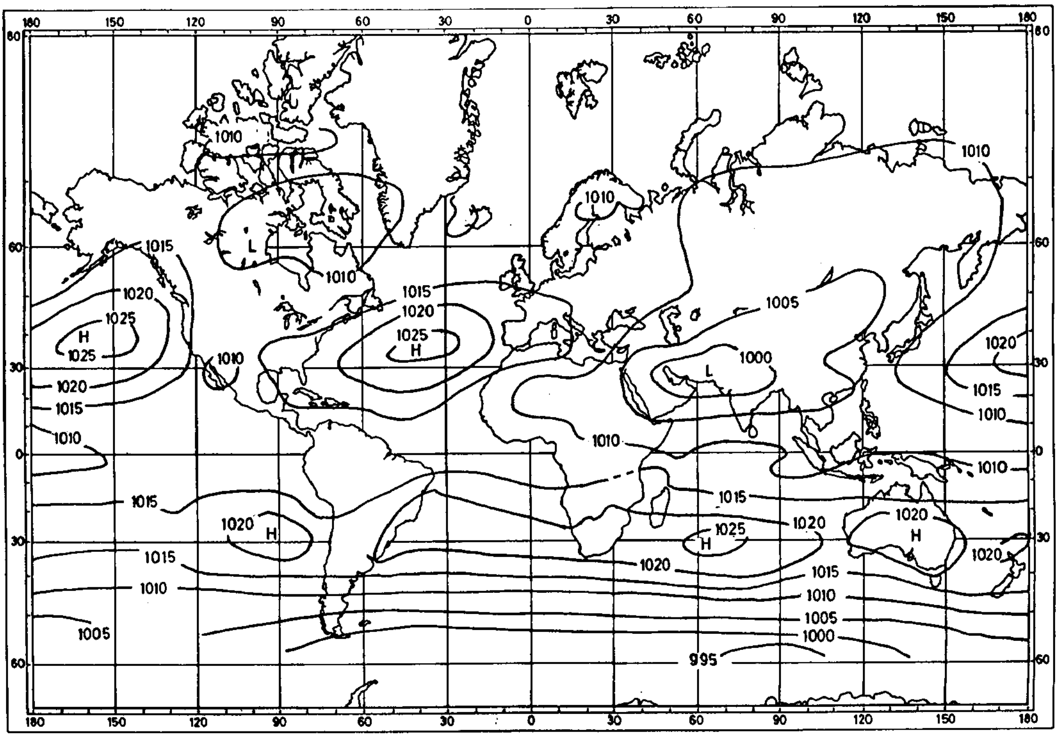

Figure 2. Average atmospheric pressure (hPa) at mean sea level in July

2.2 Frequency of very strong winds

2.2.1 Given sufficient data it is possible to predict the wind speed likely to be exceeded once in a given number of years. Figure 3 shows the maximum hourly wind speed likely to occur once in 50 years over the UK, based on data recorded up to 1971.

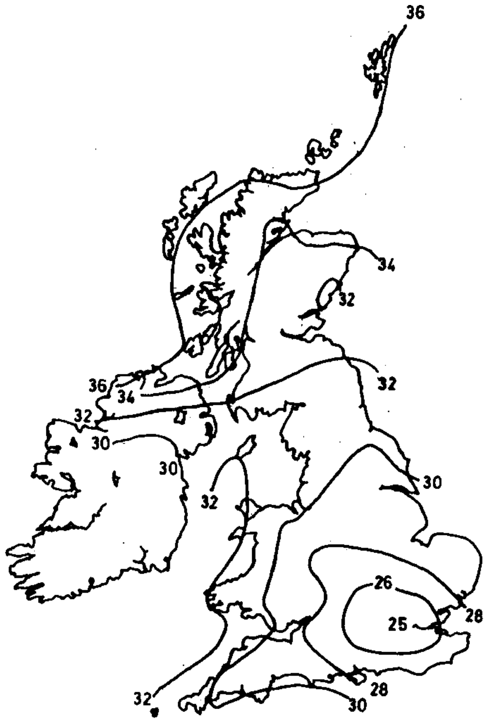

Figure 3. Maximum hourly mean wind speed (m/s), occurring once in 50 years over open level country.

2.3 Frequency of very strong winds

2.3.1 Figures 4 and 5 show the percentage frequency in the average year when the mean wind speed, (measured over an interval of 5 to 10 minutes), equals or exceeds 14 m/s and 25 m/s. The charts are to some extent subjective and they refer to the standard height of 10 metres over fairly open and low-lying ground; they should not therefore be used to infer probabilities in mountainous areas nor when special problems of aspect or exposure arise.

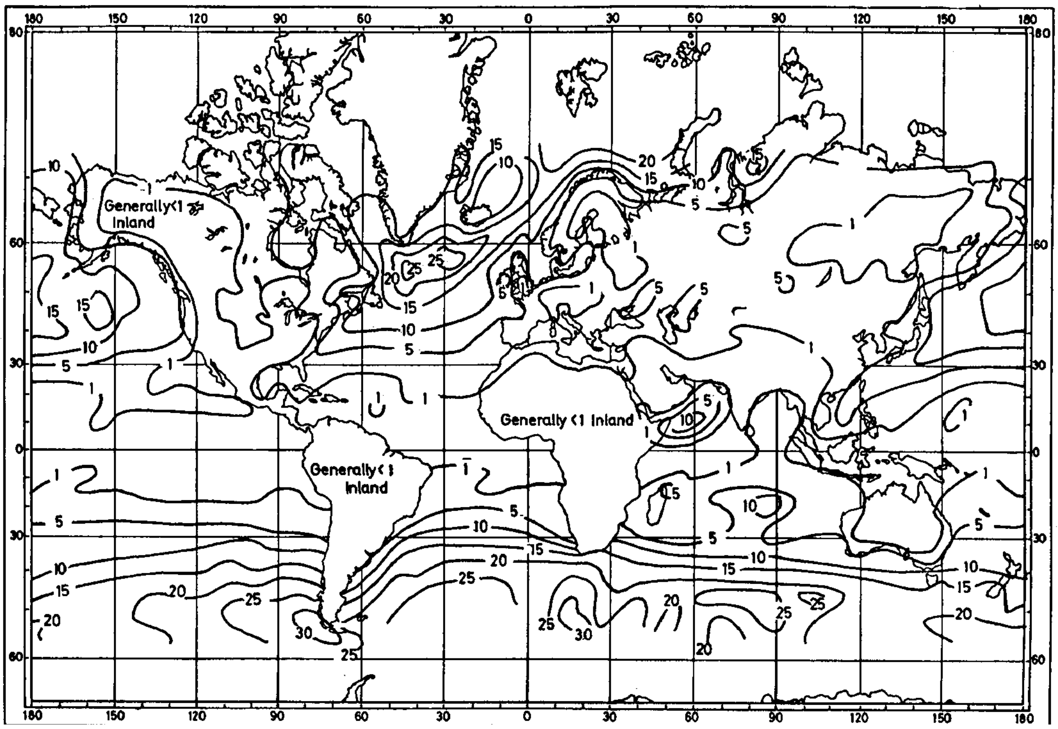

Figure 4. Percentage frequency of winds of 14 m/s or more

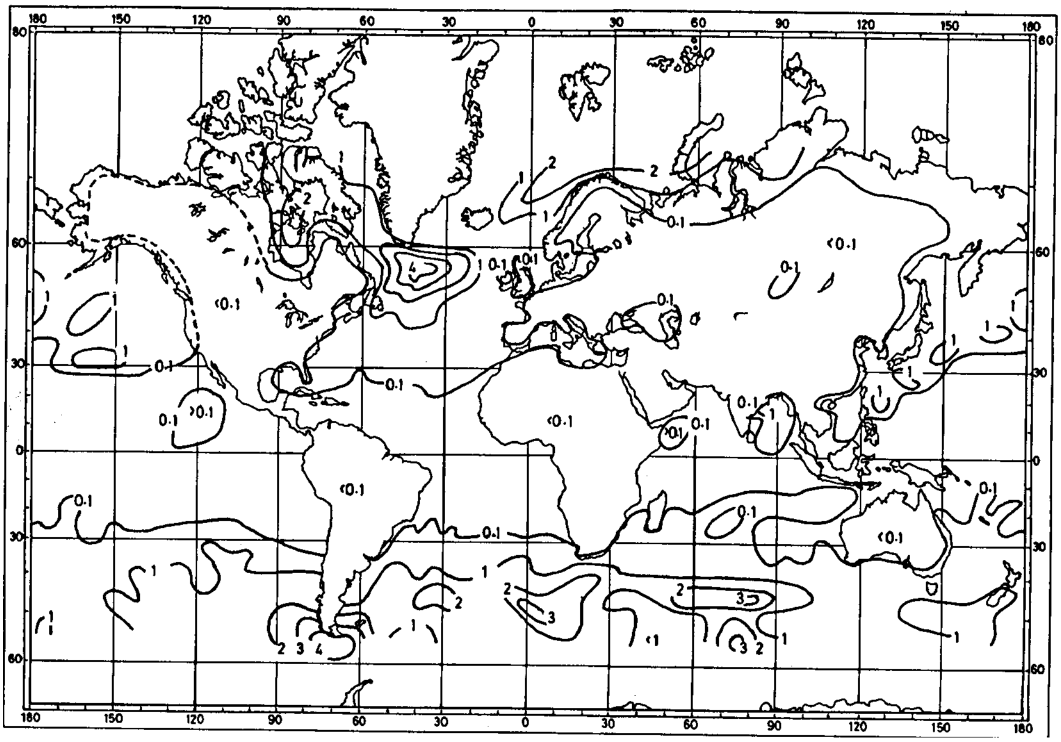

Figure 5. Percentage frequency of winds of 25 m/s or more

3 GUSTINESS

3.1 General

3.1.1 Gustiness results mainly from the roughness of the earth's surface and is accentuated when the air flows over trees, buildings and other obstacles. However it is also a feature of the eddies developed by convective currents and such currents form most readily when temperature near the surface falls off rapidly with height, i.e. usually during the hottest part of the day. Gustiness over land is therefore usually more pronounced by day than by night, whilst over the sea, where frictional effects and the diurnal temperature range are both small, gustiness is relatively slight at any time of day and is usually associated with convection which develops when cold air flows over warmer sea.

3.2 Period of measurement

3.2.1 The gust recorded by an instrument depends on the sensitivity of that instrument. For this reason it may be assumed that a speed averaged over about 3 seconds has been used for the data concerning extreme gust speeds, etc., quoted below.

3.3 Extreme gust speeds

3.3.1 Figure 6 is a world map showing the maximum gust likely to be experienced once in 10 years, based on analyses as outlined in Reference 3 and various building design codes of practice. The estimates are for the standard height of 10 metres over fairly level country and they are not applicable to mountainous regions nor to places having local peculiarities of exposure or topography; exceptionally high gusts which may occur in tropical storms are also excluded.

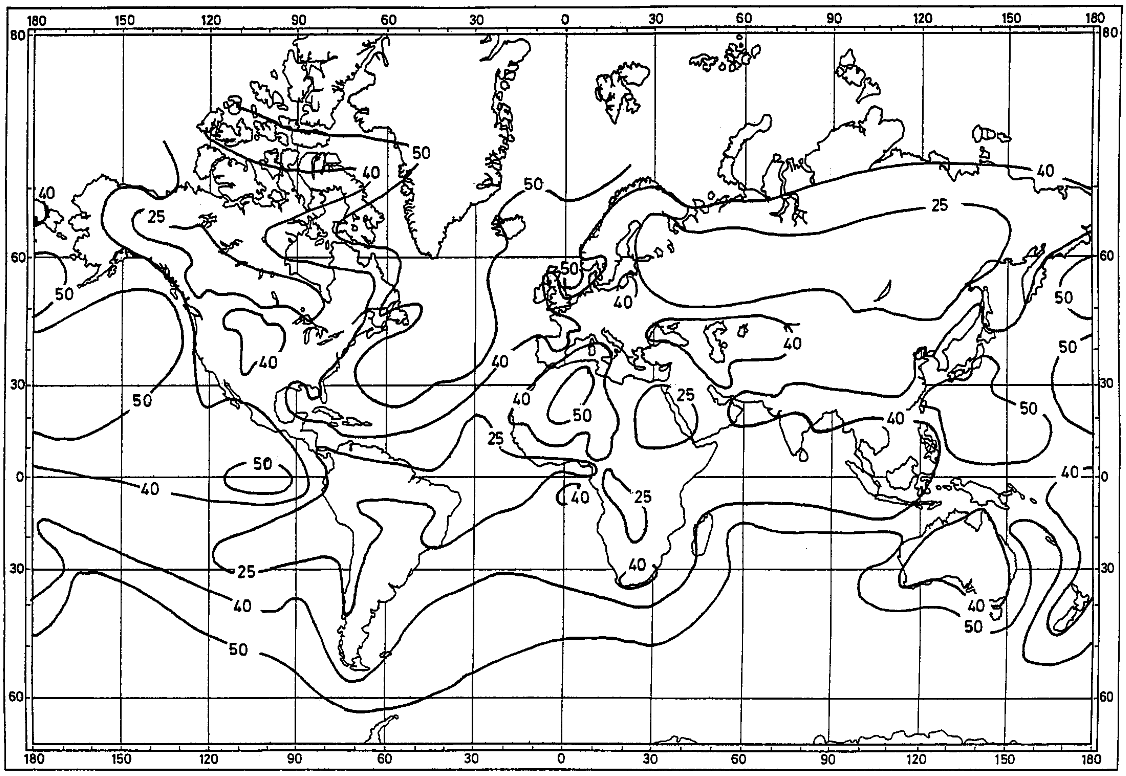

Figure 6. Maximum gust (m/s), likely to be exceeded once in 10 years

3.3.2 Figure 7 shows the maximum gust speeds likely to be experienced once in 50 years over the UK, over open level country.

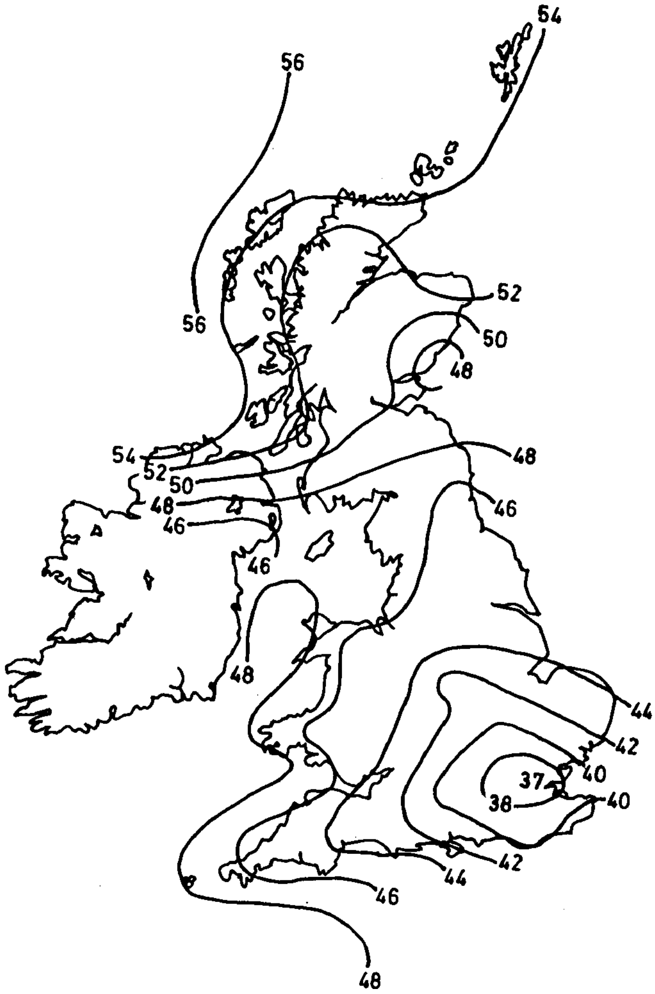

Figure 7. Maximum gust speed (m/s) occurring once in 50 years over open level country.

3.4 Gust ratios

3.4.1 The ratio of the maximum speed in a gust to the mean wind speed is known as the gust ratio and provides a measure of gustiness of the wind. This ratio depends not only on the locality and prevailing meteorological conditions, but also on the period over which the gust speed is measured.

3.4.2 For level sites in open country Table 1 gives the ratio of the probable maximum gust averaged over time (t), to the mean hourly wind speed. These factors are probably too high for open coastal exposures but will be too low for city and urban situation, and may be rather low for open, but not level, rural exposures; the ratios given in Table 2 have therefore been proposed for estimating maximum speeds over 1 minute, 30 seconds and 10 seconds respectively, using a known mean hourly wind speed.

TABLE 1

RATIO OF THE PROBABLE MAXIMUM GUST SPEED, AVERAGED OVER TIME (t), TO THE MEAN HOURLY WIND SPEED FOR LEVEL SITES IN OPEN COUNTRY

time (t)	1 hour	10 min	1 min	30 s	20 s	10 s	5 s	2 s	1 s	0.5 s
gust ratio	1.00	1.06	1.24	1.32	1.36	1.43	1.48	1.54	1.57	1.60

TABLE 2

SUGGESTED RATIOS FOR ESTIMATING MAXIMUM GUST SPEED OVER SHORT PERIODS FROM A KNOWN MEAN HOURLY WIND SPEED

	1 min	30 s	10 s
Open rural exposures	1.25	1.33	1.45
Urban and city exposures	1.45	1.60	1.80

3.4.3 Since the gust ratio is largely determined by the roughness of the terrain an indication of this roughness can be obtained from the ratio of the maximum gust measured over 3 seconds to the mean hourly wind speed, both determined from many years of data, and knowing this ratio it is possible to calculate the maximum for any time interval up to 1 hour, using the factors shown in Table 3. Owing to the dependence of the gust ratios on terrain there may be some slight differences from Tables 1 and 2.

TABLE 3

FACTORS FOR CALCULATING MAXIMUM MEAN WIND SPEED FOR VARIOUS INTERVALS USING THE MEAN SPEED MEASURED OVER THE HOUR

RATIO	CONVERSION FACTORS					
Maximum 3 sec gust/ mean hourly speed	10 min	1 min	30 s	15 s	10 s	3 s
1.4	1.05	1.17	1.22	1.27	1.30	1.40
1.5	1.05	1.20	1.26	1.33	1.37	1.50
1.6	1.06	1.23	1.30	1.38	1.43	1.60
1.7	1.06	1.25	1.34	1.44	1.50	1.70
1.8	1.06	1.27	1.37	1.48	1.55	1.80
1.9	1.06	1.28	1.39	1.52	1.60	1.90
2.0	1.06	1.29	1.42	1.56	1.66	2.00
2.1	1.06	1.30	1.44	1.60	1.71	2.10

3.5 Variation of gust with height

3.5.1 The power law variation $V_H/V_{10} = (H/10)^{\alpha}$ applies reasonably well for maximum gust speeds, but the variation of gust speed with height is somewhat less than that with the mean wind speed; the value of α for 3-second gusts in flat open country being about 0.09. In built-up areas the simple power law is not valid within the first 30 metres above rooftop, but in the 30-200 metre layer the variation accords well with a value for α of 0.1.

4 EFFECTS OF TOPOGRAPHY

4.1 General

4.1.1 Topography can influence both wind direction and speed to a considerable extent, but it is not easy to make allowances for these effects when extracting wind data for a particular place. Any allowances must be based on approximations gained from general experience rather than on specific observations. Some examples are given in the following paragraphs.

4.2 Coastal exposures

4.2.1 The speed of an onshore wind decreases steadily inland; even in the case of flat coastlines, a notable reduction in wind speed can be observed within 10 km of the coast. If tall structures form a wind break along the shore, a comparable reduction in wind speed can occur within a few hundred metres of the sea. For winds off the sea the gust ratio for 3-second gusts is about 1.5, compared with 1.75 for off-shore winds.

4.3 Hill and mountain tops

4.3.1 On hills which rise sharply from level country, or from the sea, mean wind speeds at the hill-top are little different from those upwind at the same level in the free air. They are therefore considerably greater than at the base of the hill, but with gentler slopes this difference will be less marked. Gust wind speeds at the top of a hill will also be greater than on the low ground, but this increase will be less than that of the mean wind speed.

4.4 Valley winds

4.4.1 When winds blow along, rather than across, a valley, a funneling effect may cause the wind speed in the valley to be greater than over level terrain. The most extreme effects are likely if the valley has steep sides, narrowing down wind and leads up to a pass in the hills or to low lying country beyond the high ground. The presence of a valley can also distort the direction of the general air-flow by acting as a guide or channel.

4.5 Shelter given by high ground

4.5.1 Mean wind speeds in the lee of hills are often reduced by the shelter of the high ground but gustiness may still be appreciable and lee waves may develop in suitable conditions, to give strong down-slope winds. These lee waves are stationary airwaves, set up under certain distributions of temperature and wind shear, when hills disturb the general air flow.

4.6 Trees and buildings

4.6.1 Trees and buildings can act as efficient wind breaks reducing the mean hourly wind speeds by some 5 m/s below those in the surrounding open country, and reducing the strength of short period gusts. Thus built-up and wooded regions have lower mean wind speeds but higher gust ratios than those in level country.

4.7 Special topographical winds

4.7.1 In many parts of the world particular winds have been given local names. Most of these are caused or accentuated by topographical effects, and many of them occur in mountainous country, often close to the sea, where rapid changes of temperature and topography are encountered over short distances. Examples of special winds include those channelled down valleys, such as the Bora of the Adriatic and the Mistral of the Rhone valley, and those affecting more extensive lengths of coast, such as the Berg of South Africa and the F`hn type winds of Greenland and the Antarctic Continent.

5 WIND TYPES AND EXTREME WINDS

5.1 Scale of wind systems

5.1.1 Figure 8 is a schematic diagram illustrating the relative scale and strength of meteorological wind systems. The approximate maxima of identifiable systems is 250 hours life and a diameter of 2500 km. The broken lines indicate commonly accepted limits, however, gusts within larger strong wind systems are often within the range 100-200 m/s.

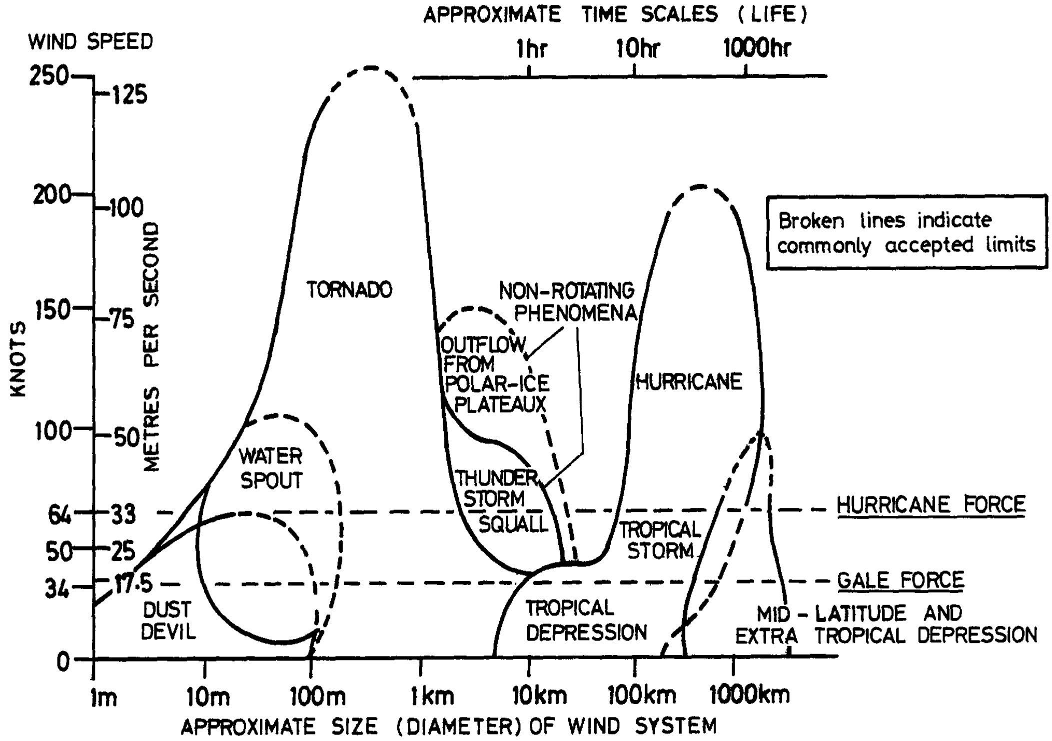

Figure 8. Characteristic wind speed size and timescale of meteorological wind systems

5.2 Terminology

5.2.1 The general term "cyclone" describes an area where atmospheric pressure is lower than in surrounding areas and the general flow of air is anti-clockwise north of the equator but clockwise in the southern hemisphere. Low-pressure systems that cause strong wind conditions may be classified but the definitions are not always exclusive and names vary from region to region.

5.3 Depressions or lows

5.3.1 These terms are applied to cyclones of middle and high latitudes or weak tropical cyclones. These features range in size from a few hundred to around 2000 km diameter and usually move west to east. Widespread and sustained strong winds are possible especially over the North Atlantic, the southern oceans south of about 40°S, and exposed coastal regions. In these regions winds may exceed 14 m/s (27 kt) for 10 - 25% of the year, however steady winds are usually less than 31 m/s (60 kt) although some gusts may exceed 51 m/s (100 kt) about once in 10 years.

5.4 Tropical storms or tropical cyclones

5.4.1 Cyclones generated over warm tropical oceans, commonly 500 -1000 km diameter, usually move east to west but tend to recurve away from the equator. Wind speeds are normally 17 - 32 m/s (34 - 63 kt) i.e. more than gale but less than hurricane force.

5.5 Hurricanes

5.5.1 By definition a tropical storm becomes a hurricane (or typhoon, cyclone, etc.) if wind speeds are 33 m/s (64 kt) or more; the upper limit is unknown but speeds around 103 m/s (200 kt) have been reliably reported. Hurricanes often travel at 15 to 30 km/h (8 - 16 kt) but can exceed 50 km/h (27 kt) especially in higher latitudes, and may last from 2 days to 2 weeks. An indication of the areas affected and probabilities is included in Figure 9.

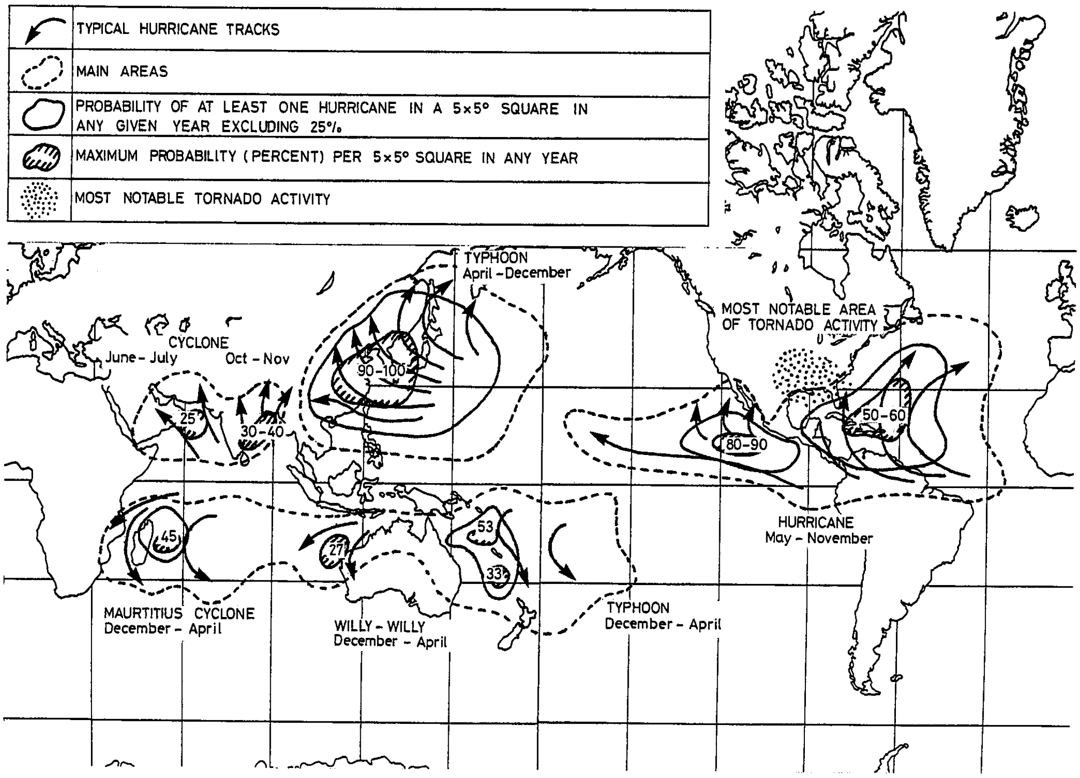

Figure 9. Areas affected by tropical storms of hurricane force

5.6 Whirlwinds

5.6.1 These narrow revolving wind storms occur commonly over most of the world. Many are small, innocuous, transient features but some are devastatingly destructive owing to the combined effects of wind strength, twisting and suction. The extreme phenomena, usually called tornadoes, are often associated with thunderstorms and may occur as a group or family of storm cells. The area most frequently affected by tornadoes is the USA where 700 - 1200 are reported each year. As in other parts of the world the most common type of tornado lasts only a minute or two and causes little damage. The path of destructive tornadoes is often 100 - 700 m wide and the track length less than 25 km and the duration perhaps 30 minutes. The most devastating tornadoes (perhaps 2% of total) may be 1.5 - 2 km wide along a track up to 450 km long and lasting 2 - 4 hours. The upper limit of wind speeds is unknown but recent estimates suggest a figure around 125 m/s (250 kt).

5.6.2 The chance of a single location of 2.59 km^2 (1 mile ^{2}) being affected by a tornado in any year is less than 1 in 1000, even in the most vulnerable parts of the USA, and the chance of a location in NW Europe being affected is estimated at less than 1 in 10,000, a return period of 1 in at least 20,000 years.

5.6.3 Whirlwinds that occur on a small scale in many parts of the World may also be vigorous enough to raise dust or even water to be visible as a dust devil or a water-spout.

5.7 Non-rotating phenomena

5.7.1 Violent winds may also occur over Polar regions where the katabatic outflow from ice plateau, enhanced by the topography can reach speeds around 75 m/s (150 kt). Elsewhere in the world, squalls associated with a downburst of air from a thunderstorm may locally generate winds of 50 m/s (100 kt) at the surface.

6 DESIGN CRITERIA

6.1 Unless overriding considerations dictate to the contrary, requirements documents should require materiel to remain safe when exposed to the conditions described in Fig 6 and that the materiel should be capable of an acceptable performance, when exposed to winds and gusts having speeds up to the maximum respective values given in Table 4.

TABLE 4

WIND AND GUST SPEEDS AT HEIGHTS OF 3 METRES ABOVE GROUND RECOMMENDED AS DESIGN CRITERIA

1 minute steady speed (m/s)	Gust speed (m/s) for shortest horizontal dimension of material					
	0.7m	1.5m	3m	8m	15m	30m
22	34	31	30	28	27	26

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CHAPTER 5-02
THE EFFECTS OF WIND

1 INTRODUCTION

1.1 Wind possesses kinetic energy by virtue of the velocity and mass of the moving air stream. When an obstacle is placed in the path of the air stream, all or part of this kinetic energy becomes transformed into pressure energy. Its intensity is dependent upon the characteristics of the object and the nature of the wind.

1.2 Wind forces are usually variable through time and space, and their damage capability is influenced by their velocity, gustiness, duration, frequency of occurrence and path width.

2 FACTORS THAT INFLUENCE WIND PRESSURE LEVELS

2.1 General

2.1.1 The basic concept of the transformation of wind velocity into pressure may be obtained from Bernoulli's law for an ideal fluid. In conditions where the airstream is brought to rest by a surface normal to the wind, the dynamic pressure on the surface, that is, the, pressure in excess of atmospheric pressure, may be taken as:

$$q = \rho \frac{V^2}{2}$$

Where q is the pressure of the wind in pascals
ρ is the density of air in kilograms per cubic metre
V is the mean velocity of the approaching wind stream in metres per second

At sea level at an air temperature of 15°C, this pressure may be taken as $0.613V^2$ pascals.

2.2 Wind force factors

2.2.1 In the lower layers of the atmosphere, surface friction reduces the airflow. The effect of surface friction diminishes with altitude, up to the level at which the airflow balances the pressure gradient. Beyond this level the wind speed is dependent on various other factors, such as pressure differentials and the geostrophic forces due to the earth's rotation.

2.2.2 Wind pressure is proportional to the square of the wind speed and is also influenced by air temperature and air density. For example, when the air temperature falls from 15°C to -17.8°C, the pressure corresponding to a given speed is increased by 13%. At an elevation of 300 metres above sea level, the pressure for a given wind speed is reduced by 3.5%, because of the reduction in air density with altitude.

2.2.3 Turbulence of the wind stream may rise from surface friction or convective activity, and usually results in gusts, causing wind pressure levels to fluctuate. The overall effect of gusts is complex and in many instances may have negligible effect on the stability of a structure. For example, a momentary rise in pressure on one part of a structure may be balanced out by a reduction in pressure elsewhere. In general, gusts having a duration greater than five seconds are considered significant in structural design; shorter gusts seldom develop substantial loads.

2.2.4 When wind is diverted by obstacles in its path, local disturbances to the airflow are produced which in certain conditions can cause damage. One effect, known as the von Karman Vortex Street, results in the formation of periodic vortices that rotate alternately in opposite directions in the wake of the wind.

2.3 Structural Factors

2.3.1 Wind pressure is also influenced by structural factors such as geometric form, aspect ratio, (that is height/base width) internal pressure where applicable, surface roughness; and the degree of shielding provided by near-by objects. These factors modify the expression for dynamic wind pressure as follows:

$$q = \frac{\rho V^2}{2} C \quad \text{pascal}$$

where C is a shape coefficient.

2.3.2 The shape coefficients of a structure are dependent on the external shape and the direction of the wind. They define the overall wind forces acting on the structure in the direction of the wind, and include coefficients derived from wind pressure. These pressure coefficients define the pressure acting normally to the surfaces, at local positions on the surface of a structure.

3 EFFECTS OF WIND PRESSURE

3.1 General

3.1.1 Most of the available data on the effects of wind pressure was obtained from wind tunnel tests on models. The information related to buildings is presented in various national codes of practice, in terms of coefficients which modify the expression for dynamic pressure.

3.1.2 In general, positive pressure is developed on any part of a building directly facing the wind whereas negative pressure (suction), occurs on leeward faces and at all points around the structure where the velocity of the diverted wind exceeds that of the approaching wind stream. The total pressure is given by the summation of all unit pressure components acting in the same direction and is usually expressed in terms of 'drag', the force in the direction of the wind, and 'lift', the force in the direction normal to the wind.

3.2 Shape

3.2.1 Wind pressure levels are usually higher on flat surfaces than on curved surfaces, because curved surfaces allow the air to flow past with less hindrance. An average building, with plane surfaces normal to the wind, may experience shape coefficients of the order of 1.3, of which 0.8 is the positive pressure and 0.5 the negative pressure. These shape coefficients, and those listed in Table 1, assume air-tight conditions and are subject to modification when air leakage through doors, windows and other apertures affects the internal pressure.

3.3 Roof slope

3.3.1 Pressure coefficients on roofs may be positive or negative, depending on the angle of incidence and height above ground. Examples of roof slope and aspect ratio are given in Figure 1, and assume that:

(a) All Buildings airtight unless otherwise indicated.

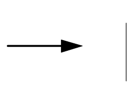
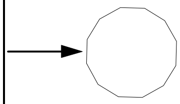
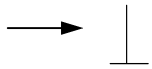
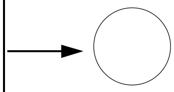
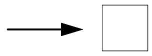
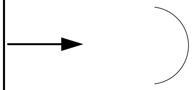
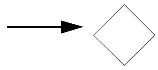
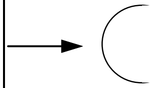
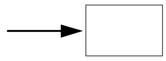
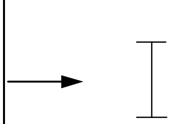
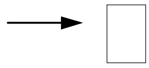
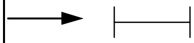
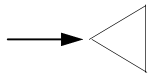
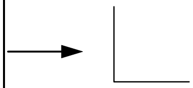
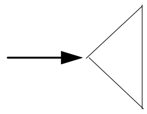
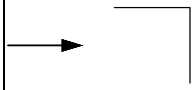
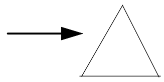
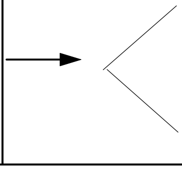
(b) The values plotted are values at C in the equation:

$$q = \frac{\rho V^2}{2} C$$

(c) $\dfrac{\text{Height to eaves}}{\text{Base width}}$ = Aspect ratio

TABLE 1

SHAPE COEFFICIENTS FOR SOLID BODIES OF 'SHEETED-IN' STRUCTURES OF INFINITE LENGTH

SHAPE	DESCRIPTION	COEFFICIENT	SHAPE	DESCRIPTION	COEFFICIENT
Simple geometric shapes 	Flat plate	2.0		12 - sided polygon	1.3(1.0) ‡
	Flat plate with one edge on ground (wall)	1.2*		Circular	1.2(0.7) ‡
	Square with face to wind	2.0 (1.2) †		Semi-circle: concave to wind	2.3
	Square with corner to wind	1.5(1.5)		Semi-circle: convex to wind	1.2
	Rectangle with narrow face to wind	1.4(0.6)	Structural members 	I-beam, web facing wind	2.0
	Rectangle with wide face to wind	2.2(1.6)		I-beam, flange facing wind	1.8
	Equilateral triangle with apex to wind	1.2(1.1) †		Angle	2.0
	Right - angle triangle	1.55		Angle	1.8
	Equilateral triangle with face to wind	2.0(1.3) †		Angle	1.45

CORRECTION FACTORS FOR ASPECT RATIO:
(Height/Base - Width)

Aspect Ratio	Factor
0 - 4	0.6
4 - 8	0.7
8 - 40	0.8
>40	1.0

Example:
For flat plate of aspect ratio 6, shape coefficient =2.0 x 0.7 =1.4

* This coefficient applies to all lengths of plate greater than the height.

† The shape coefficients for sharp-edged bodies are substantially reduced by rounding the edges. The values in parentheses refer to the values obtained with a corner radius ¼ the length of a side.

‡ Shape coefficients for rounded bodies are influenced by aerodynamic scale and surface roughness. Values of about 1.0 apply for very rough surfaces and polygon shapes: for circular pipes and tubes of normal surface roughness values about 0.7 are more appropriate.

⟶ Wind direction.

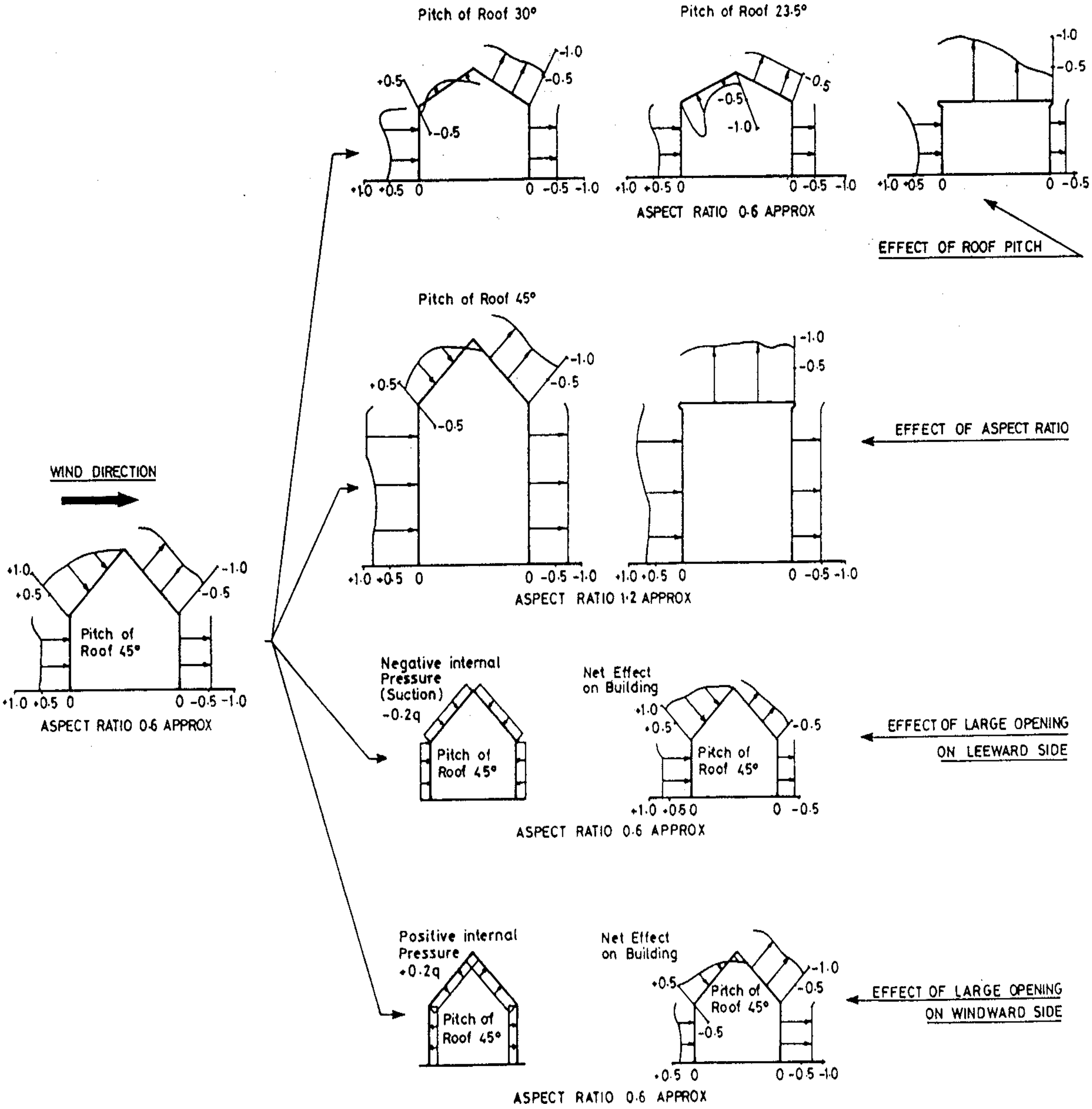


Figure 1. Wind pressure distribution on buildings - shape factor 'C'

3.4 Edges and corners

3.4.1 Wind blowing on a corner or edge of a structure can produce strong vortices, see Figure 2, which may result in suctions four or five times greater than the dynamic pressure of the wind. Typical contours of pressure coefficients produced by such vortices are shown in Figure 3.

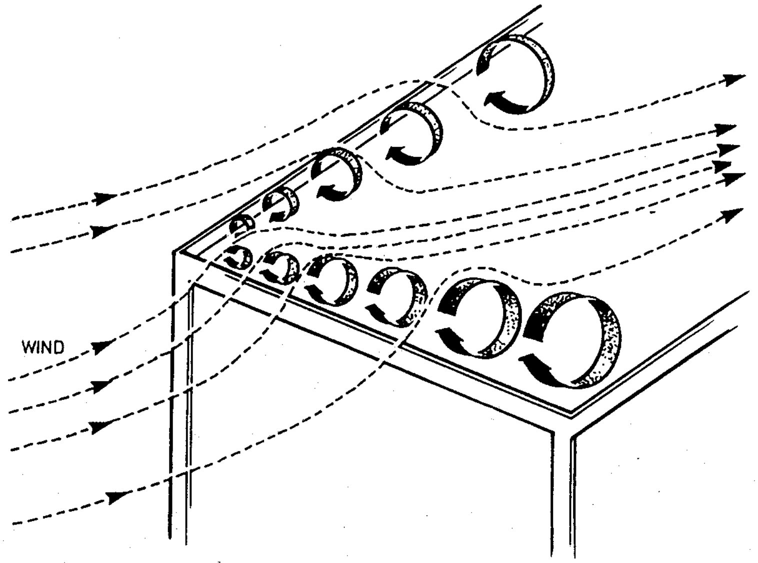


Figure 2. Vortex formation produced when a wind strikes the corner of a structure

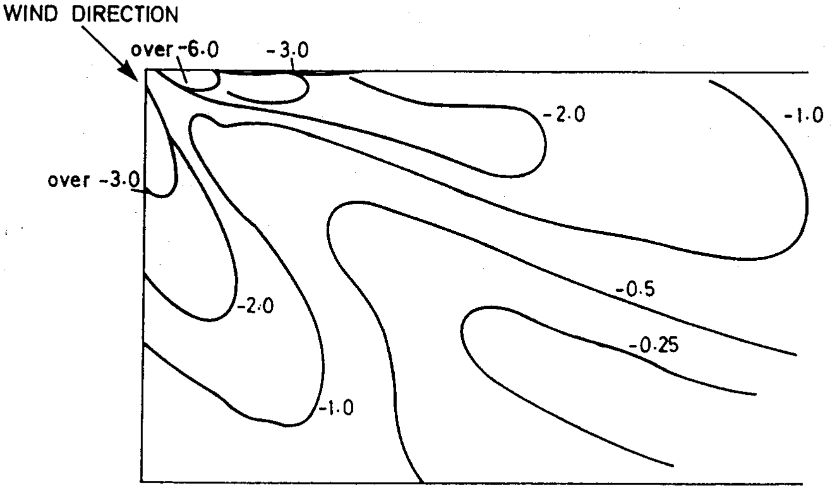


Figure 3. Contours of pressure coefficients produced by vortices

3.5 Shielding

3.5.1 Positive wind pressure on a structure sheltered by another structure generally becomes less as the space between them is reduced. It can change to a negative pressure, at a critical distance determined by the characteristics of the two structures. In certain conditions negative pressures may be produced over all surfaces of the shielded structure, thus exposing roofs, including those with very steep pitches, to the possibility of uplift.

3.6 Cylindrical or rounded objects

3.6.1 Vortices developed on cylinders and rounded bodies are shed alternately from one side and then the other. These can promote structural vibration and oscillation due to fluctuating pressures which accompany the build-up of vortices and their discharge. Vibration or oscillation can result in severe damage to tall stacks, towers, suspension bridges, and transmission lines, particularly when the motion induced by the shedding of vortices coincides with a natural frequency of the object.

3.6.2 The vibration and oscillations are influenced by the rate at which the vortices are discharged and by the Reynolds number. The former is governed by the Strouhal number (S) expressed as:

$$S = \frac{fd}{V}$$

where f is the frequency of vortex discharge
d is the transverse dimension of the body
V is the relative wind velocity

The Reynolds number (Re) is expressed as:

$$Re = \frac{\rho V d}{\mu}$$

where ρ is mass density
V is velocity
d is a characteristic dimension and
μ is the coefficient of viscosity

It is proportional to the ratio of the inertial force that is, the product of kinetic pressure and projected area, and to the viscous force which is the friction between the airflow and the object. The relationship for cylinders between Reynolds number, Strouhal number, and the 'drag' coefficient is shown in Figure 4.

3.7 Aircraft and missiles

3.7.1 Winds are known to exist at altitudes up to about 120 km but those most likely to affect the performance of flight vehicles occur below 12 km. Above this altitude the air density is such that winds create little force on the vehicle.

3.7.2 Strong winds, such as gales and hurricanes, can produce severe structural loads on missiles and supporting equipment. They can also markedly influence launch characteristics and create control and guidance problems in conditions where the wind speed or wind direction change with altitude. Aircraft take-off, landing and flight performance are greatly influenced by wind characteristics. The detailed effects of wind on missiles and aircraft control involve consideration of aerodynamics, and are outside the scope of this Standard.

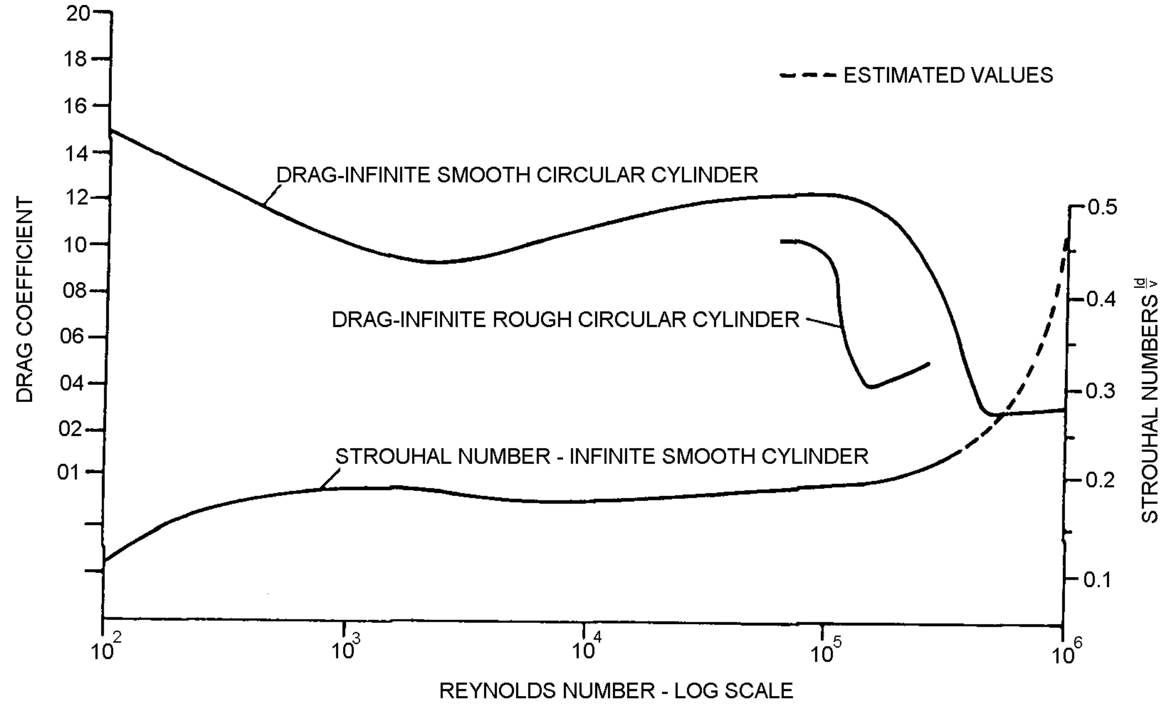


Figure 4. The relationship between Reynolds number, drag coefficient and Strouhal number as applied to cylinders

3.7.3 The effects of gusts depend on gust size and direction relative to the size and flight direction of the object. Gusts having small dimensions, relative to major dimensions of the object, cause the object to shake or jerk. Gusts larger than the vehicle produce linear acceleration, along with pronounced displacements in roll, pitch or yaw. This acceleration is greatest when the gust strikes the vehicle at an angle of 90° relative to the line of flight, and is more pronounced on lightly loaded vehicles.

3.7.4 Gusts producing accelerations of 0.1 g to 0.5 g are quite common and may cause discomfort to humans. During low flight over mountainous terrain, gusts yielding up to 5.2 g have been reported, causing great physical discomfort and high structural stress.

3.8 Textiles and fabrics

3.8.1 Textiles and fabrics can physically deteriorate because of wind pressure, and the strain experienced by some materials may contribute to their destruction by other agents. For example, fabrics are likely to become more permeable to moisture.

3.9 Radar aerials

3.9.1 The effects of wind pressure on ground based precision structures, such as rotating radar aerials, missile launchers and space trackers, are of fundamental importance in the design and functioning of such devices. Apart from structural integrity, the essential effect of wind, steady or gusting, is to impair the fundamental accuracy of the device. The detailed nature of the effects, and the measures adopted to alleviate such effects, are largely dependent upon the application of the device concerned.

4 WIND IN CONJUNCTION WITH OTHER DAMAGING AGENTS

4.1 General

4.1.1 Wind generally contributes substantially to the damage wrought by other weather conditions, such as rain, hail and sleet but in some particular instances may retard the progress of deterioration. Some examples of contributions by wind are given below.

4.2 Temperature

4.2.1 Wind may retard the progress of corrosion because of its cooling and drying effect. Cold winds can adversely affect the performance of equipment, as loss of heat is greatly increased by even moderate winds.

4.2.2 The efficiency of personnel exposed to cold weather can be profoundly affected by wind-chill. This is expressed as heat loss from exposed skin per unit area and time, and is a function of wind velocity and temperature. For example, it can be shown that at a temperature of -45 °C, an air movement of 0.05 m/s has the same wind-chill effect as a wind of 0.5 m/s at a temperature of -25 °C, or a wind of 2 m/s at -10 °C. It should be noted however, that the wind-chill index does not account for physical adaptations or adjustments and should not be applied in a rigorous manner. Examples of the wind-chill index, for varying windspeeds and temperatures, are given at Figure 5.

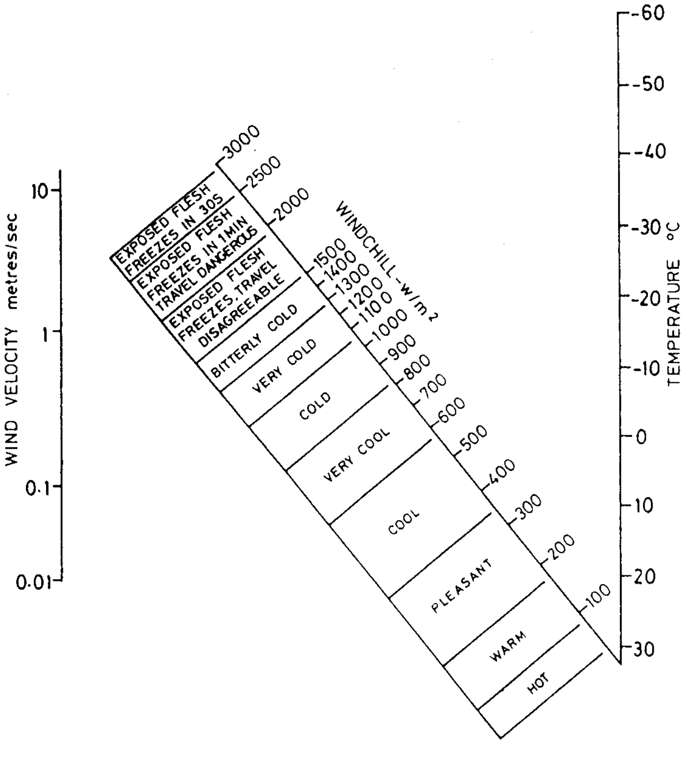


Figure 5. Wind-chill index for varying windspeeds and temperatures

4.3 Rain

4.3.1 The penetrating power of rain into pores, cracks, and crevices, is proportional to the square of the wind velocity. Erosion of plastics by rain increases rapidly with wind velocity.

4.4 Hail

4.4.1 Hail, when driven by the wind, causes increased abrasion and rapid physical damage to many materials.

4.5 Corrosives and contaminants

4.5.1 Wind can carry sea spray several miles inland. It can also cause atmospheric gases to be forced into closer contact with the surface of a material, possibly leading to a higher rate of corrosion. However, the effect of air pollutants on corrosion and health is often reduced by the dispersive action of the wind.

4.6 Dust and sand

4.6.1 Dust and sand particles scooped from the ground by the wind can remain wind-borne over long distances, causing damage by impingement, abrasion and erosion.

5 GENERAL OBSERVATIONS

5.1 The effects of wind should be taken into account by consideration of the following:

(a) An assessment should be made of the maximum wind speed, including gusts, to which a structure is liable to be subjected.

(b) The natural frequency of a structure should be considered in relation to the frequency of oscillation induced by the wind.

(c) The forces acting on a structure, for a given intensity of wind, should be calculated.

(d) The effects of local topography should be taken into account, for example, the funnelling of a wind as it progresses up a valley.

(e) The use of abrasion resistant protective coating.

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CHAPTER 6-01
RAIN

1 INTRODUCTION

1.1 Precipitation is defined as all forms of hydrometeors, both liquid and solid, which are free in the atmosphere and which reach the Earth's surface. It embraces rain, snow and hail; rain is described in this chapter and snow and hail in Chapter 7-01 of this Part of the Standard.

1.2 Precipitation intensity is defined as the rate at which precipitation falls. Although values of precipitation intensity may be considered as instantaneous rates, in practice they are averages taken over periods of one minute or longer.

1.3 Unlike air temperatures which, at any particular time, are often substantially the same (±5°C) over relatively large regions, a value of precipitation intensity is peculiar to the highly localised area where the measurement is made and, at a relatively short distance away, the intensity may differ by a factor of two or more. Thus, it is impracticable to relate precipitation intensity to specific areas of the world with adequate detail so, apart from a European rain condition, only data on a world-wide basis are given.

1.4 At altitudes below the freezing level, 4.5 km (14.8 kft) in the tropics, precipitation may occur as liquid or solid particles but above this level snow or hail will predominate.

2 AVERAGE RAINFALL

2.1 For most places the readily available rainfall data are limited to observations of the rainfall catch made once daily. These daily observations may be summarised to provide average monthly, seasonal or annual amounts; Figure 1 represents such a summary, showing the main features of the average annual rainfall over the world. From this map it can be seen that the wettest areas are mainly in the tropics. In temperate latitudes rain is most likely in coastal regions; the amounts are generally low inside the large continental land masses.

2.2 The importance of topography is shown by the heavier rainfall in mountainous regions, particularly where a mountain range runs parallel to the coast and intercepts moisture laden winds as they blow on-shore; a good example of this is the heavy rainfall of Burma and Bangladesh during the summer monsoon.

2.3 Variations in rainfall

2.3.1 When using Figure 1, or any other rainfall data quoted in this chapter, it must be remembered that whilst the pattern of rainfall is infinitely variable both in time and space, only general information can be given by means of maps or diagrams. It is therefore recommended that detailed advice on specific localities should be sought from the Meteorological Office.

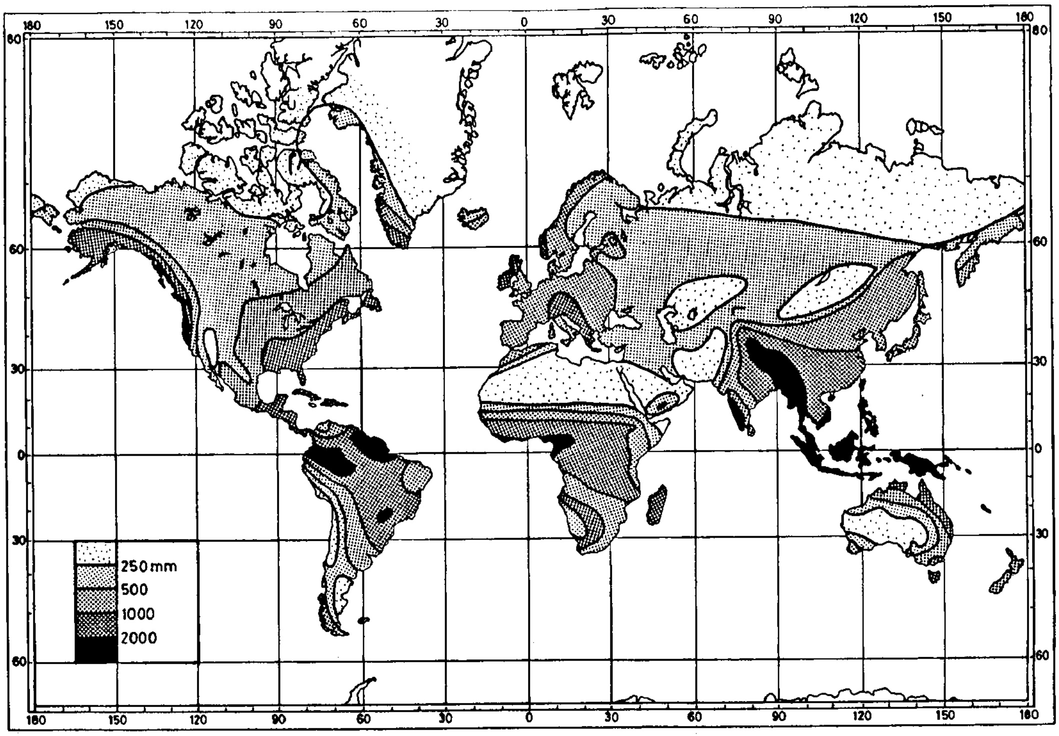


Figure 1. Mean annual rainfall (in mm) over the world

3 CHARACTERISTICS OF RAIN

3.1 Formation

3.1.1 Clouds are formed when air is cooled below its dewpoint, usually as a result of lifting and consequent expansion. At first the cloud droplets grow by the condensation of water on to them, but it can be shown that this process alone cannot produce drops of the size found in rain. Two mechanisms are thought to be important in the formation of raindrops.

3.1.2 Firstly, droplets which are slightly larger than the average will fall, relative to the air, and towards neighbouring smaller droplets, and so may collide and coalesce with some of them to become larger still. This process may continue until a droplet eventually falls out of the base of the cloud. Theoretical studies have shown that a significant amount of rain can be produced in this way, provided the cloud is several kilometres deep.

3.1.3 Secondly it is thought that when a cloud-top becomes appreciably colder than 0°C, it contains a mixture of ice crystals and supercooled water drops. At first the crystals grow by direct sublimation of water vapour on to them, but as they become larger they may collide with the supercooled droplets and other ice crystals to form snowflakes, and when these snowflakes have fallen below the level at which the temperature is 0°C they will melt to form raindrops. This mechanism is thought to be important for clouds with a top colder than about -10°C, even though some of these clouds may be only a few kilometres deep. In convective (cumuliform) cloud, graupel or small hail, rather than snowflakes, may be produced.

3.2 Types of rain

3.2.1 Rainfall is often classified according to the process causing the uplift of air initiating the rain formation; there are three main types of rain which are not mutually exclusive, and these are known as orographic, cyclonic and convective.

3.2.2 With orographic rain, the main cause is the forced ascent of moist air over high ground. The enhanced precipitation is often due to raindrops falling into the large amounts of low cloud formed by this ascent, giving rise to the 'seeder/feeder' mechanism.

3.2.3 With cyclonic rainfall, large scale uplift is associated with features of the general weather situation, such as fronts and depressions.

3.2.4 Convective rain falls from a cumuliform cloud with an unstable air mass, where columns of cloudy air can rise, and rapidly form raindrops. Rainfall intensity is typically greater than for cyclonic or orographic rain, but individual areas of rain are generally small (20 km diameter or less), with dry areas close by.

3.3 Distribution of raindrop sizes

3.3.1 Formulae are given in Reference 1 relating observed distribution of drop size at the surface, to rates of rainfall.

3.3.2 It is known that drops of a diameter greater than about 6 mm break up before reaching their terminal velocity, and this fixes the upper limit for raindrop diameter. Table 1 presents estimates of the number and size of raindrops for various rates of rainfall. It should be noted that the values quoted represent averages based on a large number of observations of size distributions, and that individual measurements of drop sizes can show wide variations about these average values.

TABLE 1

ESTIMATED NUMBER OF RAINDROPS PER CUBIC METRE FOR VARIOUS RATES OF RAINFALL

Rate of rainfall (mm/h)	Drop diameter (mm)				
	1-2	2-3	3-4	4-5	5
1	32	0.53	0.01	0	0
5	140	7.5	0.41	0.2	0
10	230	19	1.5	0.12	0.01
25	415	51	6.4	0.75	0.11
50	615	101	17	2.8	0.55
100	850	179	38	7.9	2.1
200	1140	259	113	20	6.9
500	1590	525	173	57	28
1000	1970	754	289	111	69

3.4 Terminal velocity

3.4.1 Formulae relating the terminal velocity to atmospheric conditions and height are given in References 2 and 3.

3.4.2 The rate at which a raindrop falls through still air depends both on the size of the drop and on the resistance offered by the air. The speed of fall will increase until the air resistance is equal to the weight of the drop, after which it will fall at a steady rate known as the terminal velocity.

3.4.3 Table 2 shows the variation of terminal velocity with drop size, for the following still air conditions:

Air pressure	1013 hPa
Temperature	20°C
Relative humidity	50%

TABLE 2

TERMINAL VELOCITY OF RAINDROPS IN STILL AIR

Drop diameter (mm)	Terminal velocity (m/s)
0.1	0.27
0.5	2.06
1.0	4.03
1.6	5.65
2.0	6.49
2.6	7.57
3.0	8.06
3.6	8.60
4.0	8.83
4.6	9.03
5.0	9.09
5.8	9.17

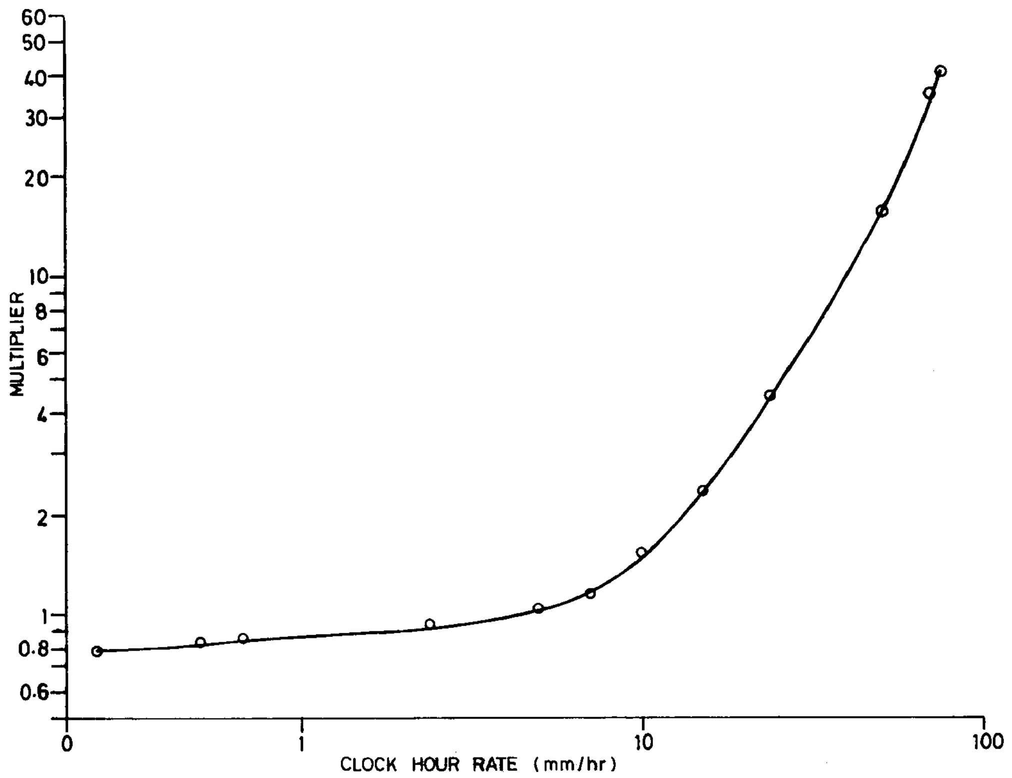
4 RATES OF RAINFALL

4.1 Instantaneous rates and clock-hour totals

4.1.1 Data on the frequency and duration of rainfall rates are relatively scarce, although the use of recording rain gauges with suitable time scales provides some information on the occurrence of specific rates of rainfall, and radar data contributes in some areas. Indirect estimates have been made from daily rainfall summaries, using regression equations based on a limited number of stations; these methods can be misleading when marked orographic or seasonal effects occur, especially at high rainfall intensities.

4.1.2 For many stations, especially in North America and Europe, routine tabulations of clock-hour rainfall amounts have been made, but are only available from respective national meteorological headquarters. Empirical formulae have been developed to make use of these clock-hour totals to derive frequencies of occurrence of specified rainfall rates. Examples can be found in Reference 4.

4.1.3 The clock-hour totals do not give probabilities for the near instantaneous rates of fall which are important in many design problems, since the rate of fall can vary widely inside any one hour. Studies have been made of the distribution of near instantaneous rates about the clock-hour total, for different rain intensities, and References 5 and 6 should be consulted for detailed information. Figure 2 may be used to convert clock-hour values to probabilities of instantaneous rainfall rates, though this curve must be interpreted with caution.



EXAMPLE: Station 'A' has 30 hours/year at clock-hour rate of 20mm/hr. Multiplier is 3.0. Station 'A' is estimated to have 3.0 x 30 = 90 hours of instantaneous rate of 20mm/hr.

Figure 2 Estimated conversion factor for converting to hours at instantaneous rate

4.2 Return period of rainfall at a point

4.2.1 The rainfall amount in a certain number of minutes or hours, which occurs once in so many years, is a quantity frequently required by civil and water engineers. Hydrologists have devised methods for estimating this amount, and details for the United Kingdom are given in Reference 8.

4.3 Frequency of instantaneous rates

4.3.1 Table 3 presents some estimates of the frequency of specified instantaneous rates of rainfall in an average year, for a number of localities. These estimates have been based in the main, on clock-hour data obtained over a number of years. To convert to percentage probability, the number of hours should be divided by 87.66.

TABLE 3

DURATION (HOURS) IN THE AVERAGE YEAR OF INSTANTANEOUS POINT RAINFALL EQUALLING OR EXCEEDING SPECIFIED RATES

Place	Rainfall rate (mm/h)					
	1	5	10	25	50	100
Aberporth	353	61	16	1.1	0.10	0+
Akrotiri	95	27	10	2.7	0.7	0.15
Birmingham Airport (Elmdon)	187	35	9.5	0.7	0.09	0.01
Changi	208	79	44	16	6	1.3
Eskdalemuir	586	109	30	2.1	0.18	0+
Freetown	380	137	81	29	11	2.8
Gibraltar	91	29	13	3.2	0.9	0.16
Hong Kong	517	138	49	14	2.9	0.6
London Airport (Heathrow)	234	41	11	1.1	0.17	0.01
Malta	111	33	13	3.8	1.0	0.20
Manchester Airport (Ringway)	308	52	13	1.1	0.16	0.02
Miami	250	70	32	15	5	1.5
Mildenhall	206	33	8.2	0.8	0.12	0.01
New Orleans	260	80	49	26	10	2.5
Tiree	205	34	9	0.5	0.04	0+
Washington	226	40	15	4	1.4	0.5

0+ = less than measurable quantity

5 HEAVY RATES OF RAINFALL

5.1 Thunderstorm rain

5.1.1 The heaviest falls of rain in short periods of time are usually associated with thunderstorms; since these are experienced at some time in most parts of the world, peak intensities of rainfall can be almost as high in temperate climates as in the wetter regions of low latitudes. Chapter 7-01 indicates the relative incidence of thunder over the world, and shows that while storms are, in general, most frequent in tropical and sub-tropical areas, they are fairly common during the summer half of the year in temperate latitudes, and are infrequent only in the Arctic and Antarctic.

5.1.2 Thunderstorms occur most frequently inland and are much less common over the open sea. Exceptions to this are some of the equatorial ocean areas and the Mediterranean, which, having relatively high temperatures in autumn and winter, can set up active convection when cold air masses move south from Europe. For further information on thunderstorms, refer to Chapter 12-01.

5.2 Prolonged heavy rain

5.2.1 Prolonged periods of heavy rainfall occur mostly in monsoon areas or in association with tropical cyclones; although heavy orographic rainfall can occur in most mountainous regions.

5.3 World-wide extremes

5.3.1 Recorded rainfalls over periods ranging from one minute to one year, taken at many places, have been used to determine an envelope which provides an approximation to the world-wide extremes of rainfall at any one point. This envelope may be expressed in the form, $R=363D^{-½}$ where R is the rainfall expressed in mm, and D is the duration expressed in hours. Table 4 shows some world-wide extreme hourly rainfall rates, covering periods from one minute to one hour, based on the formula for R. Reference 7 provides further information.

TABLE 4

MAXIMUM RATES OF RAINFALL

Period (minutes)	World-wide extreme rate of rainfall (mm/h)
1	2900
5	1200
10	900
30	550
60	380

5.3.2 For design purposes, values considerably lower than the world-wide extremes can be used, if attention is restricted to a specific region. However, since wide variations can occur both among and within regions, advice should be sought from the Meteorological Office in respect of any specific locality which may be of interest.

6 SPATIAL VARIATIONS OF RAINFALL RATE

6.1 Very large gradients exist in the rainfall rates observed over short periods between points not very far apart, but the longer the period over which the rainfall rate is determined the less is the variation with distance. Figure 3 shows the rate of decay of correlation between the rainfall at two points as the distance between them increases. The figure compares correlation's obtained for total storm rainfall, that is the amount of rain falling at any one point during the whole passage of one storm, and those for the rainfall rate averaged over one minute.

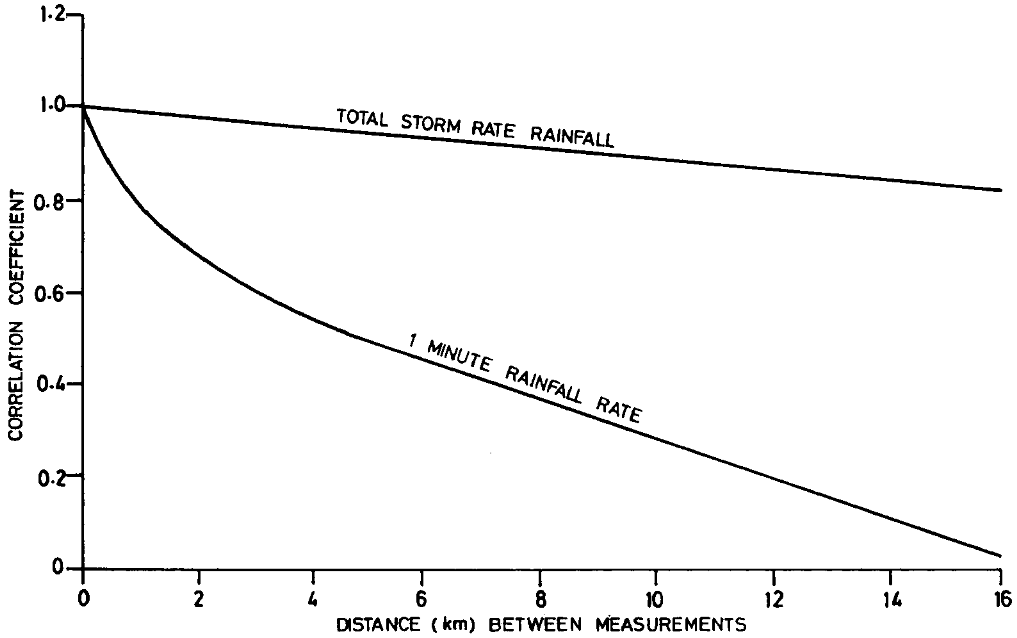


Figure 3. Average decay of correlation with distance, of rainfall rate and total storm rainfall

6.2 There is clearly a substantial improvement in correlation when accumulated rainfall is considered over a period. The rapid decay of correlation, when short period rates of rainfall are being considered, shows the need for high density observational networks if small scale details of the rainfall pattern are of importance. A spacing of about half a kilometre is needed in order to account, on the average, for 75% of the variance which occurs in the short period rates of rainfall during heavy storms.

7 HORIZONTAL EXTENT OF SPECIFIED RAINFALL RATES

7.1 Rainfall rates below 2 mm/h

7.1.1 Rain areas associated with these low rates of rainfall are often extensive, areas of 1000 to 1500 km by up to 300 km being quite common, in association with large scale features of the pressure pattern. In extreme cases the length of a rain belt can extend to as much as 6000 km.

7.1.2 In suitable conditions, orographic rainfall can extend along the whole windward side of mountain chains, such as the Atlantic coasts of Great Britain and Norway, the Pacific coast of North America, and especially the mountain chains of Asia during the summer monsoons. These rainbelts seldom exceed 250 km in width and are usually much narrower.

7.2 Rainfall rates between 2 and 10 mm/h

7.2.1 In temperate climates, rainfalls between 2 and 10 mm/h are unlikely to exceed 250 km in length. Lengths of 150 to 250 km may occur on fairly numerous occasions.

7.2.2 In tropical latitudes, rainbelts with this rainfall rate may extend up to 300 km or more in hurricanes. Monsoon rains in West India and West Africa frequently cover lengths of 1000 km and 2000 km has been exceeded at times during the summer monsoon on the southern and western slopes of the Himalayas.

7.3 Rainfall rates between 10 and 25 mm/h

7.3.1 Rainfalls between 10 and 25 mm/h are nearly always associated with convection. Individual convective clouds are rarely more than 15 km across but on occasions, for example along a cold front, the clouds may become closely linked and form a rainbelt of some 150 to 250 km in length although the width is unlikely to exceed about 15 km.

7.3.2 Similar linkages may also occur along a mountain barrier and during the most intense phase of the tropical summer monsoon, rainfalls of these intensities may occur virtually anywhere along the southern and western slopes of the Himalayas and associated ranges for 2000 km or more. Monsoon rains of these intensities may also fall in West Africa and West India, over areas some 1000 km across.

7.3.3 Similar heavy rains over an area of perhaps 300 km across may also be experienced with tropical hurricanes.

7.4 Rainfall rates exceeding 25 mm/h

7.4.1 Rainfall of these high rates is thought to be limited everywhere to one or two neighbouring convection cells. The horizontal extent of these cells is generally in the range 1 to 5 km, and is unlikely to exceed 30 km even in tropical storms. In the cores of these cells, over diameters of 2 km or less, rainfall rates will occasionally exceed 100 mm/h even in temperate climates such as the British Isles. Extreme rates recorded are of the order of 1000 mm/h occurring over a period of about one minute and thought to be associated with cells only about 0.5 km in diameter.

8 VERTICAL VARIATIONS OF DROP SIZE DISTRIBUTION

8.1 Rainfall rate below 10 mm/h

8.1.1 Most of these intensities are associated with widespread continuous rain. In these circumstances the rain formation process is due mainly to melting of snow/ice crystals, and not many large drops would be found in the cloud above the melting isotherm. Drops may grow by coalescence below the melting level or may decrease by evaporation beneath the cloud base, but radar observations suggest that there may often be no great variation in drop size distribution between the melting level and the ground.

8.2 Rainfall rates exceeding 10 mm/h

8.2.1 High intensity rain areas are associated with strong upward currents which suffice in some cases to carry large drops to great heights - close to the tropopause in some thunderstorms; moreover drops may form in the supercooled state above the 0°C level. The updraughts are usually localised although they may be widespread at mountain barriers or along fronts, etc. and they often vary in magnitude so that the distribution of cloud drop sizes may also be variable.

8.2.2 All that can be usefully said is that large drops in concentrations corresponding to high rainfall rates may be encountered at heights considerably above the 0°C level and certainly at around the -20°C level. In the heaviest showers and thunderstorms this would be in the region of 10 km, with rates exceeding 100 mm/h. Above this height and temperature level there is likely to be a rapid fall off in the concentration of large drops.

9 RAINFALL PROBABILITIES ALONG A LINE

9.1 The information given in this chapter is concerned with rainfall probabilities at a specific point, but for many purposes it is necessary to assess the chances of specified rainfall rates occurring simultaneously along given distances of horizontal tracks. Direct information of this kind is rarely obtainable but assessments can be based on point probabilities and on assumed shower models. Table 5 gives some values obtained in this way for tracks in Southern England and in Singapore.

TABLE 5

ESTIMATED DURATION (HOURS) IN THE AVERAGE YEAR WHEN STATED DISTANCES ALONG GIVEN TRACKS SIMULTANEOUSLY HAVE RAINFALL AT OR EXCEEDING SPECIFIC RATES

Location	Track length (km)	Distance along track (km)	Rainfall rate (mm/h)				
			5	10	25	50	100
S England	25	0	172	81	12.5	2.9	0.2
		5	107	20	0	0	0
		10	40	0	0	0	0
		15	0	0	0	0	0
	50	0	303	151	25	5.6	0.4
		5	221	60	6	0	0
		10	120	5	0	0	0
		15	50	0	0	0	0
		20	5	0	0	0	0
	100	0	562	292	48	11	0.9
		5	440	140	25	2	0
		10	290	50	0	0	0
		15	170	0	0	0	0
		20	60	0	0	0	0
Changi	25	0	330	280	162	82	29
		5	220	130	0	0	0
		10	100	0	0	0	0
		15	0	0	0	0	0
	50	0	570	510	310	159	56
		5	430	250	100	20	0
		10	280	100	0	0	0
		15	180	0	0	0	0
		20	100	0	0	0	0
	100	0	1050	980	600	311	111
		5	880	550	200	80	0
		10	650	280	10	0	0
		15	480	100	0	0	0
		20	300	0	0	0	0

10 DESIGN CRITERIA

10.1 Precipitation

10.1.1 For the general meteorological condition on a world-wide basis, materiel should remain safe and be capable of acceptable performance when exposed to precipitation whose intensity is attained or exceeded for only a specified small portion of the wettest month of the year. Normally, this small portion is taken to be 0.5 per cent but in some circumstances where a higher intensity may need to be specified, the value for 0.1 per cent is recommended.

10.1.2 The precipitation intensities on a world-wide basis associated with these proportions of time are given in Table 6 for a range of altitudes up to 20 km. However, for materiel destined only for Europe, the intensities at sea level may be relaxed to the values given for the European rain condition also given in Table 6.

TABLE 6

PRECIPITATION INTENSITIES

Altitude km	Intensity exceeded for 0.5% of wettest month mm/min	Intensity exceeded for 0.1% of wettest month mm/min	Estimated greatest ever precipitation mm/min
0	0.80	3.13	31
1	0.87	3.4	34
2	0.93	3.6	36
4	1.0	4.1	41
6	1.1	4.2	42
8	0.77	3.0	30
10	0.51	2.0	20
12	0.35	1.4	14
14	0.22	0.84	9
16	0.11	0.4	4
18	0.02	0.09	1
20	0	0	0
Rain Conditions			
World-wide	0.80	3.13	-
Europe	0.58	0.80	-

10.2 Rainfall

10.2.1 For rainfall, two geographical categories are considered, 'World-wide' and 'Europe'. The world-wide data are based on observations in South East Asia which is recognised as the wettest region of the world. Thus, in the region selected, materiel should remain safe and be capable of acceptable performance in rainfall whose intensity is attained or exceeded for only a specified small portion of the wettest month of the year.

10.2.2 For the general meteorological condition, this small portion should be 0.5 per cent but in some circumstances, where a higher intensity is considered necessary, the value which is exceeded for 0.1 per cent of the time is recommended. The intensities associated with these time values are given in Table 6.

10.2.3 The intensities shown in Table 6 will seldom persist for more than a few consecutive minutes. During a rainstorm the rain intensity varies widely in an unpredictable manner and it should be noted that, at least on some occasions, the highest intensities experienced during the wet seasons will exceed those for the 0.1 per cent level by factors of two or more.

10.2.4 The highest rainfall values ever recorded on a world-wide basis for three durations is quoted in Table 7.

TABLE 7

GREATEST RAINFALL INTENSITIES AT SEA LEVEL

Period	Average rate of rainfall mm/min
1 minute	31.0
42 minutes	7.3
12 hours	1.9

10.3 Immersion

10.3.1 Flooding is a possible consequence of heavy rainfall and may lead to materiel being immersed in water. Immersion is defined as the total or partial covering by water for a limited or specified period. The effects of immersion upon items of materiel are principally determined by depth and duration of immersion, both of which are affected by factors other than the climate.

10.3.2 Unless service requirements specify otherwise, depths of immersion can be taken as lying between 150 mm and 4 m, with a standard time of immersion of two hours. It should be noted that when a relatively warm item of materiel is partially or totally immersed in cooler water, a reduction in air pressure within the item may result, which in turn could cause or aggravate the ingress of moisture.

11 REFERENCES AND OTHER SOURCES OF INFORMATION

11.1 References

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11.2 Further reading

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'A Survey of Techniques for Determining Short Duration Precipitation Rate Statistics' Hanscom AFB AFGL-TR-82-0357 Air Force Surveys in Geophysics No. 441	P Tattleman and D D Grantham
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CHAPTER 6-02
THE EFFECTS OF RAIN

1 INTRODUCTION

1.1 Rainfall is one source of the moisture that is an essential factor in most forms of corrosion. In addition, it can carry soluble and insoluble contaminants of the atmosphere into close contact with materials.

1.2 The impact of raindrops can erode many materials, destroy protective coatings and bleach out preservatives and impregnants. Rain may also retard deterioration by its cleansing action, one example being the washing away of mould growth.

1.3 This chapter describes the damaging effects of raindrop impingement, for example erosion and penetration. The mechanisms of deterioration involving the presence of moisture are described in Chapters 4-02 and 8-02.

2 MECHANISM OF EROSION

2.1 General

2.1.1 The term `erosion` is used herein to describe the damage caused to solid surfaces by the impact of raindrops. The processes of material break-up are complex, and most of the available data are derived from laboratory experiments in which rainfall characteristics were simulated.

2.1.2 The mechanisms of raindrop impingement outlined below deal generally with the damage to both hard and rubbery materials. Variations are likely to occur however, depending on the characteristic properties of specific materials.

2.2 Behaviour of a raindrop on impact

2.2.1 The behaviour of a raindrop on impact depends largely on the velocity of impact. Based on laboratory observations, it is considered that with impact velocities up to approximately 300 m/s a water-drop behaves like a hard projectile on impact but retains its liquid property of flow. At greater velocities the drop behaves progressively like a hard projectile which does not flow as a result of the collision. Tests have shown that a drop colliding with 3 mm thick 1100-H14 aluminium sheet at 600 m/s makes an impression similar to that made on the same material by the impact of a 5.5 mm diameter steel sphere at the relatively slow impingement velocity of 70 m/s.

2.3 Liquid flow on impact

2.3.1 When collision occurs between a raindrop and the surface of a solid the impact pressure rises rapidly to a high value, driving the liquid that is close to the solid surface radially outwards around a central stagnation point.

2.3.2 The moving liquid is in laminar flow and the resulting pressure increases with the size of the water drop. It has been estimated that an impact pressure of approximately 200 MN/m^2 can occur at an impact velocity of 270 m/s and the radial flow of liquid attains a velocity of about 625 m/s. References 1 and 2 provide further details.

2.4 Stresses resulting from the impact of raindrops

2.4.1 The radial flow of a raindrop on impact exerts a shear stress on the solid surface over which it runs and the separate layers of water in laminar flow. When a surface protrusion exists, the flow exerts forces against the protrusion which tend to move it along the surface producing a shear stress. If the forces are sufficiently great the protrusion will break or be torn from the solid surface.

2.4.2 When a drop impinges against the surface of a rubbery material it momentarily compresses the material at the point of impact forming a cup-shaped cavity. Tensile stresses appear in the sides of the cavity as a result of local compression, and tears may form in the surface layers of the material. In addition, the volume of material previously in the place occupied by the cavity is now moved upwards and outwards around the cavity and a shear stress results.

2.5 Manifestation of erosion

2.5.1 All materials yield to some extent under the compressive load exerted by impinging raindrops. Repeated collisions can lead to surface unevenness, thereby introducing tensile stresses which in turn produce fine cracks or tears, depending upon the hardness or resilience of the material. These surface defects, when acted upon by the rapid liquid flow of collapsing raindrops, become widened and material is broken out of the surface along the cracks or tears. Holes thus formed are jagged right out to the periphery, thereby introducing new tensile stresses which result in further break-out of material. This erosive mechanism is continued until the surface is covered by overlapping holes.

3 FACTORS AFFECTING EROSION

3.1 A multiplicity of factors such as rainfall characteristics, velocity of impact, type of material, surface shape and finish, influence the rate and extent of erosion. The chief variables are described below.

3.2 Angle of impact

3.2.1 A drop of rain will be acted upon by gravity, the resistance of the air and the velocity and direction of the wind. The resultant of these effects, together with the velocity and geometry of a moving vehicle, determines the angle of impact of the rain, which in gusty conditions can vary considerably. Observations show that erosion can be expected at angles of incidence of 30° or less, the rate being a function of time and velocity. Erosion becomes progressively less at angles greater than 30° and at 75° is negligible.

3.3 Drop size and intensity

3.3.1 The rate and extent of erosion increases with increased size of raindrop, due mainly to the greater surface area affected by pressure resulting from impact and liquid flow. The rate of erosion also increases with the number and rapidity of impacts. The time interval between successive impacts on the same spot causes a build-up of stresses, which may exceed the strength properties of the material surface. Figure 1 shows a comparison of weight loss of Perspex subjected to various rainfall rates, experimentally and in flight.

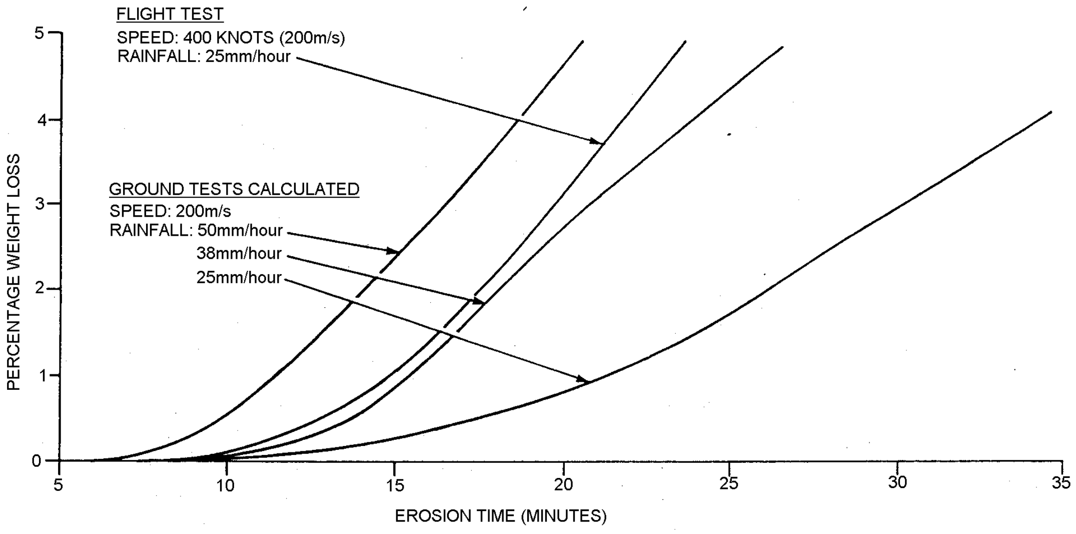

Figure 1. A comparison of weight loss by Perspex specimens on a Whirling Arm rig, and in flight

3.4 Surface shape

3.4.1 The extent of erosion is dependent on the shape of the surface of a vehicle, sharply curved leading edges being the most vulnerable.

3.5 Surface finish

3.5.1 Smooth and void free surfaces are more resistant to erosion than surfaces containing corrugations or small pin holes. However, even highly polished surfaces have a degree of irregularity which limits their resistance to attack. For example, it has been found that while electrolytic chromium plating delays the onset of erosion, it has no effect on the speed at which it progresses.

3.6 Physical properties of materials

3.6.1 To be erosion resistant, the stresses set up in a material as a result of withstanding raindrop collision must be less than the yield or ultimate strength of the material. Present observations indicate that over a wide range of different materials, properties such as surface hardness, strength, tear resistance (in the case of protective coatings), resilience or high elongation at break, are contributory factors to rain erosion resistance.

3.6.2 The correlation of erosion resistance with general physical properties is complex because a specific material may have various applications and conditions of use. Thus, steels which offer excellent resistance with increased hardness may have limited use due to brittleness. Glass has many times the erosion resistance of steel but is unlikely to be used where strength is required. Furthermore, tests indicate that soft, relatively resilient non-brittle coatings of neoprene or polyethylene have erosion resistance comparable to that of aluminium and alloy steels.

3.7 Aspects of applications

3.7.1 The erosion resistance required of materials varies considerably with operating conditions and it has been suggested that the rate of erosion is proportional to a high power of velocity.

3.7.2 The erosion resistance of coatings depends largely on their method of application. For example, poor quality coatings applied to properly prepared surfaces are often more resistant than high quality coatings applied to poorly prepared surfaces.

3.7.3 The prediction of erosion resistance is further complicated in that erosion mechanisms may change rapidly with increased speed. For example, polymeric methyl methacrylate (Perspex) is a rigid material on which initial pitting has been found to occur after 45 minutes in simulated rain of 25 mm per hour intensity and velocity of 135 m/s. However when the velocity was increased to 180 m/s initial pitting occurred after 2 minutes.

3.8 Selection of erosion resistant materials

3.8.1 For speeds up to approximately 225 m/s in rain, common alloys give good resistance, particularly stainless steel. Metals are also widely used to protect less resistant materials, for example, electro-deposited nickel is a useful sheath material. Polyethylenes have given long service on aircraft aerial masts, but brittle materials such as Perspex are subject to rapid erosion except at low angles of impact. Glass fabric/resin laminates used for strength or for electrical reasons, have poor resistance to erosion and often need some protective layer. Porous or foamed materials offer the least resistance.

3.8.2 The results of qualitative rain erosion tests for various metals, platings, non-metallic materials and protective coatings are given in Tables 1. 2 and 3. These tests were carried out on the RAE Farnborough whirling arm rig at speeds of 225 m/s, with a simulated rainfall of 25 mm/hr and a drop size of 2 mm.

3.8.3 It is beyond the scope of this chapter to include comprehensive erosion data for all known materials. However, tests made on a wide variety of materials used in different applications and under various conditions are detailed in References 3, 4 and 5.

TABLE 1

EROSION RESISTANCE OF TYPICAL NON-METALLIC MATERIALS

Description	Time (minutes)	Comments
Paint (epoxy resin base)	7	Coating (0.13 mm) completely removed
Glass fabric reinforced resin laminate	5-15	Severe erosion with 6 to 8 layers removed
Nylon or Terylene reinforced resin laminate	5	Severe erosion with tearing of reinforcement
Filament wound radome section	5	Layer 0.63 mm thick, uniformly removed
Durestos	5	Severe erosion particularly if resin starved
Honeycomb (glass fibre/ polyester) radome section	1	Eroded through outer skin(0.76 mm)
Expanded Nitrile Ebonite	½	Deep erosion depending on the number and size of cell
Borosilicate glass (annealed)	5	Deep pits
Perspex (unplasticised)	20	Severe erosion 6.5 mm deep
Quartz	6	Surface pitted
Alumina (Sintox)	4200 (plus)	Little or no erosion. Test discontinued
Steatite	290	Deeply pitted
Supramica 560	20	Severely eroded
Pyroceram 9606	2580	Slight pitting only. Test discontinued
Sapphire	1320	No visible damage. Test discontinued
Boron nitride	40	Severe erosion to depth of 6.5 mm
Silicon nitride	105	Deeply pitted
Polyethylene, normal grades	270	Eroded to depth of 3.3 mm
Polyethylene, high density types	330	Eroded to depth of 3.3 mm
Polytetrafluoroethylene	25	Eroded to depth of 3.3 mm
Polystyrene	15	Eroded to depth of 1.5 mm
Nylon 6	1080	Eroded to depth of 5 mm
Natural rubber	120	Eroded to depth of about 0.5 mm
Polycarbonate	70	Eroded through 4 mm

TABLE 2

EROSION RESISTANCE OF TYPICAL METALLIC MATERIALS AND PLATINGS

Description	Time (minutes)	Comments
Aluminium alloy DTD 150	600	Very severe erosion
Aluminium alloy DTD 423B	900	Severe pitting on leading edge
Brass BS 250	2800	Deep pits locally
Copper BS 1433	1100	Severe pitting, eroded through 2.5 mm
Magnesium alloy DTD 259	840	Severe pitting overall
Molybdenum	660	Eroded in layers to depth of 0.8 m
Stainless steel BS S521	1800	Visible erosion on leading edge, no weight loss
Anodised aluminium	720	Superficial damage
Nickel plated aluminium(unpolished)	240-480	Variable, coating eroded through
Sintered molybdenum on stainless steel	40	Eroded through coating (0.25 mm)
Micrograin electroform nickel sheath bonded to aluminium alloy	1200	Undamaged. Test discontinued -

TABLE 3

TYPICAL EROSION TESTS ON PROTECTIVE COATINGS

Coating material	Substrate	Thickness (micrometres)	Time to erode through (minutes)
Neoprene to DTD 856 (Goodyear 23/56)	Glass fabric/polyester laminate : poor quality	280	25
	: good quality	280	100 to 150
Polyurethane	Glass fabric/polyester laminate	250	80*
	Aluminium alloy	635	360*
Maranyl (methylmethoxy nylon) (cast film stuck to alloy)	Aluminium alloy	510	415
Maranyl (sprayed from solution)	Aluminium alloy	380	190
Flame sprayed nylon	Aluminium alloy	560	30
Flame sprayed alumina	Steel or laminate	380	5
Epoxy resin	Aluminium alloy	380	10
		1900	50
Hypalon	Glass fabric/polyester laminate	380	10) adhesion 40) failure

* Little damage to film in general, local failure only

4 PENETRATION BY RAIN

4.1 General

4.1.1 The penetrating power of rain is proportional to rain intensity and the square of the impact velocity; it is also influenced by the duration of rainfall and the size of raindrop.

4.2 Mechanism of penetration

4.2.1 If a material contains pores, narrow crevices or small canals then water will be absorbed as soon as rain strikes the surfaces. This absorption depends on the number and size of openings and will be rapid to start with, then tapering off as the water content increases. With materials of small pore size, the initial penetration is greatly assisted by capillary suction but the force of impact is the dominating factor with pore sizes greater than 1 mm.

4.2.2 Wind-driven raindrops tend to break-up on impact, and the resultant fine mist or spray is easily forced into pores and crevices. A further contributory factor is the difference in air pressure which may exist between a rain wetted wall surface and its dry inner surface. For example, during a rain-storm the air pressure at the outside surface is usually higher than that at the inside surface and water is forced through the material by this pressure difference.

4.3 Penetration of buildings

4.3.1 Structures consisting of mortar bonded bricks, blocks, tiles or similar units are porous and capable of absorbing moisture. Although continuous intense rain can penetrate such units, leakage usually occurs between the unit and the mortar. This is due to cracks or crevices caused by shrinkages of mortar, poorly filled joints, lack of adhesion and structural settlement. Rendering with plaster improves the tightness of the structure with consequent reduction in water penetration.

4.3.2 Rain which penetrates a wall may cause mould growth and rotting of wood-work; timber joists in masonry are particularly susceptible to this. In addition to surface wear caused by impact pressure of water-drops, disintegration can occur when moisture within the pores becomes frozen. This effect is explosive in character and over a period of years can reduce rock to gravel. Complete penetration may damage protective materials such as plasters and paints and may also cause a marked reduction in the thermal insulating properties of a wall.

4.4 Penetration of equipment

4.4.1 The need to provide air to facilitate the operation, cooling or ventilation of an equipment, often limits its ability to withstand the effects of penetrating rain. For example, aircraft engine and aircraft equipment can fail because of too much water being drawn in by air intake scoops, or by water penetrating the fuel system. Air speed indicators have been known to read incorrectly if the pitot head becomes filled with water.

4.4.2 Rain can also penetrate inadequately sealed units, in conditions where the internal air pressure is lower than the external air pressure.

5 DISTANT AND PROXIMATE RAIN

5.1 General

5.1.1 Actual physical contact with rain is not essential for some forms of deterioration. For example, the performance of radar and optical equipment is often impaired by the presence of rain within their operating range. These effects are described below.

5.2 Radar attenuation

5.2.1 In traversing space, part of the energy of a radar beam is absorbed by water-drops existing in its path. This results in the attenuation of both the transmitted radar energy and the energy of the reflected echoes from a target. Attenuation increases with rain intensity and depth of rain belt, and is most severe at wavelengths below 10 cm. The orders of attenuation likely to be experienced at various rainfall rates are indicated in Figure 2.

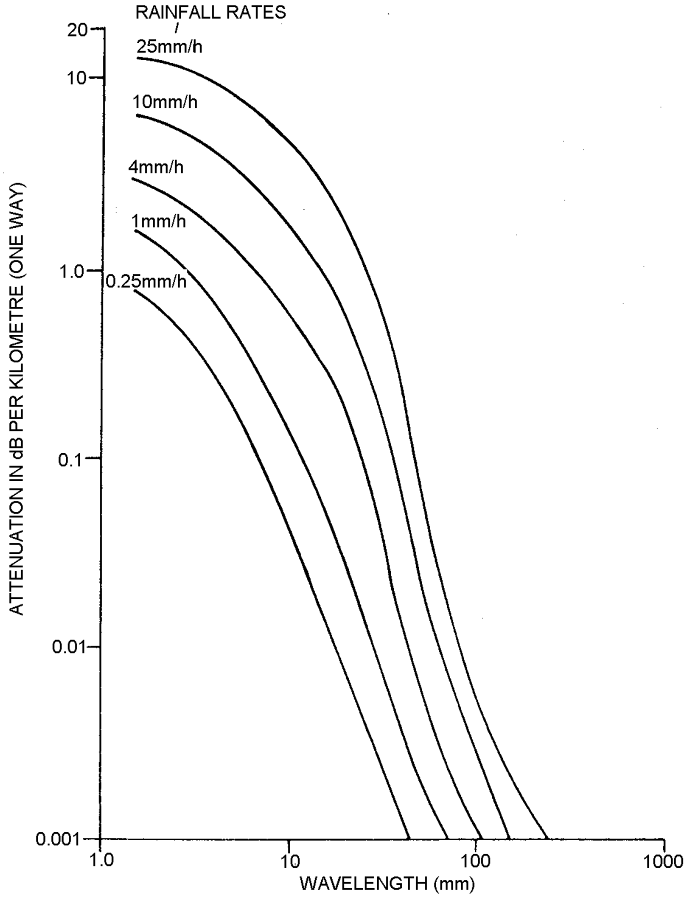

Figure 2. The attenuation by rainfall at short wavelengths

5.3 Radar clutter

5.3.1 When raindrops are irradiated by a transmitted beam of electromagnetic energy, the energy incident upon each particle is partly absorbed as heat and partly scattered in all directions. Some of this scattered energy will be in the direction of the radar receiving aerial and may appear on the display together with echoes from wanted targets. Although scattering is made use of in forms of weather radar, in other forms of radar it can produce clutter in the display to the extent of masking a wanted echo.

5.3.2 Back scattering is a function of wavelength of propagation and the number, size, shape and dielectric properties of the water particles. Probably the most severe case of reflectivity occurs when ice particles are in the process of melting and are covered with a layer of water.

5.3.3 Systems may use pulse radar, CW radar or a combination of the two, such as coherent pulse. The effects of clutter on the three types of system differ widely, and further modification may be introduced by modulation. In particular, in CW radar guidance systems, relative movement of elements of the system can produce a spreading of the clutter spectrum which may produce degradation of performance.

5.3.4 It is necessary to consider three factors; these are obscuration effects, range of the rain and its velocity components in all directions relative to the radar system.

5.4 Air transparency

5.4.1 The transparency of air during rainfall depends on numerous variable factors. These include rainfall characteristics and attendant meteorological and topographical factors which may affect illumination. The various studies made to correlate air transparency with rainfall characteristics indicate that there is no quantitative technique for forecasting the reduction in visibility during rain. However, it has been suggested that a visibility of 20 to 50 km would be reduced to between 3 and 10 km by moderate rain and to between 2 km and 4 km by heavy rain. A visibility of 3 to 10 km would be reduced to between 2 km and 4 km by moderate rain and to between 1 km and 2 km by heavy rain. Information on drizzle indicates that heavy drizzle is more effective than moderate rain in reducing visibility.

5.5 Absorption of infra-red radiation

5.5.1 All objects having a temperature above absolute zero radiate electromagnetic energy, and an appreciable portion of this energy lies in the infra-red spectrum 0.7 micrometres to 15 micrometres. Equipment used to detect infra-red radiation, such as infra-red thermal mapping systems, suffer weather limitations, in that atmospheric particles can absorb some or all of the radiated energy. Maximum absorption of infra-red occurs in 'black bodies', defined as objects that absorb all the radiation falling on them neither reflecting nor transmitting any of the radiation. Water is essentially 'black', being extremely opaque to infra-red at wavelengths longer than about 2 metres and is one of the principle absorbers of infra-red.

5.5.2 Water vapour and very small water droplets, as in fog, cause infra-red attenuation by absorption. This attenuation is almost directly proportional to the total volume of water-drops per unit volume of the atmosphere. Water-drops that are large with respect to infra-red wavelengths, for example raindrops, scatter as well as absorb the incident radiation. Since rain consists of a wide range of water-drop sizes the resolution of infra-red absorption is complex, and radiation attenuation is usually determined by combining the effects of absorption and scattering. Diagrams showing the effect of atmospheric water vapour on various absorption bands in the infra-red region are contained in Reference 6.

6 EFFECTS OF RAIN-WATER ACCUMULATION

6.1 General

6.1.1 The effects of rain-water accumulation depends on rain and intensity, and the shape, finish and porosity of the material. Besides promoting the forms of degradation described in Chapter 4-02 the accumulation of rain-water can affect the function of equipment in a number of ways. Typical examples are given below.

6.2 Effects on transparencies

6.2.1 Vision is obscured through forward facing windows by the sputtering of rain-drops and resultant water-flow, which can include the flow of water from associated surrounding surfaces. On aircraft windscreens water can build up to a depth greater than a quarter of an inch.

6.3 Ice formation

6.3.1 Water-droplets of low temperature can freeze on impact with a surface and build up a layer of ice which may seriously affect the aerodynamic properties of missiles and aircraft. For further information on the effects of ice see Chapter 7-02.

7 MISCELLANEOUS EFFECTS OF RAIN

7.1 The preceding paragraphs outline the effects of rain on buildings, equipment, materials and equipment performance. However, natural substances, such as soil and water masses, can be adversely affected by rainfall; rain erosion of soil, and flooding are examples of this.

7.2 Rain is usually accompanied by changes in other meteorological factors. For instance, air pressure falls immediately before the start of a thunderstorm, rises sharply as rain commences, and falls again as rain subsides. These changes can amplify damage initiated by the presence of rain.

8 GENERAL OBSERVATIONS

8.1 The effects of rain may be alleviated by:

(a) The use of erosion resistant materials or coatings in vulnerable areas.

(b) The careful preparation of surfaces prior to the application of protective coatings.

(c) The use of a design shape that reduces the angle of strike of raindrops.

(d) Protecting equipment against rain penetration for example, by encasement of assemblies and sealing of vulnerable cracks and crevices.

8.2 The selection of materials may be assisted by study of References 3, 4 and 5.

9 REFERENCES AND OTHER SOURCES OF INFORMATION

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DEF 1234 General Requirements for Packaging Supplies for the Service	

CHAPTER 7-01
HAIL, SNOW AND ICE

1 HAIL

1.1 General

1.1.1 Hail occurs in several forms, but usually consists of spherical stones made up of alternate layers of clear and opaque ice, though occasionally the stones are entirely of clear ice. The density of hail can vary from 0.1 to 0.9 g/cm^3 according to the structure, although ordinary hail is often assumed to have a density of 0.7 to 0.9 g/cm^3, the latter value corresponding to clear ice. Snow pellets, formerly called soft hail, consist of a central crystal covered with frozen cloud droplets, and are easily compressible, the density being about 0.3 g/cm^3 and the diameter 2 to 5 mm.

1.2 Distribution of hailstones

1.2.1 The way in which hailstones form is not completely understood, but is generally associated with active convection. The growth of large stones requires the existence of powerful updraughts and plentiful moisture; it therefore follows that hail forms mainly in warm, moist and unstable air. These conditions are broadly those required for the development of thunderstorms, and the presence of thunderstorms can be expected to indicate the possibility of hail. Figure 1 shows the world wide distribution of days when thunder is heard.

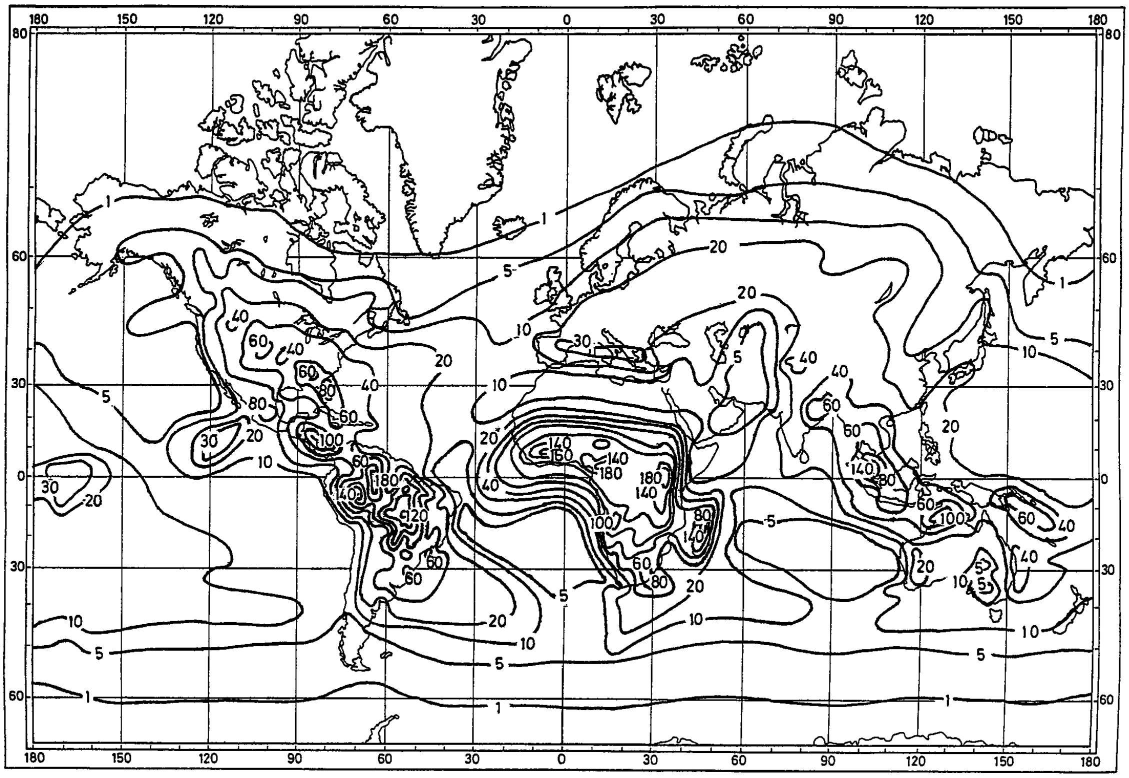

Figure 1. Average annual number of days when thunder is heard

1.2.2 There is no simple relationship between thunderstorms and hail, and hail sometimes forms in convective clouds which do not develop into thunderstorms. However, Figure 1 may be taken as an indication of the relative frequencies of large hail; except in the tropics, where the relative absence of hail may be accounted for by the greater height of the 0°C isotherm and the different configurations and strengths of updraught and downdraught, compared with the middle latitudes.

1.2.3 Although large hail requires strong convection and so is most likely over large land masses, small hail appears to be relatively frequent over the oceans. Hail is most likely in the sub-tropics and middle latitudes. In the continental areas, which are most liable to large hail, the average number of hailstorm days per year is between 5 and 10. The incidence increases to around 15 to 25 in some coastal regions; these experience the smallest hailstones. The highest number yet noted is 31 days per year, probably nearly all of small hail, in the Falkland Islands and on the weather ship formerly stationed at 52½°N 20°W. In Southern England, hail over 0.5 cm in diameter is observed on an average of four days per year, over 1 cm on one day in 10 years, and over 2 cm on one day in 100 years at any one place.

1.2.4 Estimations have been made of the frequency of encountering hailstones at different altitudes and the derived data is presented in References 1 and 2. The incidence and distribution of hail in the USA has been investigated using hail pads and radar techniques and the results are contained in References 3 and 4.

1.3 Size of hail

1.3.1 The size of hail reported as reaching the ground, is usually that of the largest stones in any given fall. No accurate observations are available of the distribution of hailstone size in a particular fall, but estimates have been made. Table 1 indicates the number of stones of a given diameter likely to be found per unit volume, on the assumption that the stone density is 0.9 g/cm^3, that the mass of airborne ice is equally divided amongst the size ranges (an assumption based on some observations of snow pellet distribution in convective clouds) and that the equivalent rainfall rates are reasonable.

TABLE 1

NUMBER OF HAILSTONES PER CUBIC METRE (AT ABOUT 4000 M LEVEL) FOR SPECIFIED MAXIMUM HAILSTONE SIZE, AND FOR SPECIFIC RANGES OF STONE SIZE

Range of stone diameter (cm)	Size or largest stone (cm) in hailstorm		
	3	6	10
	Numbers per cubic metre		
0-1	22	9	7
1-2	0.8	0.35	0.27
2-3	0.17	0.07	0.06
3-4	-	0.03	0.02
4-5	-	0.01	0.01
5-6	-	0.0007	0.005
6-7	-	-	0.0003
7-8	-	-	0.002
8-9	-	-	0.0015
9-10	-	-	0.001
Equivalent rainfall (mm/hr)	250	300	500

1.3.2 On theoretical grounds, the maximum size of hailstones is about 13 cm, and stones up to this diameter have been reported. The Coffeyville, Kansas hailstone of 3 September 1970 was irregular in shape with a diameter of about 13.8 cm. Since warm, moist and unstable air is required for the formation of hail, the size observed varies with locality. In polar regions hail at ground level is rare and is most likely to be in the form of graupel, with stones less than 1 cm in diameter. Large hail is also rare over the open seas, the maximum diameter being about 1.5 cm.

1.3.3 The largest hail, and that which causes most damage on the ground, is usually confined to the interiors of continents, and is most likely in middle latitudes and the sub-tropics. The probability of large hail does not continue to increase towards the Equator, and in equatorial regions hail occurs only infrequently near the coasts and at low levels. However, larger land areas and greater elevation both favour an increase in large hail, and stones up to 2.5 cm in diameter have been known to fall at the higher tropical stations. For further information, the Meteorological Office should be consulted.

1.4 Terminal velocity

1.4.1 The terminal velocity of large hail may be determined from the equation:

$$V = \frac{(2\,\sigma\,gd)^{1/2}}{(3\rho\,C_D\,)^{1/2}}$$

where d = stone diameter, σ = stone density, ρ = air density, g = acceleration due to gravity, C_D = drag coefficient and V = terminal velocity. It should be noted that the terminal velocity is relative to the air movement.

Inside the hail storm cloud there are updraughts and downdraughts, and the hail can be moving upwards, downwards, or indeed be stationary relative to the ground. This can result in a range of impact angles for in-flight collision.

1.4.2 Empirical values of C_D, for normal sea level values for g and ρ taking $\sigma = 0.9\text{g/cm}^3$ lead to the terminal velocities presented in Figure 2, which is based on the equation:

$$V = kd^{½}$$

where the terminal velocity V is measured in m/s, the diameter d in cm and the constant k = 14.7

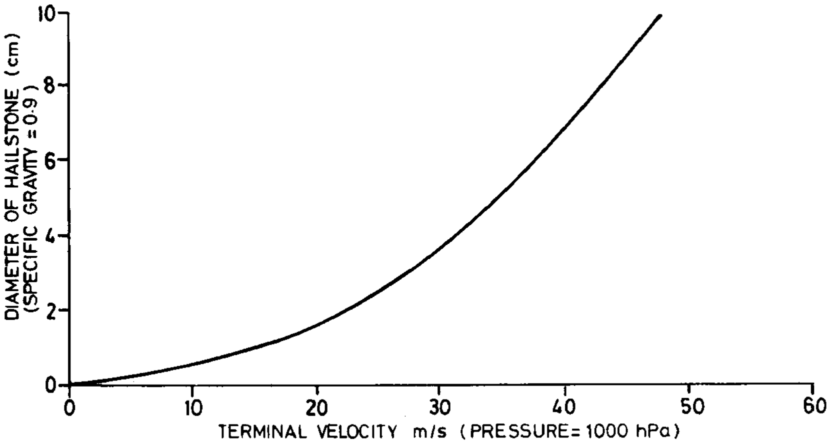

Figure 2. Relationship between diameter and terminal velocity of spherical hailstones (SG = 0.9)

A better estimate of the constant k has been given as 16.3 in Reference 5 and using this value, the variation of kinetic energy of the hailstone at terminal velocity with its diameter is given by the equation

$$KE = 0.0626\ d^4$$

where the kinetic energy is measured in Joules.

1.5 Seasonal variation

1.5.1 Seasonal variation varies with locality. Over continents large hail is most common in the late spring and summer when surface heating and convection are most pronounced. However, in some enclosed seas, such as the Mediterranean, the flow of cold air from higher latitudes across the relatively warm water produces a maximum hail occurrence in autumn and winter. Over the oceans and on coasts, when the prevailing wind is on-shore, this seasonal variation is less marked.

1.5.2 Over south-eastern England, most small hail occurs in the months March to May and most large hail during April to July. However, in northern and western coastal areas of the United Kingdom hail is mostly small and occurs mainly between November and April.

1.6 Diurnal variation

1.6.1 The large hail of continental areas is most likely to fall during the late afternoon and evening, and it is probable that some 85% of damaging hail occurs between 1300 and 2200 hours local time. In contrast the small hail of coastal regions and open seas exhibits little diurnal variation.

1.7 Duration

1.7.1 The most frequent duration of a hailstorm, at any point on the ground in the British Isles is about 2 minutes, with extremes in the range 10 seconds to 45 minutes. Long durations of hail are probably due to more than one storm cell, but excluding such occurrences, the average duration is about 5 to 6 minutes.

1.8 Diameters of hail cells

1.8.1 At ground level the diameter of a hail cell is most frequently about 2 to 3 km. A study of damaging hailstorms showed a range from a few metres to 120 km with 50% within 2 to 5 km. This suggests that the typical hail core of a mature storm is roughly circular in section, with a diameter of about 3 km, with occasional merging of neighbouring cells forming more extensive areas of hail.

2 SNOW

2.1 General

2.1.1 Data on the frequency and intensity of snowfalls are even more limited and there are added complications due to the variation of temperature with height and the occurrence of snow being dependent on elevation.

2.1.2 Snow is precipitation in the form of ice crystals; these crystals may exist singly, but more often they coagulate to form snow flakes. The crystals may be formed either by the spontaneous freezing of supercooled water drops at a temperature below -40°C, or more likely by the diffusion and direct condensation of water vapour onto suitable freezing nuclei in an ice-saturated atmosphere at much higher threshold temperatures. The ice particles then start to fall, when collisions with any supercooled droplets result in growth by accretion to form snow pellets.

2.2 Distribution of incidence of snow

2.2.1 After falling below the altitude at which the temperature reaches 0°C, snow flakes begin to melt. Therefore the occurrence of snow at ground level is usually associated with temperatures of 2°C or lower, with persistent snow occurring at temperatures of 0°C or below.

2.2.2 Figures 3 and 4 show the average altitude above mean sea level (MSL) of the 0°C isotherm for January and July, and are a guide to the land elevation at which snow may be expected to lie during these months, but it must be noted that considerable variations can occur about these mean values.

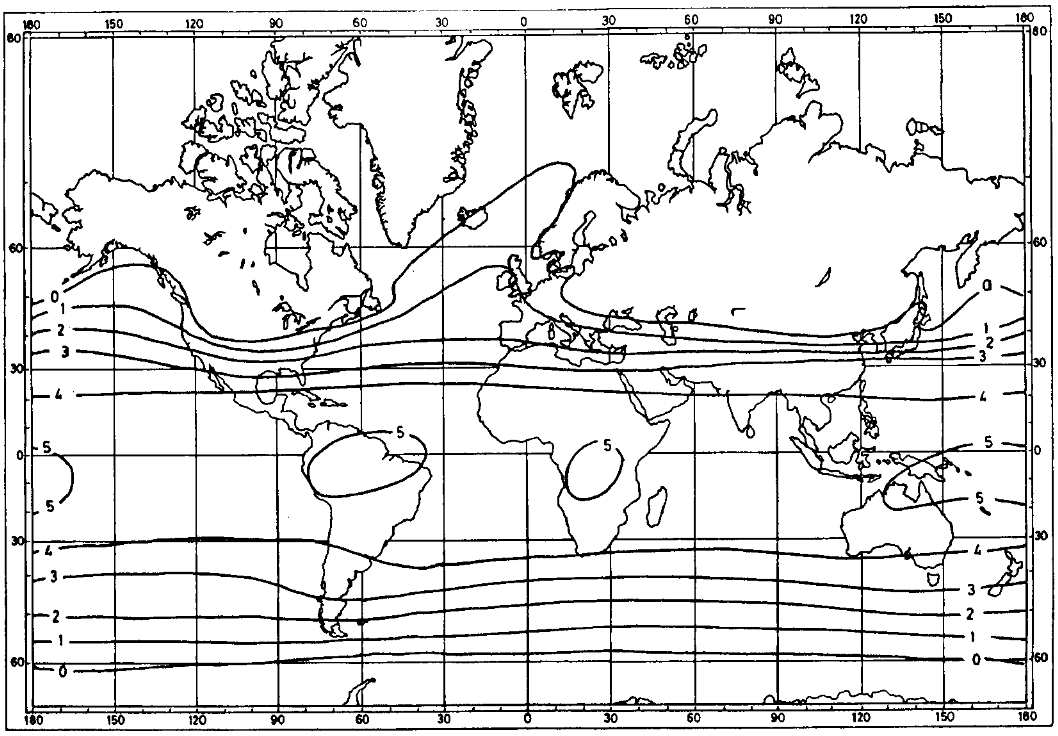

Figure 3. Height above MSL (in thousands of metres) of the 0°C isotherm in January

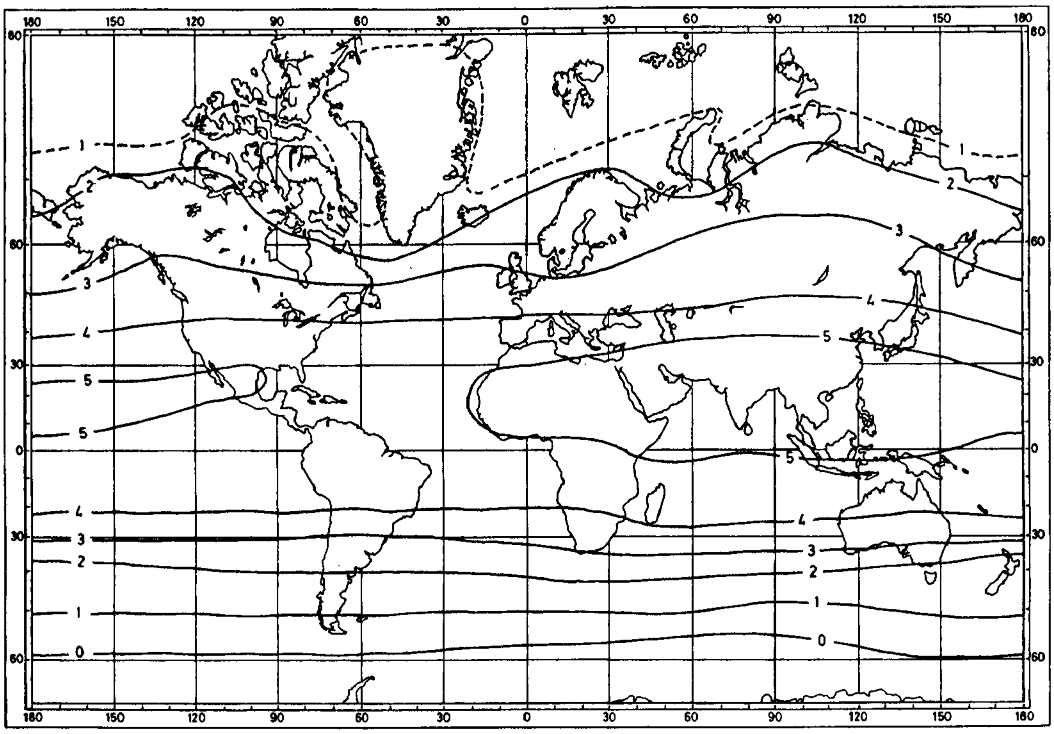

Figure 4. Height above MSL (in thousands of metres) of the 0°C isotherm in July

2.2.3 Figure 5 shows the percentage of time, throughout the year, when temperatures will be 0°C or below, and so indicates the relative tendency for snow to lie.

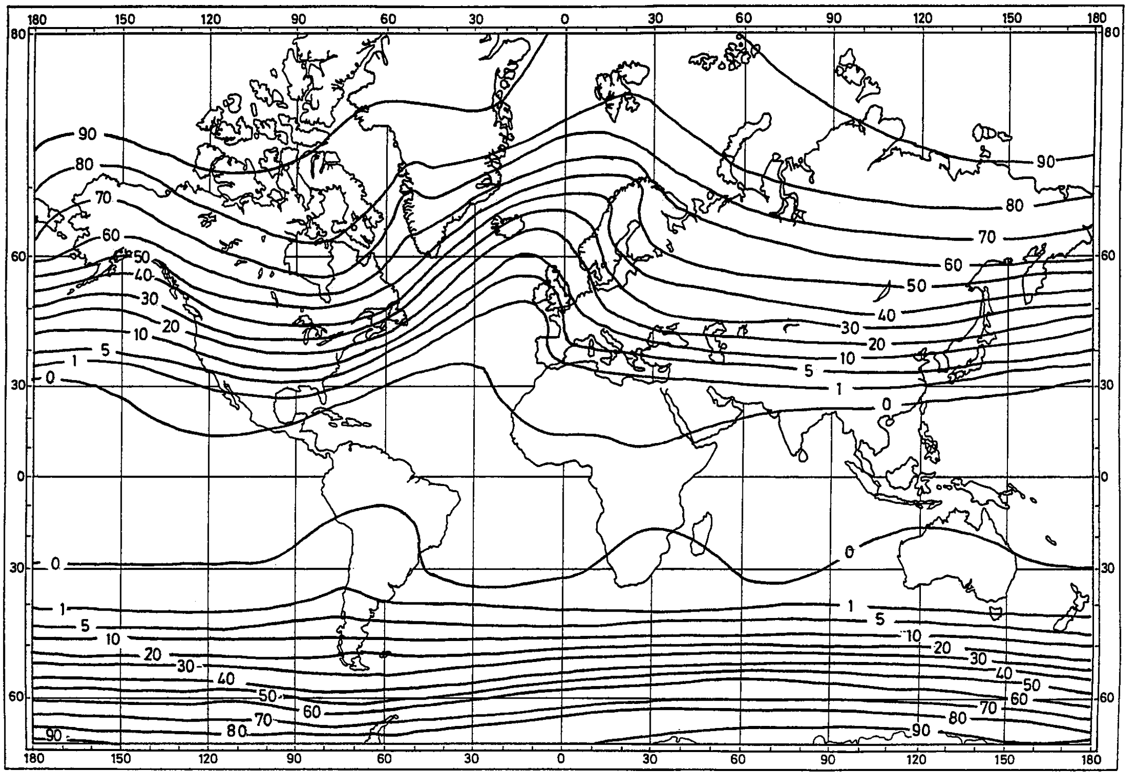

Figure 5. Percentage probability of occurrence of a temperature of 0°C or below (MSL)

2.2.4 There are large areas of the world where snow never occurs at low levels, for example between latitudes 30° North and 30° South. It is rare at mean sea level, although occasional snowfalls are experienced in South China in most winters. Between the 30° parallels snow does occur on ground above about 2500 metres, and outside this latitude band the frequency increases with increase of latitude.

2.2.5 In temperate climates, snow is much less frequent over the sea than over the land; although the heaviest snowfalls are most likely in coastal regions, where relatively mild and damp air masses off the sea move across the cold land. This effect may be increased if a range of hills parallel to the coast causes uplift. Owing to the low absolute humidity, the interior regions of large continents rarely experience high rates of snowfall; but any snow which does fall, may remain for long periods in the low temperatures of the continental winter. Heavy snowfalls may be associated with the convection set up within cold air-masses which have crossed warmer seas, and then later move inland.

2.3 Mass, size, and fall-speed of snow

2.3.1 Table 2 gives the relationship between the mass and the maximum linear dimensions of the various crystal forms. These relationships represent mean values, and any measurements made on individual crystals would show some variation from this mean.

TABLE 2

SNOW CRYSTALS: RELATION BETWEEN MASS (m) IN MILLIGRAMMES AND DIAMETER (d) IN MILLIMETRES OF THE SPHERE WHICH JUST CONTAINS THE CRYSTAL

Crystal Type	Mass/diameter relationship
Snow pellets	$m = 0.065d^3$
Rimed plates and stellar dendrites	$m = 0.027d^2$
Powder snow and spatial dendrites	$m = 0.010d^2$
Plane dendrites	$m = 0.0038d^2$
Needles	$m = 0.029d$ (d = length)

(A dendrite is a branched ice crystal)

2.3.2 Fall velocities of crystals, other than needles, rime and snow pellets, are almost independent of their dimensions, but the forms just mentioned show an increase in velocity corresponding with growth in size. Table 3 give the relationship between diameter, mass and fall velocity of six typical forms of snow crystal.

TABLE 3

RELATION BETWEEN DIAMETERS, MASSES AND FALL VELOCITIES OF SNOW CRYSTALS

Crystal Type	Diameter (mm)	Mass (mg)	Fall speed (cm/s)
Needle	1.53	0.004	50
Plane dendrite	3.26	0.043	31
Spatial dendrite	4.15	0.146	57
Powder snow	2.15	0.064	50
Rimed crystals	2.45	0.176	100
Graupel	2.13	0.80	180

3 ICE

3.1 General

3.1.1 Ice forms on objects when fog, cloud or rain is present at temperatures below 0°C; or when the object itself is below this temperature, and also below the frost point of the air surrounding it. Although this section deals mainly with ice formation on ground objects, it is also important to aircraft, and ice at upper levels is discussed briefly. There are three main types of icing although intermediate and mixed types do occur.

3.2 Types of ice

3.2.1 Hoar frost is a feathery deposit of ice crystals, and has a density of about 0.1 g/cm^3 or less. It forms on objects which are at temperatures below 0°C, by sublimation of water vapour; that is, the water changes directly from vapour to solid without passing through the intermediate liquid stage. For this process to occur, the temperature of the object must also be below the frost point. Any water vapour in excess of that required to achieve saturation with respect to ice will be deposited to produce the hoar frost, but the weight of such deposits is usually small.

3.2.2 Rime occurs when supercooled water drops freeze on contact with objects at temperatures below 0°C, and this implies the presence of fog or cloud consisting of such drops; the deposit comprises opaque white ice, which grows out to windward on exposed objects. Rime density may be anything between 0.3 and 0.9 g/cm^3. The amount of rime deposited depends on the wind speed, duration of time in cloud or fog, amount of free water in the air, and drop size distribution of the liquid water; and also on the aerodynamic flow past the object which determines the efficiency of catch.

3.2.3 This 'catch efficiency' is greatest for objects with a small radius of curvature, and therefore ice collects most readily on such items as the supporting guys of a mast. However, as the ice accumulates, the effective shape of the object changes, and so alters the catch efficiency which then becomes more difficult to define. When the rime is accompanied by strong winds, large droplets can spread appreciably before freezing, and the rime may then take the form of glazed ice. This differs from usual rime in that it is tough and difficult to remove, whereas normal rime can be broken off readily even though it may grow more than a metre into the wind.

3.2.4 Glazed frost, known as black ice or glazed ice, consists of a layer of clear ice deposited on surfaces where temperatures are below 0°C. A layer of smooth ice is formed when rain falls on a freezing surface, or when warm moist air follows a prolonged period of severe frost, for example with the arrival of a warm front. The ice deposit continues to grow until the warm air brings the temperature of the surface up to 0°C. This type of ice is tough and hard to remove, and can reach a considerable thickness, although the conditions which favour its formation are normally transient and occur only infrequently.

3.3 Conditions suitable for ice formation

3.3.1 Hoar frost requires cooling of the air and of the object on which it is to form, and so is usually associated with conditions favouring radiation cooling such as clear still nights.

3.3.2 Rime requires an adequate supply of liquid water and therefore, other things being equal, the probability increases with altitude on exposed hillsides; the risk being multiplied by a factor of 5 to 10 between mean sea level and 1000 metres. The stronger the wind, the more liquid water drops reach the object in a given time, and the faster the ice builds up; while the greater wind strength also increases the strain on cables, guys, etc.

3.3.3 Really serious icing may be due to a combination of rime and precipitation ice; a high water content of the air being a necessary requirement. In the British Isles, winds from between south and west are most likely to possess this high water content while winds from between north and east are more likely to have the required freezing temperatures. Prolonged icing is most likely over hill and mountain ranges, particularly in cooler maritime climates with winds off the sea. Localities where very large deposits of rime ice can build up include the hills and mountains of west Scotland, west Norway, west Japan and Greenland.

3.3.4 Glazed frost needs air with temperatures higher than 0°C above a warm frontal surface, with a sub-zero air layer below, to supercool the failing rain droplets. It is rarer than rime, and often restricted in area, but affects low ground as much as high ground. In winter it occurs quite often in eastern Canada, occasionally in eastern and northern Europe and more rarely in Britain.

3.4 Water content of fog, cloud and rain at temperatures below 0°C.

3.4.1 It is necessary to distinguish between fog and cloud, since there are important differences. The free liquid content of fog seldom exceeds 0.1 to 0.3 g/m^3, but in cloud it may be as high as 3 g/m^3 at heights around 2500 metres above sea level, and more at higher altitudes.

3.4.2 For those localities likely to be covered by cloud at temperatures below 0°C, usually the windward slopes of hills and ridges rising above the general ground level, the free liquid water content may be appreciable when the cloud cover occurs. In extensive layer type clouds the amount of liquid water may average about 0.5 g/m^3, and for convective cloud below 2500 m the average may exceed 1 g/m^3.

3.4.3 Peak values in cloud associated with forced ascent over high ground or in convective cloud would be about 3 g/m^3, with temperatures between 0°C and -10°C at altitudes up to 2500 m. The peak values in convective clouds would usually last only a few minutes, but in layer cloud the maximum could be of much longer duration. The median diameter of supercooled cloud droplets is about 20 micrometres, which is similar to that in freezing fog.

3.4.4 Freezing rain usually falls when the temperature is between 0°C and -4°C, with a liquid water content of around 0.15 g/m^3. Rain drops are likely to be of the order of 1 mm in diameter but could approach 5 mm on rare occasions.

3.5 Altitude variations

3.5.1 All the three main types of ice can be experienced at any level, but for practical purposes only rime and glazed frost present a hazard to aircraft and guided missiles in flight.

3.5.2 The free water content of ascending air can be estimated, and it is possible to show that this reaches maximum values of about 8 g/m^3 in tropical clouds at heights of about 8 km above the cloud base and at temperatures around -10°C. In temperate climates the maximum is about 5 g/m^3 at heights of about 6 km and temperature around -25°C.

3.5.3 Strong updraughts favour the carrying upwards of substantial amounts of supercooled water, and therefore favour ice formation. It follows that icing is most likely in the region of active frontal clouds, at heights corresponding to temperatures between 0°C and -15°C; or in convection clouds at even lower temperatures. For an appreciation of aircraft icing problems see Reference 6.

3.5.4 Over Britain and surrounding areas, icing is also common near the tops of fair-weather strato-cumulus layers in winter and spring, though rare in the first few hundred metres above the sea in these conditions. Reference 7 contains additional data for the operation of helicopters.

4 DESIGN CRITERIA

4.1 Hail

4.1.1 In those regions of the world where hail is most intense, there are, on average, two hailstorms during the most severe month for hail in each year. The average duration of each storm is about ten minutes. In view of the briefness of these periods, hail is not an essential consideration in the design of most materiel. Exceptions are where hail could endanger life or essential equipment.

4.2 Snowload

4.2.1 'Snowload' is defined as the weight per unit area of snow accumulation on the ground and items of materiel are considered to experience the same snowload as the adjacent ground though, in practice, it is usually somewhat less.

4.2.2 The effects of the structural load imposed by the accumulation of snow should be taken into account for materiel such as buildings, shelters, vehicles and other relatively large items which are exposed to snow in the regions of the M3 and C categories described in Chapter 1-01 of this Part.

4.2.3 The frequency of snow clearance is a principal factor determining the snowload on materiel, so that for portable and mobile materiel three categories are defined in Chapter 7-02 of this Part of the Standard. The snowloads, associated with each of these categories of materiel are given in Table 4 and are those which, on average, are equalled or exceeded once in any ten consecutive years. The highest values of snowload are also quoted.

TABLE 4

SPECIFIED LIMIT AND HIGHEST RECORDED SNOWLOADS

Type of materiel	Period of snow accumulation	Specified limit of snowload kg/m^2	Highest recorded snowload kg/m^2
Semi-permanently installed	Whole season	240	586
Temporarily installed	Single snow storm	100	191
Portable	24 hours	50	113

4.2.3 Snowloads on materiel at sea are generally not sufficient to present a hazard. However, if snowloads are to be taken into consideration in this environment for a particular item of materiel, then the value given in Table 4 for portable materiel should be used. Snow loading is not applicable to the air environment.

4.3 Ice accumulation

4.3.1 The accumulation of ice on items of materiel should be taken into consideration in its design if it could enter the regions of the M3 and C categories. The principal sources of this ice are frosting, freezing rain, re-freezing of thawing snow and freezing of condensation. The thickness of the ice will depend upon the period of exposure, the contours of the item of materiel and the heat dissipation of the materiel if operating.

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CHAPTER 7-02
THE EFFECTS OF HAIL, SNOW AND ICE

1 INTRODUCTION

1.1 The ice forms discussed in this chapter have a common denominator in that they are all the solid state of water, however, they represent different kinds of environmental hazard. For instance, hailstones can cause damage by impact with ground installations, or flight vehicles while heavy snow falls create the hazard of structural loading. The toughness and adherence of ice enable rime and glazed frost to build up on vertical or fast moving surfaces. Such accumulations can affect the function of radar systems, jam control surfaces, shift the centre of gravity of missiles, or impair the performance of aircraft.

2 HAIL DAMAGE

2.1 General

2.1.1 Many well documented reports are in existence concerning hail damage to aircraft in flight. There is little information available which is directly relevant to the effects of hail damage to missiles that is not of a classified nature. Very little information is available on the effects of hail on ground installations.

2.2 Aircraft operation and extent of hail damage

2.2.1 The extent of hail damage sustained in flight is a function of the stone size, hardness and aircraft speed. Cases of damage inflicted by hailstones as small as 1 mm in diameter have been reported, but serious damage usually involves encounters with larger stones. It must be pointed out that most of the observations relate to aircraft flying at subsonic speeds; the effect of hail encounters involving supersonic vehicles is likely to result in much more severe damage.

2.2.2 An analysis of 47 cases showed that the leading edges, engine cowlings and cooling fins were the most susceptible to damage. The nose and cockpit areas also suffered considerably in several instances. Turrets, radar coverings, aerial loop housings and landing and navigational lights were the chief accessories subject to damage. Reference 1 gives full histories of the hail encounters, and photographs of the damage.

2.3 Estimation of hailstone size from aircraft damage

2.3.1 An estimate of the maximum hailstone size likely to be encountered by aircraft has been made by analysis of photographs of actual hail damage. The estimate indicated a largest hailstone size of approximately 50 mm in diameter. The kinetic energy of impact of such a stone, assuming a specific gravity of 0.91 at an air speed of 90 m/s is 250 joules.

2.3.2 In a separate investigation, 96 cases of hail damage were analysed to determine the size of hailstones. The results are given in Table 1. It should be noted that since the aircraft flights were not uniformly distributed over the various height ranges, Table 1 cannot be used to infer the distribution of hail encounters with height.

TABLE 1

SIZE OF HAIL ENCOUNTERED IN FLIGHT

Height km	Diameter in millimetres ± 6mm								
	6	6-19	19-32	32-45	45-57	57-70	70-83	83-95	95-110
	Number of Cases								
15-12			1						
12-9		5	5	1	2				
9-6	1	4	2	2	1				
6-3	8	3	3	4	1		1		
3-0	10	20	12	8		1			1
Total	19	32	23	15	4	1	1	0	1
	Percentage								
Total	20	33	24	16	4	1	1	0	1

2.4 Experiments using simulated hailstones

2.4.1 In order to establish some relationship between the extent of hail damage, hailstone size and impact velocities, ice spheres of various sizes were fired at typical wing sections. The following conclusions were drawn:

(a) The extent of damage varies with the mass of the hailstone, the impact velocity and the impact angle and the thickness, strength and shape of the material.

(b) Leading-edge dents 2.5 mm deep and sufficiently large to require repair, were produced on a wing section, 1 mm 75S-T aluminium, by:

(i) A 20 mm ice sphere at 190 m/s

(ii) A 32 mm ice sphere at 135 m/s

(iii) A 48 mm ice sphere at 95 m/s

A wing section, 1.1 mm 24S-T aluminium, was damaged to the same extent by ice spheres of the same three sizes, at speeds of 135, 80 and 55 m/s respectively.

(c) 50 mm hailstones cause extensive damage to aircraft at speeds above 135 m/s. At 170 m/s, a 48 mm ice sphere caused the surface of a 75S-T aluminium skin to stave in over an appreciable area; at 130 m/s it had the same effect on a 24S-T aluminium skin.

(d) Hailstones less than 20 mm in diameter do not cause significant damage at aircraft speeds between 90 and 135 m/s.

2.5 Risk of hail encounters related to altitude

2.5.1 Hail of any size is unlikely to be encountered above approximately 10 to 14 km above sea level in the middle latitudes, and 17 to 18 km above sea level in the tropics.

2.5.2 An analysis of 188 cases of hail damage to USAF aircraft attempted to relate the incidence of damaging hail with altitude. Figure 1 shows the result of this analysis. The validity of this histogram is questionable, as no figures were available on the percentage of flying in various altitude bands. However, the main peak clearly occurs in the 1. 5 to 3 km above sea level band, but the other peaks are probably the result of more frequent flying at these altitudes. By analysing a further group of 62 hail encounters that occurred in the region above 7.5 km above sea level, a more reliable indication of the variation of hail frequency with altitude at higher levels was obtained, and the results are shown in Figure 2.

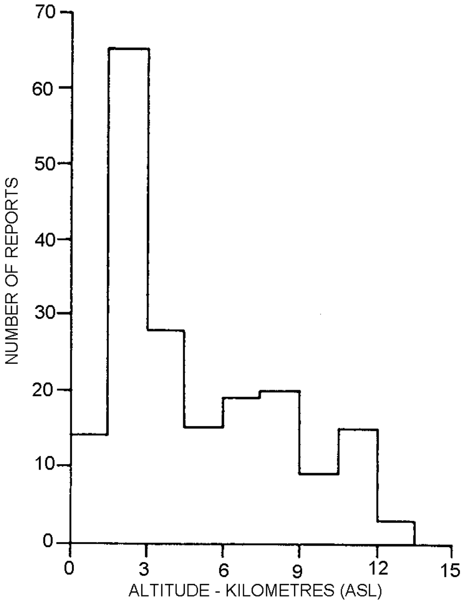

Figure 1. Frequency of hail incidents as a function of altitude

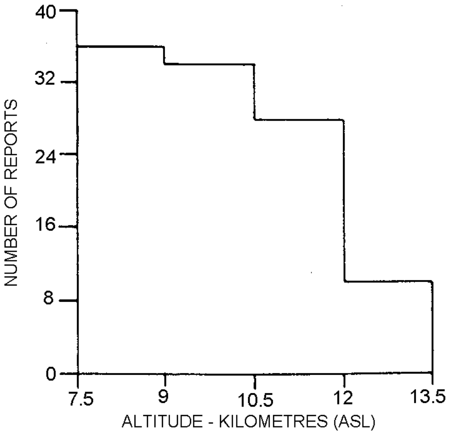

Figure 2. Frequency of hail incidents above 7.5 km, as a function of altitude

2.5.3 As the hail incident frequency roughly compares with the amount of flying at the various levels it is impossible to state that the danger of encountering hail diminishes with altitude. There is insufficient data to enable any generalizations to be made on how the maximum size of hailstones varies with height, although Table 1 gives some information.

2.6 Risk of hail encounters related to geographical location

2.6.1 Reports of damaging encounters with large hail, that is 20 mm to 50 mm in diameter, are mainly confined to continental and coastal areas in the middle latitudes. There is little information on the size of hail in the polar regions, but an estimate suggests a maximum stone size of 10 mm, the risk to subsonic aircraft being consequently small. Isolated reports exist of slight damage being inflicted during flights in the tropics, but in these regions hailstones are seldom greater than 15 mm diameter.

2.7 Risk of hail encounters related to seasons and time of day

2.7.1 Figures 3 and 4 show the hourly and monthly distribution of hail encounters. These histograms were constructed from analysis of encounters over the United States. The diurnal variation shown in Figure 3 is roughly applicable to other continental areas, but hail over coastal regions and oceans probably has no marked daily pattern. The seasonal variation differs with locality, but over the continents damaging hail occurs mainly in late spring and summer.

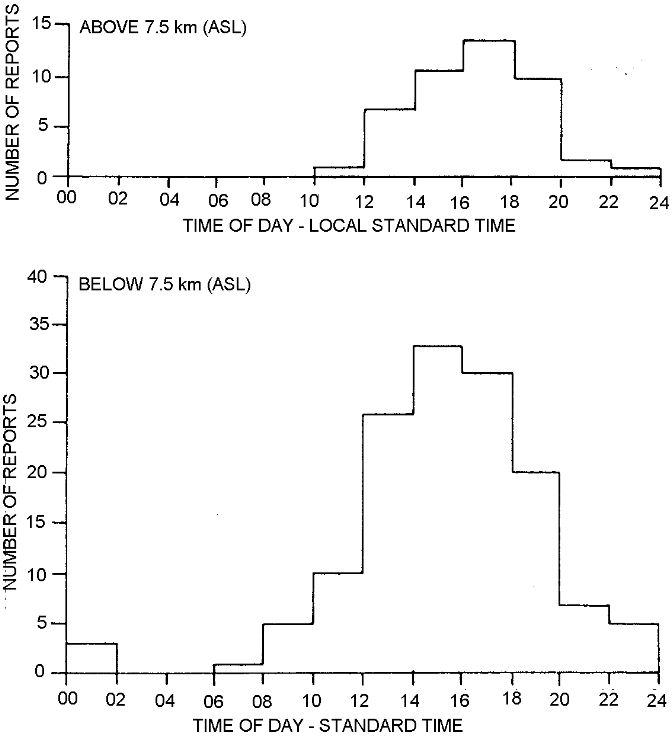

Figure 3. Frequency of hail incidents, as a function of time of day

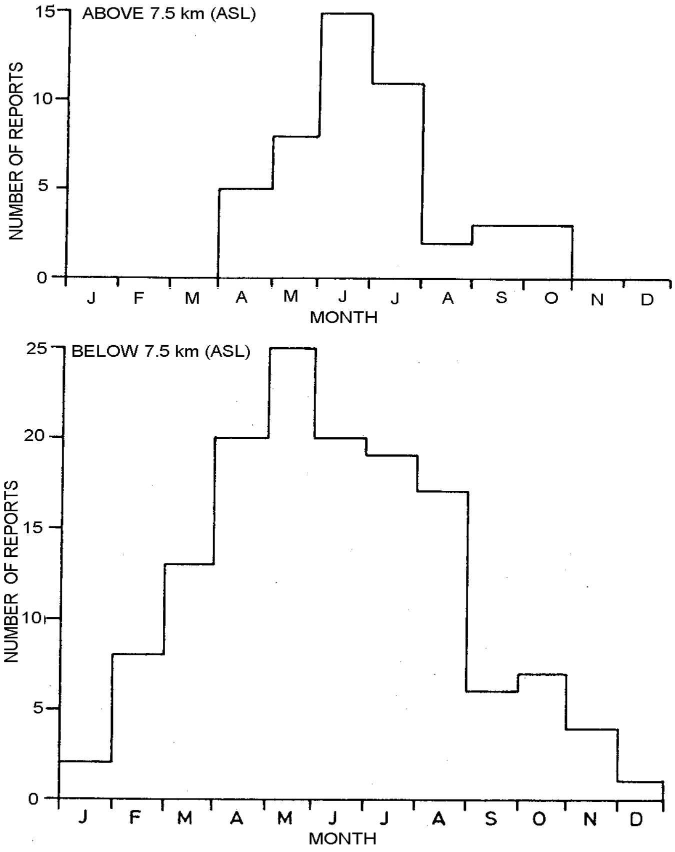

Figure 4. Frequency of hail incidents, as a function of month

2.8 Terminal velocity and kinetic energy of hail

2.8.1 The dynamics of large hailstones have been investigated, to determine the kinetic energy on reaching the ground. The terminal velocity is a function of the stone size, and this relationship is examined in the previous chapter. Information is also given on the variation between the size and maximum kinetic energy, that is, kinetic energy at its terminal velocity.

2.9 Hailstone size

2.9.1 The maximum size of the hailstones reaching the ground is of importance in estimating the possibility of damage, and reference should be made to the previous chapter.

2.10 Reports of hail damage to ground equipment

2.10.1 Although only isolated reports of damage to ground equipment exist, principally to roofing materials, there can be little doubt that damage could be sustained by impact of the large hailstones.

3 SNOW

3.1 General

3.1.1 Snow can affect equipment in a number of ways:

(a) By accumulating on surfaces and imposing a structural load.

(b) By clogging exposed mechanisms and blocking air intakes.

(c) By sifting into equipment compartments. This hazard is greatest when the snow is fine and windblown, enabling it to gain access through small cracks and crevices.

(d) By covering radomes and aerials and impairing their electrical performance. The effect of precipitation in the form of snow on radar propagation, as opposed to snow cover, is discussed later.

3.1.2 The accumulation of snow on the ground can impede transport, but this is not dealt with here.

3.2 Possible magnitude of snow level

3.2.1 In certain places, such as the mountain regions of the Northern United States, snow on the ground may accumulate to very great depths. At Mount Ranier, Washington, US, for instance, the snowfall averages 15 metres annually and accumulates to a depth of 3.7 m. The snow is highly compacted and has an average specific gravity of 0.5. This would result in a snow load on the ground of 1830 kg/m^2. A snow load of this magnitude, accumulating on the horizontal surfaces of a structure or equipment, could cause collapse or damage unless suitable design criteria have been adopted.

3.3 Permanently sited structures and equipment

3.3.1 For permanently sited structures or equipment, the design criteria, with respect to snow load, is generally based on the maximum measured depth of snow on the ground. In one method of computing the anticipated snow load the extreme maximum snow depth record is selected and converted to a load by assuming a given snow density, and then adding the maximum weight of rain that might be expected to fall in one day in early spring. The last factor is included because of the prevalence of roof failures during the early spring rains. Fuller information on this method of calculating maximum snow loads on horizontal surfaces is given in Reference 2.

3.3.2 A more recent statistical method of obtaining a figure for snow cover, together with the probability of its being exceeded in any one year, is described in Reference 3.

3.3.3 It should be noted that these calculations for snow loads apply to horizontal surfaces. Equipment with no horizontal surfaces and whose sloping surfaces are greater than the angle of repose of snow, approximately 60°, need not be designed to support any snow load.

3.4 Portable or mobile structures and equipment

3.4.1 For portable or mobile materiel, the snowloading will be directly related to the frequency of snow clearance. Therefore, three categories of materiel are defined, each having a distinctly different frequency of snow clearance during deployment. in Service. The three categories are:-

(a) Semi-permanently installed materiel. This group applies principally to semi-permanent installations, which, although demountable, are not very mobile. In general, snow would not be removed between snowfalls and therefore the loading is due to the whole season's accumulation.

(b) Temporarily installed materiel. This type applies to large items such as portable hangars upon which snow collects. The snow is cleared between storms and the snow loading is therefore the amount resulting from any single snowstorm.

(c) Portable materiel. This applies to small items such as tentage, which may be moved daily. Distortion arising from snowloading will make daily clearing essential and consequently, accumulations of snow will not exceed those resulting from a 24-hour snowfall.

3.4.2 The snow loads apply only to unheated horizontal surfaces, and are regarded as valid for any location with snow risk.

3.5 Windblown snow

3.5.1 Windblown snow may gain access to the interior of equipment compartments, where it may remain either as a snow deposit, or melt and possibly re-freeze as solid ice. The equipment may become clogged by snow, and mechanisms become inoperative. If the snow melts, the risk of moisture effects on materials and components is present.

3.5.2 A snow-bearing wind encountering an obstacle will experience a change of velocity which may lead to the formation of drifts. Drift formation on critical areas can be minimized by erecting collection or blower fences or, in the case of roads, streamlining the road section.

3.6 Visibility in snow

3.6.1 The reduction in visibility caused by precipitation depends upon the characteristics of the precipitation, for example, its size, nature and intensity. To a lesser extent, it depends upon the increase in humidity caused by evaporation from the precipitation itself. The reduction in air transparency caused by drizzle and rain is described in Chapter 6-02.

3.6.2 Visibility is often reduced below 1000 metres in moderate snow, while it may fall to between 50 and 200 metres in heavy snow. The effect of snow is more fully examined in Reference 4, which also relates the expected visibility to the rate of snowfall.

4 EFFECT OF HAIL AND SNOW ON RADAR PERFORMANCE

4.1 General

4.1.1 Precipitation impairs radar propagation by attenuating the radar energy and by producing unwanted echoes, known as clutter, on the radar display.

4.1.2 The effect of rain on radar is discussed elsewhere in this Standard, and the following comments are concerned with the modification of these effects when the precipitation is in the form of hail or snow.

4.2 Attenuation

4.2.1 The current knowledge of attenuation by hail and dry snow is incomplete in detail, but it is known to be considerably less than that by rainfall of comparable intensities. Melting snow gives rise to significant attenuation which is probably at least as great as that by rain of similar intensity, particularly at wavelengths of 5 cm and below.

4.3 Clutter echoes

4.3.1 Snow and hail less than 5 mm in diameter, produce echoes only approximately 1/5th as intense as rain of equivalent precipitation rate. This is because the dielectric constant of ice is much less than that of water at centimetre wavelengths. If, however, the hail or snow is in the process of melting and is covered with a layer of water, it will scatter the radar energy at least as effectively as water drops of the same size.

4.3.2 The echoes produced by large hailstones will, in general, be stronger than that from rain at the same precipitation rate.

5 ICE

5.1 General

5.1.1 The majority of the quantitative investigations and reports on the effects of ice accretion are concerned with aircraft operation. The performance of an aircraft or missile may be impaired, for example, by ice accumulating on the external surface, by blocking of air intakes or by locking controls. Unprotected missiles carried externally on a parent aircraft will be subject to the same icing risk as the airframe. Although no information is available on the occurrence or effect of missile icing in the free flight phase, it is probable that icing will occur at low flight velocities in unfavourable meteorological conditions.

5.1.2 The principal reported effects of icing on ground objects are those due to structural loading and the electrical characteristics of ice deposits.

5.1.3 The accumulation of ice on ships can effect their stability and the operation of equipment installed on the open decks.

5.2 Icing of aircraft

5.2.1 Clouds consisting wholly or in part of supercooled water droplets are of common occurrence in the atmosphere. Such droplets are in an unstable state and will freeze when subjected to mechanical shock. It is the process of supercooled water droplets impinging on an aircraft that is the basic cause of icing.

5.2.2 Dangerous icing conditions are normally only encountered in clouds within a certain temperature range. For this reason the meteorological factors affecting icing are concerned with temperature and the constitution of clouds, that is, supercooled water content and drop size.

5.2.3 Supercooled water droplets may exist in the atmosphere down to a temperature of -40°C, below this temperature even the smallest drops freeze. Aircraft icing is thus normally confined to the temperature band 0°C to -40°C, with the greatest hazard in the upper half of this temperature range. Occasional reports of icing at lower temperatures may be explained by the adherence of ice crystals.

5.2.4 The heights of the 0°C and -40°C bands vary with the prevailing weather situation, the season of the year and geographical situation. Charts showing the average height of the 0°C isothermal surface over the world, for representative months, are contained in Reference 5. Examination of more detailed information than is given by the average height of the 0°C surface, has indicated that:

(a) Airframe icing may occur in the British Isles at heights above 1200 m above sea level at any time of the year, but in summer it usually occurs only above 2700 m above sea level. In the months November to April inclusive, it may occur below 1200 m above sea level.

(b) Near the equator, airframe icing will not occur below 3000 m above sea level.

5.2.5 The rate of accumulation of ice on an aircraft flying in icy conditions depends upon the amount of free supercooled water per unit volume of air and upon the drop size. The rate of ice accumulation increases with drop size and the supercooled water content of clouds. Information on the drop size and supercooled water content of various types of clouds is contained in Reference 5.

5.2.6 The three main types of icing accretion that occur on the ground, namely, hoar frost, rime and glazed frost (sometimes called glaze ice) may also form on aircraft in flight. As on the ground, intermediate types may occur and two types can exist simultaneously on different parts of the aircraft. The most important factors influencing the type of ice accretion are drop size and the degree of supercooling. Large drops at temperatures just below 0°C favour the formation of glazed frost, while smaller drops at lower temperatures tend to produce rime ice.

5.2.7 The rate of ice accretion depends upon the airframe characteristics and the aircraft speed, the main factors being as follows:

(a) Ice formation occurs primarily on the leading edges of the airframe, although it is not confined to these areas. The smaller the radius of curvature of the leading edges, the greater is the efficiency of catch of the supercooled droplets. Thus parts of the aircraft having small radius of curvature, such as aerials, wing and tail leading edges, air intake edges and the entry guide-vanes of jet engines, are more liable to icing than the bluffer shaped parts of the airframe.

(b) The relative motion between the aircraft and the surrounding air results in 'kinetic heating' of the airframe. The magnitude of kinetic heating is small on low speed aircraft (about 1 °C rise on a leading edge moving in clear air at 52 m/s) but it increases with the square of the aircraft speed. In cloud the temperature rise is less, owing to the presence of water droplets causing evaporative cooling.

(c) Calculations have been made, for various cloud conditions at various aircraft speeds and pressure levels, of the ambient air temperature which because of kinetic heating will give a temperature of 0°C at the aircraft leading edge surfaces thus affording protection from icing. This calculated temperature is known as the 'threshold icing temperature'.

(d) As an example, an aircraft flying at a speed of 260 m/s, in cloud consisting of supercooled water droplets of density 0.5 g/M^3 at a pressure level of 500 hPa, would be safe from airframe icing with ambient temperatures down to -15°C; while at a speed of 360 m/s in the same conditions the aircraft would be protected down to -31°C. If ice crystals are present in the cloud in addition to supercooled water droplets, the threshold temperatures are considerably higher.

(e) An icing hazard associated with high speed flight occurs during the penetration of ice crystal clouds. At speeds above 335 m/s at temperatures below -40°C the wing surface temperatures may be raised above 0°C and ice crystals intercepted by the leading edges may melt sufficiently to enable them to adhere.

5.2.8 The severity of icing is defined as the rate of accumulation of ice by weight per unit area per unit time. However, normal practice among pilots is to rate the icing severity as 'heavy (or severe) ' 'moderate' or 'light' and although these classifications are highly subjective it has been suggested that among experienced pilots the term severe represents an icing rate of about 4 $g/cm^2/hr$.

5.2.9 The following generalizations have been made with regard to severity of icing in different cloud types at various temperatures:

(a) With convective clouds (Cumulus and Cumulonimbus), at heights where temperatures are between about -20°C and -40°C, the chance of moderate or severe icing is small except in newly developed cloud. However, light icing is possible. At heights where the temperature is between about -20°C and 0°C, the rate of icing may be severe over substantial depth of cloud for a wide range of cloud base temperatures.

(b) In layer clouds, (Stratocumulus, Altocumulus and Stratus) 900 m thick, having a temperature at the top of the cloud between 0°C and -10°C, moderate icing may be experienced. If the cloud top temperature is less than -10°C the icing is likely to be light.

(c) With Altostratus and Nimbostratus clouds the chances of severe icing are small, and any light icing is probably confined to a shallow layer of cloud about 300 m thick immediately above the 0°C level.

(d) Cirrus clouds normally consist entirely of ice crystals, which do not usually constitute an icing hazard to aircraft except in high speed flight.

(e) Icing tends to be more severe in Orographic clouds, that is clouds formed when air is forced to rise over hills and mountains, than in clouds formed by other means away from high ground. Some indication of the chance of icing in cloud can be obtained from Table 2, prepared from reports from weather reconnaissance aircraft.

TABLE 2

NUMBER OF REPORTS OF ICING

Cloud type	Rime ice			Glaze ice			Total reports	
	Light	Moderate	Heavy	Light	Moderate	Heavy	Ice	No ice
Stratus	0	0	0	0	0	0	0	88
Stratocumulus	57	30	5	5	0	0	97	114
Cumulus	35	11	8	15	10	3	82	19
Cumulonimbus	0	2	2	1	0	2	7	0
Nimbostratus	11	11	3	0	2	3	30	3
Altostratus	9	4	0	2	1	0	16	85
Altocumulus	49	20	3	5	3	0	80	88
Altocumulus & Altostratus	30	5	1	1	0	0	37	47

5.2.10 The principal ways in which icing affects performance are through alteration in aerodynamic properties, increased weight, interference with control surfaces, and to a lesser extent, reduction in efficiency of measuring instruments and communication facilities. The principal factors are as follows:

(a) Ice formation on the leading edges of the airframe causes changes in the pattern of the airflow round the affected part. Such a formation causes decreased lift and increased drag, and could possibly introduce buffeting of the tail. Control of the aircraft can be endangered by the build up of ice on the leading edges of the fin and rudder. Ice accretion on other parts of the wing and fuselage can also lead to a considerable increase in drag.

(b) Icing adds to the total weight of an aircraft but this is generally not of primary importance. The most serious effect is due to the unequal distribution of ice, which may set up vibrations in a particular component or throughout the aircraft.

(c) Ice can accumulate on the leading edges of movable control surfaces, interfering with the control of the aircraft. If the icing is severe the gap between the control surface and the fixed surface ahead of it can become blocked, thus restricting or preventing movement of the control surface.

5.2.1 Effects of icing on turbine and jet engines.

(a) The air intakes of turbine and jet engines are subject to icing during flight in supercooled droplet cloud. The parts most susceptible to icing are those with a small radius of curvature, such as the rim of the intake, the guide and swirl vanes.

(b) Centrifugal compressors are relatively unaffected by any but the severest icing conditions. On the other hand, axial flow compressors are much more sensitive to icing which may lead to loss of power, possible compressor stall, flame out and even damage to the vanes.

(c) In general, icing is directly proportional to the rate of air intake, and thus to the number of engine revolutions per minute. At speeds above about 130 m/s the icing rate increases with the increase of air speed, but below this speed the icing rate tends to be independent of speed changes.

5.2.12 Reference 5 provides more detailed information on the accretion of ice on aircraft.

5.3 Icing of ground objects

5.3.1 Reports of mechanical damage due to ice loading are mainly restricted to the overhead wire systems of electrical power, telephone and telegraph networks. Glazed frost, although of rarer occurrence than the other icing forms is undoubtedly responsible for most of this damage. Its greater specific gravity, high degrees of tenacity and the fact that its formation is normally associated with high winds account for this.

5.3.2 Ice loads commonly inflict damage on wire systems through unequal loading or unloading of lines. The most frequent type of damage to overhead lines in Great Britain is caused by ice falling off conductors, which then rise abruptly and come in contact with higher level conductors causing a short circuit, which may burn and rupture the affected wires. Cases of wire breakages due to the dead weight of ice are rare, but even moderate winds of 4 to 6 m/s can cause extensive damage when acting on ice laden lines.

5.3.3 Apart from one or two isolated reports of damage to buildings due to excessive ice loads, little information is available on instances of structural failure. However, in the design of structures for areas subject to icing risk, the effect of ice loading should be considered, especially if the structure has members of small cross section, such as an aerial array.

5.3.4 Estimation of ice loads

(a) The procedure generally employed to estimate ice loads on horizontal surfaces is to obtain information on the amount of precipitation at sub-freezing temperatures for the region in question. It is usually assumed that the weight of this precipitation represents the ice load on a horizontal surface.

(b) The estimation of ice accumulation on vertical surfaces and wires, from meteorological data, is difficult. Among the meteorological factors that have to be considered are wind velocity, air temperature, relative humidity, rate of and duration of precipitation, or water content of cloud or fog, and size and temperature of the drops. In addition, characteristics of the structural member or wire, such as size, conductivity and specific heat must be known. Attempts have been made to establish empirical relationships between the meteorological variables and the weight of observed ice accumulations on power lines, but the practical value of this work has been questioned.

5.3.5 The electrical characteristics of rime ice may be summarized as follows:

(a) The material is non-magnetic, possessing a relative permeability of one.

(b) The relative permittivity (dielectric constant) has a value between 2.0 and 3.1. The permittivity increases with density and age, but decreases with temperature. It is constant with frequency over the band 200 Hz to 150 MHz.

(c) The loss tangent of rime ice is generally a small quantity, with a value of approximately 0.04 at 500 MHz. The losses increase sizeably with frequency and age. A small increase in loss occurs with density and temperature.

5.3.6 The principal electrical effect of ice is due to the accumulation of deposits on aerials and radomes, where it results in a loss of efficiency and distortion of the transmission pattern. The implications of this can apply throughout the radar, infra-red and visible frequency spectrum. Ice accumulation on a missile radome can result in the inability of a weapon to home on to its target, or even render operation of the weapon system impracticable. Although a thin layer of ice may be acceptable in some systems, in others an ice thickness at launch of more than approximately 0.25 mm might result in failure of the guidance system to lock onto its target.

5.3.7 Increases in losses have been reported with overhead electrical power networks, due to greater leakage over insulators because of ice accretion.

5.3.8 Icing of piston engine air intakes and induction systems results in loss of power by obstruction of the air passages, although the hazard has been reduced by the introduction of heaters and sheltered air intakes. In addition, movable parts may freeze up and become inoperative. Two forms of engine icing can occur at air temperatures above 0°C, throttle icing and fuel evaporation icing, details are as follows:

(a) The increased velocity of the air through the carburettor choke and past the throttle butterfly causes a lowering of the air temperature, and surfaces in contact are cooled locally. At air temperatures up to 5°C, with free water present, ice will build up on the exposed surfaces. This is known as throttle icing.

(b) Fuel-evaporation icing is caused by evaporative cooling of all surfaces which are wet with fuel. If the surface is cooled below the local dew point, or if free water is present and the local temperature is below 0°C, ice will form and may build up on the surface. Float-type carburettors which mix fuel with the air before the throttle, causing fuel evaporation to take place during the throttle process, are especially liable to this form of icing trouble. The degree of cooling will depend on fuel volatility, pressure in the induction system, inlet air temperatures and humidities, and the local air fuel ratio. The interaction of the various factors is complex but, in general, serious quantities of ice do not form with inlet air temperatures above 25°C whatever the humidity, or with relative humidities below 60% at any temperature. The most severe icing for a given relative humidity occurs with inlet air temperatures around 13°C.

5.4 Ice accumulation on ships

5.4.1 The most severe icing occurring on ships is that formed from freezing spray. This may be expected whenever the air temperature falls below the freezing point of sea water (approx. -2°C), and the wind, steepness of the wavefronts, and speed and lines of the ship are such that spray is blown over the vessel. The rate of ice accumulation due to freezing spray may be very high. Ships in a headwind in the Barents Sea have reported an ice build up rate on the sides and superstructure of 4 cm/hr.

5.4.2 The weight of ice may affect the stability of a ship, particularly when it accumulates on the masts and upperworks. The overall efficiency of the ship may also be lowered due to the icing of aerials, radomes, and equipment exposed on the open decks.

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CHAPTER 8-01
DELETERIOUS ATMOSPHERES

1 INTRODUCTION

1.1 Atmospheric pollution is a world-wide hazard and a vital factor in the selection of materials used in the design of materiel which may be subjected to a wide variety of operational, transportation and storage environments.

1.2 Pollution of the atmosphere by salt, combustion products, gases, dust and other contaminants results in the formation of deleterious atmospheres which may cause or accelerate the deterioration of materials through chemical or electrochemical attack. However, some pollutants mentioned in this chapter, such as carbon monoxide and carbon dioxide, although harmful to human health, do not affect most materiel.

1.3 Large quantities of pollutants are discharged into the atmosphere from the industrial and domestic use of coal, oil and other products. The main pollutants are normally carbon dioxide, sulphur dioxide, nitrogen oxides, smoke and acids.

2 SOURCES OF AIR POLLUTION

2.1 In this chapter the term air pollution refers to the outside atmosphere and not the interior of buildings or vehicles.

2.2 The sources of air pollution may be naturally occurring or derived from industrial activities; those chiefly associated with corrosion are listed below.

2.2.1 Natural sources include volcanic ash, soil and sand particles, sea salt nuclei, agricultural matter and airborne micro-organisms. Saline atmospheres arising from sea-water are included in this chapter, but hazards due to dust and sand are covered by Chapter 9-01 and biological hazards by Chapter 11-01.

2.2.2 Industrial and other man-made sources include power generation, chemical plants, transport, quarrying, domestic heating, waste disposal, agricultural fertilizers, sprays and dusts.

3 AIR POLLUTANTS

3.1 Classification

3.1.1 Pollutants may be classified as gases, vapours, or particulate matter consisting of solid particles and liquid droplets. Particles may be further divided into two categories, that is, large particles that settle rapidly and small particles that remain in suspension in the air for varying periods of time.

3.1.2 An estimation of particle sizes and settling rates is shown in Table 1 (Merriman), relating to the air pollution which typically results from quarrying limestone. However, the dry deposition velocity at the surface is more important than the settling rate, since turbulent motions will dominate the vertical distribution of particles.

TABLE 1
PARTICULATE CHARACTERISTICS

Particle diameter	Description	Rates of settling for limestone	Remarks
Micrometers	Heavy dust or grit		Particles fall with increasing velocity Particles fall with constant velocity Velocity of fall (v) in metres per minute $v = 6.86 \sqrt{\rho d}$ ρ = Density of particle d = Diameter of particle micrometers
7000			
		1295 m/min	
5000			
3000			
2000			
1000		582 m/min	
700			
500		411 m/min	
250	Dust		
200			
100		43 m/min	
		11 m/min	
50			
20			
10		0.44 m/min	
		0.11 m/min	
5			
2			Velocity of fall (v_1) m/min $v_1 = 0.16 \times 10^3 \rho d^2$ ρ = Density of particle d = Diameter of particle in micrometers
1	Fume	312 mm/h	
		81 mm/h	
0.5			
0.2			
0.1	Smoke	3 mm/h	
0.05			
0.02			
0.01			

3.2 Industrial

3.2.1 Table 2 lists the main pollutants and typical industrial and domestic sources (Merriman; QUARG 1993). The estimated content in air which may be found in urban industrial areas is given in the form of parts per million parts of air (ppm) where such information is available. Also indicated is the toxicity threshold generally accepted as the maximum allowable concentration for health safety. Statutory long and short term maximum levels are to be found in EH40/9 'Occupational exposure limits 1994' published by the Health and Safety Executive. This publication is updated annually. Limits tend to be rather higher than the toxicity thresholds given below.

TABLE 2

AIR POLLUTANTS AND TYPICAL SOURCES

Pollutant	Source
Sulphur compounds e.g. sulphur dioxide (SO_2)	Combustion of coals, coke, tars, heavy petroleum products and gas; power stations, desulphurising plants, roasting and sintering of ores and pyrites, oil refineries, manufacture of paper, plastics and sulphuric acid Toxicity threshold SO_2: short term 0.2 ppm annual 0.05 ppm Content in air SO_2: urban mean 0.02 ppm urban peak 0.5 ppm DoE air quality bands: v good <0.06, good 0.06-0.12, poor 0.13-0.39, v poor >0.4 ppm
Carbon dioxide (CO_2) and Carbon monoxide (CO)	Incompletely burned fuel will produce carbon monoxide in addition to carbon dioxide. Petrol-engine vehicles are the main source of carbon monoxide. Toxicity threshold CO_2: 5000 ppm CO: short term 100 ppm 8 hours 10 ppm Content in air CO_2: 340 ppm : urban mean 2 ppm : 1-hour peak 20 ppm
Nitrogen compounds e.g. nitrogen dioxide (NO_2)	Petrol and diesel engine exhausts, manufacture of nitric acid and nitrates, power stations Toxicity threshold NO_2: short term 0.2 ppm 4 hours 0.08 ppm Content in air NO_2: urban mean 0.03 ppm urban 98% 0.08 ppm

TABLE 2 CONTINUED

Pollutant	Source
Ozone (0_3)	High voltage electrical equipment; internal combustion engines (by sunlight on NO_2 emitted, in presence of hydrocarbons). Toxicity threshold O_3: short term 0.1 ppm long term 0.03 ppm Content in air O_3: summer aft. mean 0.04 ppm 1-hour peak 0.1 ppm DoE air quality bands: v good <0.05, good 0.05-0.9, poor 0.09-0.17, v poor >0.18 ppm
Fluorine compounds (eg HF)	Manufacture of aluminium, steel, cement, superphosphates and glass; also fuels. Toxicity threshold 3 ppm Content in air 0.1 ppm
Chlorine and hydrochloric acid	Manufacturers of chlorine-based chemicals
Hydrocarbons	Domestic heating, installations, furnaces. Petrol exhaust, evaporation and refining. Diesel exhaust. Solvents.
Dust and grit (active or inert mineral or organic particles)	Windborne from ground, stockyards etc. or entrained by industrial emissions, from mineral extraction etc.
Aerosols*	Small droplets of sulphuric acid, tarry matter and hydrocarbons. Diesel exhaust. PM^{10} (particulate matter of <10µm diameter) has a serious effect on health in very low concentrations.
Fumes	From volatilisation of heavy metals, acids and exhausts of motor vehicles.

*Term applied to a suspension of fine particles of solid or liquid in a gaseous medium.

3.2.2 Some air pollutants are the result of reactions that occur in the atmosphere the most important of these are as follows:

(a) Sulphur dioxide is the most common sulphur compound pollutant, and is oxidised in a moist atmosphere to sulphuric acid, which may be washed to the surface by rain or deposited in fog.

(b) Under the photo-chemical action of solar radiation, particularly in the presence of ultra-violet light, nitrogen oxides and the hydrocarbons in the atmosphere can give rise to ozone. The present of ozone accelerates the oxidation of sulphur dioxide to sulphuric acid; and nitrogen dioxide to nitric acid.

(c) Carbon dioxide, in the presence of moisture, produces the weak carbonic acid, but this is not deleterious to materiel.

(d) Gaseous chlorides may react with other pollutants to form particulate matter, or be absorbed by particulates, thereby becoming true aerosol pollutants.

3.2.3 If exposure to ozone needs to be taken into consideration when designing particular items of materiel, the concentrations given in Table 3 should be taken as representing the meteorological conditions at altitudes from sea level to 30 km.

TABLE 3

OZONE CONCENTRATION AT ALTITUDE

Altitude km	Ozone concentration µg/m^3
0	220
1	205
2	190
4	170
6	170
8	460
10	735
12	865
14	975
16	1100
18	1075
20	845
22	730
24	650
26	505
28	430
30	330

NOTE: The greatest ozone concentration ever recorded in the open at sea level due to natural conditions was 325 µg/m^3 (0.16 ppm).

3.3 Marine

3.3.1 The atmosphere over the open sea and in coastal areas contains sodium chloride in the form of solid particles or as minute drops of saline solution containing, in addition, small amounts of other constituents which for corrosion purposes may be neglected.

3.3.2 Concentration levels of saline atmospheres are influenced by the degree of atmospheric evaporation of sea-water and upon dispersion factors such as wind. Coastal areas and tide-swept harbours usually have lower air salinity values than over the open sea.

3.3.3 Extreme values are generally found in sub-tropical regions subjected to high evaporation. In precipitation, salt fall amounting to 5000 kg ha^{-1} year^{-1} has been reported at Fort Sherman in the Panama Canal Zone. Recorded daily averages at the same station exceeded 5200 mg m^{-2} day^{-1} in March 1964. From air pollution data in the same Zone, daily max concentrations of chloride of 0.15 mg/m^3 are recorded.

3.3.4 Figures 1 and 2 (Brierley) indicates the sea-salt distributions over the land masses of the world. The values given in Figure 1 represent nominal values, the data is not comparable from area to area or from year to year. Figure 2 outlines areas in terms of salt fall intensity. Both figures are based on the results of widespread systematic and local surveys. Maximum levels recorded between 1959 and 1962 at coastal beaches in Great Britain were 136 mg m^{-2} day^{-1} while levels in India for Bombay and Cochin were 20 and 65 mg m^{-2} day^{-1} respectively.

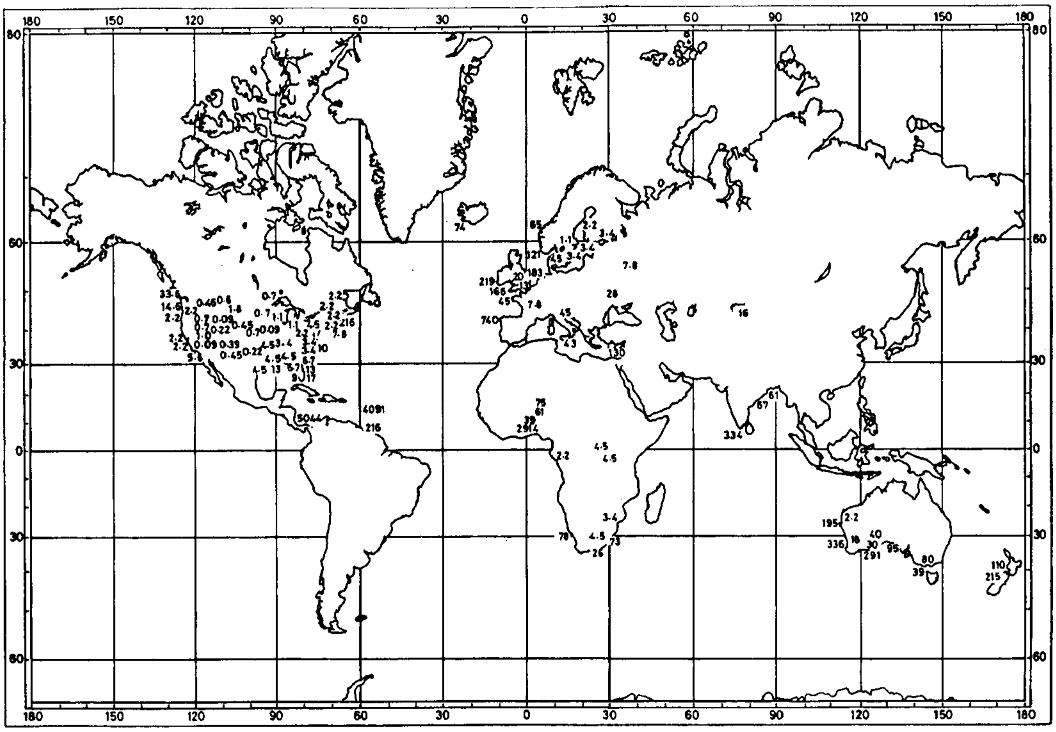
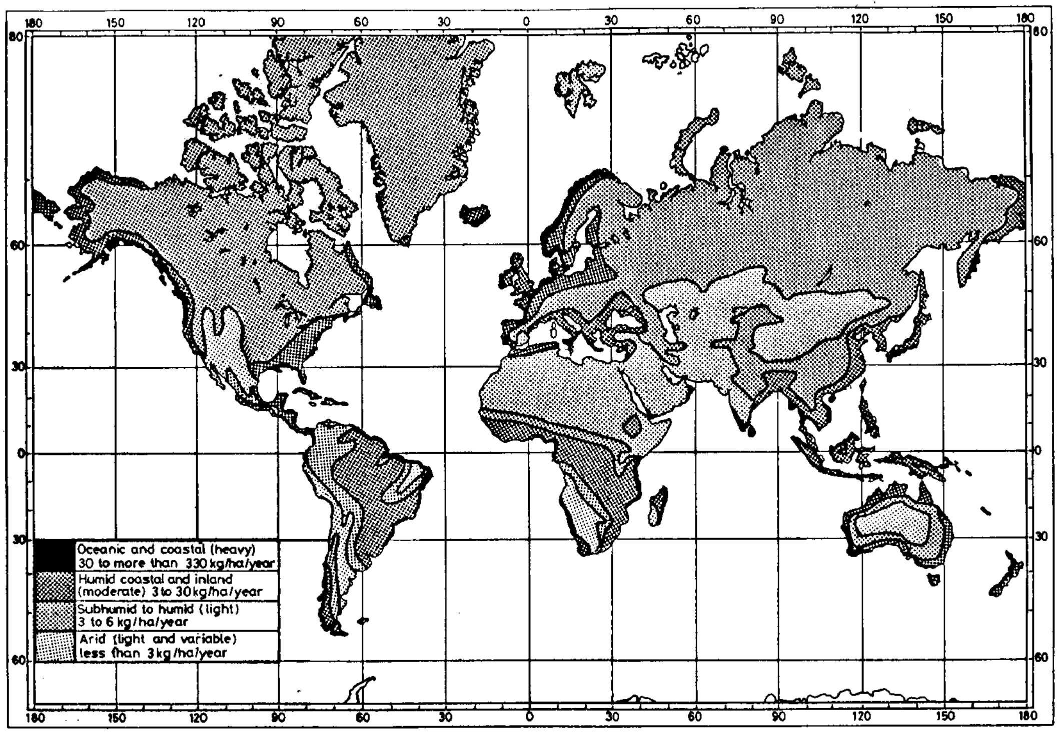


Figure 1 Chloride in precipitation - kg ha^{-1} $year^{-1}$

Note: 1kg ha^{-1} $year^{-1}$ = 0.274 mg m^{-2} day^{-1}



Oceanic and Coastal (heavy) - 30 to more than 330 kg/ha/year

Humid coastal and inland (moderate) - 3 to 30 kg/ha/year

Subhumid to humid (light) - 3 to 6 kg/ha/year

Arid (light and variable) - less than 3 kg/ha/year

Figure 2 Generalised atmospheric sea-salt areas

3.3.5 Salt particles resulting from atomisation in surfs and breakers generally settle at distances governed by particle size and direction and velocity of wind, causing atmospheric salinity values to fall rapidly with the distance inland from the coast.

3.3.6 At a tropical surf beach at Lagos, Nigeria, salt deposition levels up to 2000 mg m^{-2} day^{-1} have been recorded whereas at Port Harcout, 40 km inland, the levels are of the order of 10 mg m^{-2} day^{-1}(Ambler and Bain). However, in arid tropical regions where precipitation is rare, fine salt may become admixed with sand and dust and be carried several hundred kilometres inland by even moderate winds. Wind-borne saline pollution may also be present near inland salt lakes especially when dried up, e.g. the Aral Sea and Lake Eyre in Australia.

3.3.7 A graph showing salt deposition values at various distances from the sea-shore is given in Figure 3 (Rychtera and Bartakova).

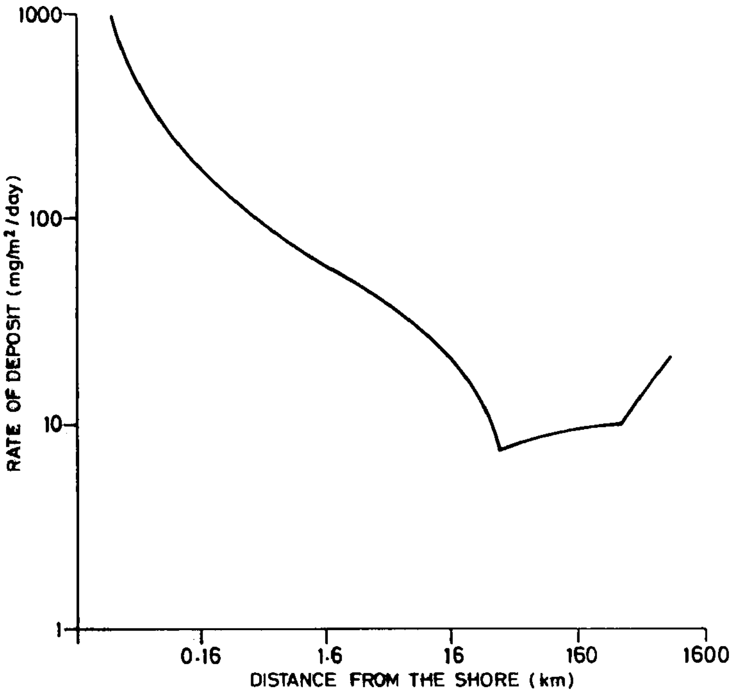


Figure 3. Sodium chloride deposit (on wet linen) varying with Distance from the sea-shore (measured in Africa)

4 FACTORS AFFECTING DELETERIOUS ATMOSPHERES

4.1 General

4.1.1 Air pollution levels depend principally on the quantity, type and rate of introduction of pollutants into the atmosphere, on source elevation and on the ability of the atmosphere to disperse these pollutants. These characteristics vary according to the geographical area, topography, meteorological conditions and the environment created by the population. The main factors which affect air pollution are described below.

4.2 Industrial activity

4.2.1 The pollutant content of the atmosphere decreases with the distance from its source. In industrial towns in some parts of the world concentrations of smoke may be in excess of 1000 µg/m^3 at times, whereas 100 µg/m^3 is now rarely exceeded in most British cities. Sulphur dioxide is still emitted by electricity power stations, while vehicles emissions have become the major source of pollution in many areas.

4.3 Topography

4.3.1 The topography of the surrounding area of a particular site may affect the concentration levels of polluted atmospheres in a number of ways; for example, industrial areas situated near large tracts of water may give rise to smog conditions and the proximity of large hills or mountains may either assist or counter the dispersal of pollution, depending on their orographic characteristics.

4.3.2 A suitable topography for dispersing pollutants is one of flat terrain, low-lying or elevated, permitting free movement of air with negligible channelling or ponding effects.

4.4 Temperature

4.4.1 Temperature affects the activity of deleterious atmospheres in a number of ways. Various pollutants react to solar radiation and moisture and become corrosive agents, and an increase in ambient temperature usually accelerates the rate of chemical reaction. Adverse effects of temperature reductions include increased concentration of gaseous pollutants such as sulphur dioxide from space-heating requirements, and the formation of dew which may contain corrosive products.

4.4.2 The temperature versus height distribution also affects pollutant dispersion. Where a large decrease of temperature with an increase in height occurs, the air is unstable and turbulence and vertical mixing of material take place readily. However, when there is a small decrease or increase (inversion) of temperature with an increase in height, the air is stable with negligible turbulence and the effect at the ground usually depends on whether this stable layer is at ground level or aloft. If aloft, pollutants may rise if they have some initial buoyancy, accumulate under the temperature 'lid' and be brought down to the ground in high concentrations by convection currents arising from vigorous mixing of the air between the surface and the elevated stable layer. If the stable layer extends from the ground surface upwards, vertical diffusion of pollutants is restricted and they tend to spread horizontally. Low level stabilisation is usually accompanied by calm or light winds which give rise to a limited volume of air for pollutant dispersion.

4.4.3 Temperature inversions resulting in fog or mist generally occur in stagnant weather conditions unfavourable for dispersion of air pollutants. During the London fog of 1962, ten times the normal concentration of smoke and twenty times the average concentration of sulphuric acid were recorded.

4.4.4 Heat sources such as buildings and motor vehicles can provide energy for convective mixing which can intensify vertical mixing in the presence of light wind.

4.5 Humidity

4.5.1 The presence of moisture in the atmosphere favours the oxidation of industrial pollutants such as sulphur and nitrogen compounds, resulting in the formation of acid mist or vapour. In coastal areas the atmosphere is generally saline, containing salt in the form of solid particles or as minute drops of saline solution, depending on the relative humidity.

4.5.2 The amount of water vapour in the atmosphere depends largely upon the prevailing type of air mass and the rate of evaporation. Evaporation is further influenced by season, prevailing climatic conditions, the humidity of the soil and various other factors. The effect of moisture content on atmospheric corrosivity is complex. However, it is generally agreed that in the presence of air pollution, corrosion increases slowly as relative humidity values increase from 30% to 65% approximately. The latter value is referred to as the critical relative humidity value above which corrosion accelerates rapidly. A diagram showing the influence of critical humidity on the rusting of mild steel is given in Figure 4.

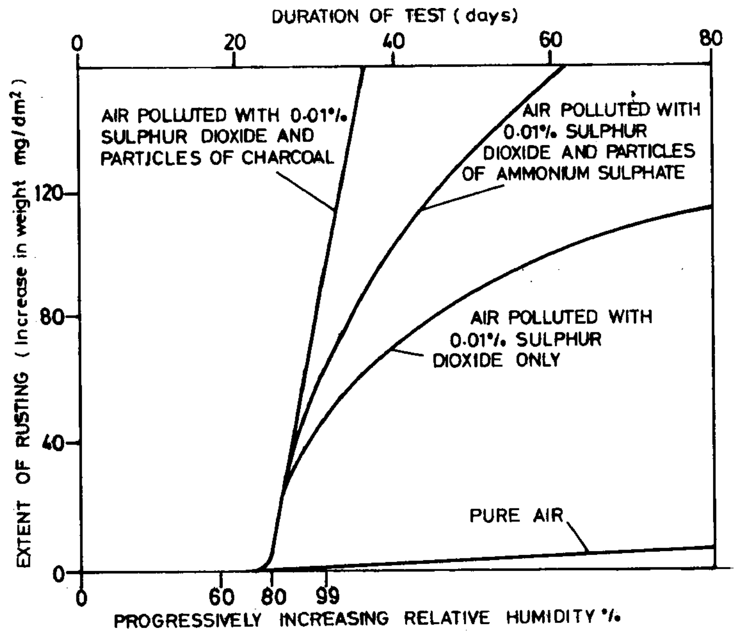


Figure 4. The influence of critical relative humidity, together with atmospheric pollution, on the rusting of mild steel

4.6 Wind

4.6.1 Air turbulence generally assists in the dispersal of atmospheric pollution, the levels decreasing with increasing wind velocity; that is the volume of air into which pollutants are emitted is directly proportional to wind speed, whereas pollutant concentration is generally inversely proportional to wind speed, though not at ground level from an elevated source. Winds can result in a build-up of pollution by causing, for example, aerodynamic downwash of stack effluents. The inland penetration distance of airborne salt or saline particles from coastal areas is also influenced by wind.

4.7 Rain

4.7.1 Rain is normally saturated with oxygen and nitrogen and generally contains impurities originating from sea-water, industrial waste, sewage and other sources. Rain may also contain acid impurities caused by the atmospheric reaction of air pollutants during the formation of raindrops.

4.7.2 The effect of rain on deleterious atmospheres is complex. Light rain or mist generally assists corrosion, whilst heavy precipitation may have preventive effects due to its cleansing action.

4.7.3 A further effect is that rain is usually accompanied, or preceded, by turbulent air conditions, which generally assist in the dispersal of air pollution.

4.8 Seasonal changes

4.8.1 Climatic seasons are generally characterised by changes in temperature, humidity, and precipitation levels. The effects of such factors have already been described. In temperate climates such as Great Britain, pollution levels are highest during the winter months, due to meteorological factors and the increased use of coal, coke and oil for heating purposes. Ozone concentrations are higher in the warmer, sunnier months, while nitrogen dioxide and carbon monoxide levels remain near-constant.

4.9 Diurnal variations

4.9.1 Relative humidity values are likely to vary considerably during the course of a day and are usually coincident with changes in air temperature.

Such diurnal variations can arise when the air mass:

(a) Radiates or absorbs heat

(b) Is in contact with a surface of higher or lower temperature

(c) Mixes with cooler or warmer air currents

(d) Moisture content increases owing to rainfall

4.9.2 The greatest diurnal variations in relative humidity are likely to occur in regions subjected to considerable daily temperature changes such as in the mountains and in arid tropical regions. For example, a temperature drop of 17°C in Alexandria resulted in an increase in relative humidity from 2% to 88% within a period of 2 hours.

4.9.3 Air pollution levels in a given locality are subject to variation due to varying degrees of industrial and domestic activity. In general, lower levels are likely to occur during the night, but corrosive effects of air pollution may not diminish in similar proportion because of the influence of atmospheric factors such as humidity.

4.10 Air pollution control and abatement

4.10.1 Air pollution levels are influenced by continually changing conditions resulting from the progressive development of a community, such as industrial growth and the consequent increase in population, domestic dwellings, motor vehicles and fuel combustion appliances.

4.10.2 To counter the increase in air pollution from these factors world-wide, organisations are engaged in the elimination and control of emitted pollutants. With the introduction of new combustion techniques, the use of smokeless fuels in plant and dwellings and the creation of smokeless zones, the level of air pollution in many industrial towns has been reduced. For example, mean urban concentrations of black smoke in the United Kingdom have dropped from over 130 μg/m^3 in 1962 to 15 μg/m^3 in the 1980's and sulphur dioxide in London (County Hall) from 300 μ/m^3 up to 1965 to 50 μg/m^3 by 1985.

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CHAPTER 8-02
THE EFFECTS OF CORROSIVES AND CONTAMINANTS

1 INTRODUCTION

1.1 Materiel can deteriorate through interaction with the corrosive agents contained in either natural or induced atmospheres. In addition, various substances can contaminate by contact and thus promote various mechanisms of deterioration.

1.2 This chapter describes the effects of corrosive atmospheres and contaminating substances, and is divided into two main sections, corrosion and contamination.

2 CORROSION

2.1 General

2.1.1 Corrosion may be defined as the deterioration or destruction of materials by chemical or electro-chemical attack. This chapter is principally concerned with corrosion occurring as a result of moisture formation, and consequent chemical reaction in the presence of impurities inherent in the material or contained in the atmosphere. The essential phenomena of corrosion for all metals and alloys are much the same, examples differing in degree but not in kind.

2.1.2 The deterioration of materials, and the corrosive effects of the atmosphere are greatly influenced by climatic factors. Although some specific effects of these factors are included herein, more detailed information is given in the chapters describing the effects of these other climatic factors.

2.2 Mechanisms of metal corrosion

2.2.1 It is possible to divide the processes of metal corrosion into two main groups. These are 'dry' metal-gas reactions, of which oxidation, scaling and tarnishing are the most important forms and 'wet' metal-liquid reactions, which require the presence of an aqueous electrolyte to enable cathodic and anodic processes to take place on the metal surface.

2.2.2 In pure dry air at normal temperatures, 'dry' corrosion is limited on most metals to the formation of an invisible thin film of oxides. Significant visible corrosion involves an acceleration of the process of 'dry' corrosion, or the breakdown of the oxide film and the intervention of a 'wet' metal-liquid reaction.

2.2.3 Some metals, such as aluminium and silicon form an oxide film so impervious that it virtually suppresses any metal-liquid reaction, but in general the oxide films are neither stable nor homogeneous enough to inhibit 'wet' corrosion.

2.2.4 The most commonplace form of accelerated 'dry' corrosion is the tarnishing caused by some air pollutants, such as silver by hydrogen sulphide, which can result in increased resistance across, or welding of, electrical contacts. Such films are composed of mixtures of oxides and sulphur compounds, and their formation is usually more rapid in an atmosphere containing ozone.

2.2.5 The process of 'dry' corrosion is also accelerated by an increase in temperature. At temperatures above approximately 200°C the oxide film thickens with prolonged heating to form a visible scale. High local temperatures, produced for example when electrical arcing is present, may cause accelerated 'dry' corrosion at switch contacts. Further information on the subject of high temperature corrosion is contained in Chapter 2-02.

2.2.6 Apart from tarnishing, any corrosion of consequence at normal temperatures requires the presence of an aqueous electrolyte. Visible wetting of the metal surface is not necessary, an invisible absorbed film of moisture being sufficient to support 'wet' atmospheric corrosion.

2.2.7 It has been found that for any given environment there is a 'critical relative humidity' below which 'wet' atmospheric corrosion is negligible. This humidity threshold is determined largely by the nature of any contaminants such as dust particles or corrosive gases present in the atmosphere and characteristics of the metal surface. The concept of critical relative humidity is described in Chapter 4-02, and information on the effect of dust particles in atmospheric corrosion is contained in Chapter 9-02.

2.2.8 In essence, the electro-chemical mechanism of 'wet' corrosion is a reaction involving oxidation and reduction at a metal-liquid interface, with consequent transfer of electrons through the metal, and ions through the liquid. The reaction is largely accomplished by the action of a network of electrolytic cells on the metal surface, the driving force being the effective potential difference existing between the anode and cathode areas. Metal ions go into solution at the anodes, the amount of metal dissolved being proportional to the current flowing. Thus, if the metal is clean and dry, the resistance to the passage of ionic current will be very high, and no significant corrosion will occur. When an electrolyte is present however, a current may flow and corrosion take place. Further information is given in References 1-6.

2.3 Factors influencing the rate of metal corrosion

2.3.1 The initial tendency of metals to corrode, the rates of corrosion and their extent are influenced by many factors, some of which are described below.

2.3.2 Material factors, such as the uniformity of structure and composition of a metal, affect the rate of corrosion. For example, copper steels corrode much more slowly in air than ordinary iron and steel, and experience indicates that a sulphur content in steel greater than 0.06% has an accelerating influence on the rate of corrosion in certain media, particularly in industrial atmospheres.

2.3.3 Figure 1 illustrates variations in corrosion of different steels in rural and industrial atmospheres and Table 1 indicates the relative corrodibility of some common metals and alloys in different environments. The table is intended to give only a very approximate idea of the relative rating of the metals listed; this rating will vary with changing conditions of service, or of the corrosive solution.

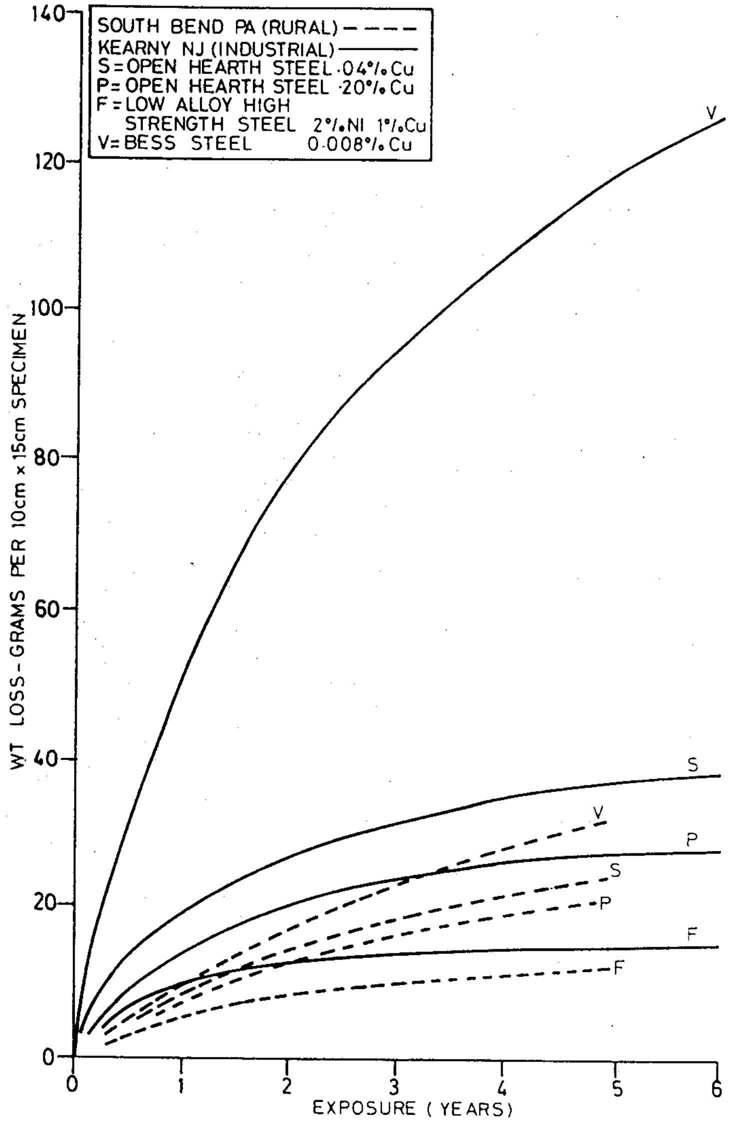

Figure 1. Effect of steel composition on corrosion in industrial and rural atmospheres

2.3.4 The presence of dissolved oxygen is usually essential for the continuity of corrosion of most metals. If the oxygen supply is limited, the polarizing or insulating film of hydrogen produced at cathodic areas will slow down the corrosion rate. Exceptions to this are stainless steel and aluminium, where a supply of oxygen is beneficial as it maintains the protective oxide-skin in good repair.

Table 1: RESISTANCE TO CORROSION OF SOME COMMON METALS AND ALLOYS

Class of material	Nominal Composition						Atmospheres				Water				Acids, moderate concentration 5–15%					Alka-lies		Salt solutions medium concentra-tion		
	Carbon	Chromium	Nickel	Silicon	Copper	Other constituents	Seashore	Industrial	Domestic	Mine	Sea	Saline with H_2S	Brackish with NaCl	Wet steam	HCl	H_2SO_4	HNO_3	Acetic	Phosphoric	1-20% sol	Fused	NH_4Cl	$MgCl_2$	$MgSO_4$
Ingot iron or wrought iron	0.03				0.08		P	P	F	P	F	F	F	FG	P	P	P	P	P	G	G	P	FG	FG
Low-carbon steel	0.10				0.08		P	P	F	P	F	F	F	FG	P	P	P	P	P	G	G	P	FG	FG
Copper and high tensile steels	0.10				0.25		F	F	F	P	F	P	F	FG	P	P	P	P	P	E	G	P	FG	FG
Hot-galvanised iron and steel							G	G	FG	PF	FG	FG	FG	FG	P	P	P	P	P	P	F	P	FG	FG
Calorized iron and steel							G	G	P	P	P	P	P		P	P	P	P	P	F	F	P	P	P
Grey cast iron	2.8 graphite, 0.7 combined carbon						F	FG	G	F	F	F	F	F	P	P	P	P	P	G	G	P	FG	FG
High-silicon iron	0.60			14.25			E	E	E	G	E	E	E	E	FG	E	E	G	G	FG	P	G	G	G
Nickel cast iron	3.30		3.50	1.50			FG	FG	F	F	FG	FG	FG	F	P	P	P	P	P	GE	FG	P	FG	FG
Chromium cast iron	2.50	25.00		2.00			G	G	G	G	FG	FG	FG	G	P	P	G	G	F	E	FG			
Ni-Cr-Cu cast iron	3.00	2.00	14.00	1.50	6.00		G	G	G	F	G	G	G	G	F	F	P	FG	FG	FG	E	FG	G	G
Nickel steel:																								
Low	0.18		3.00				FG	FG	F	F	F	FG	F	F	P	P	P	P	P	GE	G	P	FG	FG
High	0.30		28.00				G	G	G	FG	G	G	G	G	F	FG	P	FG	F	E	G	FG	G	G
Chromium steels:																								
5% Cr	0.15	5.00				Mo 0.5	F	F	F	P	F	P	F	FG	P	P	P	P	P	G	FG	P	P	FG
7% Cr	0.15 max	7.00		0.75		Mo 0.5	F	F	F	P	P	P	P		P	P	P	P	P	G		P	P	F
9% Cr	0.15 max	9.00		0.50		Mo 1.0	F	F	F	P	P	P	P		P	P	P	P	P	G		P	P	F
12% Cr	0.10 max	12.00					G	G	G	F	PF	PF	PF	G	P	P	G	G	F	G	P	F	F	G
17% Cr	0.10 max	17.00					G	G	G	FG	PG	PG	PG	G	P	P	E	E	P	G	P	FG	G	G
17% Cr, 4% Mo	0.10 max	17.00				Mo 4.0	G	G	G	FG	PG	PG	PG	G	P	P	G	G	F	G	P	FG	G	G
27% Cr	0.35 max	27.00		0.75		Ni 0.25	GE	G	E	GE	G	FG	FG	E	P	P	E	F	G	G	P	E	E	E
Silcrome: (8% Cr, 3% Si)	0.45	8.25		3.50			F	FG	F	F	PF	PF	PF	FG	P	P	FG	FG	P	G	P	F	F	FG
Cr-Ni steels:																								
8-20	0.20	8.00	20.00				G	G	G	FG	PG	F	FG	GE	P	FG	F	G	FG	E	G	FG	G	G
18-12, 2½% Mo	0.15	18.00	12.00			Mo 2.5	E	E	E	E	FE	FE	FE	E	PF	G	E	E	E	E	F	GE	G	G
18-8	0.10	18.00	8.00				E	G	E	FE	FG	PG	FG	E	P	PG	E	E	E	E	F	G	G	G
18-12	0.10	18.00	12.00				E	G	E	FE	PG	PG	PG	E	P	F	E	G	G	G	F	G	G	G
18-35	0.50 max	18.00	35.00	1.00			E	G	E	FG	PG	PG	PG	E	F	G	G	G	G	E	G	G	G	G
25-12	0.25 max	25.00	12.00				E	G	E	G	G	PG	G	E	F	F	E	E	E	E	G	G	G	GE
25-20	0.25 max	25.00	20.00	1.50			E	G	E	G	G	E	G	E	F	F	E	G	G	E	FG	G	G	G
Stellite	3.0 max	30.00				Co 55.0, W 15.0	E	E	E	E	E	E	G	E	F	F	FG	E	E	E		G	G	E
Hastelloy A			55.00			Mo 20.0, Fe 20.0	G	G	G	F	G	F	G	E	G	G	P	E	E	E	P	G	G	G
Hastelloy B			64.00			Mo 28.0, Fe 6.0	G	G	G	G	G	E	E	P	E	E	P	E	E	E	P	E	E	E
Hastelloy C		14.00	58.00			Mo 17.0, W 5.0, Fe 6.0	E	E	E	E	E	E	E	E	G	E	G	E	E	E	P	E	E	E
Hastelloy D			85.00	10.0	4.0		G	G	G	P	G	F	F	G	G	E	P	E	E	E	P	G	G	E
Commercially pure nickel			99.20				E	G	E	FG	FE	FE	FE	E	FG	FG	P	FG	FG	E	E	G	G	G
Nickel alloys:																								
Monel metal	0.15		67.50	0.50	28.50	Mn 1.50	E	G	E	PE	GE	GE	GE	E	FG	G	P	FG	G	E	E	GE	GE	E
Nickrome 60-15	0.12	15.00	60.00				E	G	E	G	FE	FE	FE	E	F	F	F	G	G	G	G	G	E	G
Inconel 14% Cr		14.00	80.00			Fe 6.0	E	G	E	G	FE	FE	FE	E	F	F	F	G	G	E	G	G	E	G
80% Ni 20% Cr		20.00	80.00				E	G	E	G	FE	FE	FE	E	FG	FG	G	G	G	E	G	G	E	G
Commercially pure copper					99.90		G	G	G	FG	G	PF	FG	G	PG	FG	P	FG	FG	G	F	FG	G	G
Copper alloys:																								
Red brass					85.00	Zn 15.0	G	G	FG	FG	G	PF	FG	G	PF	FG	P	FG	FG	G	F	FG	G	G
Tobin bronze					60.00	Zn 39.2, Sn 0.75	G	FG	FG	F	G	F	FG	G	P	F	P	F	F	FG	PF	F	FG	FG
Phosphor bronze					95.00	Sn 5.0	G	FG	G	F	G	FG	G	G	P	FG	P	FG	FG	G	F	FG	G	G
Silicon bronze				3.00	95.00	Mn 1.0 or Zn 1.5, Sn 0.5	G	G	G	FG	PG	PF	PG	G	F	FG	P	G	G	FG	F	FG	G	G
Aluminium bronze			0.50		90.00	Al 9.0, Fe 0.5	G	G	G	FG	G	G	G	G	F	FG	P	FG	FG	FG	PF	FG	G	G
Nickel silver			20.00		75.00	Zn 5.0	G	G	G	G	GE	FG	FG	G	F	G	P	FG	FG	E	FG	G	G	G
Admiralty metal					70.00	Zn 29.0, Sn 1.0	G	G	G	FG	FG	FG	FG	G	P	FG	P	FG	FG	FG	F	FG	G	G
Commercially pure aluminium						Al 99.20	GE	E	FG	PG	G	G	PG	G	P	F	P	G	P	P	P	F	G	G
Aluminium alloys:																								
3S						Al 98.8 Mn 1.2	GE	E	FG	PG	G	G	PG	G	P	F	P	G	P	P	P	F	G	G
Alclad 3S	Duplex product; 10% Al alloy over 3S						E	E	GE	PG	GE	GE	PG	G	P	F	P	G	P	P	P	F	GE	GE
24S-T					4.50	Mn 0.6, Mg 1.5, Al bal	PG	FG	PF	P	P	P	PF	F	P	P	P	F	P	P	P	P	P	P
Alclad 24S-T	Duplex product; 5% Al coating over 24S-T						E	E	GE	PG	GE	GE	PG	G	P	P	P	F	P	P	P	F	GE	GE
61S-T		0.25		0.60	0.25	Mg 1.0, Al bal	GE	E	FG	PG	G	G	PG	G	P	F	P	G	P	P	P	F	G	G
Commercially pure magnesium							G	G	F	P	P	P	P	P	P	P	P	P	F	E		P	P	P
Cast magnesium alloys	ASTM AZ63, AZ92, AZ90						F	G	F	P	P	P	P	P	P	P	P	P	F	E		P	P	P
Wrought magnesium alloys	ASTM M1, AX31X, AZ61X, AZ80X						G	G	F	P	F	F	F	P	P	P	P	P	F	E		P	P	P
Commercially pure tin							G	G	E		G		G	G	P	P	P	P	P	F	P			
Commercially pure lead					0.06	Pb 99.90	G	G	PG	G	G		G	G	F	E	P	P	G	P	P	FG	FG	G

Key to Table 1

E - Excellent; almost unlimited service	F - Fair
G - Good; will give good service	P - Poor

2.3.5 Dissolved oxygen may be derived from atmospheric gaseous oxygen which dissolves at a rate inversely proportional to the oxygen concentration of the electrolyte, that is, the rate is highest when the electrolyte contains no dissolved oxygen. High concentrations of dissolved oxygen tend to stimulate corrosion reactions, for example aerated salt and alkali.

2.3.6 The pH value indicates the acid or alkaline properties of an electrolyte. Acids, in which hydrogen-ions predominate, have pH values less than 7; alkalies have excess quantities of hydroxyl-ions, and have pH values greater than 7. The pH value of pure neutral water is 7, having equal quantities of hydrogen-ions and hydroxyl-ions.

2.3.7 There is no relationship that is generally applicable between the pH value and the rate of corrosion. For example, most aluminium alloys are inert to strong nitric or acetic acids, but are readily attacked by dilute sulphuric or hydrochloric acids. Similarly, solutions with a pH value of 11.7 may not attack aluminium alloys provided silicates are present, but in the absence of silicates, attack may be appreciable at a pH as low as 9. 0. While in electrolytes containing chloride, certain aluminium alloys undergo less attack in the pH range 5. 5 to 8.5 than in distinctly alkaline or acid solutions.

2.3.8 Agitation of an electrolyte by physical movement of the material, or by atmospheric factors, tends to accelerate corrosion. This effect is due to the higher rate at which corrosive chemicals are brought to the corroding surface and to the higher rate of diffusion of the corrosion product. Another effect of agitation is to hinder or prevent the formation of protective oxide films.

2.3.9 The presence of air pollutants at the surface of materials generally increases the rate of corrosion. The most common are sulphur dioxide in industrial areas and salt in marine atmospheres. One effect of air pollutants is to increase the conductivity of an electrolyte. Figure 1 and Figure 2 show examples of corrosion in different atmospheres.

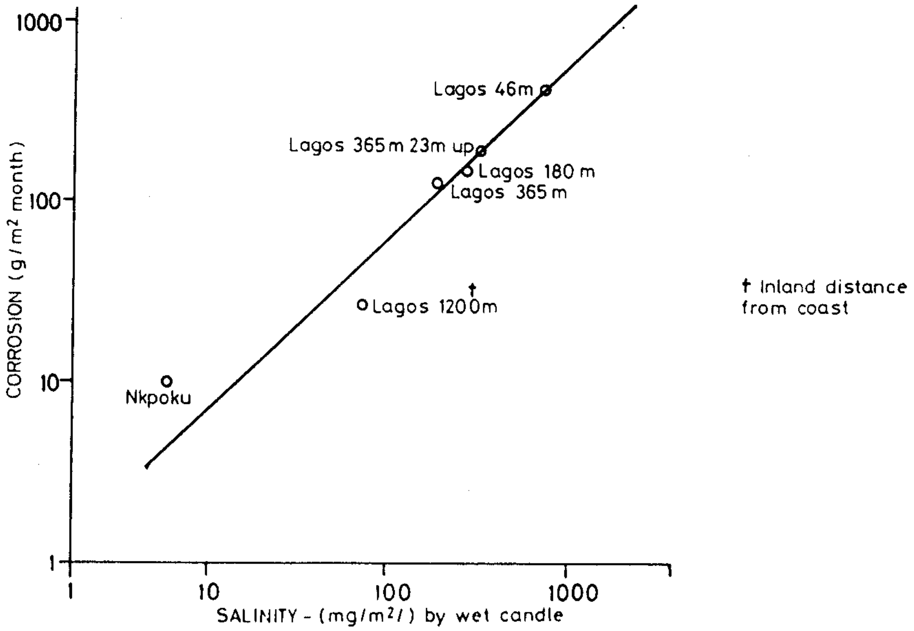

Figure 2. Relation between corrosion of mild steel and salinity, in Nigeria

2.3.10 Different substances, such as acids, salts or gases, in contact with adjoining parts of the same surface, can create local potential differences that can result in marked pitting. Similar results may occur when the concentration of one substance is greater at one point than another point on the same surface. Visible quantities of electrolyte are not necessary for corrosive action to proceed, slight condensation, or even the transfer of perspiration from handling the material, being sufficient to cause corrosion under certain environmental conditions.

2.4 Wet candle method of measuring atmospheric salinity (Figure 2 refers).

2.4.1 A surgical bandage wrapped round a glass cylinder is kept wet by the tails dipping in distilled water. The apparatus is suitably protected from rain and sun, and after the required period of exposure the salt content of the moisture is determined.

2.5 Effects of protective film

2.5.1 Metals have an inherent tendency to form a surface film of oxide when exposed to air; this film, in most cases gives some initial protection against corrosion. Films vary in thickness and character with different metals and alloys and provide varying degrees of protection. For example, aluminium and silicon form a very thin adherent film which is impervious to many environments, and the corrosion rate is greatly impeded or completely stifled.

2.5.2 The presence of a film obstructs the progress of further corrosion, and must be removed or become porous for corrosion to proceed. In the general case, the rate of destruction of this film is determined by the effective concentration of dissolved oxygen in an electrolyte next to the metal, and this, in turn, depends upon the impurity content of the electrolyte and other variables. For example, when iron is exposed in dry air for an appreciable time, it develops a protective film containing oxygen which tends to insulate the metal from moisture. This film, however, is quickly broken down when sulphur dioxide is present.

2.5.3 Any discontinuities in the protective film such as in crevices or under washers, can create potential differences that promote localized electro-chemical corrosion resulting in marked pitting.

2.6 Bimetallic corrosion

2.6.1 If two dissimilar metals in electrical contact are bridged by an electrolyte, the anodic or baser metal may experience greater corrosion than when it is connected to a metal similar to itself. Although the potential difference existing between the metals is the driving force for the electro-chemical reaction, its magnitude is not always a reliable guide to the degree of corrosion suffered at any particular bimetallic contact. Further information is given in Reference 7.

2.7 Effect of organic vapours

2.7.1 Metals enclosed in restricted spaces can be corroded by organic vapours given off by wood, glue, paint, varnish, resin, preservatives and similar materials. Usually the concentration of such vapours is negligible in the open atmosphere because of adequate air circulation, and corrosion generally occurs only on metal parts enclosed during use or in storage. Corrosion by organic vapours can occur in temperate conditions, mainly during storage. Its incidence is likely to be greater in tropical conditions because increased temperature increases the rate of corrosive reaction, whilst increased humidity promotes and accelerates attack. Further information on corrosion by organic vapours and appropriate preventive measures is contained in References 8 and 9.

2.7.2 The metals most susceptible to this type of corrosion are cadmium, lead, magnesium and zinc.

3 DETERIORATION OF NON-METALLIC SUBSTANCES

3.1 Introduction

3.1.1 Most non-metallic substances are capable of absorbing contaminated moisture, and are thus subject to deterioration when exposed to corrosive atmospheres. Some effects on the more common materials are given below. The deterioration of materials by other agents, such as solar radiation or micro-organisms, are described in the relevant chapters of this Standard.

3.2 Wood

3.2.1 The deterioration of wood, by swelling, shrinking, warping and loss of strength, is mainly due to the effects of temperature and humidity. These are described in Chapters 2-02 and 4-02. Deposition by particulate matter causes surface discolouration, and the acid content of such matter may attack subsequent paint coatings.

3.3 Paper and cardboard

3.3.1 These materials contain fibrous, non-fibrous and resinous constituents most of which are readily attacked by corrosive atmospheres. Typical effects are embrittlement, diminishing folding endurance and loss of electrical characteristics and tensile strength.

3.3.2 Materials used in electrical engineering are usually impregnated to give protection against absorption of contaminated moisture. However, impregnation does not usually completely prevent absorption, as many of the internal spaces are too small to permit penetration by the impregnant.

3.3.3 Pollutants such as dust and smoke can cause permanent defacement and discolouration and may give rise to chemical attack caused by reaction between contaminated moisture and the normal constituents of the material.

3.4 Leather

3.4.1 The manufacture of leather involves the use of chemicals, vegetable tannins, lubricants, colouring dyes and finishing waxes or plastics. Leather offers relatively good resistance to climatic conditions, and can be made to withstand certain specific deteriorating influences by the use of suitable tanning agents.

3.4.2 Finished leather contains acidic moisture as an integral part of the tanning process; the intake of foreign substances by absorption may modify the pH value of its moisture content, causing hydrolytic instability which may then result in detannage.

3.4.3 Deterioration by exposure to the atmosphere is largely attributed to sulphur dioxide oxidizing when absorbed at the surface of leather fibres. The extent of damage is generally in proportion to the total amount of sulphuric acid absorbed by the material. Typical forms of damage are loss of strength, embrittlement, discolouration and disintegration.

3.5 Textiles and cordage

3.5.1 Textiles may contain moisture repellent substances, impregnants and fungicides, in addition to their basic organic, inorganic and synthetic constituents. Their reaction to corrosive atmospheres is complex, and varies according to the materials used in their manufacture.

3.5.2 Deposition of solid and liquid particles degrades the appearance of most textiles, and may also promote chemical reaction in cellulosic material such as linen and cotton. Deterioration is generally more rapid when the atmosphere contains even small quantities of acidic contaminants such as sulphur dioxide. Typical forms of damage are loss of tensile strength, loss of electrical characteristics and discolouration.

3.6 Plastics and rubbers

3.6.1 These materials are largely synthetic, and contain various substances intended to enhance or diminish certain properties. The end product can be any one of innumerable chemical and physical structures depending on the application required, and in consequence, the reaction of specific products to outdoor exposure can vary considerably according to their constituents and processes. Plastics and rubbers are not amenable to preservative treatment after fabrication, and their resistance to deteriorating agents is built in by appropriate selection of basic ingredients.

3.6.2 The resistance of some plastics and rubbers to deterioration by corrosive atmospheres is summarised in Table 2. This table serves as a guide to the resistance of various types of material against deterioration by substances which may be contained in corrosive atmospheres. The data for each material do not cover all the products in that class. The materials listed are not pure polymers, but are formulated products which are commercially available. For detailed information see References 10, 11 and 12.

3.6.3 Typical forms of damage include loss of strength, loss of electrical characteristics, surface crazing and cracking, loss of transparency and discolouration. Deterioration of rubber is usually more severe when the material is under strain or subjected to flexing, and when the material is exposed to ozone. Further information on the effects of ozone can be found in Chapter 3-02.

TABLE 2

DETERIORATION RESISTANCE OF PLASTICS AND RUBBERS

Material	Resistance to:	
	Acids and Alkalies	Organic Solvents
Allyl resins (cast)	very good	excellent
Aniline-formaldehyde resin	fair	very good
Butadiene-acrylonitrile	very good	very good
Butadiene-styrene	very good	good
Casein plastics	poor	excellent
Cellulose acetate-butyrate	fair	widely soluble
Cellulose acetate (high acetyl)	fair	widely soluble
Cellulose acetate (moulding)	fair	widely soluble
Cellulose nitrate	fair	widely soluble
Chlorinated rubber	good	fair
Cold-moulded plastics	fair	good
Ethyl cellulose	very good	widely soluble
Glyceryl phthalate (alkyd)	good	good
Isobutylene-isoprene	excellent.	very good
Melamine-formaldehyde resin (asbestos filler)	good	excellent
Melamine-formaldehyde resin (cellulose filler)	good	excellent
Neoprene	very good	very good
Nylon (moulded)	fair	excellent
Phenol-formaldehyde resin cast (no filler)	fair	good
Phenol-formaldehyde resin moulded (mineral filler)	fair	excellent
Phenol-formaldehyde resin (woodflour filler)	fair	excellent
Phenol-furfural resin (mineral filler)	fair	excellent
Phenol-furfural resin (woodflour filler)	fair	excellent
Polyacrylic ester	very good	very good
Polyester resins (flexible)	very good	very good
Polyester resins (rigid)	very good	very good
Polyethylene	excellent	very good
Polymethyl methacrylate (cast)	very good	fair
Polymethyl methacrylate (moulded)	very good	fair
Polystyrene	good	fair
Polysulphide	good	excellent
Polytetrafluoroethylene	excellent	excellent
Polyvinyl butyral (flexible)	good	fair
Polyvinyl butyral (rigid)	good	fair
Polyvinyl carbazole	good	fair
Polyvinyl chloride-acetate (flexible)	very good	fair
Polyvinyl chloride-acetate (rigid)	excellent	fair
Polyvinyl chloride (plasticized)	very good	fair
Polyvinylidence chloride (moulding)	excellent	excellent
Polyvinyl formal	good	good
Rubber (extruded)	fair	excellent
Shellac compound	very poor	good
Silicon rubber (mineral filler)	very good	very good
Urea-formaldehyde resin (cellulose filler)	fair	very good

3.7 Paints, varnishes and lacquers

3.7.1 These materials consist of an organic film-forming component called the vehicle, to which pigments and dyes may be added.

3.7.2 Atmospheric contaminants, such as sulphur dioxide and hydrogen sulphide, will react with many common paints. For example, sulphur dioxide may react with the vehicle of wet or fresh paint to form soluble compounds that cause the paint to dry tacky. Lead pigments, such as white lead, can combine with hydrogen sulphide causing rapid darkening of the coating similar to that attributed to the accumulated deposit of soot and carbonaceous pollutants.

3.7.3 The presence of salt in the atmosphere increases conductivity, favouring the formation of local electro-chemical cells. This in turn encourages osmosis through coatings, which in combination with electrolysis, can result in severe blistering.

3.7.4 In general, lacquers are the least durable against severe exposure. Stoving paints and two part cold-curing paints are more durable than air-drying paints, especially when moisture and chemical agents such as sulphur dioxide are present. All organic coatings are liable to be degraded by solar radiation and variations in temperature and humidity.

4 CONTAMINANTS

4.1 General

4.1.1 Contaminants can cause materiel to become defective over varying periods of time and in numerous ways. The general effects are given below, but further information on the effects of specific contaminants, such as dust and sand, or micro-organisms are contained in the relevant chapters of this Standard.

4.2 Effects on materiel

4.2.1 The contamination of lubricating oils by insoluble metallic or dust particles can cause the breakdown of lubricant films and abrasive wear of bearing surfaces. Liquid contaminants such as petrol or kerosene may act as solvents to the lubricant, while continued contact with water may result in the emulsification of the oil.

4.2.2 Organic oils and fats readily combine with atmospheric oxygen, causing them to become acidic. This may result in a change of state to an elastic solid form. Mineral oils are comparatively inert, and significant contamination or changes in properties due to chemical reactions normally only occur at high temperatures. Information on the effects of heat on the performance of lubricants and greases is contained in Chapter 2-02.

4.2.3 Soluble and insoluble particles contained in fluids and semi-solids can cause deterioration of materials by chemical reaction, abrasion and erosion. In flow systems, partial or complete blockage of filters, oilways, valves, nozzles, bleeds and other flow components will cause malfunction in equipment performance.

4.2.4 The most prevalent and the most troublesome contaminants in flow systems are solid particles, varying in size from 0.5 micron to several hundred microns. In high pressure hydraulic systems, the fluid may become initially contaminated by the products of mechanical wear. This initial contamination is carried around the circuit at speeds which may at times approach 300 m/s and thereby becomes a powerful erosive agent. This process can result in a build-up of contaminants, the seriousness of which depends on the performance requirements of the equipment. For example, with systems requiring very precise control, usually achieved by close clearances in servo valves and other components, clearances are adversely affected by contaminants.

4.2.5 Engine wear and performance characteristics are considerably affected by contaminants derived from the products of combustion, such as carbons and acids. For example, deposition of carbon on the flame tubes of atomising jets gives rise to local overheating, which may cause decay and burning through the combustion chamber. Particles of carbon may also cause the gradual erosion of turbine blades.

4.2.6 General information on the effects of liquid propellants on humans, metals and organic materials is given in Table 3. Further information on the effects of lubricants on materials is given in References 10 and 13.

TABLE 3

SOME PHYSICAL PROPERTIES OF LIQUID PROPELLANTS

Propellant	Biological Effects	Effects on Metals	Effects on organic Materials	Fire Risk
Liquid Oxygen	Bad 'burns' after several seconds exposure	Embrittles most	Embrittles many	High
Liquid Hydrogen	Bad 'burns' after several seconds exposure	Embrittles most	Embrittles many	High
Nitric Acid	Very toxic, attacks flesh rapidly	Highly corrosive	Reaction	High but easily diluted
Hydrogen Peroxide (80%)	Poison, attacks flesh	Corrosive, catalydes by many	Reaction often spontaneous	High but easily diluted
Kerosene	Mildly toxic	None	Moderate solvent	Moderate
Ethyl Alcohol (100%)	Intoxicating	None	Solvent	Moderate
Petrol	Mildly toxic	None	Solvent	High
Nitro-Methane	Mildly toxic	Corrosive	Good solvent	Explosive when hot

4.2.7 Some plastics, when in contact with another, can suffer loss of plasticizer by migration into the contacting surface resulting in the deterioration of either one or both components. An example of this is the marring of nitro-cellulose by flexible polyvinyl chloride compositions.

4.2.8 Under enclosed conditions silicone vapour can contaminate electrical contacts such as plugs and sockets, switch and relay contacts and brush gear of all kinds.

5 GENERAL OBSERVATIONS

5.1 The deterioration of materials by contact with corrosive atmospheres or contaminating substances can be combatted by the following procedures:

(a) Initial preparation of a surface by appropriate processes, prior to the application of protective treatment.

(b) Utilisation of suitable protective materials and finishes.

(c) Utilisation of materials that are compatible with their intended environment.

(d) Provision of a conditioned environment.

(e) Hermetic sealing.

(f) Employment of suitable packaging materials during storage and transportation.

(g) Careful handling to avoid corrosion and contamination on unprotected materials, and to prevent damage to protective oxide films or coatings.

(h) Avoidance of abrasive and chemically reactive cleaning agents.

(j) Control of internal contamination.

5.2 The composition of specific products of a given class of material, for example rubber, may vary considerably, thus affecting their tendency to deteriorate. Therefore the potential for variation in response should be borne in mind when selecting materials and methods of protection.

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CHAPTER 9-01
DUST AND SAND

1 INTRODUCTION

1.1 Minute solid particles are always present in the atmosphere and are of importance to the formation of clouds and of precipitation since they serve as condensation nuclei. However, this chapter is concerned only with air lifted dust and sand particles which have comparatively short residence times in the atmosphere.

1.2 The extent to which dust and sand penetrate the atmosphere depends on several factors. The primary requirements for a dust storm include the existence of loose dry soil and a strong wind, whilst a deep layer of convection will favour the upward distribution of the dust. Extreme conditions occur over desert terrain. The critical wind velocity depends on the size and distribution of particles and so is extremely variable from one region to another. Dust storms are more likely by day than by night and are more likely in dry summer months than in rainy winter months.

1.3 In those regions which are part cultivated land and part desert the wind-blown material is likely to consist of a true mixture of sand and dust, but even in a true sand desert region some dust particles are likely to be present.

2 CLASSIFICATION OF DUST AND SAND

2.1 'Dust' and 'sand' are terms for solid non-cohesive particulate matter, usually of mineral origin, found on the surface of the earth or suspended in the atmosphere. The range of particle diameters of sand and dust together extends from about 0.1 to 2000 µm, the latter value being the lower limit for very fine pebbles. Although dust and sand are normally differentiated on the basis of particle diameters, no universally accepted demarcation value exists.

Dispersive systems in air consisting of particles below 1 µm are termed smoke and fumes.

2.2 In this Standard, a classification based on their different aerodynamic behaviour is adopted. Particles of less than 75 µm diameter can remain suspended in the atmosphere by natural turbulence of the air for very long periods, even years. These are termed 'dust' by most authorities. Conversely, those greater than 150 µm diameter are unable to remain airborne unless continually subjected to strong natural winds, powerful air flows or the turbulence which may be caused, for example, by aircraft, helicopter or convoys of land vehicles. These particles are termed 'sand'. Over the intermediate range of diameters from 75 to 150 µm, there is a gradual transition in settling times and the particles are variously referred to as 'dust' or 'sand' in different documents.

2.3 For the purposes of laboratory simulation the recommended demarcation value for distinguishing sand from dust is 149 µm, which is the diameter of the smallest particles retained by a No 100 US or British Standard Sieve.

3 SAND - DISTRIBUTION AND HARDNESS

3.1 Distribution

3.1.1 Sand is distributed widely over the Earth's surface. There are vast sandy regions in the Sahara and in Saudi Arabia as well as significant areas in most the world's deserts. (Table 1). 'Ergs' or 'sand seas' cover only a proportion of the deserts listed in Table 1. All the continents have sandy beaches of various widths and there are large deposits at or near the surface in mainly inland areas formerly covered by water. On account of this widespread occurrence of sand, it should be assumed that most forms of materiel for use by NATO forces will be exposed to sandy conditions during their service life.

TABLE 1

MAJOR DESERTS OF THE WORLD

Name	Location	Estimated area in square kilometres
Sahara	North Africa	8000000
Libyan	Libya	1700000
Gobi	Mongolia	1000000
Ordos	(Part of Gobi)	Unavailable
Ala Shan	(Part of Gobi)	Unavailable
Turfan Depression	(Part of Gobi)	Unavailable
Rub Al Khali	SE Saudi Arabia	650000
Kalahari	South Africa	500000
Great Sandy	North West Australia	415000
Great Victoria	South West Australia	325000
Takla Makan	China	325000
Syrian	North West Arabian Peninsula	325000
Arunta	Central Australia	310000
Kara-Kum	USSR	270000
Arabian	Eastern Egypt	260000
Nubian	North East Sudan	260000
Thar or Indian	North West India	260000
Kyzyl-Kum	USSR	235000
Gibson	Western Australia	220000
Atacama	Northern Chile	180000
Nafud	Saudi Arabia	130000
Namib	SW Africa	80000
Dasht-e-Lut	Eastern Iran	50000
Dasht-e-Kavir	North Central Iran	45000
Peski-Muyan-Kum	USSR	45000
Mohave	Southern California, USA	35000
Sechura	North Western Peru	25000

3.2 Hardness

3.2.1 Hardness and Angularity are usually the most important characteristics of sand grains. On a world-wide basis, the majority of sands are composed of quartz (SiO_2), which, in its most common form, has a hardness of 7 on the Mohs scale. Other minerals which may be found in sand range from hardness 2 for white gypsum to hardness 9 for those containing corundum.

3.2.2 Table 2 is derived from Reference 2, and shows the principle constituents of natural dusts and sand, and the relative hardness of the particles. Minute quantities of other minerals such as zircon, garnet, mica, magnetite, etc. may also be found. In addition, particulates resulting from industrial processes, as well as microscopic vegetable and microbiological entities, may be present in dust. On a world-wide basis, the majority of sands are composed of quartz.

TABLE 2

CONSTITUENTS OF NATURAL DUSTS

Constituent	Composition	Hardness (Mohs Scale)
Quartz	SiO_2	7
Feldspars		
	$K\,Al\,Si_3O_8$ or $Na\,Al\,Si_3O_8$ or $Ca\,Al_2Si_2O_8$	6
Limestone	$Ca\,CO_3$ and $Mg\,CO_3$	3
Clay	$H_4\,Al_2\,Si_2\,O_9$	2

3.2.3 Although in time, grains of sand become rounded by mutual abrasion, those having angular shape are found in substantial proportion in most samples of sand. The latter arise from the tendency of some rock-forming minerals, particularly quartz, to fracture along cleavage planes through impact action.

3.2.4 In general, the movement of sand by wind pressure is confined to the air layer within the first metre above the ground. Even within this layer, about half the sand grains (by weight) move within the first 10 mm above the surface and most of the remainder are within the first 100 mm. As a consequence of the low elevation at which the majority of sand grains move, most abrasion damage caused by sand outside high wind periods is at or near ground level.

4 DUST - DISTRIBUTION, CONCENTRATION AND PARTICLE SIZE

4.1 Distribution

4.1.1 In contrast to sand, dust particles, on account of their low terminal velocity, can remain suspended in air indefinitely and may settle on surfaces anywhere.

4.1.2 In dry conditions, soils with more than 9 percent by weight of dust particles become at least moderately dusty and those with 14 per cent or more are potentially very dusty. Thus, as over 40 per cent of the land surface of the world, excluding Antarctica, is classified as moisture deficient and a further 40 per cent is seasonally dry, dust must be expected to be present over most of the land surfaces of the world for substantial parts of the year. Even in regions and seasons of heavy rainfall, dust continues to create problems where the protective cover has been broken. Many moist areas are so well drained that most unprotected soil becomes dust in a remarkably short time after heavy rain.

4.1.3 There is evidence that dust problems are aggravated by higher atmospheric temperatures, by relative humidities below 30 per cent and by the drying action of winds, though to what extent is not known quantitatively.

4.2 Concentration

4.2.1 The concentration of dust and sand in the atmosphere varies widely with geographical locality, local climatic conditions and the degree of activity taking place. Under suitable conditions enormous additions of dust may be injected locally and temporarily at the surface whilst the suspended dust drifts away with the wind.

4.2.2 Table 3 indicates typical concentrations encountered in various regions within an area having a temperate climate. Degrees of visibility and concentrations at various altitudes over an Australian desert are given in Table 4. Tables 3 and 4 are derived from Reference 1.

TABLE 3

TYPICAL DUST CONCENTRATIONS IN VARIOUS TEMPERATE REGIONS

Region	Average dust concentration mg/m^3
Rural and suburban	0.05 to 0.11
Metropolitan	0.11 to 0.46
Industrial	0.46 to 1.71

TABLE 4

VARIATION OF CONCENTRATION OF DUST WITH INCREASING ALTITUDE

Weather condition	Height (m)	Air temperature (°C)	Mean concentration mg/m^3
Clear to slight haze	150	33	0.21
	300	30.5	0.22
	600	30	0.17
	1200	29	0.14
	1800	19	0.05
Slight haze	150	34	0.24
	300	33	0.26
	600	32	0.20
	1200	27	0.14
	1800	21.5	0.19
Moderately dense dust storm	150	27	2.01
Visibility 300 m	300	25	17.42
Wind 10-13 m/s	600	24	6.96
	900	23	1.80
	1200	22	0.64

4.2.3 Probably the most effective dust production agent is man himself, especially when he is equipped with machinery to increase his speed and mobility. Tanks, trucks, bulldozers, artillery, aircraft and marching troops are effective in the destruction of protective cover and the consequent generation of small particles to such an extent that dust problems must be expected nearly everywhere these activities take place. Possible exceptions are those locations which are under permanent snow, ice or water cover, and where precipitation is so frequent that the surface never dries out.

4.2.4 Levels as high as 3500 mg/m^3 occur adjacent to tanks moving across deserts, measured about 2 metres above ground. Table 5 is derived from Reference 1 and shows average concentrations surrounding a tank operating over desert terrain.

TABLE 5

AVERAGE DUST CONCENTRATIONS SURROUNDING A TANK OPERATING OVER DESERT TERRAIN

Position	Mean concentration mg/m^3	
	Single	Convoy
Crew compartment (hatches open)	212	282.6
Crew compartment (hatches closed)	635.9	-
Engine compartment	6006.1	-
1.2 metres above carburettor	141.3	459.3
2.4 metres above carburettor	42.4	141.3

4.2.5 Chepil and Woodruff have related the visibility, V, to the dust concentration, C, at a height of 2 m, by the equation $V = 25100C^{-0.8}$, where V is in m, and C in mg/m^3. They have also stated that over the lowest 6 m of the atmosphere $C \alpha h^{-0.28}$ where h is the height in metres. Thus for a visibility of 30 m the average dust concentration 2 m above the ground would be 4500 mg/m^3 reducing to 3300 mg/m^3 at 6 m above ground. Visibilities as low as 15 m can occur in severe dust storms; although likely to be rare, the dust concentrations would then be 10700 mg/m^3 at 2 m and 7900 mg/m^3 at 6 m. Further information is given in Reference 6.

4.2.6 It should be noted that Chepil and Woodruff's formulae apply only to the region of the observations in Kansas and Colorado, and to the active area of a dust storm. They do not apply in the dust cloud at some distance from the storm area or at heights greater than 6 metres above the ground.

4.3 Particle size

4.3.1 Particle size refers to the mean diameter. The following sub-divisions of the overall size range of airborne desert dust and sand have been proposed by Heywood, based on the falling velocities of the particles:

(a) 'Instantaneously airborne dust' comprises small pebbles and large particles greater than 150 μm with a falling velocity in still air exceeding 1 m/s. The larger particles in this category are raised by artificial means, such as vehicles and aircraft and missile propulsion systems, and are unlikely to remain in suspension for more than a few seconds. 'Instantaneously airborne dust' generally forms less than 50% by weight of the total material in suspension.

(b) For 'temporarily airborne dust' the particle size range is between 2 μm and 150 μm and the falling velocity in still air 0.002 to 1 m/s. Dust in this category may be raised by artificial means or natural winds, and the settling velocity is sufficiently low for the dust to remain in suspension for a considerable time, particularly if the air flow is turbulent. Particles in this size range comprise between 50% and 100% by weight of the total dust suspension.

(c) 'Very slow settling dust' comprises dust with a particle size below 2 μm. The period of suspension will depend on the terminal velocity of the particle. A particle of diameter 2 μm has a terminal velocity of about 0.003 m/s, and if raised to a height of 1 kilometre it would take about 30 days to fall to the ground even if the up currents no longer existed. Hence it is not surprising that dust clouds can cover very large distances (several 1000 km). The proportion by weight for this range is generally less than 3% of the total dust in suspension.

4.3.2 The particle size distribution may be stated on a percentage weight or count basis, sometimes in terms of the percentage by weight of the particle that will pass through sieves of varying mesh sizes.

4.3.3 Particle size distributions to be expected in dust storms at various heights are illustrated in Table 6 and derived from Reference 1. It should be noted that these data are given as percentage by count and cannot be directly compared with size data given on a weight basis.

TABLE 6

VARIATION OF PARTICLE SIZE DISTRIBUTION WITH HEIGHT OF DUST STORM

Height (m)	Particle Size Distribution µm (per cent by count)				
	0-5	5-10	10-20	20-40	Over 40
150	25.0	35.0	30.0	8.0	2.0
300	43.0	31.0	19.5	5.6	0.9
600	50.0	28.0	15.5	4.5	2.0
900	66.5	22.0	9.0	2.1	0.4
1200	64.0	21.0	11.5	2.8	0.7

4.3.4 Figure 1 shows the particle size distribution of samples obtained from the air filters of vehicles operating in various geographical localities. Figure 2 gives distributions of larger samples, probably road dusts, obtained from abroad. Superimposed on these graphs is the distribution for the British Standard dust test.

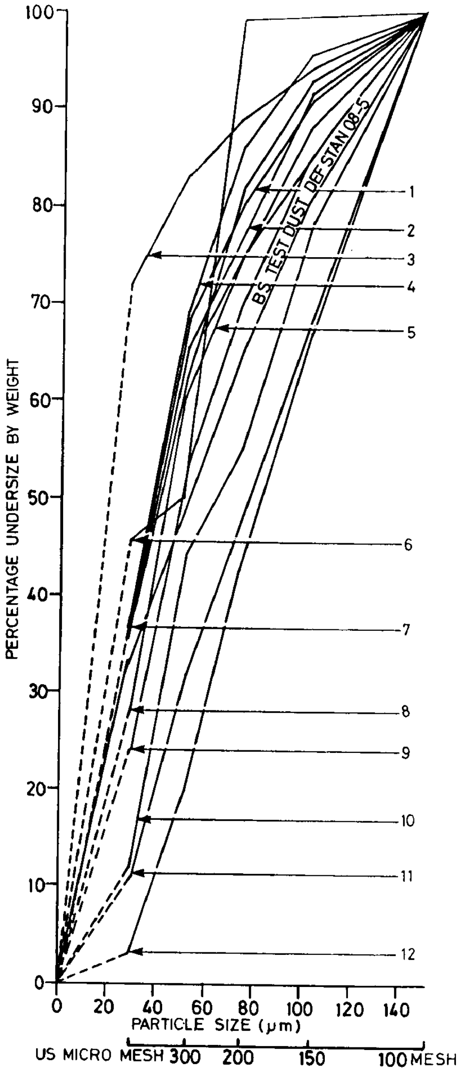

Figure 1
Particle-size distribution of standard dusts and dusts from paper elements received from abroad.

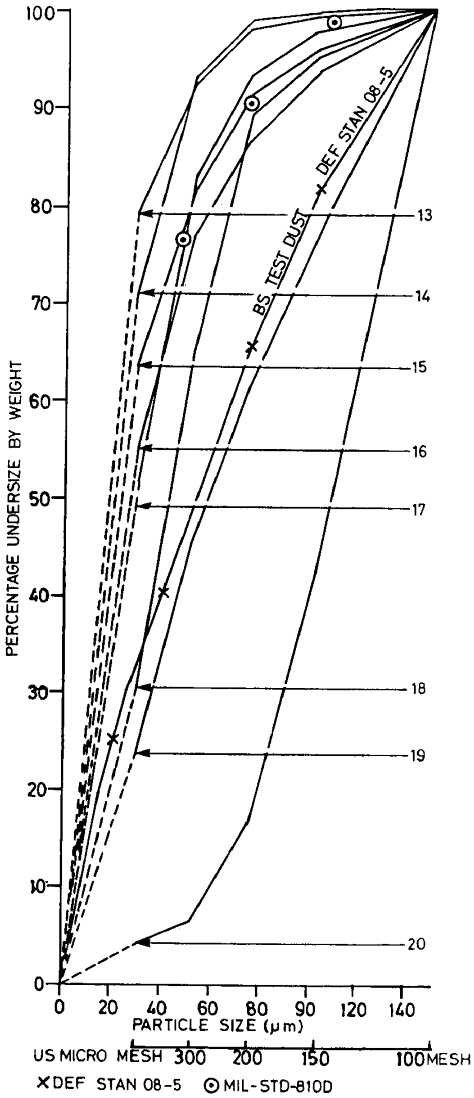

Figure 2
Particle-size distribution of standard dusts and dusts received from abroad.

5 FACTORS AFFECTING THE DUST AND SAND ENVIRONMENT

5.1 The severity of the dust and sand condition will be influenced by the following environmental factors.

5.2 Geographical distribution

5.2.1 The physical geography of the earth's surface will tend to define those areas where high concentrations of airborne dust and sand may be encountered. Such extreme dust and sand conditions will occur over desert terrains. The major deserts of the world are listed in Table 1.

5.3 Wind

5.3.1 Wind will affect the environment by carrying surface dust and sand into suspension. The critical pick-up velocity will depend on the particle size and degree of coherence of the surface. The action of wind on dust and sand is examined in detail in References 3, 4 and 5.

5.3.2 Clements' studies of the vertical distribution of wind-blown dust and sand have shown that 95% of the particulate material by weight is carried within the first 250 mm of the ground, whilst in general, the movement of sand by wind pressure is confined to the air layer within the first metre above the ground. Even within this layer, about half the sand grains (by weight) move within the first 10 mm above the surface and most of the remainder are within the first 100 mm.

5.3.3 Small particles of less than 10 µm reach a height of over 1524 m. The upper limit for dust has been stated as 3048 m, but may reach the tropopause in some areas.

5.4 Temperature, humidity and precipitation

5.4.1 High air temperatures associated with low relative humidities will aid in drying out the soil in addition to the drying action of any winds and increase the probability of encountering dust. Temperature gradients may produce convection currents that will carry dust to high altitudes.

5.4.2 Precipitation has an opposite effect, higher rainfall intensities lower the dust concentrations.

6 DESIGN CRITERIA

6.1 Dust concentrations from three distinctly different scenarios are given in Table 7. Materiel should remain safe and be capable of acceptable performance when exposed to dust concentrations given for those scenarios most representative of its locations and modes of deployment.

TABLE 7

CONCENTRATIONS OF DUST IN THE ATMOSPHERE

Dust Concentration	Scenario
180 mg/m^3	Typical of dust picked up and transported by fresh winds (typically 18 m/s) in locations remote from normal military activities.
1.0 g/m^3	Occurs where there is a military presence. Though considerably greater than for natural dust storms, it is a realistic level for military activities on a world-wide basis.
2.0 g/m^3	Representative of the most arduous conditions associated with aircraft, particularly helicopters, operations. In addition to dust, the rotor downwash of helicopters is strong enough to raise sand grains to considerable heights.

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CHAPTER 9-02
THE EFFECTS OF DUST AND SAND

1 INTRODUCTION

1.1 Dust and sand may act as physical agents, chemical components, or both, in promoting the deterioration of materials or function of equipments.

1.2 Dust and sand may act as unwanted abrasives on moving components of machinery, and even stationary surfaces can be damaged by the abrasive action of windblown particles. Alternatively, the effect may depend on the physical and chemical nature of the particulates and the nature of the material with which they are in contact. Thus a film present on the surface of a metal may accelerate corrosive action, while a similar deposit on an insulator surface can impair its electrical properties.

2 ABRASIVE EFFECTS

2.1 Abrasion of surfaces

2.1.1 Dust and sand, under the dynamic influence of winds of high velocity, can act as damaging abrasives of stationary surfaces, and instantaneously airborne particles thrown up in the wake of moving vehicles can have a similar effect. Abrasive action of this kind can promote or accelerate the corrosion of metallic surfaces by removing protective coatings or by disturbing semi-protective films of corrosion products. The cutting effect of windblown dust and sand is very noticeable on wooden objects such as telephone or telegraph poles situated in desert areas. Glass components such as car windscreens can become pitted and frosted during sandstorms.

2.1.2 The degree of surface abrasion will depend on the velocity of the impinging particles relative to the surface. A marked deterioration in the optical quality of aircraft windscreens has been reported after test flights at heights of 60 m and speeds of between 290 to 320 m/s over the North Africa deserts.

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

2.1.4 Painted identifications and instructions at grease points, external electrical sockets, fuelling points, etc, can be obliterated or rendered illegible by the abrasive action of dust and sand.

2.2 Abrasive wear of mechanisms

2.2.1 Abrasive wear may be defined as the scrubbing or cutting action of extraneous material introduced between two rubbing or sliding surfaces. Mechanisms that require air for operation, such as the internal combustion engine, are particularly susceptible to abrasive wear through the introduction of airborne dust and sand, although the effect can be mitigated by air filtering.

2.2.2 Many investigations have been carried out in an attempt to relate environmental properties to abrasive wear and to establish criteria for the design of efficient air filters. In one series of tests on aircraft engines, dust was artificially introduced into the intake system and engine wear measured in terms of metal removed from piston rings and cylinders. Some of the results of the investigations, showing the rate of metal removal as functions of dust size and weight of dust fed, are illustrated in Figure 1.

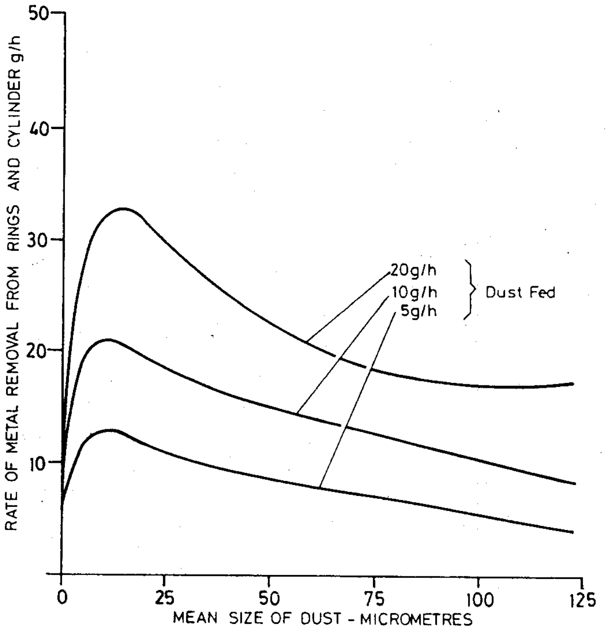

Figure 1. Effect of dust size on total metal removed on rings and cylinders at various feed rates

3 CORROSION OF METALS

3.1 General

3.1.1 Dust and sand, in conjunction with other environmental factors such as moisture, can be responsible for the commencement and acceleration of the corrosion of metals. Films of particulate matter deposited on metal surfaces may be a mixture of inert, chemically active, absorbent or non-absorbent particles and therefore the resulting corrosive processes are complex.

3.2 The effect of dust and sand in corrosive processes

3.2.1 Chapters 8-01 and 8-02 should be consulted for information on the nature and occurrence of corrosive atmospheres, corrosive processes and factors influencing corrosion.

3.4 Chemically inert particles

3.3.1 Inert particles that are hygroscopic will commence to absorb moisture and any corrosive vapours present in the atmosphere, at low relative humidities. The particles, in this instance, act as vehicles for the aqueous electrolyte by which the electrochemical reaction of atmospheric corrosion proceeds and enhance the corrosive effect. The effect of particles of charcoal, an inert absorbent, on the rusting of iron in the absence and presence of sulphur dioxide is illustrated graphically in Figure 2.

3.3.2 Inert non-absorbent particles have little effect on the corrosive process except by helping to retain the moisture and by screening the metal at the point of contact, causing differences in the concentration of oxygen over the surface. These differences may cause intensive localised corrosion to occur.

3.3.3 The effect of silica particles, which are an inert non-absorbent, on the rusting of iron in the presence of sulphur dioxide, is shown in Figure 2.

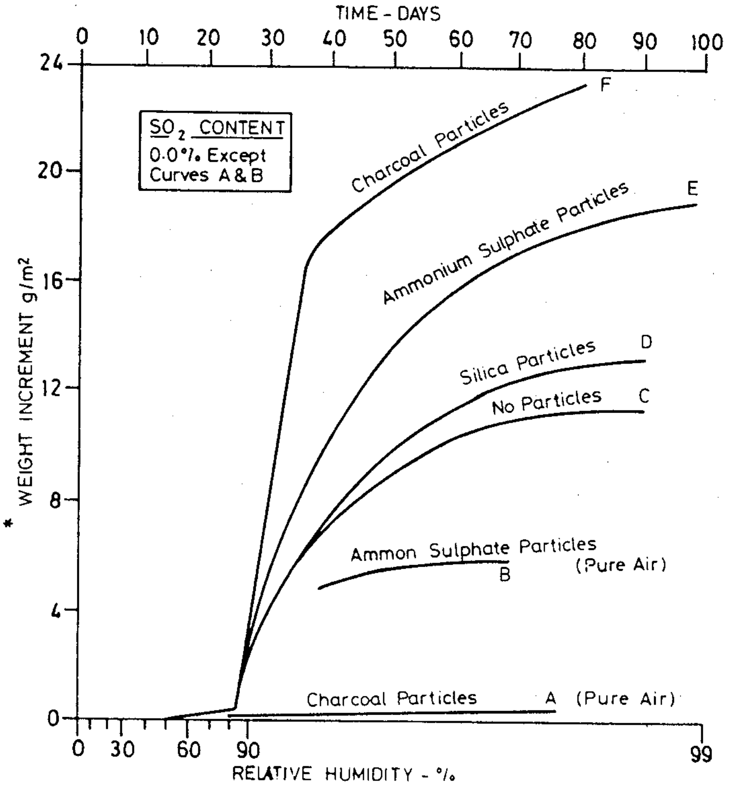

Figure 2. Influence of particles on rusting of iron in the presence of sulphur dioxide and increasing humidity

3.4 Chemically active particles

3.4.1 Particles originating from natural or industrial sources may be chemically active and provide corrosive electrolytes when dissolved. Many clays, a principle source of natural outdoor dusts, are hydrated silicates of aluminium and give alkaline reactions, while several of the soluble salts contained in soil particles are sulphates giving acid reactions.

3.4.2 The rusting of iron can be accelerated by the presence of ammonium sulphate particles. These occur as a dust in urban areas.

3.4.3 Calcium carbonate in the form of seashell fragments occurs as the dominant constituent of dust on coral islands and can prove corrosive. Volcanic ash can accelerate the rusting of iron.

4 THE CONTAMINATION OF ELECTRICAL INSULATOR SURFACES

4.1 Sand and the majority of dusts usually deposited on insulant surfaces are poor conductors in the absence of moisture. The presence of moisture, however, will result in the dissolving of the soluble particles and the formation of conducting electrolytes. The insoluble particles present will tend to retain the electrolyte on the surface and increase the effective thickness of the moisture film. The formation of such films is promoted by an environment where dry, dusty periods and wet, humid periods alternate.

4.2 As a result of the conductivity of such surface films, the leakage currents flowing over contaminated power line insulators can be of the order of one million times those which flow through clean, dry insulators. The flash-over voltages on dirty and wet insulators, clean and wet insulators, and clean and dry insulators are compared in Figure 3.

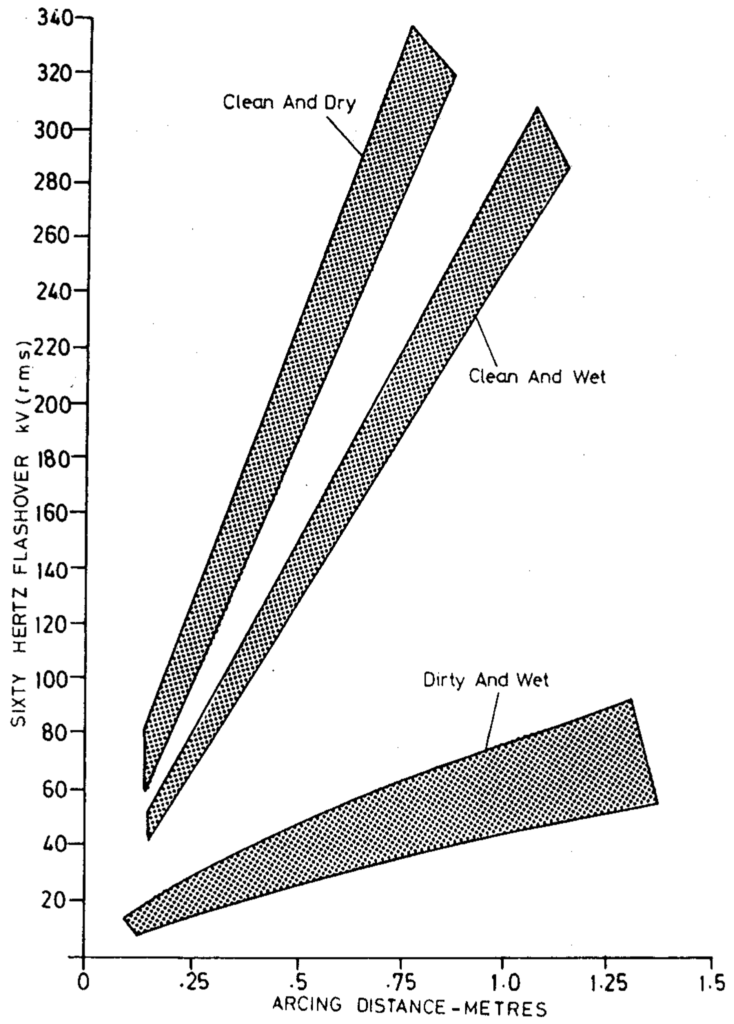

Figure 3. Sixty cycle flashover voltage of dirty insulators of various types and sizes, plotted as a function of the arcing distance

4.3 If the insulant is in a strong electric field, such as power line insulators, the build up of the film will also be encouraged by the attraction of airborne particles to the areas having steep voltage gradients.

5 MISCELLANEOUS EFFECTS

5.1 Promotion of mould growth

5.1.1 Dust adhering to the surface of materials may contain organic substances that provide a source of food for micro-organisms. Surfaces of materials such as ceramics and optical glasses, that are not normally susceptible to microbial attack when dust free, may therefore become overgrown with moulds. The nature and effect of such biological hazards are discussed in Chapters 11-01 and 11-02.

5.2 Mechanisms

5.2.1 The intrusion of dust and sand can interfere with the operation of mechanisms. The first evidence of contamination is usually an increase in friction levels, followed by slower response and reduction in sensitivity of the mechanism. Eventually complete seizure may result.

5.3 Electrical contacts and connectors

5.3.1 As stated previously, sand and the majority of dusts are poor electrical conductors when dry, therefore particles deposited on switch, relay or any electrical contacts can impair operation by increasing the contact resistance.

5.3.2 Dust and sand accumulating in electrical connectors can make mating or disconnection difficult.

5.4 Cooling systems

5.4.1 A reduction in heat transfer rates can be caused by the formation of insulating layers and can lower the efficiency of cooling systems.

5.5 Bearing greases

5.5.1 The exposed bearing greases of vehicles are particularly liable to caking and drying by the action of dust and sand.

5.6 Electrostatic effects

5.6.1 The electrostatic charges produced by friction of the particles in sand storms can interfere with the operation of equipment and sometimes be dangerous to personnel. The breakdown of insulators, transformers and lightning arresters, and the failure of car ignition systems has been known to occur as a result of such charges. The electrostatic voltages produced can be large. Voltages as high as 150 kV have made telephone and telegraph communications inoperable during sand storms.

5.7 Internal combustion engines

5.7.1 Dust can penetrate and cause malfunction of both compression ignition and spark ignition engines.

5.8 Paint films

5.8.1 Particles adhering to a newly applied and tacky paint film can spoil the finish. A chemical effect can be superimposed on the purely physical one, when particulates contaminate fresh paint films containing certain drying oils. Paint films can lose their protective properties by cracks prematurely induced by 'stress raisers' such as particles.

6 WEAPON OPERATION

6.1 The components of a weapon system and its support services may be affected by the dust and sand environment in any of the ways described previously in this chapter. The following specific deleterious effects have been reported:

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

(b) The sensitivity of the guidance system can be reduced because radomes and star tracking windows have been abraded.

(c) Explosions or motor burn-out have occurred because of hot spots produced in cooling passages of regeneratively cooled liquid rocket engines.

(d) Dust and sand in propellants or propellant systems can clog up fuel metering passages and provoke erratic operation or even explosions. Explosions have also been caused by particulate impurities contacting heavily concentrated hydrogen peroxide.

7 GENERAL OBSERVATIONS

7.1 The deleterious effects of the dust and sand environment can be combatted by one or a combination of the following procedures:

(a) Provision of a conditioned environment. This measure may only be necessary where the vulnerability of equipment and extremes of climate combine.

(b) Placing equipment in a pressurised container.

(c) Inclusion of air filters at the air intakes of equipment compartments.

(d) Hermetic sealing.

(e) Adoption of designs that hinder formation of dust and sand films on surfaces.

(f) Use of materials or protective coatings that resist the abrasive action.

(g) Screening of exposed surfaces or bearings liable to abrasion.

(h) The earthing of equipment installed in localities having sand storm risk, to avoid build-up of electrostatic charges.

7.2 The selection of materials and protective coatings having good abrasion resistance may be assisted by careful study of the relevant publications such as References 2, 3, 4 and 5. The subject of hermetic sealing is discussed in Reference 6. Articles and books dealing with the subject of air cleaning and filtering are included in the annotated bibliography of Reference 1.

8 REERENCES AND OTHER SOURCES OF INFORMATION

8.1 References

1 'Effect of, Design Criteria for, and Preventative Measures against Climatic and Environmental Extremes in Guided Missiles'. WADC Tech. Rep. 53-124, June 1953. — Booz, Allen and Hamilton

2 DEF 5000
General Requirements for Service Telecommunication Equipment.

3 Ministry of Aviation AvP24.
General Design Requirements for Aircraft Equipment for Service Aircraft.

4 DEF STAN 07-85
Design Requirements for Weapon Systems (Guided Weapons, Torpedoes and Airborne Armament Stores).

5 Defence Guide DG-8
Treatments for the Protection of metal Parts of Service Stores and Equipment against Corrosion.

6 DEF-CP-1.
Code of Practice for the Climate Proofing of Electrical Equipment.

8.2 Further reading

'A Study of Windborne Sand and Dust in Desert Areas' US Army Natick Lab. Tech. Rep. ES-8 AD No. 417036, August 1963.	T Clements et al
'Erosion of Aircraft windscreens by Sand and Dust Particles in High Speed, Low Altitude Flight' RAE, Farnborough, Tech. Note Mech. Eng. 342.	F L C Terry
'Tropicproofing Electrical Equipment' Morgan Grampian Books Ltd., London.	M Rychtera and B Bartakova
'An Investigation into Engine Wear Caused by Dust' Australia Aeronautical Research Consultative Committee, Report ACA-50, July, 1950.	R V Pavia
'Study of Atmospheric Corrosion on Metals'. Transactions of Faraday Society, Volume 31, Page 1668, 1935.	W H J Vernon
'Deterioration of Materials' Rheinhold Publishing Corporation (USA).	G A Greathouse and C J Wessel
'Insulator Surface Contamination' AIEE, New York, Tech. Papers 48-255, January, 1949.	H Frey
'The Dust Environment and its Effect on Dust Penetration'. WADC Tech. Rep. 56-556, ASTIA Doc. No. AD 110472 September, 1956.	J Pauly

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CHAPTER 10-01
ATMOSPHERIC PRESSURE

1 INTRODUCTION

1.1 The pressure of the atmosphere on a given surface is the force per unit area due to the weight of air in the column extending from the surface to the outer limit of the atmosphere. As the level of the surface is raised, the weight of air above this surface is reduced; in other words, pressure decreases with increase of altitude.

1.2 The unit of pressure in the metric system is the Newton per square metre (N/m^2) or Pascal (Pa); but in meteorology the unit used almost universally is the hectopascal (hPa), equal to 100 N/m^2. The millibar (mbar, mb), equivalent to the hectopascal in all but name, is being phased out by the World Meteorological Organisation. At sea level the average pressure is a little over 1000 hPa.

1.3 Pressure varies with altitude, therefore a standard altitude must be used for comparative pressure readings. By international agreement all pressures are corrected to mean sea level (MSL) if the observing station is below about 500 metres; for higher levels the reduction procedures are decided by regional agreement. It may be noted that near sea level the average decrease of pressure due to increase in height is about 12 hPa per 100 metres.

1.4 This chapter is mainly concerned with pressure changes near the earth's surface but the closing paragraphs briefly discuss pressure in the upper air.

2 PRESSURE DISTRIBUTION

2.1 Average values

2.1.1 Figures 1 and 2 show the average distribution of sea level pressure in January and July, the following points being worthy of note:

(a) Anticyclones are generally centred over land masses in the winter of each hemisphere, as a result of the cold dense stagnant air; a good example is the 'Siberian High' in January. In summer the areas of highest pressures are found over the oceans, for example the 'Azores High' in July.

(b) Depressions favour the oceans in winter, with both the North Pacific and North Atlantic having marked areas of low pressure in January. In summer the hot interiors of continents give rise to heat lows, as over South Africa and South America in January and over Northwest India and South-west United States in July.

(c) Pressure gradients are greater in winter, particularly over the Northern hemisphere, resulting in the stronger winds characteristic of that season.

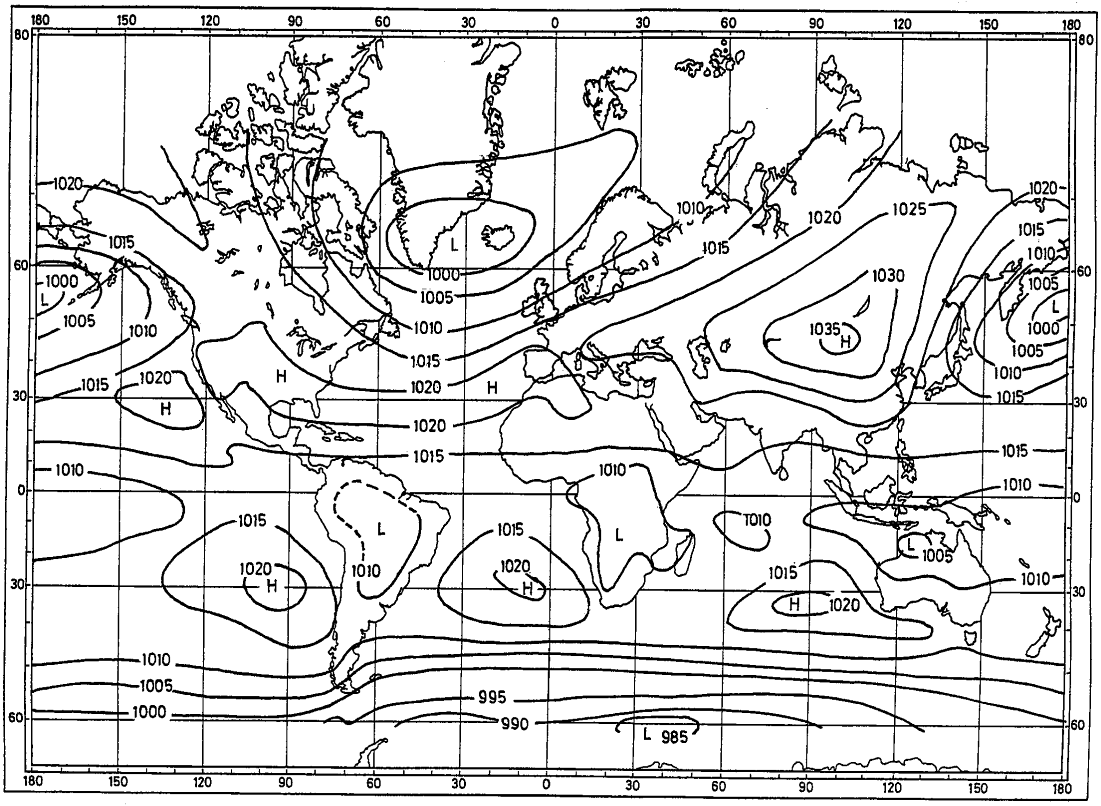

Figure 1. Average Pressure (hPa) at Mean Sea Level in January

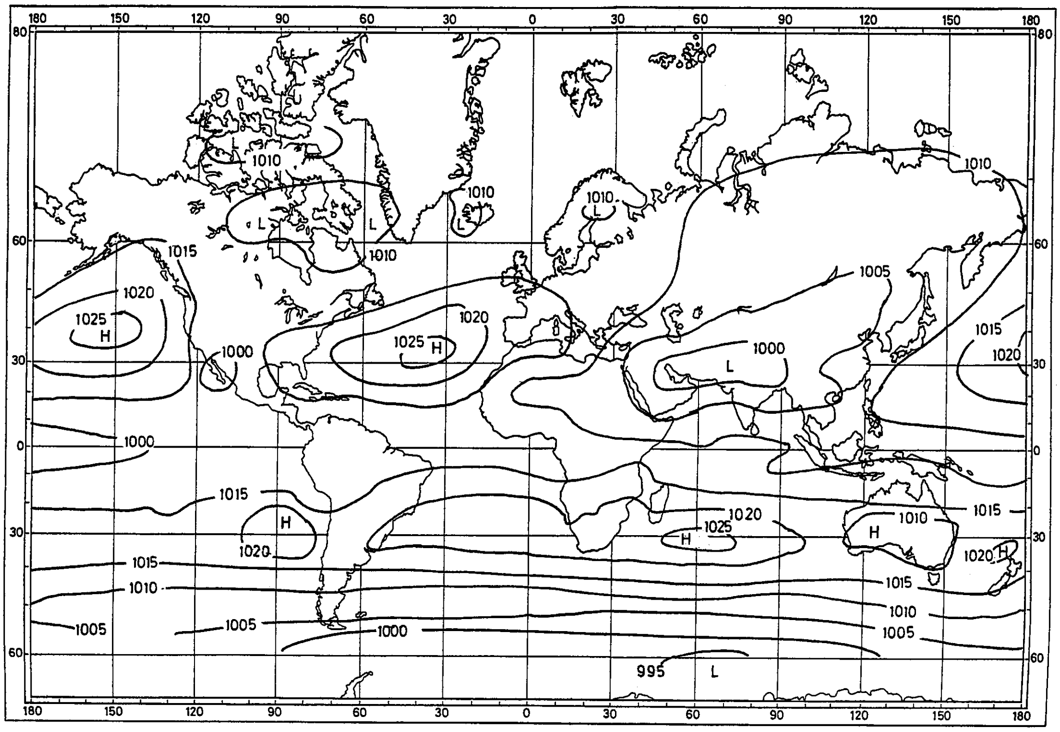

Figure 2. Average Pressure (hPa) at Mean Sea Level in July

2.2 Departures from average

2.2.1 Although it is possible to calculate the standard deviation of pressure (as indicated in later paragraphs for upper air pressures) this parameter will have only limited meaning, since pressure (unlike temperature) does not follow a predictable distribution. A better representation of pressure variations, for a selection of stations in different climatic regions, can be given by means of probability plots as in Figures 3 and 4 where the horizontal axis indicates the percentage probability of the actual pressure being less than the figure indicated on the vertical axis.

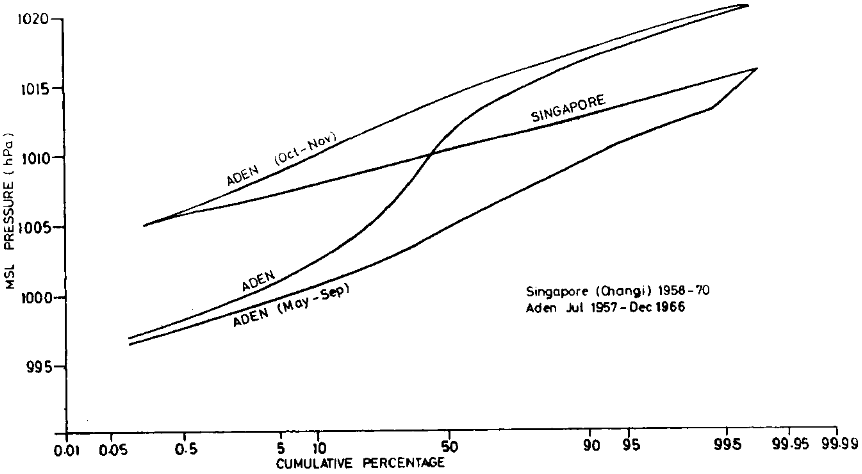

Figure 3. Probability plot of MSL pressure at Singapore and Aden

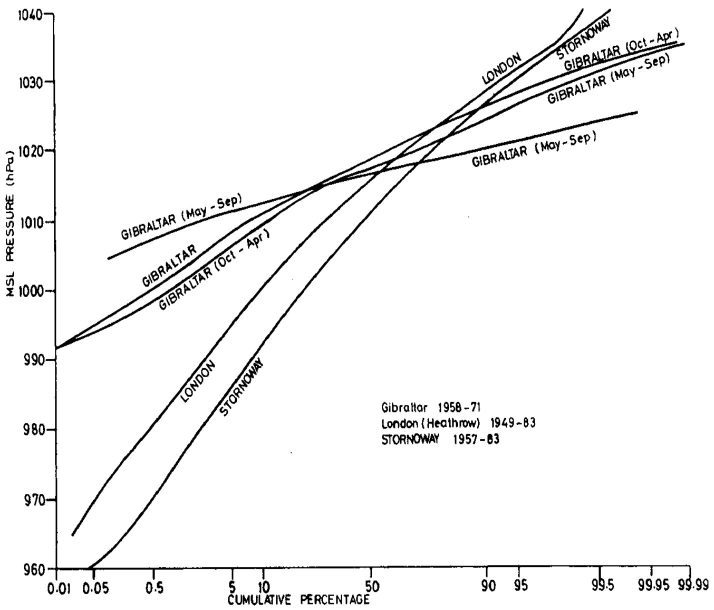

Figure 4. Probability plot of MSL at Gibraltar, London and Stornoway

2.2.2 Three broad types may be identified:

(a) The equatorial, as represented by Singapore, where the pressure seldom varies by more than 5 hPa from its mean value at any time of the year.

(b) Climates whose pressure regime is associated with the winter and summer monsoon, of which Aden is an example. Here the graph for the whole year shows an S-shaped distribution but the near-linear curves for the separate winter and summer seasons imply almost normal distributions.

(c) Temperate climates in which the average pressure varies little from month to month but where the lower extremes are further from the mean than are the upper extremes, a distribution which is negatively skew rather than normal. Stornoway and London (Heathrow) Airport are included as examples of this type.

2.2.3 Stations such as Gibraltar have a Mediterranean climate and exhibit a distribution somewhere between the Equatorial and Temperate.

2.3 Diurnal and semi-diurnal variations

2.3.1 Mean sea level pressure has a systematic diurnal and semi-diurnal variation. This variation is dependent on season and latitude but generally shows minima at about 0400 and 1600 hours and maxima around 1000 and 2200 hours local time. At latitudes of 50° North or South the variations generally have amplitudes of about 0.7 hPa on either side of the mean. This is small compared with the pressure changes caused by the mobile weather systems affecting these latitudes. Near the Equator, however, the day to day weather movements produce only small pressure changes, and systematic diurnal variations (approximately 2 hPa on either side of the mean) are much more obvious on the barograph trace.

2.4 Extremes of pressure

2.4.1 Stations on high ground will naturally stand a greater chance of record low pressure readings, while those on land below sea level will stand a greater chance of record highs, (the highest surface stations are in China, at about 4700 m, and report station-level pressures around 570 hPa). For extremes of pressure to be comparable, readings must be adjusted to compensate for variations in altitude. Mean Sea Level is normally taken as a standard.

2.4.2 If sea level values alone are considered, then the nine highest were all observed in the USSR during the cold Asian winter, with an extreme maximum of 1083.9 hPa at Agate (67 N, 93 E, approx. 263 m) at 1200 GMT on 31 December 1968, when the air temperature was -46°C. In January the 'Siberian High' exceeds 1057 hPa on 1% of occasions. The highest value measured in North America was 1070.1 hPa on the Alaska-Yukon border on 6 January 1909, while the British maximum was recorded at Glasgow in 1896 when a pressure of 1053.8 hPa was reached.

2.4.3 At the other end of the scale the pressure is reported to have fallen to 870 hPa on 12 October 1979 at 17° N, 138° E, in the eye of a typhoon, and on 18 August 1927 a value of 886.6 hPa was observed on a ship east of Luzon in the Philippines. The lowest pressure recorded in a United States hurricane, was at Matecumbe Key, Florida on 2 September 1935 when the pressure fell to 892.3 hPa. The lowest recorded in Great Britain, was 925.5 hPa on 26 January 1884 at Ochertyre, Tayside. In January the 'Icelandic Low' is below 953 hPa on 1% of occasions.

2.5 Variations of pressure with distance

2.5.1 The correlation of sea level pressure between stations over Europe falls from a value of 0.9, for two stations within 350 km of each other, to zero when the distances between them exceeds about 3000 km. These correlation coefficients may be taken as applying approximately to stations in other parts of the world at similar latitudes, and for a more detailed consideration of this question References 1 and 2 should be consulted. Table 1 gives the percentage occurrence of specified pressure differences within 100 km of Berlin, for the four seasons and for the year as a whole.

TABLE 1

PERCENTAGE OF OCCURRENCE OF SPECIFIED PRESSURE DIFFERENCES WITHIN 100 km OF BERLIN

Pressure difference (hPa)	0-0.2	0.3-1.0	1.1-2.1	2.2-3.1	3.2-3.9	4.0-5.9	6.0 or over
Winter	3.0	24.8	44.8	26.7	3.4	0.7	0.0
Spring	2.9	39.4	46.3	12.6	1.6	0.0	0.0
Summer	4.7	57.2	36.2	6.5	0.0	0.0	0.0
Autumn	1.8	37.7	41.2	18.0	2.9	0.0	0.0
Year	3.1	36.8	42.1	15.9	2.0	0.2	0.0

2.5.2 When considering pressure correlations at upper levels, the rate of decay with distance, at 100 hPa, is almost identical with that near sea level; but while the 0.9 circle retains a radius of some 350 km throughout the troposphere, the correlation falls to zero within a little over 2000 km at levels between 500 and 300 hPa.

3 RELATIONSHIP BETWEEN PRESSURE AND ALTITUDE

3.1 International Standard Atmosphere

3.1.1 A hypothetical atmosphere, corresponding approximately to the average state of the real atmosphere, has been adopted internationally and is described in International Standard No ISO 2533. An examination of the data in ISO 2533 shows that the pressure decreases by approximately half of its value for each 5 km increase in altitude. A specific reference atmosphere has also been devised for aerospace purposes, and is included in International Standard No ISO 5878.

3.2 Departures from Standard

3.2.1 Although it has been noted earlier that pressure frequencies approximate only roughly to normal distributions, the assumption of a normal distribution may be used, together with mean heights and standard deviations, to determine approximately the frequency with which a given pressure occurs at a specific height. Reference 3 should be consulted for maps showing the mean height of standard isobaric surfaces over the world for the four mid-season months of January, April, July and October. To supplement this, mean heights and standard deviations of pressure levels have been computed for seven stations based on observations extending over a period of ten years, and these data are presented in Table 2. Further details for the United Kingdom, including monthly frequency tables for a larger range of pressure levels, can be found in Reference 4.

3.2.2 Pressure changes in the upper air depend not only on changes in the pressure at sea level but also on variations in the temperature of the air up to the level concerned. Pressure falls off more rapidly with height when the air is cold and dense than when it is warm and relatively light. This complicated relationship between temperature, altitude and pressure makes it difficult to summarise pressure changes adequately, and detailed information for conditions in a specific locality should be sought from the Meteorological Office.

4 DESIGN CRITERIA

4.1 Materiel should remain safe and be capable of acceptable performance at all values of atmospheric pressure from the highest to the lowest recorded for each environment to which the materiel will be exposed.

4.2 The highest value of atmospheric pressure recorded at sea level is 1084 hPa. The lowest value recorded at the sea surface is 870 hPa, and the lowest value for the highest ground elevation contemplated for the operation, storage and transportation of materiel of the NATO forces is 503 hPa.

TABLE 2

ALTITUDE CORRESPONDING TO SELECTED PRESSURE LEVELS FOR SELECTED STATIONS

			Altitude (m)			
Station	Month	Pressure level (hPa)	Mean	Std deviation	Max	Min
STANLEY Lat. 51 42 S Long 57 52 W Period 1958/67	Jan	700	2 872	89	3 072	2 617
		500	5 242	120	5 707	5 116
		300	8 990	171	9 400	8 590
		200	11 630	154	12 030	11 260
		100	16 120	96	16 360	15 860
		50	20 630	91	20 850	20 400
		30	24 030	121	24 220	23 840
		25	-	-	-	-
	Apr	700	2 847	95	3 090	2 570
		500	5 362	128	5 733	5 078
		300	8 860	183	9 380	8 460
		200	11 460	166	11 980	11 060
		100	15 900	123	16 310	15 570
		50	20 290	138	20 650	19 880
		30	23 760	140	23 870	23 250
		25	-	-	-	-
	Jul	700	2 855	106	3 117	2 619
		500	5 345	133	5 693	5 067
		300	8 810	180	9 300	8 430
		200	11 350	176	11 900	10 960
		100	15 670	165	16 080	15 200
		50	19 910	218	20 300	19 320
		30	23 000	129	23 310	22 810
		25	-	-	-	-
	Oct	700	2 887	97	3 101	2 617
		500	5 400	126	5 675	5 079
		300	8 900	171	9 270	8 490
		200	11 480	169	11 840	11 040
		100	15 850	176	16 190	15 330
		50	20 240	253	20 750	19 550
		30	23 290	222	23 890	23 100
		25	-	-	-	-

TABLE 2 cont'd

ALTITUDE CORRESPONDING TO SELECTED PRESSURE LEVELS FOR SELECTED STATIONS

Station	Month	Pressure level (hPa)	Altitude (m)			
			Mean	Std deviation	Max	Min
NICOSIA	Jan	700	3 020	58	3 161	2 861
Lat. 35 09 N		500	5 577	83	5 794	5 296
Long 33 17 E		300	9 130	122	9 450	8 740
Period		200	11 730	120	12 080	11 410
1960/69		100	16 090	93	16 530	15 850
		50	23 570	92	21 030	20 030
		30	24 740	98	23 870	23 150
		25	-	97	24 990	24 520
	Apr	700	3 052	50	3 175	2 892
		500	5 652	74	5 825	5 394
		300	9 260	109	9 490	8 860
		200	11 880	105	12 140	11 510
		100	16 240	79	16 470	15 920
		50	20 540	76	20 760	20 340
		30	23 760	88	23 150	24 730
		25	24 930	81	23 150	24 730
	Jul	700	3 125	26	3 181	3 020
		500	5 847	42	5 932	5 691
		300	9 680	65	9 820	9 420
		200	12 480	71	12 640	12 170
		100	16 780	70	17 060	16 440
		50	20 950	58	21 130	20 710
		30	24 210	62	24 390	24 040
		25	25 400	81	25 580	25 190
	Oct	700	3 125	39	3 218	3 006
		500	5 766	59	5 898	5 580
		300	9 430	89	9 660	9 160
		200	12 070	104	12 340	11 770
		100	16 370	89	16 620	16 040
		50	20 650	85	20 980	20 200
		30	23 870	101	24 180	23 350
		25	25 050	107	25 280	24 790

TABLE 2 cont'd

ALTITUDE CORRESPONDING TO SELECTED PRESSURE LEVELS FOR SELECTED STATIONS

Station	Month	Pressure level (hPa)	Altitude (m)			
			Mean	Std deviation	Max	Min
GIBRALTAR Lat. 35 09 N Long 05 21 W Period 1960/69	Jan	700	3 089	67	3 217	2 874
		500	5 677	92	5 858	5 392
		300	9 270	129	9 610	8 900
		200	11 870	130	12 250	11 560
		100	16 170	103	16 500	15 600
		50	20 430	107	20 780	20 090
		30	23 600	105	23 930	23 280
		25	24 750	156	24 620	24 530
	Apr	700	3 074	64	3 231	2 867
		500	5 675	94	5 893	5 536
		300	9 280	142	9 600	8 850
		200	11 890	140	12 250	11 540
		100	16 230	97	16 510	16 020
		50	20 530	74	20 750	20 320
		30	23 750	99	24 020	23 530
		25	24 920	97	23 230	24 670
	Jul	700	3 202	30	3 294	3 113
		500	5 901	55	6 916	5 783
		300	9 640	52	9 770	9 470
		200	12 340	68	12 540	12 120
		100	16 630	60	16 840	16 360
		50	20 890	67	21 140	20 690
		30	24 130	85	24 340	23 920
		25	25 330	76	25 540	25 180
	Oct	700	3 130	56	3 250	2 946
		500	5 770	73	5 909	5 514
		300	9 450	100	9 680	9 060
		200	12 080	109	12 400	11 750
		100	16 350	85	16 670	16 060
		50	20 620	92	20 950	20 190
		30	23 840	94	24 220	23 570
		25	25 010	117	25 420	24 810

TABLE 2 cont'd

ALTITUDE CORRESPONDING TO SELECTED PRESSURE LEVELS FOR SELECTED STATIONS

Station	Month	Pressure level (hPa)	Altitude (m)			
			Mean	Std deviation	Max	Min
LERWICK Lat. 60 08 N Long 01 11 W Period 1960/69	Jan	700	2 891	138	3 208	2 467
		500	5 384	165	5 744	4 924
		300	8 860	211	9 290	8 300
		200	11 410	200	11 850	10 860
		100	15 750	205	16 220	15 050
		50	20 020	271	20 600	19 100
		30	23 600	376	24 050	22 050
		25	24 750	431	25 300	23 110
	Apr	700	2 917	110	3 178	2 556
		500	5 425	144	5 723	5 035
		300	8 920	185	9 350	8 420
		200	11 530	158	11 950	11 040
		100	16 010	153	16 400	15 460
		50	20 450	174	20 810	19 880
		30	23 710	282	24 120	22 660
		25	24 850	246	25 300	24 190
	Jul	700	2 993	84	3 199	3 648
		500	5 576	108	5 841	5 228
		300	9 180	150	9 580	8 790
		200	11 850	129	12 260	11 510
		100	16 440	83	16 690	16 140
		50	21 020	77	21 230	20 690
		30	24 420	99	24 670	24 160
		25	25 690	96	25 910	25 430
	Oct	700	2 934	124	3 192	2 580
		500	5 490	158	5 816	5 113
		300	9 050	214	9 480	8 540
		200	11 670	201	12 130	11 210
		100	16 090	139	16 480	15 720
		50	20 480	142	20 940	19 990
		30	23 720	178	24 160	23 060
		25	25 880	202	25 370	24 280

TABLE 2 cont'd

ALTITUDE CORRESPONDING TO SELECTED PRESSURE LEVELS FOR SELECTED STATIONS

Station	Month	Pressure level (hPa)	Altitude (m)			
			Mean	Std deviation	Max	Min
GAN Lat. 00 41 S Long 73 09 E Period 1960/69	Jan	700	3 127	11	3 152	3 093
		500	5 840	15	5 872	5 800
		300	9 650	26	9 720	9 570
		200	12 380	41	12 490	12 240
		100	16 510	69	16 750	16 260
		50	20 460	84	20 640	20 160
		30	23 560	140	23 870	23 070
		25	24 730	114	25 050	24 480
	Apr	700	3 130	10	3 167	3 101
		500	5 850	13	5 889	5 810
		300	9 670	21	9 740	9 600
		200	12 410	35	12 500	12 250
		100	16 550	66	16 790	16 250
		50	20 530	77	20 720	20 280
		30	23 700	116	24 000	23 380
		25	24 910	121	25 200	24 660
	Jul	700	3 129	10	3 156	3 100
		500	5 840	13	5 873	5 804
		300	9 640	21	9 710	9 570
		200	12 370	31	12 450	12 270
		100	16 510	50	16 650	16 280
		50	20 620	72	20 830	20 430
		30	23 830	106	24 030	23 560
		25	25 010	113	25 230	24 720
	Oct	700	3 130	8	3 157	3 099
		500	5 840	11	5 881	5 811
		300	9 660	19	9 730	9 590
		200	12 390	32	12 510	12 280
		100	16 520	55	16 800	16 340
		50	20 580	74	20 890	20 400
		30	23 730	132	24 150	23 360
		25	24 940	103	25 160	24 760

TABLE 2 cont'd

ALTITUDE CORRESPONDING TO SELECTED PRESSURE LEVELS FOR SELECTED STATIONS

Station	Month	Pressure level (hPa)	Altitude (m)			
			Mean	Std deviation	Max	Min
MUHARRAQ Lat. 26 16 N Long 50 37 E Period 1960/69	Jan	700	3 116	34	3 193	2 946
		500	5 753	52	5 922	5 523
		300	9 440	79	9 710	9 140
		200	12 110	99	12 390	11 790
		100	16 350	87	16 610	16 040
		50	20 450	79	20 680	20 010
		30	23 620	83	23 830	23 160
		25	24 770	77	25 010	24 550
	Apr	700	3 128	28	3 126	3 030
		500	5 791	44	5 918	5 634
		300	9 490	71	9 670	9 230
		200	12 170	88	12 400	11 890
		100	16 430	83	16 690	16 070
		50	20 540	92	20 760	19 830
		30	23 760	94	23 970	23 540
		25	24 950	82	25 180	24 720
	Jul	700	3 126	19	3 183	3 074
		500	5 879	21	5 953	5 823
		300	9 750	26	9 830	9 660
		200	12 550	36	12 670	12 430
		100	16 800	59	17 070	16 580
		50	20 840	56	21 030	20 620
		30	24 060	65	24 230	23 870
		25	25 260	71	25 420	25 090
	Oct	700	3 175	19	3 224	3 116
		500	5 870	26	5 932	5 759
		300	9 630	52	9 750	9 440
		200	12 330	71	12 510	12 070
		100	16 520	72	16 770	16 240
		50	20 650	70	20 830	20 160
		30	23 870	96	24 080	23 230
		25	25 050	78	25 280	24 820

TABLE 2 cont'd

ALTITUDE CORRESPONDING TO SELECTED PRESSURE LEVELS FOR SELECTED STATIONS

Station	Month	Pressure level (hPa)	Altitude (m)			
			Mean	Std deviation	Max	Min
CRAWLEY Lat. 51 05 N Long 00 13 W Period 1960/69	Jan	700	2 963	116	3 202	2 601
		500	5 490	146	5 822	5 102
		300	9 101	189	9 430	8 510
		200	11 580	176	12 000	11 100
		100	15 940	142	16 400	15 430
		50	20 260	176	20 740	19 560
		30	23 420	212	24 190	22 590
		25	24 560	256	25 650	23 700
	Apr	700	2 976	90	3 222	2 664
		500	5 518	115	5 835	5 149
		300	9 050	153	9 460	8 530
		200	11 650	134	12 040	11 180
		100	16 100	109	16 370	15 670
		50	20 510	122	20 790	20 080
		30	23 770	145	24 150	23 320
		25	24 940	164	25 350	24 460
	Jul	700	3 081	73	3 272	2 863
		500	5 701	100	5 942	5 433
		300	9 360	147	9 670	9 020
		200	12 020	140	12 360	11 710
		100	16 500	83	16 760	16 260
		50	20 990	74	21 250	20 740
		30	24 360	93	24 660	24 040
		25	25 580	112	25 890	25 220
	Oct	700	3 032	112	3 283	2 716
		500	5 629	146	5 948	5 232
		300	9 240	202	9 660	8 670
		200	11 870	199	12 320	11 340
		100	16 220	130	16 510	15 910
		50	20 580	121	20 850	20 200
		30	23 780	147	24 120	23 330
		25	24 930	168	25 320	24 430

4.3 The highest and lowest values of atmospheric pressure estimated for a range of altitudes up to 30 km are given in Table 3.

TABLE 3

ATMOSPHERIC PRESSURE AT ALTITUDE

Altitude	Atmospheric pressure	
km	Highest recorded hPa	Lowest recorded hPa
0	1084	870
1	930	842
2	821	736
4	643	548
6	501	406
8	385	296
10	294	215
12	226	154
14	168	111
16	123	79
18	88	56
20	65	40
22	45	28
24	35	20
26	26	14
28	20	10
30	15	7

NOTE: It should be noted that not all the highest or lowest pressures at the various altitudes occurred simultaneously nor necessarily at the same location, and the set of values given in the Table does not represent a specific pressure-altitude profile.

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3 'Upper Winds over the World-Parts 1 and 2' London, Meteorological Office Geophysical Memoir No. 103, 1960 — H Heastie and P M Stephenson

4 'Met 0 910 a - f, 'Upper-air Summaries 1961-70' Meteorological Office (Met O 3)

5 ISO 2533, plus addenda - 'Standard Atmosphere'

6 ISO 2878, plus addenda - 'Reference Atmosphere for aerospace use'

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CHAPTER 10-02
THE EFFECTS OF AIR PRESSURE

1 GENERAL INTRODUCTION

1.1 Pressure can adversely affect materials, equipment and personnel. The effects depend largely on the physical and operational characteristics of the object and in the case of humans the degree of physical fitness. Other atmospheric variables, such as air temperature, may contribute to damage initiated by air pressure.

1.2 Aerodynamic effects associated with air pressure, such as lift and drag, are not dealt with in this chapter. Pressure effects caused by wind are described in Chapter 5-02. Over-pressure caused by blast is referred to in Part 5.

2 EFFECTS ON AIRBORNE EQUIPMENT

2.1 Introduction

2.1.1 A vehicle moving within the Earth's atmosphere is subject to two primary pressure effects, one due to air pressure which reduces with increasing altitude and the other due to the rate of change of pressure due to increasing or decreasing altitude. The relationship between altitude and atmospheric pressure is given in Chapter 10-01. Maximum rates of climb and descent vary with the type of aircraft or missile, but for rates of climb of the order of 250 m/s and descent of the order of 350 m/s the associated maximum rates of change of pressure are about 2300 and 2800 $N/m^2/s$ respectively, at normal operating altitudes.

2.1.2 Secondary pressure effects arise within equipment compartments of vehicles from the use of atmospheric air for cooling, as air taken inboard will have its pressure increased either by a ram duct or compressor in order to overcome the equipment pressure losses. Secondary pressures may be calculated from standard pressure drop/flow tables, or from standard expressions such as the Fanning equation.

2.1.3 Compressor and conditioning air plants have a rating related to ambient pressure, and need special consideration particularly where fans are working close to the stall condition.

2.2 Pressurized compartments

2.2.1 Personnel and equipment may be adversely affected by low air pressure or a high rate of change of pressure. In aircraft cabin and equipment compartments the air pressure is normally maintained above that of the pressure of the outside atmosphere by an amount known as the pressure differential. For example an aircraft flying at 14.3 km with a cabin 'altitude' of 2.4 km has a cabin pressure differential of 62 kN/m^2. Pressurization is covered in the books and publications given under Further Reading.

2.2.2 In the event of a pressure cabin becoming punctured, decompression will follow at a rate dependent upon the size of hole, size of pressure cabin and the pressure differential. The effect may be explosive and cause structural collapse. More commonly, rapid decompression may result from failure of the cabin pressurization system. Airborne systems may be required to remain operational in such circumstances or alternatively, to sustain no permanent damage during decompression, so that they can be used following a return to normal conditions.

2.3 Pressurized canisters

2.3.1 Occasionally, cannisters are designed to release air pressure as altitude increases and recover this during descent via the aircraft pressurizing system. Failure of the pressurizing system can result in a pressure differential, the importance of which increases as the rate of change of pressure increases. The maximum rate of change of pressure, although dependent on vehicle performance, usually occurs at the lower altitudes.

2.3.2 Rate of change effects occur during climb and descent. Pressure differentials which exceed the design value may cause the deformation of canister or structural compartments, and in extreme cases may cause a canister to explode or implode. Whilst the deformation may be insufficient to cause direct failure, secondary effects such as the relative movement of internal components may lead to functional defects.

2.4 Electrical and electronic equipment

2.4.1 Air cooling of equipment becomes more difficult as altitude increases owing to reduced air density. The heat which may be transferred by natural convection is proportional to the square root of the density of cooling air and at 15 km the cooling effect is approximately 0.4 that at sea level. Cooling by forced convection is proportional to the air density to the power 0.8 and again at 15 km the cooling effect is approximately 0.22 times the effect at sea level. At an altitude of approximately 100 km, equating to an air pressure of 0.013 N/m^2, air can no longer be considered as a heat conductor.

2.4.2 It follows that at high altitudes the working temperatures of heat-producing components in missiles and aircraft may rise beyond their safe operating levels. In some instances equipment is derated for high altitude operation. One example is the derating of an ac generator, from 22.5 kVA up to 9 km to 15 kVA up to 15 km.

2.4.3 When silicone compounds are used for improving thermal contact or for seals and gaskets, migration can occur with resulting contamination of nearby electrical contacts.

2.4.4 The moisture content of air at 12 km is of the order 2000 times less than that at sea level. At low altitudes, the water vapour and oxygen in the air provide a lubricating film on the sliding surface of the brushes of rotary equipment; this is not adequately maintained above 6 km and increased friction develops. The exceptional dryness of the atmosphere at high altitudes causes increased brush wear. Brushes containing cadmium iodide and lead chloride are less susceptible to this form of wear, and impregnated or cored brushes, which carry a material capable of forming a film to replace the normal commutator film, have been used with some success.

2.4.5 With increasing altitude the insulating effect of air decreases and flash-over between voltage carrying conductors occurs more readily. The breakdown voltage is lowest between air spaced conductors which are pointed or have sharp edges, but this is dependent on the field concentration at the conductors.

2.4.6 Some examples of the low pressure effects of altitude on flash-over voltages are given in Table 1. In a low pressure environment the intensity of an electric arc is increased. Thus contacts are more easily damaged, and resistors, capacitors and transformers may develop internal arcing.

TABLE 1

EXAMPLES OF EFFECT OF ALTITUDE ON FLASH-OVER VOLTAGES IN AIR

Atmospheric pressure (absolute) hPa	Altitude (metres)	Flash-over voltage kV (peak) for sphere gaps (temperature 20 °C)		
		Diameter/spacing of spheres (cm)		
		6.25/0.5	12.5/1	25/4
1015	0	17.2	31.7	112
980	300	16.8	30.6	108
945	600	16.2	29.6	105
845	1500	14.7	26.7	94.4
700	3000	12.6	22.6	79
575	4500	10.5	18.8	66
470	6000	9.2	15.7	54.6

2.4.7 If voltages are not high enough or the air pressure not low enough to support flash-over, minute arcs, known as corona discharge, may occur in conductors where strong electric fields exist such as aerial masts and rf power cables. This discharge causes energy loss which can be appreciable on high voltage transmission lines. It produces radio interference and breakdown on solid insulation surfaces, for example tracking between the poles of multiway connectors. Corona discharge will produce ozone, which can cause the oxidation of rubber and various synthetic formulations. It also produces oxides of nitrogen which combine with moisture to produce acids which can attack metals and many materials. It should be noted that corona discharge caused by the build up of static electricity can occur on large surfaces such as those of aircraft.

2.5 Seals and gaskets

2.5.1 Rapid changes in pressure can cause distortion of seals and gaskets, leading to a breakdown of the seal. This can cause moisture to accumulate within the sealed container, or in the space between double seals. Such moisture may result from rain penetration, or from condensation following the replacement of dry internal air with moist external air. This breathing effect may lead to equipment failure by corrosion or malfunction.

2.5.2 Combustible gases, usually a mixture of hydrocarbon vapours and air, may seep into equipment and create a potentially explosive atmosphere. Electrical flash-over or a spark from rotary equipment, contacts, etc. may ignite these gases and cause fire or an explosion. However, this danger does not increase uniformly with altitude because although the possibility of electrical discharge increases with height, the explosive mixture becomes more difficult to ignite as atmospheric pressure decreases.

2.6 Lubricants

2.6.1 The evaporation rate of liquids increases with altitude as well as temperature, and many lubricants having a relatively high vapour pressure are rendered useless in conditions of low air pressure. In general, coefficients of friction between moving surfaces rise sharply with cold welding being an extreme effect. In the absence of moisture, graphite becomes an abrasive.

3 EFFECTS ON INTERNAL COMBUSTION ENGINES AND PROPULSION UNITS

3.1 Internal combustion engines are usually rated according to their operating altitude. On high altitude ground the most noticeable effect of low air pressure on engine performance is poor power and acceleration. For non-supercharged engines, as altitude increases the power rating must be reduced. Changes in ambient air pressure affect the thrust of a rocket motor.

4 EFFECTS ON CORROSION AND CONTAMINATION

4.1 Atmospheric pressure can influence contamination and the rate of corrosion. For example, the pressure of air above a corroding solution is one of the factors which determine the rate of absorption of gaseous oxygen. Rapid changes in air pressure can agitate an electrolyte, causing corrosive chemicals to be brought to the corroding surface at a faster rate resulting in a higher rate of diffusion of the corrosion product. Evaporation of the electrolyte from secondary cells takes place more rapidly when the air pressure is low, thus contaminating the air and materials. The mechanisms of deterioration by corrosion and contamination are described in Part 5.

5 AIR PRESSURE EFFECTS ON HUMANS

5.1 Introduction

5.1.1 At altitudes above 3 km the efficiency of personnel is adversely affected by anoxia. This becomes more acute with increasing altitudes and at 12 km useful consciousness cannot be retained for longer than approximately one minute.

5.1.2 In the event of failure of the cabin pressurization in an aircraft, flight personnel become affected by the reduced air pressure at high altitude, and by the changes in air pressure during ascent or descent. The physical and mental response of a human to these effects is influenced by the altitude, rate of change of pressure, length of exposure, amount of physical exertion, and individual factors such as physical fitness and degree of fatigue.

5.2 Decompression

5.2.1 Decompression causes the expansion of free gases in body cavities, and the evolution of gases, principally nitrogen, which escape from solution in the blood and tissue fluids. The most frequent manifestations of decompression sickness are 'bends' and 'chokes'. Bends are characterized by pain in and about the muscles and bone, especially in the joints of the knee and shoulder. Small joints of the hands, wrists and ankles are also commonly involved. Choke symptoms begin with a burning sensation in the substernal region of the thorax or deep respiratory passages. The burning pain becomes more severe, and is accompanied by a non-productive cough. This leads to strenuous breathing and a suffocation sensation.

5.2.2 Severe symptoms of decompression sickness are unlikely to occur below 7 km, but for each 100 man-hours at 7.5 km there is the probability of a single incident serious enough for flight termination, and ten incidents which are tolerable and not serious enough to terminate a flight. For each 100 man-hours at 10 km the serious incident rate increases to three and the tolerable rate to thirty.

5.3 Recompression

5.3.1 In order to combat the effects of decompression it is usual to descend to a lower altitude. During descent recompression occurs and the effects depend primarily upon the rate of descent. Two common effects are otitis media, an inflammatory condition of the ear, and sinusitis, an inflammatory condition of the nose.

5.4 Effects on vision

5.4.1 The visual system is particularly sensitive to lack of oxygen and even at altitudes below 3 km it has been found that there is a fall off in adaptation to light or dark.

5.4.2 There are additional problems associated with flight by day at high altitudes. First the problem of glare caused by the reversal of light distribution where the bright cloud floor and horizon are below and the darker blue sky is above. Second the problem of air-to-air search due principally to the difficulty in focusing the eyes in a sky devoid of cloud and constituting an empty visual field.

6 GENERAL OBSERVATIONS

6.1 The effects of air pressure can be mitigated by the following procedures:

- (a) The use of materials capable of withstanding the intended pressure environment.
- (b) Installation of equipment in pressurized aircraft compartments.
- (c) Pressurization of equipment installed in unpressurized compartments.
- (d) Adequate venting to accommodate rapid pressure equalization.

7 FURTHER READING

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CHAPTER 11-01
BIOLOGICAL HAZARD

1 INTRODUCTION

1.1 The danger of biological attack is almost universal and there are many agents of attack with various actions. The main attacking agents and their mode of action may usefully be summarized as shown in Table 1.

TABLE 1

MAIN CAUSES OF BIOLOGICAL ATTACK

Agent		Action
Micro-organisms:	Fungi Bacteria Algae	Chemical and soiling
Insects		Mechanical
Rodents		Mechanical
Marine Organisms:	'Borers'	Mechanical
	Fouling Organisms	Mechanical and corrosive

1.2 Hazards due to other agents are considered to be of minor importance and have been omitted. These include the corrosive action of juices secreted by some plants, the mechanical action due to the growth of the larger trees, which may be sufficiently great to destroy the foundations of a building or to break cables, and the damage caused by animals such as monkeys and elephants. Birds in flight can be a hazard to aircraft, and in the region of bird colonies widespread droppings can create corrosion problems.

1.3 In addition, some agents which are mentioned have other modes of action which have not been included; for example both rodents and insects are occasionally responsible for chemical corrosion or soiling.

2 FUNGI

2.1 General

2.1.1 The name fungus is used to denote members of a large heterogeneous group of organisms within the plant kingdom, of which there are about 100 000 known species. Most fungi are so small that they can be observed only with the aid of a microscope. The terms 'mould' and 'mildew' although not exactly defined in the biological sense, are used by both biologists and laymen to refer to small non-parasitic fungi, such as those which do not live on other living organisms.

2.1.2 A fungus can, in general, be divided into two parts: the vegetative and the reproductive. The vegetative part, known as the hypha, is essentially a threadlike filament normally having a diameter between 2 and 20 micrometres and may be several centimetres long. In the simplest fungi the hyphae are merely continuous tubes of living matter; in others they are divided by cell walls, called septa, into separate cells. Collectively the hyphae are referred to as the mycelium. The mycelium, together with the reproductive spores, are commonly observed on mouldy bread, shoes, oranges, etc.

2.1.3 Unlike most plants, fungi contain no chlorophyll, the green colouring matter with which plants utilise the sun's energy to manufacture their food from absorbed raw materials. Thus they have to rely on the food in the substratum on which they grow. However, the structure of the cell walls only allow them to absorb this food if it is in solution. To achieve this, the fungi secrete enzymes via their hyphae. This substance converts the food into a soluble form which can then be readily absorbed.

2.1.4 In the vast majority of cases the unit of reproduction is the spore. Normally it is unicellular and microscopic, though occasionally, giants 500 micrometres in length occur. They may be produced directly via the hyphae or from a structure created for this specific purpose, as in the mushroom. From a functional viewpoint spores may be divided into two classes each of which may be produced by the same plant: those which can be produced rapidly and in large numbers but have little resistance to adverse environmental factors, and those which are comparatively few in number but much more resistant to adverse conditions. The former enable the fungus to spread rapidly during good growing conditions and the latter enable it to survive hard times such as winter or drought and have been known to survive for many years in a dry condition.

2.2 Growth and survival factors

2.2.1 In order to adapt themselves to changes in their environment or food supply, most species of fungi can slightly change their characteristics and needs over several generations. This may be a very short time; in many cases the whole cycle from spore to spore can be completed in few days. In addition, it should be noted that the conditions required for the production and dispersal of spores are generally more exacting than those for growth and survival.

2.2.2 The precise minimum, maximum and optimum temperatures for growth appear to be a matter of debate between the various authorities. This may be because these values vary from one species to another. However, in general, the minimum is 2°C to 5°C, the maximum 40°C to 50°C and the optimum 22°C to 27°C. In addition, there are a few fungi that can grow at and below 0°C, and a species has been reported growing at a maximum of 62°C. They are, of course, capable of surviving even greater extremes in a quiescent state.

2.2.3 The optimum humidity for the growth of nearly all moulds is 95-100% rh. If submerged in water, however, most fungi will not grow. Any reduction from this optimum will mean a reduced growth rate and few species will grow at less than 70% rh.

2.2.4 A suitable source of carbon which can be absorbed as food is essential to fungi for their growth. Almost all naturally occurring carbon containing compounds together with many synthetic organic compounds of a similar structure, can be used by fungi as a source of food.

2.2.5 Most fungi are strictly aerobic; that is they cannot grow in complete absence of free oxygen. In the small number of cases where fungi grow in water, they always do so in a few centimetres near the surface.

2.2.6 All fungi can utilise an organic supply of nitrogen and a few can also use an inorganic source such as ammonia. Nitrogen, other than as a gas, is essential for the growth of fungi.

2.2.7 Other elements required for the growth of fungi include sulphur (as sulphate), potassium, phosphorus (as phosphate) and magnesium. In some cases minute traces of iron, zinc, manganese, molybdenum, or calcium are required, though in such small quantities that only in a few fungi is there a clear picture of these requirements. Some fungi also require a supply of certain vitamins for growth.

2.2.8 It has been verified experimentally that moving air of less than 100% rh will cause mould to dry more rapidly than still air of the same relative humidity and hence inhibit growth. Optimum growth conditions occur in still air.

2.2.9 Ultra-violet is known to inhibit the growth of most fungi, although daylight normally has no effect. In a very few instances daylight can influence growth and indeed can cause it to increase. However, the production and dispersal of spores is light dependent in many species.

2.2.10 Most fungi grow best in a slightly acid medium within the range pH 5 to pH 6.5. This varies from one species to another but few will grow at all below pH 3 or above pH 9.

2.3 Habitat and geographical distribution

2.3.1 Since fungi can survive adverse growth conditions in a quiescent state and can gradually evolve to survive more extreme conditions, and since new species are still being identified, it is not possible to define exactly the geographical areas in which fungi will grow. There are, however, certain tendencies which are relevant.

2.3.2 Fungi of one sort or another are found in the soil, water and air over a large part of the earth's surface, whilst others live on or upon both living and dead animals and plants. Those found in the air do not grow there, but are in the form of spores. Most live in the soil and only about 2% live in water; in both cases they grow in the few centimetres just below the surface.

2.3.3 The best conditions for most types of mould growth are in humid tropical areas, although deterioration due to mould is not confined to the tropics. Equally serious damage can occur in temperate regions, though not so rapidly, and at least one species of mould is often found in the form of spores in the air over arctic regions.

2.3.4 Conditions favourable for mould growth may easily be created artificially inside a building or equipment. Those which are parasitic upon particular animals or plants are among the few which are restricted to geographical regions.

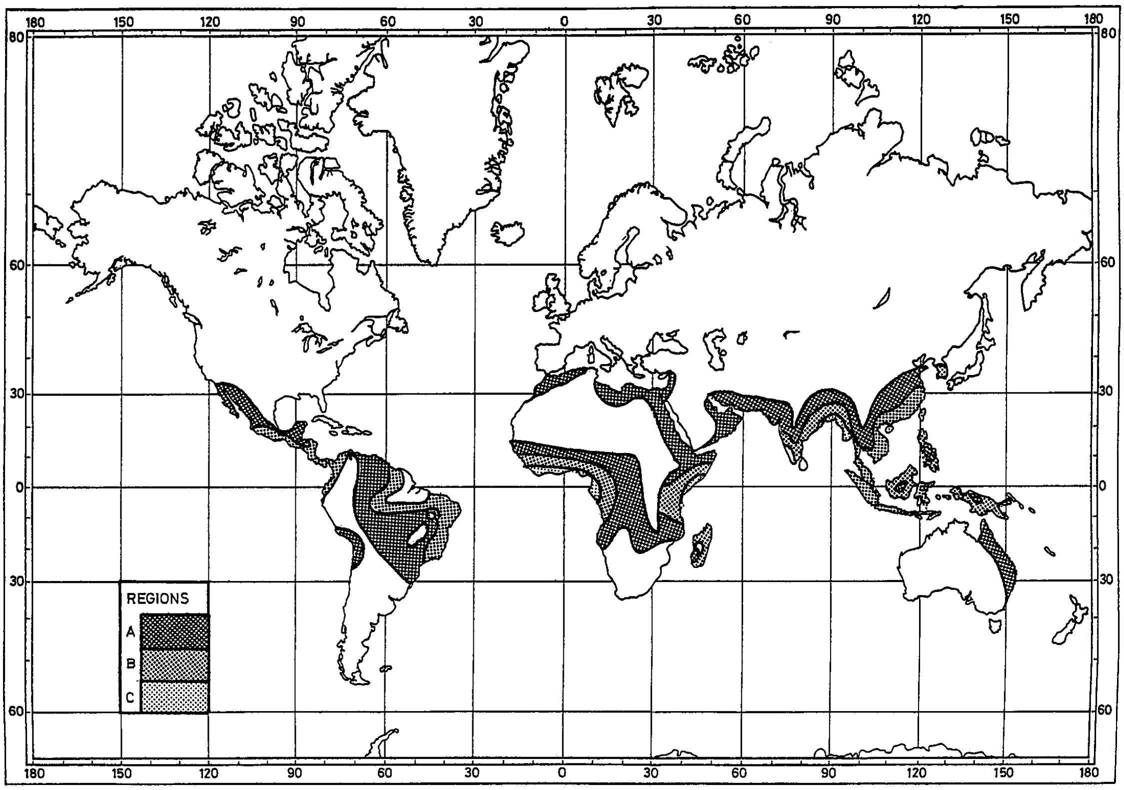

Figure 1. Map of regions with different degrees of fungal corrosion

2.3.5 The map in Figure 1 shows areas in which climatic conditions are most favourable for fungal corrosion. It is based on an analysis of relative humidity and temperature data from approximately 2000 meteorological stations throughout the world, as follows:

Region A - includes areas with at least one month a year in which the mean monthly relative humidity is from 70% to 75% in the hours from noon to 2 pm, and with a mean monthly minimum temperature at the same time of not less than 15°C.

Region B - includes areas where the equivalent relative humidity is from 75% to 80%, again with the same temperature as Region A.

Region C - includes areas where the equivalent relative humidity is greater than 80%, again with the same temperature as Region A.

2.3.6 It should be noted that the above climatic conditions do not take account of other naturally occurring factors mentioned earlier, such as air flow. It also does not cover cases where favourable conditions may be artificially induced, inside buildings or containers for example. Nevertheless, within these limits, it does provide a useful indication of the natural liability to attack by micro-organisms.

3 BACTERIA

3.1 General

3.1.1 Bacteria are found in a variety of shapes and forms. They are generally unicellular organisms of the plant kingdom, between 0.5 and 10 micrometres in length and 0.3 to 2 micrometres in diameter. Some species of bacteria can move and possess flexible hair-like projections which enable them to do so, whilst others are carried along in the medium in which they grow. Protection is afforded in some cases by a gelatinous sheath or capsule, but in others this is absent.

3.1.2 A mature cell may reproduce by simply dividing in two. Later these two may divide again and so on at intervals as small as 15 minutes. Many bacteria can also produce spores. However unlike the fungi, these spores are produced inside the bacterial cell, with normally one spore per cell. These spores are more resistant to heat and drying than ordinary cells, and they have been known to survive for many years in a dry state.

3.1.3 Like fungi, bacteria possess no chlorophyll and secrete enzymes to digest food into a soluble state before absorbing it through the cell walls. Also like fungi, they can evolve and adapt themselves to new conditions.

3.2 Growth and survival factors

3.2.1 Because of their minute size, similarity of action to fungi and their association with the same environments, some of the properties and actions of bacteria have not been isolated or fully identified. In addition, bacteria can evolve and adapt themselves to new conditions. It can be seen therefore that much more information is required. That which is available is summarised below.

3.2.2 Bacteria are less sensitive than fungi to temperature. The extreme growing temperatures are a matter of debate but generally the range is from -3°C to +75°C. Like fungi, they can also survive even greater extremes in the quiescent state. Optimum growth temperatures are generally higher than for fungi.

3.2.3 They normally require the presence of water for growth and can flourish even when submerged in water. Consequently they are found growing in conditions which are wetter than are characteristic for most fungi.

3.2.4 Many bacteria can make use of carbon only when supplied in an organic form. However, others can grow in a medium devoid of organic material and make use of carbon dioxide as their source of carbon.

3.2.5 Some bacteria are aerobic, others are anaerobic and will grow only in the absence of oxygen, whilst still others can live either with or without oxygen.

3.2.6 Various bacteria can utilise organic and/or inorganic sources of nitrogen.

3.2.7 Some vitamins and associated compounds have proved necessary to all bacteria, whilst others are found to be required by only one or two species. Those bacteria which can grow in media devoid of any organic materials obtain their energy requirements from the oxidation of inorganic compounds such as ammonia, various compounds of sulphur and some compounds of iron.

3.2.8 Most bacteria are active in the range of pH 6 to pH 8, but they can survive both higher and lower pH values. Some bacteria can survive in up to a 12% sulphuric acid solution.

3.3 Habitat

3.3.1 Bacteria occur in soil, in natural bodies of water, in the air and internally as causal agents of diseases in animals and plants. Most live in the soil, generally in wetter and slightly more alkaline conditions than fungi, and are capable of surviving greater extremes of environment.

3.3.2 It is not possible to define exactly in which geographic areas bacteria will grow, and only those which are parasitic upon particular plants or animals are at all restricted geographically.

4 ALGAE

4.1 Algae are rudimentary members of the plant family, and unlike fungi contain chlorophyll and are capable of photosynthesis. The form of the algae can vary considerably from unicellular to complex multicellular. Their methods of reproduction can also vary, being both asexual and sexual.

4.2 They occur in fresh and salt water, in and on the soil, and in moist places varying from snow and ice to hot springs. Variations in size cover a range from a few micrometres to greater than 30 metres.

5 INSECTS

5.1 General

5.1.1 There are more than 500 000 different kinds of insects, with a wide range of eating habits and behaviour patterns. Hence many articles made from materials of animal or vegetable origin, and synthetic materials of a similar structure, are damaged or destroyed by insects. Unlike micro- organisms, the predominant method of attack is mechanical.

5.1.2 Two categories of damage can be distinguished. The first concerns damage by insects to indigestible materials which are used in building nests, etc., or form a barrier between the insect and its goal, or which are damaged in their search for food. The second concerns damage to materials used as food; wood, paper, rayon and other cellulose derivatives, for example.

5.1.3 The life span of the insects considered here is from two months to twenty years. They may be destructive in the larval stage or the mature stage, or sometimes in both.

5.2 Habitat

5.2.1 Most of the destructive insects are restricted geographically by the availability of their natural food. However, as most forms of life grow more profusely in the tropics, it is here that insect damage is greatest.

5.2.2 Species of termite confined mainly to the tropics are generally considered to be the most destructive of all insects. Other insects mainly confined to tropical areas include mud wasps, woolly bears, carpenter bees and certain species of beetles, moths, ants and spiders, although strictly spiders are of the Arachnida class.

5.2.3 Insects considered to be more universal in their distribution include cockroaches, crickets, grasshoppers, clothes moths, powder-post beetles, carpet beetles, hide and skin beetles, silverfish, ants, wasps, and insects attacking stored grain and cereals and other foods. In most cases the home of the insect is inside the material which it attacks.

6 RODENTS

6.1 Of the many forms of mammals in the world which cause damage, rodents are the most common. They vary in size from the small 15 gram mice to the large field rodents of 5 kg or more. All possess chisel-like incisor teeth especially adapted for gnawing, and the damage thus caused is usually the result of their search for food or nesting material. They are found in all parts of the world, even in arctic regions.

7 MARINE ORGANISMS

7.1 Borers

7.1.1 There are two types of borers, the Molluscan borers and the Crustacean borers. In the former, the animal head or entire body is enclosed in a bi- valve shell which has become a cutting tool. In the latter, boring is accomplished by means of a strong pair of mandibles.

7.1.2 Borers spread by swimming which can only be done during their larval stage; this varies in duration from a day to a week. Their destructive life begins after this stage. In some waters the attack is most destructive between the tide levels, whereas in others it is most destructive at a depth of 9 to 12 metres or more, or at the mud line. They do not grow in strong currents. In the tropics their destructive action may be several times that found in temperate waters, but they flourish even within the Arctic Circle.

7.2 Fouling organisms

7.2.1 Fouling organisms include barnacles, seaweeds, corals, sea anemones, sea squirts, clams, oysters and mussels.

7.2.2 Some of these provide an environment in which bacteria flourish and cause corrosion, such as dead organisms trapped by barnacles on ship's hulls. Various forms of fouling are found in all parts of the world.

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CHAPTER 11-02
THE EFFECTS OF BIOLOGICAL HAZARDS

1 INTRODUCTION

1.1 This chapter outlines the main effects and severity of biological attack. No distinction is made between damage which occurs in a natural environment and that which results from an artificially created environment, such as in a warehouse.

1.2 Information on the main agents of biological attack and their preferred environments may be found in the previous chapter.

2 FUNGI

2.1 There are three ways in which fungi may cause damage. Each can occur independently, or in association with one or both of the others.

2.1.1 A material may be a food for the fungi, in which case the material is gradually eaten away.

2.1.2 The waste products of fungi are excreted as juices, many of which are corrosive and cause damage to the substrate on which the fungi are growing. Thus it is possible for fungi to damage a material even though it is not a source of food. For example the minute impurities in finger prints on glass have been known to support growths whose corrosive waste products have etched the surface of the glass. In addition, the mould coating has the effect of retaining moisture and retarding the drying-out process.

2.1.3 Fungus may hinder the efficient operation of equipment, even though it has not caused damage to any material part. Examples of this are soiling in optical equipment, or the formation of undesirable conducting paths in electrical equipment.

2.2 Effects of fungi on various materials

2.2.1 Wood in contact with the ground is particularly prone to decay by fungi. If, however, it is kept off the ground in a dry, well ventilated place it is much more resistant, and if the wood contains less than 20% water it is not attacked at all. Resistance to attack varies from one species to another, and heartwood is always less liable to attack than sapwood. In use, wood is normally coated or impregnated in some manner. This may modify its resistance to fungal attack.

2.2.2 Many fungi cause very little mechanical damage to the wood on which they live but are found to discolour it. A table of the resistance of some types of wood to wood-staining fungi is given in Reference 2.

2.2.3 Paper, cardboard, and similar products are all susceptible to attack. The basic constituent, cellulose, is affected as well as other substances used during manufacture such as starch, gelatine, etc. The effects are generally revealed as patches of surface discolouration, followed by complete disintegration of the paper. However, mould growth occurs after moisture pick up, and its damaging effects are often considered to be second to those of moisture.

2.2.4 Paints and varnishes are made of a complex mixture of oils, cellulose derivatives, solvents, plasticizers, thinners, etc, some of which may be susceptible to attack. Almost all paints will support mould growth under favourable conditions. A few are resistant, but others have been known to support mould even in cold storage rooms.

2.2.5 The liability of a paint or varnish to attack is dependent on the type of substance and surface on which it has been placed, and upon climatic conditions, such as sunlight, moisture, etc. A table of the resistance of electrical insulating varnishes to moulds is given in Reference 2.

2.2.6 Natural cellulosic fibres such as cotton, sisal, hemp, flax and jute are all highly susceptible to attack, although protein fibres such as wool and silk are not quite so liable. Asbestos fibres are of mineral origin and resistant to attack.

2.2.7 Synthetic fibres show some variation in their resistance, but are generally superior to natural cellulosic fibres. Fibre forms of cellulose acetate (Celanese, Tricel), regenerated protein (Vicara), polyamides (Nylon), polyesters (Terylene, Dacron), polyacrylonitrile (Orlon, Acrilan), polyvinylidene chloride (Saran, Velon), vinyl chlorideacrylonitrile co-polymers (Dynel, Vinyon N), vinyl chloride-vinyl acetate co-polymers (Vinyon), and glass all have excellent resistance or are inert to fungi. This list is not exhaustive, other examples may be found in Reference 5.

2.2.8 Fibres may have pigment added or be coated, and synthetic fibres may have other additives which can support growth (see also the section on plastics). In use, when these fibres are in the form of a cloth or cord, they can easily hold moisture and impurities which will nourish moulds.

2.2.9 Tanned leather generally has hygroscopic substances on its surface, such as dextrin, starch, glycerine or sugar, which are often used for dressing, and may support mould growth. Similarly, greases, oils and emulsions used for lubricating leather may also support mould growth. In general, chrome-tanned leather is more resistant than vegetable tanned leather. However, the mould rarely attacks the leather to any significant extent, even when a profuse growth is found on its surface.

2.2.10 Plastic and rubber materials are not subject to deterioration in quite the same manner as other materials such as wood. They nearly always contain one or more additives for example, a plasticizer to reduce the natural brittleness of the plastic, resin to increase the rigidity, pigments for colouring, fillers, stabilizers, etc. Each one is added for a specific effect on the final product and each has a different effect on the final resistance against attack. Hence, to predict the resistance of a given plastic or rubber requires a knowledge not only of the material, but also of all its additives, which may constitute as much as 50% of the total. Further information is given, some in tabular form, in References 1, 2, 3, 4 and 5.

2.2.11 In certain circumstances moisture rather than mould will contribute to the deterioration of a plastic material, and since it is not possible to have mould growth without the presence of moisture, there is some controversy about which factor contributes most.

2.2.12 From investigations it is clear that a given plastic may not support the growth which is found on it, but is merely holding impurities on its surface which nourish the mould, without damaging the plastic itself. Results of specific investigations are detailed in Reference 3.

2.2.13 Other organic materials likely to be attacked include most foodstuffs, adhesives, glues, inks, etc. There are also reports of deterioration of some hydrocarbons, especially jet fuels; in this case the fungi are found in association with bacteria, and the precise manner of deterioration is not clear. The metabolic products of cladosporium resinae, the 'kerosene fungus' that grows at the jet fuel/water interface, are corrosive to aluminium alloy fuel tanks.

2.2.14 Glass is not a source of food, but its surface is readily covered with moisture to which organic particles will adhere. This favours mould growth which in turn soils and may even etch the surface, thus affecting the efficient use of optical instruments. In addition, canada balsam which is often used to cement lenses together, is also susceptible.

2.2.15 Other materials which it is claimed have been damaged include mica, cement, stone, plasters and even metals. though in all these cases the damage is rarely significant and only occurs infrequently and in specialized circumstances.

3 BACTERIA

3.1 Introduction

3.1.1 Bacteria are generally too small to impair the operation of equipment. They can, however, utilise a material directly for food and thus damage it. In addition, they can cause corrosion when obtaining their energy from chemical reaction or by their waste products. They mostly live in the soil near the surface, and it is here that they can cause most damage. Even so, it is generally considered that in most cases more damage is caused by fungi than by bacteria.

3.2 Effects of bacteria on various materials

3.2.1 Wood, leather, paper products and most associated materials, for example finishes, glues, etc, are all liable to bacterial attack in varying degrees. Natural fibres, of both animal and plant origin are attacked by bacteria. The effect on synthetic fibres is not clear, though it appears to be similar to that due to fungal attack, that is, viscose rayon, cellulose nitrate and a few others are prone, but generally they are resistant. Most paints and varnishes are attacked by bacteria and so are some rubbers and plastics. However, deterioration of these latter generally occurs only in some specialized circumstances, as when permanently submerged in water. As with fungi, it is often one of the many additives which are attacked, rather than the basic material itself. Petroleum fuels and insulating oils are among the hydrocarbons which are deteriorated by bacteria.

3.2.2 Bacterial attack is generally first noticed as a discolouration of the material concerned. In some instances, however, such as insulating oils and the rubber-covering of cables, low insulation resistance is often the first indication.

3.3 Bacterial corrosion

3.3.1 Bacterial corrosion is the term used to describe corrosion due to bacteria obtaining their energy requirements from chemical action and to bacterial waste products. In these cases the materials are not used as food. Ferrous metals are most liable to this method of corrosion, but there are examples of attack on stone, rubber and non-ferrous metals. The organisms induce a chemical reaction, for example oxidation, and use the chemical energy thus liberated. Although this means of corrosion is almost exclusively bacterial, it is occasionally applicable to mould.

3.3.2 Bacterial corrosion may be one of the following types:

(a) Corrosion due to acid formation

(i) One of the main forms of corrosion is attributable to the oxidation of inorganic sulphur compounds to sulphuric acid by the members of the Thiobacillus species. These are fairly common in soil and water. In the process, they generate and can survive in solutions of up to 12% sulphuric acid. Iron and concrete pipes, buildings and vulcanised rubber are among objects thus corroded.

(ii) Another form of corrosion is caused by oxidation of iron pyrites to sulphuric acid by the Ferrobacillus species. These are often found in association with Thiobacillus. Ferrobacillus is responsible for the problems arising from acid water in gold and bituminous coal mines corroding pumping machinery.

(iii) Moulds of cellulose bacteria, which ferment cellulosic material to organic acids, cause corrosion known as 'phenol corrosion'. This can lead to the etching and pitting of stored or buried lead and other cables and also of the paper or other cellulosic materials within.

(b) Corrosion at neutral pH values

(i) Corrosion is often brought about by cathodic depolarization, attributable to bacteria containing an active hydrogenase. This type of corrosion is complex and its exact mechanism is still a matter of debate, but there is no doubt that the sulphate reducing bacteria are the cause. They are anaerobic, are commonly found in waterlogged soil or water and some of them survive and flourish at temperatures around 40°C. They have been responsible for the corrosion of iron and steel in waterlogged soils, electrical transformers, hot water systems, etc.

(ii) Corrosion often occurs following differential aeration caused by the different seasonal water levels found in flood water pipes, and is attributable to deposits formed by iron bacteria and other micro-organisms. These form insoluble or partly soluble products that can adhere as films or tubercles to metal surfaces such as the inside of metal water supply pipes.

(iii) Another form of corrosion is due to bacterial metabolism. Certain bacteria produce chemicals simply as the waste product of their digestive systems. These may be corrosive and yet are not acids of the type discussed previously. Corrosion of this form can occur remote from the site of bacterial growth; for example the copper heaters and valves in a high-pressure steam unit showed sulphide corrosion, though the ambient temperature was between 120°C and 175°C. The corrosive material was hydrogen sulphide, formed by bacteria growing in the cooler water of the reservoir at the expense of sulphite used to de-oxygenate the boiler water.

3.3.3 Corrosion may also occur because of the loss of a protective coating which has provided food for the bacteria. Examples are the removal of asphalt, waxy, or polyester coatings by bacteria in the soil. In addition, corrosion may be increased by the joint action of several of the different types of bacteria in the same area.

4 INSECTS

4.1 General

4.1.1 Liability to attack by insects is greatest on the ground, in the ground, or in buildings in which there is poor drainage or poor ventilation, or unhygienic conditions.

4.2 Various materials attacked by insects

4.2.1 Wooden products are particularly subject to attack by termites which use the cellulose for food, and by powder post beetles whose larvae feed on wood. Damage caused by both of these insects can be severe in tropical regions.

4.2.2 Paper is attacked by many insects, particularly termites, cockroaches, silverfish and bookworms.

4.2.3 Paints and varnishes are attacked incidentally by termites, if they bar the termites from a source of food.

4.2.4 Among the many insects causing damage to textiles and cordage, are clothes moths, woolly bears, silverfish, etc. A comprehensive list is given in Reference 1.

4.2.5 Leather products are attacked by termites, hide and skin beetles and carpet beetles, etc.

4.2.6 Red ants and termites can penetrate most plastics and rubbers, if they form a barrier between the insect and a source of food, they rarely form a source of food in themselves. Nevertheless, it has been stated that the only plastic not attacked during a series of tests, was cellulose acetate. These insects are at their most destructive in the soil, underground cables being especially vulnerable.

4.2.7 Other materials which are not of animal or vegetable origin are rarely attacked by insects, unless they bar the way to food.

5 RODENTS

5.1 A wide variety of materials are subject to damage by rats, mice and other rodents. They can ruin textiles by their droppings and urine, or by shredding the cloth for nesting. They may gnaw holes in wooden, cardboard or plastic packing cases, exposing the contents to attack by moisture, insects, moulds and bacteria. In their search for shelter, rodents may undermine foundations, or ruin the insulation of buildings, refrigeration units and electrical cables.

5.2 Whilst there is agreement that, under duress, rodents will attack most of the softer materials and even some metals in their search for food, there is not agreement on whether the plastics, paper, wood, etc, are attacked as a source of food.

6 MARINE ORGANISMS

6.1 Borers

6.1.1 Borers are found mainly in salt water, though some species thrive in fresh water. They live primarily on wood, where they can cause severe damage. They can penetrate the insulation of electrical cables, especially of the gutta-percha type and also score, and even break through, some protective armouring. The caulking on the bottom of wooden boats is attacked and occasionally they bore through clay, sandstone, shale, marble and inferior concrete.

6.2 Fouling organisms

6.2.1 Fouling organisms can produce very serious problems wherever they are encountered. They attach themselves to both wooden and metal hulls of ships, and can raise the cost of driving the ship by 25-30%. Another form of damage is in their growth inside inlet pipes, from the sea or fresh water, to cooling systems. In addition, they can penetrate coatings of pitch, etc, and in so doing trap dead matter giving rise to bacterial corrosion.

7 BIRDS

7.1 Hazards created by birds fall into two categories:

(a) Damage to aircraft by striking birds in flight.

(b) Corrosion problems created by widespread droppings near to bird colonies.

8 GENERAL OBSERVATIONS

8.1 A very large number of materials in general use are liable to spoilage by micro-organisms, insects, etc. It is possible to limit this damage in a number of ways:

(a) By hermetic sealing.

(b) By using only materials which have had fungicides or other protective compounds included during their manufacture.

(c) By suitably coating the material, component or equipment after manufacture.

8.2 If hermetic sealing is not possible, the use of gaskets, etc, should be considered, although 'breathing' must be avoided or a build-up of moisture will occur and increase the danger of spoilage.

8.3 In almost all cases the risk will be reduced if the moisture content is kept low.

8.4 Care must be taken that, in any particular application, a fungicide or protective coating does not have deleterious side effects. For example, copper compounds are sometimes used, but can cause deterioration of natural rubbers.

8.5 Lists of suitable materials, their degree of resistance, methods of preservation and treatment are given in many publications. The primary Government publications relevant to the subject are given as References 6, 7, 8, 9 & 10. These should be carefully studied.

9 REFERENCES AND OTHER SOURCES OF INFORMATION

9.1 References

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2	'Tropicproofing Electrical Equipment' Morgan Grampian Books Ltd., London.	M Rychtera and B Bartakova
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8	DEF STAN 07-85 - Design Requirements for Weapon Systems.	-
9	BS 1133 - Protection against Spoilage of Packages and their Contents by Micro-Organisms, Insects, Mites and Rodents.	-
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CHAPTER 12-01
ATMOSPHERIC ELECTRICITY

1 INTRODUCTION

1.1 Atmospheric electricity is considered as an environment because of induced electro-magnetic effects and the possibility of direct damage due to lightening strikes.

1.2 Precipitation charging constitutes an induced environment and is dealt with in Part 5.

1.3 Other allied topics dealt with elsewhere are the structure of the atmosphere (see Chapter 2-01) and the world-wide incidence of thunder-storms (see Chapter 7-01).

1.4 Certain other electrical phenomena, such as those in the Van Allen belt region, which could constitute a radiation hazard occur too far from the earth's surface, at approximately 1000 km, to be within the scope of this Standard.

2 FAIR WEATHER ELECTRICITY

2.1 Factors involved in the electrical properties of the atmosphere include electric fields, currents and conductivity, and positive and negative ions of a wide range of size.

2.2 In fair weather the horizontal layering of the atmosphere produces a predominately vertical gradient varying from less than 10 V/m at 10 km to about 100 V/m at the earth's surface, as shown in Figure 1.

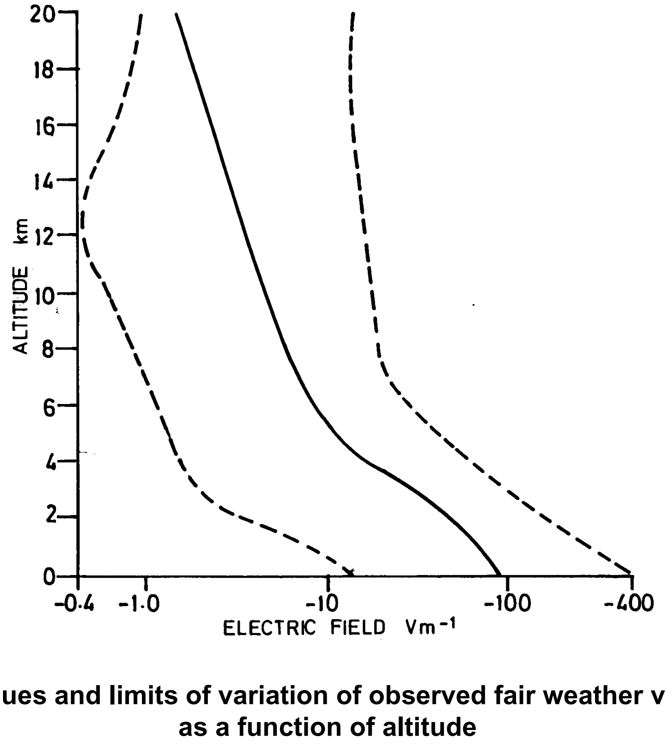

Figure 1. Average values and limits of variation of observed fair weather vertical electrical field as a function of altitude

2.3 The fair weather field can have significant effect in special cases such as a missile controlled by wire from a helicopter, where circulating currents may be produced by the missile moving in a region where the electrostatic potential is different from that in the vicinity of the helicopter.

2.4 In the troposphere, the region up to about 8 km above the poles and about 16 km above the equator, factors which have an important influence on the electrical properties include air mass motions, pressure systems, temperature gradients and water vapour distribution, which together control the distribution of charged and uncharged aerosols and radioactive particles of terrestrial origin.

2.5 These influences are greatest in the Exchange Layer, which varies in height up to about 3 km above the earth's surface. Within this layer are small scale convection currents which carry the surface air, together with ions and nuclei which it contains, to the top of the region, ensuring thorough mixing. The upper boundary is often visible as the level of fine weather cumulus clouds or haze, and is markedly indicated by electrical measurements. Temperature inversion, that is temperature increasing with height, has a profound effect on the exchange mechanisms.

2.6 According to the laws of electrostatics, over 90% of the earth's negative charge should leak off in about ten minutes due to the conductivity of the air, but the net charge remains practically constant. Thunderstorms and shower clouds appear to act as generators that drive current upward in the reverse direction to the current flow in fair weather areas.

2.7 The potential gradient in undisturbed fair weather areas has the same diurnal variation over all the earth, when referred to universal time. This is in phase with the diurnal variation of world-wide thunderstorm activity. The potential difference between the earth and the ionosphere, that is the region beyond the stratosphere, is about 275 kV.

2.8 When clouds are present their surfaces become electrically charged, the distribution of charge depending , largely on temperature gradient. When the accumulation of charge is sufficient, discharge occurs and thunderstorm conditions prevail, the effects of which completely mask the fair weather field distribution.

3 THUNDERSTORM ELECTRICITY

3.1 General

3.1.1 Thunderclouds are of the cumulo-nimbus type and the distributions of electric charges within the clouds are very complex. References 1 and 2 describe theoretical models of the charge structure within thunderclouds. The information in these is briefly summarised below in a simplified form.

3.2 Charge distribution in thunderclouds

3.2.1 As a result of measurements of electric fields by freely ascending balloons over a period of three years a simplified model of the distribution of charges in a 'typical' thundercloud is shown in Figures 2 and 3.

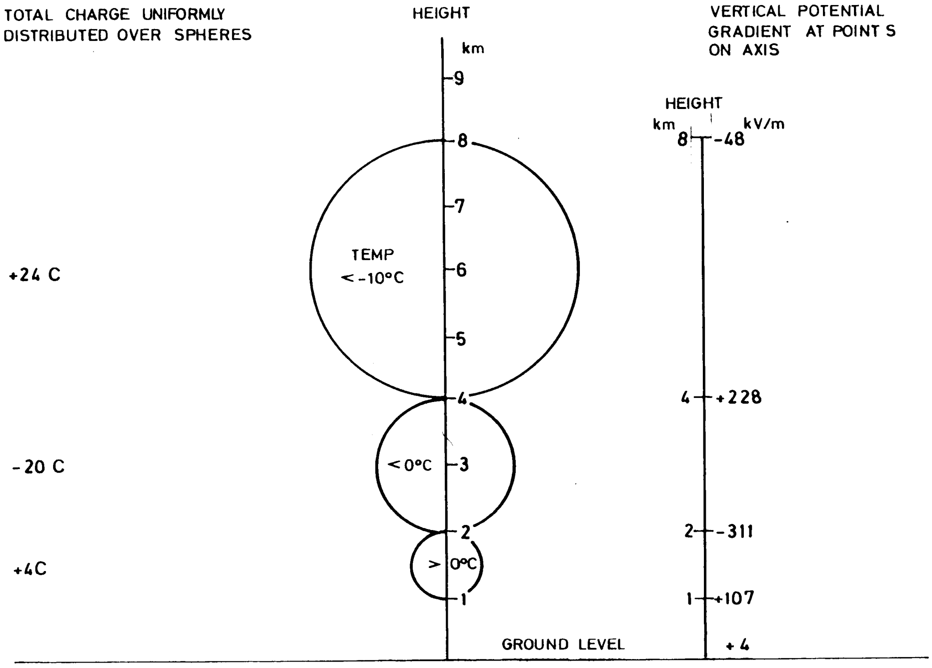

Figure 2. Vertical electric field associated with an idealised thundercloud (after Simpson)

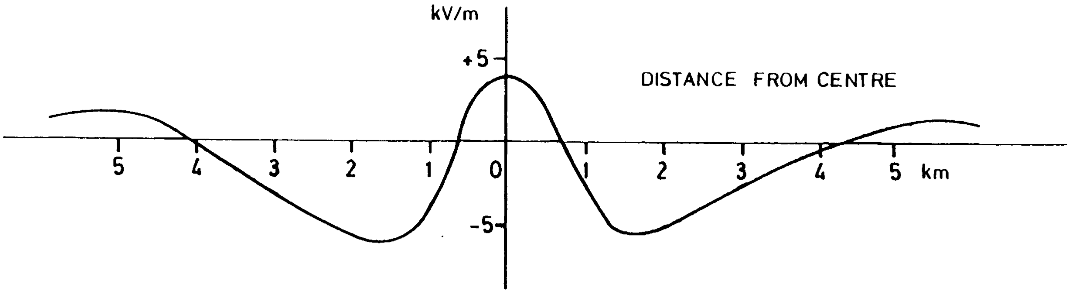

Figure 3. Horizontal distribution of electric charge at ground level

3.2.2 Only eight storms were assessed but the findings indicate:

(a) Each thundercloud had a positive charge in its upper half, in which the temperature was always below -10°C.

(b) Below this region was a negatively charged volume at a temperature usually below 0°C.

(c) Below the negatively charged portion there was in most cases a positively charged region, mostly above 0°C.

3.2.3 The generation of the positive and negative charges in the main body of the cloud was ascribed to the impact of ice-crystals and that of the positive electricity in the base of the cloud to the breaking of rain-drops in an ascending current of air.

3.2.4 It was noted that there was a remarkable absence of large fields within the clouds. The magnitude of the fields was mostly of the order of 10^4 V/m except in relatively small regions where there was great electrical activity and in which lightening discharges originated. There was no evidence of large horizontal sheets of positive and negative electricity with fields of the value required to produce an electrical discharge (taken to be 10^6 V/m as water or ice particles are present).

3.2.5 According to the model charge distribution as shown in Figure 2, the vertical potential gradient at points on the axis would be as shown on the right hand side of the figure. Figure 3 shows the horizontal potential gradient at ground level, at different distances from the centre of the storm.

3.2.6 These considerations present a gross over-simplification of conditions which are not only intrinsically complex but are also extremely difficult to observe because of the elusiveness of lightning.

3.2.7 Separate observations made at a mountain observatory in Germany , where over sixty storms were examined over a four year period, highlighted certain additional features of thundercloud structure, as described below.

3.2.8 A thundercloud may be considered electrically as consisting of a number of columnar main cells, up to about 1 km in diameter subdivided into sub-cells about an order smaller in linear dimensions. The main cells are characterised by a three stage circulation of air as follows:

(a) An updraught of warm, moist air, pulsing the cloud top to heights where copious amounts of rain and snow can be formed.

(b) The development of intense electric charges, especially on frozen cloud droplets and on snow particles, accompanied by violent air disturbances in which a strong downdraught occurs side by side with the updraught.

(c) A predominance of descending air.

3.2.9 The sub-cells are associated with turbulence and probably account for the local character of high electric fields and for the complicated nature of thunderstorms.

3.2.10 The configuration of charges in a mature thunderstorm cell has the appearance of two groups of dipoles, which follow each other downward, an ice particle dipole with a concentrated upper charge of negative sign, followed by a snow dipole with a concentrated upper positive charge. Lightening exchange between these upper space charges gives the illusion of one slanted dipole.

3.2.11 Very strong electric fields are set up within and beneath the cloud, and when the field exceeds the breakdown value discharge occurs from cloud to cloud or cloud to earth.

3.3 Cloud to earth discharges

3.3.1 A typical lightning discharge from cloud to earth begins with a leader stroke which proceeds in a series of steps until it strikes the ground. It ionises its transit path and a return stroke travels to the cloud, radiating electromagnetic fields of frequencies ranging from less than 1 Hz to those in the visible spectrum.

3.3.2 There usually follows a succession of return strokes, each preceded by a 'dart' leader. Small currents continue to flow in the intervals between the return strokes and may persist for half a second or more.

3.3.3 The charge in complete discharges varies from about 5 Coulombs to well over 100 Coulombs with a median value in the region 5-10 Coulombs.

3.3.4 The high current portion of the discharge begins just after the leader contacts the ground. Crest currents of up to about 150 kA have been measured; a typical value is 20 kA. The crest is reached in 1 to 10 µs, with an average of about 2 µs; the average time to fall to half value is 40 µs, with a range of 20 to 200 µs.

3.3.5 Maximum radiation occurs at a frequency of approximately 10 kHz. For two particular storms, the power measured at 10 km distance had average values of about 50 kW in a 300 Hz band centred at 6 kHz, and 100 mW at 10 MHz.

3.4 Ball lightning

3.4.1 Ball lightning may present a hazard to ground installations but due to the nature of its occurrence, very little is known of its detailed properties. Over one hundred reported occurrences of fire balls are recorded in Reference 3, which appeared to be electrical in character and which were occasionally accompanied by severe explosions. Although the reality of ball lightning is established, insufficient is known to enable environmental or design engineers to make allowances for the phenomenon.

4 THE OCCURRENCE OF LIGHTNING

4.1 A world map showing the average number of days per annum on which thunder is heard is given in Chapter 7-01. At any given time the total number of storms in progress over the earth's surface is about 2000; the daily occurrence is about 50000.

4.2 The aural method of recording storm severity makes no distinction between cloud-to-ground discharges and cloud-to-cloud discharges which have no direct effect on ground installations. Lightning discharges are better monitored by lightning counters, as described in Part 5. When a counter is set to be triggered by field strengths exceeding 3 V/m in a 1-50kHz frequency band, the count represents the number of discharges within a distance of approximately 30 km.

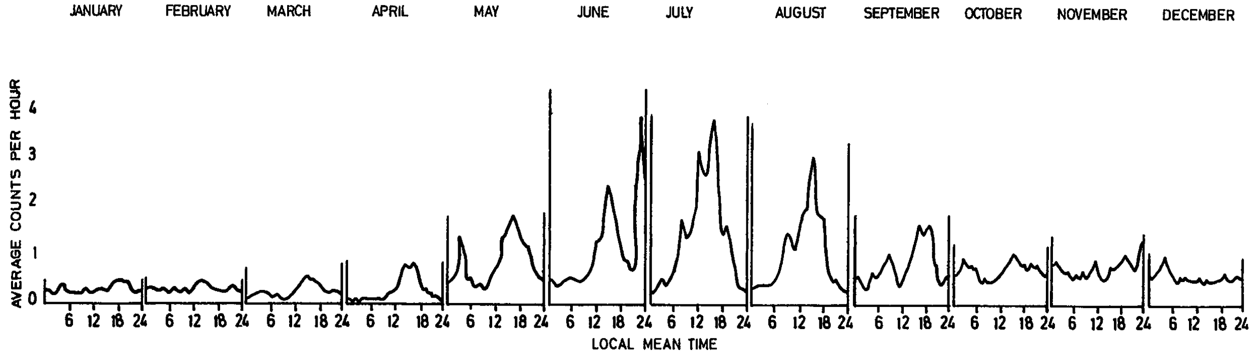

Figure 4. Average count of lightning flashes per hour for 1958-65 at Slough

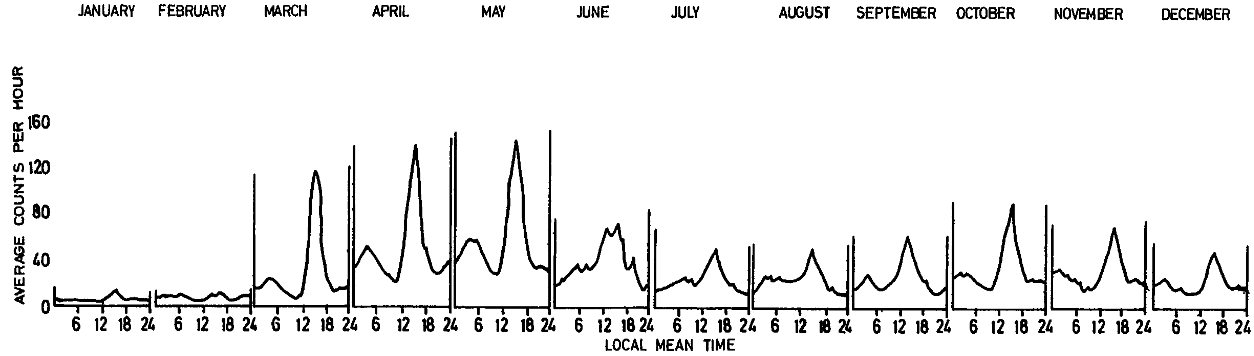

Figure 5. Average count of lightning flashes per hour for 1961-64 at Singapore

4.3 Reference contains an analysis of data from lightning counters installed in a temperate country (the United Kingdom) and in the tropics (Singapore) over periods of several years. The average counts for each hour of the day are compared for each month of the year in Figures 4 and 5.

4.4 In temperate lands where there are few thunderstorms, the occurrence of an exceptionally protracted and severe storm may markedly affect the average incidence (see the June data depicted in Figure 4). The ratio of summer to winter counts for the afternoon period in the United Kingdom was about six.

4.5 The seasonal variation in lightning discharges recorded in the UK was considerably less than the seasonal variation in the number of days on which thunder was heard. This is in accordance with the greater electrical activity of winter frontal type storms as compared with the heat-type storms which occur on summer afternoons.

4.6 The peak months were June, July and August in the UK and March, April and May in Singapore; at both places the peak time of day was the afternoon. The incidence of recorded lightning counts was approximately 50 times as great at Singapore as in the UK.

4.7 Attempts have been made to correlate the occurrence of radio noise with that of thunderstorms. For a three year period at Singapore the number of atmospherics appeared to vary approximately as the square of the number of thunderstorm days, 10^4 counts corresponding to ten thunderstorm days. The world distribution and characteristics of atmospheric radio noise are described in Reference 5.

5 REFERENCES AND OTHER SOURCES OF INFORMATION

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