NASA SP-8084

NASA
SPACE VEHICLE
DESIGN CRITERIA
(ENVIRONMENT)

SURFACE ATMOSPHERIC EXTREMES (LAUNCH AND TRANSPORTATION AREAS)

REVISED
JUNE 1974

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria have been developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work are issued as separate monographs as soon as they are completed. A list of monographs published in this series can be found on the last page.

These monographs are to be regarded as guides to design and not as NASA requirements except as may be specified in formal project specifications. It is expected, however, that the monographs will be used to develop requirements for specific projects and be cited as the applicable references in mission studies or in contracts for the design and development of space vehicle systems.

This is a revision of the monograph on surface atmospheric extremes that was issued in May 1972. The current version was prepared by Glenn E. Daniels of Marshall Space Flight Center and coordinated by Scott A. Mills of Goddard Space Flight Center.

The revision provides new information on temperature, rainfall, pressure, and ice formation at launch sites on the basis of new meteorological data and development of existing data. The new monograph also gives more definitive guidance on lightning in the form of three lightning models, one of which was developed for the NASA Space Shuttle.

Comments concerning the technical content of these monographs will be welcomed by the National Aeronautics and Space Administration, Goddard Space Flight Center, Systems Reliability Directorate, Greenbelt, Maryland 20771.

June 1974

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

For sale by the National Technical Information Service
Springfield, Virginia 22151
Price — $4.00

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SURFACE ATMOSPHERIC EXTREMES (LAUNCH AND TRANSPORTATION AREAS)

1. INTRODUCTION

Extreme values of surface and low-altitude atmospheric parameters for the Earth are important considerations in space vehicle design, test, and operations. Such data are required to define ambient conditions for fabrication, storage, transportation, test, launch, and flight. This monograph provides criteria on atmospheric extremes from the surface to 150 meters for geographical locations of interest to NASA as shown in Figure 1. Thermal parameters (temperature and solar radiation), humidity, precipitation, pressure, and atmospheric electricity (lightning and static) are presented.

The thermal environment can pose serious problems in the form of differential heating of structural parts. Temperatures are also critical from the standpoint of fuel consumption and lubrication. Temperatures of interior compartments and of the accompanying instrument systems are related to the proper operation of the instruments and to the health and efficiency of the occupants in the case of manned spacecraft. Because the temperature of a surface is a function of the heat transfers that take place, attention must also be given to extremes of solar radiation at or near the ground.

Various corrosive processes and other material deterioration are favored by high humidity. High humidity can degrade the performance of electrical equipment and encourage bacterial and fungal growth. Low humidity may contribute to the splitting of organic materials and to the danger of static electricity. Humidity extremes also can cause discomfort and have unhealthful effects.

Precipitation of all forms can affect the performance of equipment and prevent or delay execution of a particular space vehicle project. Accumulated snow may cause stress on a surface, and snow particles may penetrate openings in equipment and thus cause critical components to malfunction. Hail may cause structural damage because of weight and velocity of fall, and accumulated hail may produce stress.

Although daily changes in surface atmospheric pressure are relatively small, they can be significant in design because they may affect the strength and stability of sealed compartments. Information on pressure extremes is also needed for the design and operation of certain instruments such as barometers and baroswitches. Sealed compartments fabricated at relatively high elevations require vents to prevent collapse when moved to lower elevations.

Atmospheric electricity can endanger persons and damage space vehicles before and after launch by the buildup of potential gradients and by lightning stroke. Radio transmission, telemetry, and guidance can be affected adversely. Assessment and control of electrostatic

Figure 1. Areas of interest for NASA launches and transportation.

charges resulting from atmospheric conditions as well as charges that are induced by handling, testing, launch, and flight operations are the subject of a separate monograph now in preparation (NASA SP-8111, Assessment and Control of Electrostatic Charges).

A number of surface environments of concern in space vehicle design are not presented in this monograph. Low altitude winds are treated in references 1 and 2. Another design criteria monograph (ref. 3) gives data on ground wind loads.

Some of the criteria presented herein apply to specific launch, test, or transportation areas, i.e., Kennedy Space Center, Wallops Island, Space and Missile Test Center*, White Sands Missile Range, Edwards Air Force Base, West Coast Transportation, River Transportation, Gulf Transportation, and Panama Canal Transportation. Available data also are provided for the entire continental United States in case other geographical areas become important in future space programs. For other parts of the world the U. S. Army reference on climatic extremes is useful**.

2. STATE OF THE ART

2.1 Solar Radiation

2.1.1 Solar Constant

The thermal equilibrium of a space vehicle depends largely on absorption of solar radiation at visible wavelengths. Therefore, the extraterrestrial flux of solar radiation at 1 AU (the solar constant) is of prime importance in radiation studies***. The value of 1.940 cal cm^{-2} min^{-1} (0.1353 w cm^{-2}) has been adopted as the solar constant in a separate NASA design criteria monograph (ref. 4).

2.1.2 Solar Radiation at Earth's Surface

2.1.2.1 Spectral Distribution

The spectral distribution of solar radiation is required for selecting materials for space vehicle construction because materials absorb and radiate differently in various parts of the spectrum. Various spectral components of solar radiation are altered by atmospheric absorption and scattering. Reference 5 is a typical study of the near solar spectral distribution at the Earth's surface for different path lengths and atmospheric constituents. Other spectral studies are contained in references 6 through 9.

The spectral distribution at the Earth's surface adopted for this monograph was derived from that given in reference 4 and takes into account absorption by one atmosphere of extreme clearness.

2.1.2.2 Extreme of Solar Radiation

There have been different approaches for establishing realistic extremes for solar radiation at particular locations. The use of mean values as an indication of probable values could result

*At Vandenberg Air Force Base, California.

**Anon., "Research, Development, Test, and Evaluation of Material for Extreme Climatic Conditions," U. S. Army Regulation AR 70-38, Headquarters, Dept. of the Army, May 5, 1969.

***Thekaekara, M. P. and Drummond, A. J., "Standard Values for the Solar Constant and its Spectral Components," Nature, Physical Science, vol. 229, January 4, 1971, pp. 6-9.

in using heat loads which would be exceeded 50 percent of the days. Use of statistics of daily totals (ref. 10) also would be unrealistic in many design problems because the rapid variations during a 24 hour period are not taken into account. In contrast, reference 11 uses frequency distribution statistics for each hour throughout the day.

The extreme values adopted for this monograph are based on ten years of data recorded at Apalachicola, Florida and Santa Maria, California (refs. 2 and 11). The Apalachicola, Florida data (ref. 11) was the basis for the adopted radiation values given in column 4 of table I which were adjusted to make the total area under the solar radiation curve (column 5) equal to 0.1111 w cm^{-2} (1.59 cal cm^{-2} min^{-1}).

Global radiation was measured with a pyranometer and consisted of direct solar radiation falling on a horizontal surface and the diffuse radiation from the total sky hemisphere. An empirical estimate of the diffuse sky radiation was subtracted from the global radiation, and the result was divided by the sine of the Sun's altitude*. This was added to the previously estimated diffuse component to yield total normal incident radiation.

2.2 Temperature

Temperature records have been kept for a sufficiently long period at the launch sites and other stations of interest to provide a valid sample for statistical analysis. Such data and analysis are quite useful to the space vehicle design engineer.

2.2.1 Air Temperature

Reference 2 contains analyses of maximum and minimum temperatures in the United States on the basis of at least 15 years of data for most of the Weather Bureau stations used. Figure 8 (sec. 3.1) summarizes the foregoing information with maps of the United States having isotherms of extreme maximum and minimum temperatures. For a given area the absolute extreme usually is not given unless a first order Weather Bureau station is located therein. Extreme temperature values are given in detail in table III (sec. 3.1).

2.2.1.1 Risk Percentages

High temperature climatology on a worldwide basis is treated in reference 12 which is a study made in conjunction with the revision of Military Standard 210A, Climatic Extremes for Military Equipment (ref. 13). In reference 12, the sum of the mean and mean daily range of temperature for the warmest month are used to establish temperatures which are expected to be exceeded 1, 5, and 10 percent of the time (risk percentages). For these data, the maximum temperatures for which hardware is designed can be specified in terms of risk.

*Elevation angle of the Sun above the horizon.

2.2.1.2 Duration

Temperature duration may also be critical in design, and some statistical studies have emphasized this point. Reference 14 covers the statistical distribution of temperature duration above or below a specified value and is based on hourly data from station records. Reference 15 discusses forecasting. Reference 16 contains a duration study of high temperatures at Yuma, Arizona and selected midwestern stations. Reference 17 uses a similar approach. Temperature durations are also discussed in reference 18, and prediction methods of temperature durations are covered in reference 19.

2.2.2 Skin Temperatures

In computing skin temperatures, the assumption of no wind and surface emissivity (and absorptivity) of 1.0 ensures the representation of extreme skin temperatures for objects located near the ground, i.e., the black body surface temperature. The temperature rise of a surface exposed to the Sun, however, will be lower than that of a perfect black body for three reasons (ref. 11):

- The absorptivity of a surface will be lower than that of a black body.
- Because of wind and thermal gradients near the surface, convection will increase the amount of heat transfer, resulting in a lower temperature for the surface.
- The surface may not be normal to the Sun.

2.2.3 Compartment Temperatures

Ambient air temperatures exceeding 40°C (104°F) are common in desert climates because of the heat transfer processes of conduction and convection. Furthermore, temperatures may be much higher inside unvented vehicles exposed to the sun when solar radiation absorbed by the vehicle skin is reemitted at longer wavelengths to inside compartments.

Compartment temperatures measured within a B-47 bomber on the ground at Yuma, Arizona, indicated a maximum interior air temperature of 84.4°C (184°F) (ref. 20). An item of equipment located in the cockpit area reached 100.6°C (213°F). During the experiment, which took place in August 1958, the maximum outside air temperature was 43.3°C (110°F). Figure 2 shows curves of temperature versus time for selected days during the period. These curves show the temperature of an item of equipment inside the cockpit and the temperature of the interior air. Reference 21 is another study on compartment temperatures.

2.3 Humidity

2.3.1 Current Investigations and Concepts

Studies of humidity are concerned with greater accuracy in measurements and the representation of temporal and spatial distributions (ref. 22).

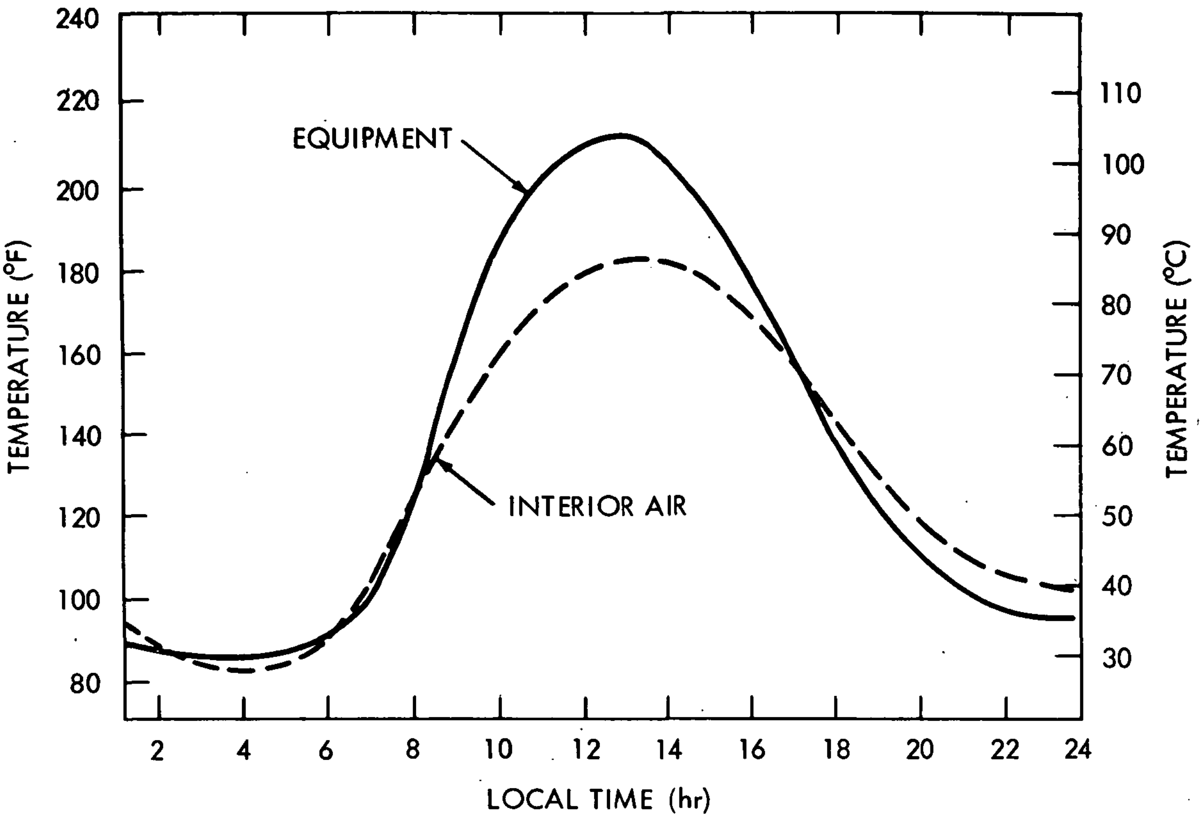


Figure 2. Time vs temperature inside a B-47 bomber (Based on ref. 20).

In keeping with revisions of atmospheric criteria for military purposes, reference 23 gives diurnal cycles of extreme humidity for designated areas of the world in terms of risk percentages (sec. 2.2.1.1) rather than absolute extremes. Effects of high temperature and humidity on humans and equipments are presented in reference 24 which stresses the need for humidity tests under actual environmental conditions. The Atmospheric Humidity Atlas - Northern Hemisphere (ref. 25) presents percentile maps of mixing ratios and dew points and discusses methods for determining probabilities of dew point duration. World-wide values of high dew points are given in reference 26.

2.3.2 Humidity Effects

High humidity, especially when accompanied by high temperatures, may affect space vehicles adversely as follows:

- Condensation on dust particles may produce a corrosive solution.
- Highly conductive salt solutions often develop when a film of salt absorbs water in a high-humidity ocean area. Corrosion of metals is possible if the solution reacts chemically.

- Even without the presence of salt or dust particles, high-humidity conditions may harm electrical equipment.

- An environment of high humidity and high temperature favors the growth of bacteria and fungi.

- When moist air is cooled, e.g., when taking on fuel, ice may form to hinder the operation of equipment. Also, water droplets or ice crystals may cover optical surfaces such as television camera lenses.

- Air conditioning loads depend on humidity.

Low relative humidity occurs with high temperatures such as when the Sun heats enclosed storage areas or vehicle compartments above ambient temperature. The resulting low relative humidity can cause materials in the enclosed spaces to dry and split.

2.3.3 Humidity Variations

The description of humidity variation in terms of vapor concentration (absolute humidity) is convenient for the design engineer. Therefore, vapor concentration cycles for specific locations have been compiled in reference 2.

2.4 Precipitation

For some design purposes, precipitation statistics should be considered. The instantaneous rate of rainfall, for example, is significant in the operation of certain equipment. Reference 27 presents the probabilities of instantaneous (1 min) rainfall rates being exceeded at locations and rainfall index (the ratio of the average annual total precipitation to the number of days of occurrence). These theoretically derived rates are compared with observed data. The report also considers rainfall rates for different durations (5 min to 24 hrs) and the risk of such rates occurring within a specified time period (2, 5, 10, and 25 years). The frequency of occurrence of rainfall rates is also discussed in reference 18. Precipitation statistics applicable for design at specific test and launch sites are given in reference 2 and include data for snow and hail as well as rain. This information has been used for this monograph.

2.5 Pressure

Most surface pressure data are published after reducing to equivalent sea level pressure. Unfortunately, data in this form are of little value for design purposes unless the area of concern is near sea level. For design purposes, the true value of the pressure at the surface at the location is required, i.e., the station pressure. To prepare design maps for reference 2, the only available extreme pressure data (highs and lows) was given as sea level data. Therefore, assumptions had to be made in the mean temperature layer between the station and sea-level, and this could result in error in converting the given sea-level data to the station pressure. The error, however, is much less than if sea-level pressure is used when station pressures are required (ref. 28).

Data from references 2 and 28 are used in this monograph. Tabulation of extreme pressure values (sea-level) for given periods of record at selected cities in each of the states (ref. 29) also was used. References 30 and 31 discuss recent high pressure values for North America which are considered further in reference 32. Earlier discussions on pressure extremes are found in references 33 and 34.

2.6 Atmospheric Electricity

The atmosphere of the Earth at all times has an electrical charge. The ionosphere, which is the upper limit of the conducting layer, has a positive charge with respect to the Earth's surface of about 360 000 volts. The variation of charge in the atmospheric field with altitude is non-linear. The greatest variation occurs near the surface, but it decreases to about 4 volts m^{-1} at about 10 to 12 km (ref. 35). Near the surface the field varies considerably from a low during fair weather to the highest values when fully developed cumulo-nimbus clouds are overhead.

On a day without clouds, the potential gradient in the atmosphere near the surface of the Earth is relatively low (<300 volts m^{-1}), but when clouds build up, the potential gradient near the surface of the Earth increases because of charges in the clouds. If the clouds become large enough to have droplets of sufficient size to produce rain, the atmospheric potential gradient may be sufficient to result in a lightning discharge which would require gradients of greater than 500 000 volts m^{-1}.

2.6.1 Fair Weather

The fair-weather potential gradient measured near the ground is on the order of 100 to 300 volts m^{-1} and is negative; i.e., the Earth is negatively charged and the atmosphere above the Earth is positively charged. The fair-weather value of 100 to 300 volts m^{-1} will vary somewhat at a specific location and will also be somewhat different at various locations. These variations in fair weather will be caused by the amount of particulate matter in the atmosphere such as dust and salt particles, atmospheric humidity, and instrument location and exposure. This fair-weather potential gradient over a 100-meter high vehicle could result in a 10 000-volt or greater potential difference between the air near the ground and the air around the vehicle top. The vehicle could assume this charge if not grounded. Factors that affect the general atmospheric electric field and its variations are discussed in references 36 through 45.

2.6.2 Clouds

2.6.2.1 Induced Charges

When clouds develop, the potential gradient at the ground increases. This increase may be great enough on days with scattered cumulus clouds to produce severe shock from charges induced on metal cables of captive balloons. Similar induced charges on home television antennas have been great enough to explode fine wire coils in the antenna circuits. Damage to equipment connected to outside wires or antennas can be prevented by suitable lightning arresters with air gaps close enough to discharge the circuit before the voltage reaches high values. On very high objects such as Saturn vehicles similar charges may result from the increased potential gradient on cloudy days, especially if the humidity is low. More information on charge accumulation and its control is given in NASA SP-8111 (Assessment and Control of Electrostatic Charges).

2.6.2.2 Corona Discharge

Increases of atmospheric potential gradient from cloud buildup may cause exposed sharp points to become ionized by corona discharge. As the potential increases to values between 20 000 to 100 000 volts m^{-1}, the discharge may become visible. On aircraft flying through active electrical storms, corona discharge streamers are often seen on antennas and propellers. The corona discharge may be quite severe when lightning storms or large cumulus cloud developments are within about 16 kilometers (10 miles) of the launch pad. Seldom does a corona discharge exceed 100 000 volts m^{-1}. Corona discharge may cause explosive gases to ignite or damage improperly grounded electrical equipment (refs. 5 and 39).

2.6.3 Precipitation

A charge may develop on an object in motion from impact of raindrops, ice particles, dust, or other nuclei in the atmosphere; an object at rest also may be charged if it is not grounded. Discharge occurs if this charge reaches the breakdown value of air (about 3×10^6 volts/m at sea level, refs. 2 and 43) at the object's sharpest exterior point. In case of low humidity, an ungrounded vehicle on the launch pad builds up charge more readily. For high objects such as Saturn vehicles, precipitation retards charge buildup by serving as a conductor in carrying off charge accumulation.

2.6.4 Lightning

Information on electric field charges associated with electrical storms is found in references 37, 39, 40, 43, 46, 47, and 48.

When the cloud development reaches the cumulo-nimbus state, lightning charges result if the potential gradient at some location reaches a value equal to the critical breakdown value of air which is about 3×10^6 volts m^{-1} at sea level (refs. 2 and 43).

2.6.4.1 Surface Electric Fields

Electrical fields measured at the surface of the Earth are much less than the critical breakdown value of air during lightning discharges because of three effects: (1) Most clouds have centers of both polarities which tend to neutralize values measured at the surface. (2) Each charge in the atmosphere and its image within the Earth resembles an electrical dipole; the intensity of the electrical field decreases with the cube of the distance from the dipole. (3) The atmospheric electric field measured over land at the surface is limited by discharge currents arising from grounded points, such as grass, trees, and other structures, that ionize the air around the points, thus producing screen space charges. For these reasons, the measured electrical field at the surface is never more than about 15×10^3 volts m^{-1}.

The potential gradient values indicated by measuring equipment at the surface are high when the charged cloud is directly overhead. As the distance to the charged center of the cloud becomes greater, the readings become lower (zero at some distance from the cloud) and then change to the opposite sign at greater distances (refs. 43 and 48).

2.6.4.2 Lightning Discharges

When lightning strikes an object, the current flows through all exposed materials. The distribution of current among these paths varies inversely with their resistances. Thus, if a launch complex with a vehicle is struck, the current that flows through the vehicle can be significant.

Although only about 20 percent of lightning flashes are between cloud and ground, they are important because of their destructive potential. Figure 3 shows the generalized wave shape of a lightning stroke (ref. 43); the current decreases exponentially after each stroke. Figure 4 shows the statistical distribution of maximum peak currents in lightning strokes (ref. 38).

The lightning discharge to ground which appears to the eye as a single flash is usually made up of three or four strokes. These strokes are preceded by a leader stroke of lesser intensity. Knowledge of the physics involved in a typical cloud-initiated lightning flash is provided in references 36, 37, 49, 50, and 51.

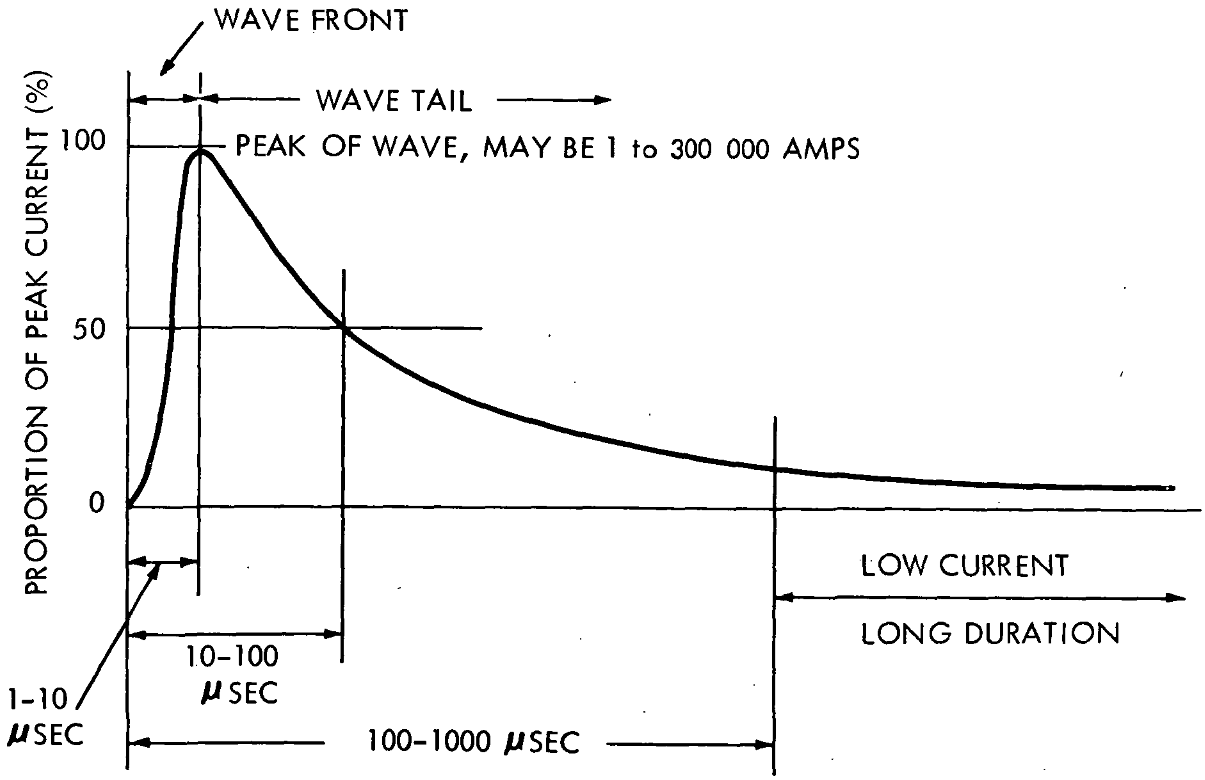


Figure 3. Generalized wave shape of discrete lightning-stroke current (ref. 43).

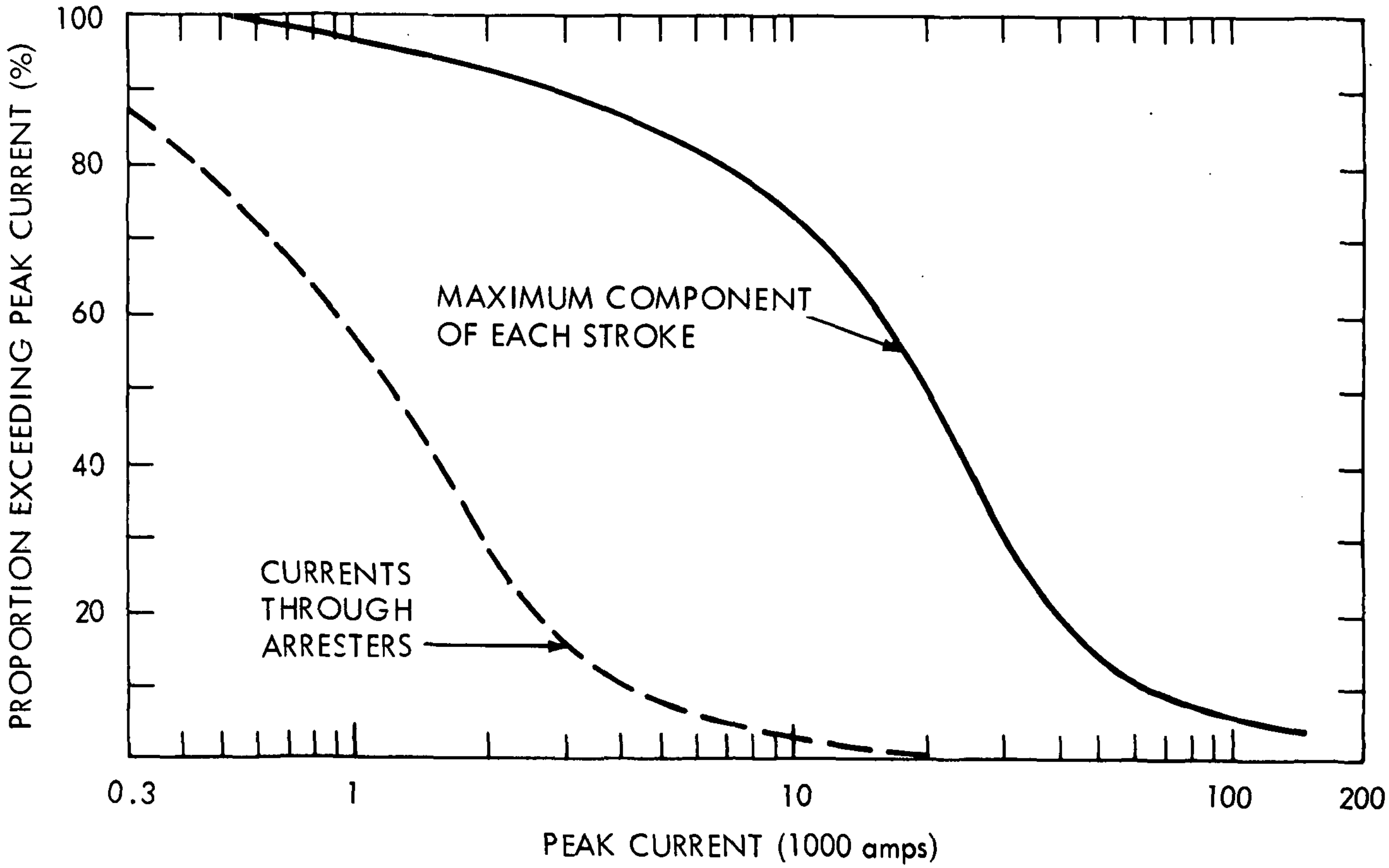


Figure 4. Distribution of peak currents in lightning strokes and currents discharged by arresters (ref. 38).

Although cloud-initiated flashes that transfer negative charge to the ground (negative current) are most common, three other types of lightning flashes have been observed: cloud-initiated flashes that transport positive charge to Earth (positive current), ground-initiated flashes that transfer negative charge to Earth (negative current), and ground-initiated flashes that transport positive charge to Earth (positive current) (refs. 49 through 52).

The positive current lightning flashes (cloud- and ground-initiated) constitute 15 percent of the lightning flashes between clouds and Earth. Positive current flashes tend to have higher peak currents, have more charge, and have higher heating effects than the negative current flashes. Even though positive currents are less frequent, they are important because of their extreme characteristics and because most lightning triggered by space vehicles can be expected to be of this type (refs. 38, 48, 49, 50, 52, 53, and 54).

A lightning model was developed for design of the NASA Space Shuttle (ref. 55) from measurements of Florida lightning by Uman (ref. 56) and work by Pierce and Cianos (ref. 57). This model has been adopted for this monograph to describe a very severe stroke and is designated Model 1 (fig. 21, sec. 3.5.3). Models 2 and 3 have been adopted to describe lightning strokes with 98 percentile and average currents; they were taken from reference 2.

2.6.4.3 Lightning Statistics

Various statistics are available on lightning flashes. These include statistical estimates of the yearly number of flashes to structures of various heights (ref. 58) and the statistical distribution of peak currents in lightning (ref. 37). Other characteristics of lightning flashes are given in references 37, 38, 41, 46, 52, 53, and 54. Frequency distributions of peak current from other studies are given in reference 37. Applicable portions of the foregoing information have been adopted for this monograph and are given in section 3.

3. CRITERIA

The extreme values of surface and low-altitude environmental data presented here should be used for space vehicle design and operations.

3.1 Thermal

3.1.1 Solar Radiation

3.1.1.1 Spectral Distribution

Table I (column 4) gives the values of solar radiation to be used for all areas of NASA interest and contiguous United States as shown in figure 1. Column 2 of table I gives the values of solar spectral irradiance outside the atmosphere at 1 AU in the wavelength range from 0.12 μm to 1000 μm; column 4 gives the associated values for solar radiation at sea level after it has passed through one extremely clear air mass. Part of the same data is shown in figure 5 in which columns 2 and 4 and a black body curve for T = 5762°K are plotted in the wavelength range from 0.1 to 2.6 μm.

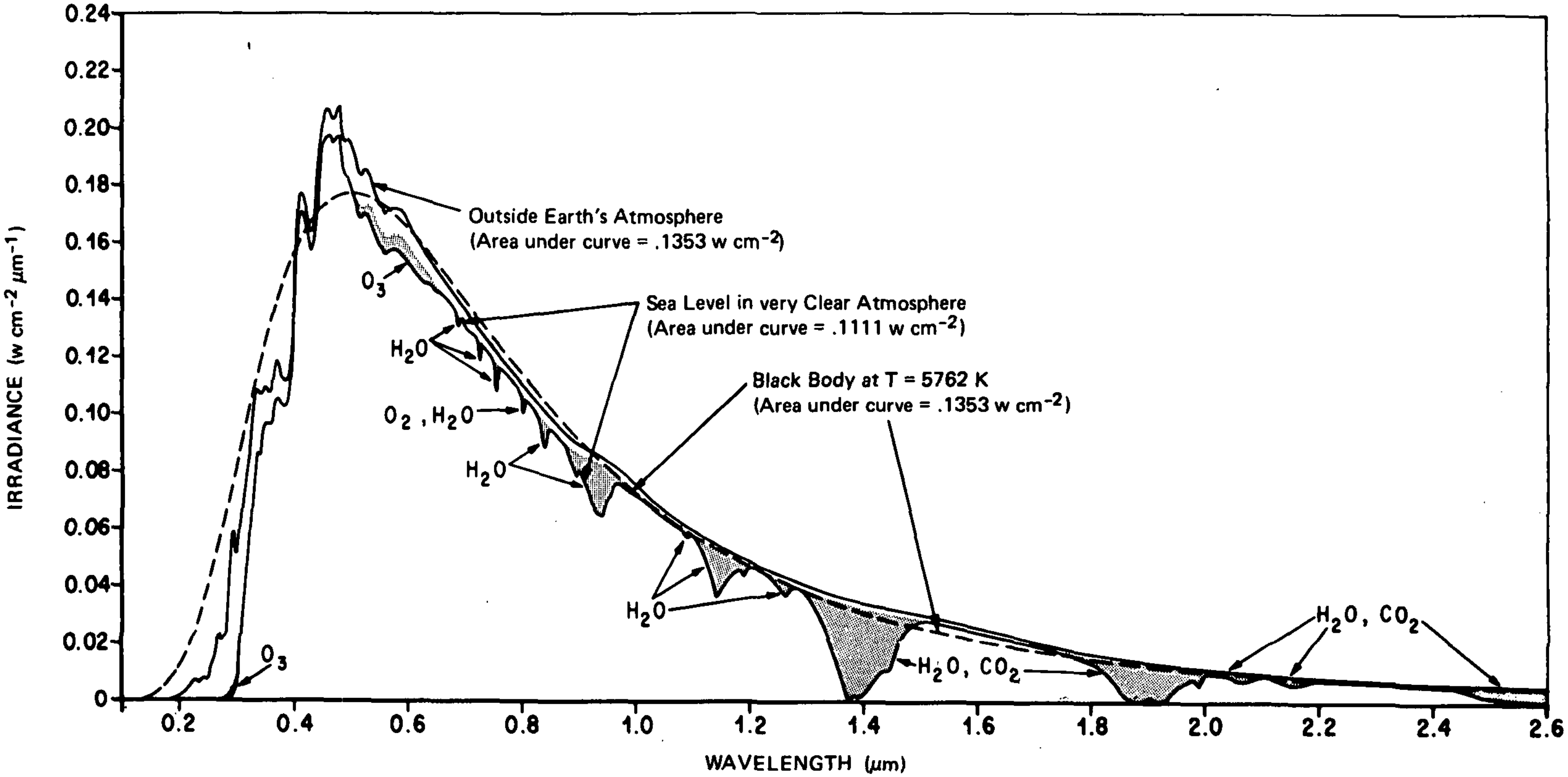


Figure 5. Normally incident solar radiation at sea level on very clear days (sec. 2.1.2.2), solar spectral irradiance outside the Earth's atmosphere at 1 AU (ref. 4), and black body spectral irradiance curve at T = 5762°K (normalized to 1 AU).

Table I

SOLAR SPECTRAL IRRADIANCE (OUTSIDE ATMOSPHERE) AND SOLAR RADIATION AFTER ABSORPTION BY CLEAR ATMOSPHERE

1	2	3	4	5	6
Wavelength, λ (μm)	Solar Spectral Irradiance (w cm^{-2} μm^{-1})	Area under Solar Spectral Irradiance Curve (w cm^{-2})	Solar Radiation after One Atmosphere Absorption (w cm^{-2} μm^{-1})	Area under One Atmosphere Solar Radiation Curve (w cm^{-2})	Portion of Solar Radiation after One Atmosphere Absorption for Wavelength < λ (%)
0.120	0.000010	0.00000060	0.000000	0.000000	0.00
0.140	0.000003	0.00000073	0.000000	0.000000	0.00
0.150	0.000007	0.00000078	0.000000	0.000000	0.00
0.160	0.000023	0.00000093	0.000000	0.000000	0.00
0.170	0.000063	0.00000136	0.000000	0.000000	0.00
0.180	0.000125	0.00000230	0.000000	0.000000	0.00
0.190	0.000271	0.00000428	0.000000	0.000000	0.00
0.200	0.00107	0.000010	0.000001	0.000000	0.00
0.210	0.00229	0.000027	0.000003	0.000000	0.00
0.220	0.00575	0.000067	0.000007	0.000000	0.00
0.225	0.00649	0.000098	0.000007	0.000000	0.00
0.230	0.00667	0.000131	0.000008	0.000000	0.00
0.235	0.00593	0.000162	0.000007	0.000000	0.00
0.240	0.00630	0.000193	0.000007	0.000000	0.00
0.245	0.00723	0.000227	0.000008	0.000000	0.00
0.250	0.00704	0.000263	0.000008	0.000000	0.00
0.255	0.0104	0.000306	0.000012	0.000000	0.00
0.260	0.0130	0.000365	0.000015	0.000000	0.00
0.265	0.0185	0.000443	0.000021	0.000000	0.00
0.270	0.0232	0.000548	0.000026	0.000000	0.00
0.275	0.0204	0.000657	0.000023	0.000000	0.00
0.280	0.0222	0.000763	0.000025	0.000000	0.00
0.285	0.0315	0.000897	0.000036	0.000001	0.00
0.290	0.0482	0.001097	0.000055	0.000001	0.00
0.295	0.0584	0.001363	0.000066	0.000001	0.00
0.300	0.0514	0.001638	0.006677	0.000035	0.03
0.305	0.0603	0.001917	0.019830	0.000134	0.12
0.310	0.0689	0.002240	0.029084	0.000279	0.25
0.315	0.0764	0.002603	0.038941	0.000474	0.42
0.320	0.0830	0.003002	0.047684	0.000712	0.64
0.325	0.0975	0.003453	0.062018	0.001022	0.92
0.330	0.1059	0.003961	0.073829	0.001392	1.25
0.335	0.1081	0.004496	0.080896	0.001796	1.61
0.340	0.1074	0.005035	0.084636	0.002219	1.99
0.345	0.1069	0.005571	0.087080	0.002655	2.39
0.350	0.1093	0.006111	0.091327	0.003111	2.80
0.355	0.1083	0.006655	0.092186	0.003572	3.40
0.360	0.1068	0.007193	0.092857	0.004036	3.63

Table I (continued)

1	2	3	4	5	6
Wavelength, λ (μm)	Solar Spectral Irradiance (w cm^{-2} μm^{-1})	Area under Solar Spectral Irradiance Curve (w cm^{-2})	Solar Radiation after One Atmosphere Absorption (w cm^{-2} μm^{-1})	Area under One Atmosphere Solar Radiation Curve (w cm^{-2})	Portion of Solar Radiation after One Atmosphere Absorption for Wavelength < λ (%)
0.365	0.1132	0.007743	0.099873	0.004536	4.08
0.370	0.1181	0.008321	0.105507	0.005063	4.55
0.375	0.1157	0.008906	0.104596	0.005586	5.03
0.380	0.1120	0.009475	0.102971	0.006101	5.49
0.385	0.1098	0.010030	0.102273	0.006613	5.95
0.390	0.1098	0.010579	0.103977	0.007132	6.42
0.395	0.1189	0.011150	0.114309	0.007704	6.93
0.400	0.1429	0.011805	0.137403	0.008391	7.55
0.405	0.1644	0.012573	0.158076	0.009181	8.26
0.410	0.1751	0.013422	0.168365	0.010023	9.02
0.415	0.1774	0.014303	0.170576	0.010876	9.79
0.420	0.1747	0.015183	0.167980	0.011716	10.54
0.425	0.1693	0.016043	0.162788	0.012530	11.28
0.430	0.1639	0.016876	0.157596	0.013318	11.99
0.435	0.1663	0.017702	0.159903	0.014117	12.71
0.440	0.1810	0.018570	0.174038	0.014988	13.40
0.445	0.1922	0.019503	0.184807	0.015912	14.30
0.450	0.2006	0.020485	0.192884	0.016876	15.19
0.455	0.2057	0.021501	0.195904	0.017656	16.07
0.460	0.2066	0.022532	0.196761	0.018839	16.96
0.465	0.2048	0.023560	0.196923	0.019824	17.84
0.470	0.2033	0.024580	0.195480	0.020801	18.72
0.475	0.2044	0.025600	0.196538	0.021784	19.61
0.480	0.2074	0.026629	0.197523	0.022772	20.50
0.485	0.1976	0.027642	0.186415	0.023704	21.34
0.490	0.1950	0.028623	0.183962	0.024624	22.17
0.495	0.1960	0.029601	0.183177	0.025539	22.99
0.500	0.1942	0.030576	0.179814	0.026439	23.80
0.505	0.1920	0.031542	0.176146	0.027319	24.60
0.510	0.1882	0.032492	0.172660	0.028183	25.37
0.515	0.1833	0.033421	0.168165	0.029023	26.13
0.520	0.1833	0.034337	0.168165	0.029864	26.88
0.525	0.1852	0.035259	0.169908	0.030714	27.65
0.530	0.1842	0.036182	0.168990	0.031559	28.41
0.535	0.1818	0.037097	0.166788	0.032393	29.16
0.540	0.1783	0.037997	0.163977	0.033211	29.90
0.545	0.1754	0.038882	0.160917	0.034015	30.62
0.550	0.1725	0.039751	0.158256	0.034806	31.33
0.555	0.1720	0.040613	0.157798	0.035595	32.05
0.560	0.1695	0.041466	0.155504	0.036373	32.75

Table I (continued)

1	2	3	4	5	6
Wavelength, λ (μm)	Solar Spectral Irradiance (w cm^{-2} μm^{-1})	Area under Solar Spectral Irradiance Curve (w cm^{-2})	Solar Radiation after One Atmosphere Absorption (w cm^{-2} μm^{-1})	Area under One Atmosphere Solar Radiation Curve (w cm^{-2})	Portion of Solar Radiation after One Atmosphere Absorption for Wavelength < λ (%)
0.565	0.1705	0.042316	0.156422	0.037155	33.45
0.570	0.1712	0.043171	0.157064	0.037940	34.16
0.575	0.1719	0.044028	0.157726	0.038729	34.87
0.580	0.1715	0.044887	0.157339	0.039516	35.57
0.585	0.1712	0.045744	0.157064	0.040301	36.28
0.590	0.1700	0.046597	0.155963	0.041081	36.98
0.595	0.1682	0.047442	0.154311	0.041852	37.68
0.600	0.1666	0.048279	0.152844	0.042616	38.37
0.605	0.1647	0.049107	0.151100	0.043372	39.05
0.610	0.1635	0.049928	0.150000	0.044122	39.72
0.620	0.1602	0.051546	0.146972	0.045592	41.05
0.630	0.1570	0.053132	0.145370	0.047045	42.30
0.640	0.1544	0.054689	0.144299	0.048488	43.66
0.650	0.1511	0.056217	0.142547	0.049914	44.94
0.660	0.1486	0.057715	0.141523	0.051329	46.22
0.670	0.1456	0.059186	0.140000	0.052729	47.48
0.680	0.1427	0.060628	0.137211	0.054101	48.71
0.690	0.1402	0.062042	0.134807	0.055449	49.93
0.700	0.1369	0.063428	0.131634	0.056766	51.11
0.710	0.1344	0.064784	0.129230	0.058058	52.27
0.720	0.1314	0.066113	0.126346	0.059321	53.41
0.730	0.1290	0.067415	0.124038	0.060562	54.53
0.740	0.1260	0.068690	0.121153	0.061773	55.62
0.750	0.1235	0.069938	0.118750	0.062961	56.69
0.800	0.1107	0.075793	0.106442	0.068283	61.48
0.850	0.0988	0.081030	0.095000	0.073033	65.76
0.900	0.0889	0.085723	0.080090	0.077037	69.36
0.950	0.0835	0.090033	0.077314	0.080903	72.84
1.000	0.0746	0.093985	0.071730	0.084490	76.07
1.100	0.0592	0.100675	0.056923	0.090182	81.20
1.200	0.0484	0.106055	0.046538	0.094836	85.39
1.300	0.0396	0.110455	0.036000	0.098436	88.63
1.400	0.0336	0.114115	0.002240	0.098660	88.83
1.500	0.0287	0.117230	0.027333	0.101393	91.29
1.600	0.0244	0.119885	0.023461	0.103739	93.40
1.700	0.0202	0.122115	0.019423	0.105681	95.15
1.800	0.0159	0.123920	0.013826	0.107064	96.40
1.900	0.0126	0.125345	0.000126	0.107077	96.41
2.000	0.0103	0.126490	0.009809	0.108057	97.29
2.100	0.0090	0.127455	0.008653	0.108923	98.07

Table I (continued)

1	2	3	4	5	6
Wavelength, λ (μm)	Solar Spectral Irradiance (w cm^{-2} μm^{-1})	Area under Solar Spectral Irradiance Curve (w cm^{-2})	Solar Radiation after One Atmosphere Absorption (w cm^{-2} μm^{-1})	Area under One Atmosphere Solar Radiation Curve (w cm^{-2})	Portion of Solar Radiation after One Atmosphere Absorption for Wavelength < λ (%)
2.200	0.0079	0.128300	0.007596	0.109682	98.76
2.300	0.0068	0.129035	0.006538	0.110336	99.34
2.4	0.0064	0.129695	0.006153	0.110951	99.90
2.5	0.0054	0.130285	0.001080	0.111059	100.00
2.6	0.0048	0.130795	0.000005	0.111060	100.00
2.7	0.0043	0.131250	0.000004	0.111060	100.00
2.8	0.00390	0.131660	0.000004	0.111061	100.00
2.9	0.00350	0.132030	0.000004	0.111061	100.00
3.0	0.00310	0.132360	0.000003	0.111061	100.00
3.1	0.00260	0.132645	0.000002	0.111062	100.00
3.2	0.00226	0.132888	0.000002	0.111062	100.00
3.3	0.00192	0.133097	0.000002	0.111062	100.00
3.4	0.00166	0.133276	0.000001	0.111062	100.00
3.5	0.00146	0.133432	0.000001	0.111062	100.00
3.6	0.00135	0.133573	0.000001	0.111062	100.00
3.7	0.00123	0.133702	0.000001	0.111062	100.00
3.8	0.00111	0.133819	0.000001	0.111063	100.00
3.9	0.00103	0.133926	0.000001	0.111063	100.00
4.0	0.00095	0.134025	0.000001	0.111063	100.00
4.1	0.00087	0.134116	0.000001	0.111063	100.00
4.2	0.00078	0.134198	0.000000	0.111063	100.00
4.3	0.00071	0.134273	0.000000	0.111063	100.00
4.4	0.00065	0.134341	0.000000	0.111063	100.00
4.5	0.00059	0.134403	0.000000	0.111063	100.00
4.6	0.00053	0.134459	0.000000	0.111063	100.00
4.7	0.00048	0.134509	0.000000	0.111063	100.00
4.8	0.00045	0.134556	0.000000	0.111063	100.00
4.9	0.00041	0.134599	0.000000	0.111063	100.00
5.0	0.0003830	0.13463906	0.000000	0.111063	100.00
6.0	0.0001750	0.13491806	0.000000	0.111063	100.00
7.0	0.0000990	0.13505506	0.000000	0.111063	100.00
8.0	0.0000600	0.13513456	0.000000	0.111063	100.00
9.0	0.0000380	0.13518356	0.000000	0.111063	100.00
10.0	0.0000250	0.13521506	0.000000	0.111063	100.00
11.0	0.0000170	0.13523606	0.000000	0.111063	100.00
12.0	0.0000120	0.13525056	0.000000	0.111063	100.00
13.0	0.0000087	0.13526091	0.000000	0.111063	100.00
14.0	0.0000055	0.13526801	0.000000	0.111063	100.00
15.0	0.0000049	0.13527321	0.000000	0.111063	100.00
16.0	0.0000038	0.13527756	0.000000	0.111063	100.00

Table I (continued)

1	2	3	4	5	6
Wavelength, λ (μm)	Solar Spectral Irradiance, (w cm^{-2} μm^{-1})	Area under Solar Spectral Irradiance Curve (w cm^{-2})	Solar Radiation after One Atmosphere Absorption (w cm^{-2} μm^{-1})	Area under One Atmosphere Solar Radiation Curve (w cm^{-2})	Portion of Solar Radiation after One Atmosphere Absorption for Wavelength < λ (%)
17.0	0.0000031	0.13528101	0.000000	0.111063	100.00
18.0	0.0000024	0.13528376	0.000000	0.111063	100.00
19.0	0.0000020	0.13528596	0.000000	0.111063	100.00
20.0	0.0000016	0.13528776	0.000000	0.111063	100.00
25.0	0.000000610	0.13529328	0.000000	0.111063	100.00
30.0	0.000000300	0.13529556	0.000000	0.111063	100.00
35.0	0.000000160	0.13529671	0.000000	0.111063	100.00
40.0	0.000000094	0.13529734	0.000000	0.111063	100.00
50.0	0.000000038	0.13529800	0.000000	0.111063	100.00
60.0	0.000000019	0.13529829	0.000000	0.111063	100.00
80.0	0.000000007	0.13529855	0.000000	0.111063	100.00
100.0	0.000000003	0.13529865	0.000000	0.111063	100.00
1000.0	0.000000000	0.13530000	0.000000	0.111063	100.00

3.1.1.2 Extreme Radiation in East and West

Figure 6 gives the extremes of solar radiation versus time of day during June (month when the Sun is nearest the zenith) for areas of interest in eastern United States. Two sets of values are plotted, global radiation and total normal incident radiation as developed in section 2.1.2.2.

Figure 7 gives the same data as figure 6 but for the western regions of the United States.

3.1.1.3 Extreme Radiation for All Areas

For applications such as space shuttle design in which all areas must be considered, table II gives extreme solar radiation values.

3.1.2 Temperature

3.1.2.1 Extreme Air Temperatures

Figure 8 consists of maps of contiguous United States that show extremes of high and low temperatures near the ground. Table III gives in detail extremes of air temperature and diffuse sky radiation temperature at the locations of interest.

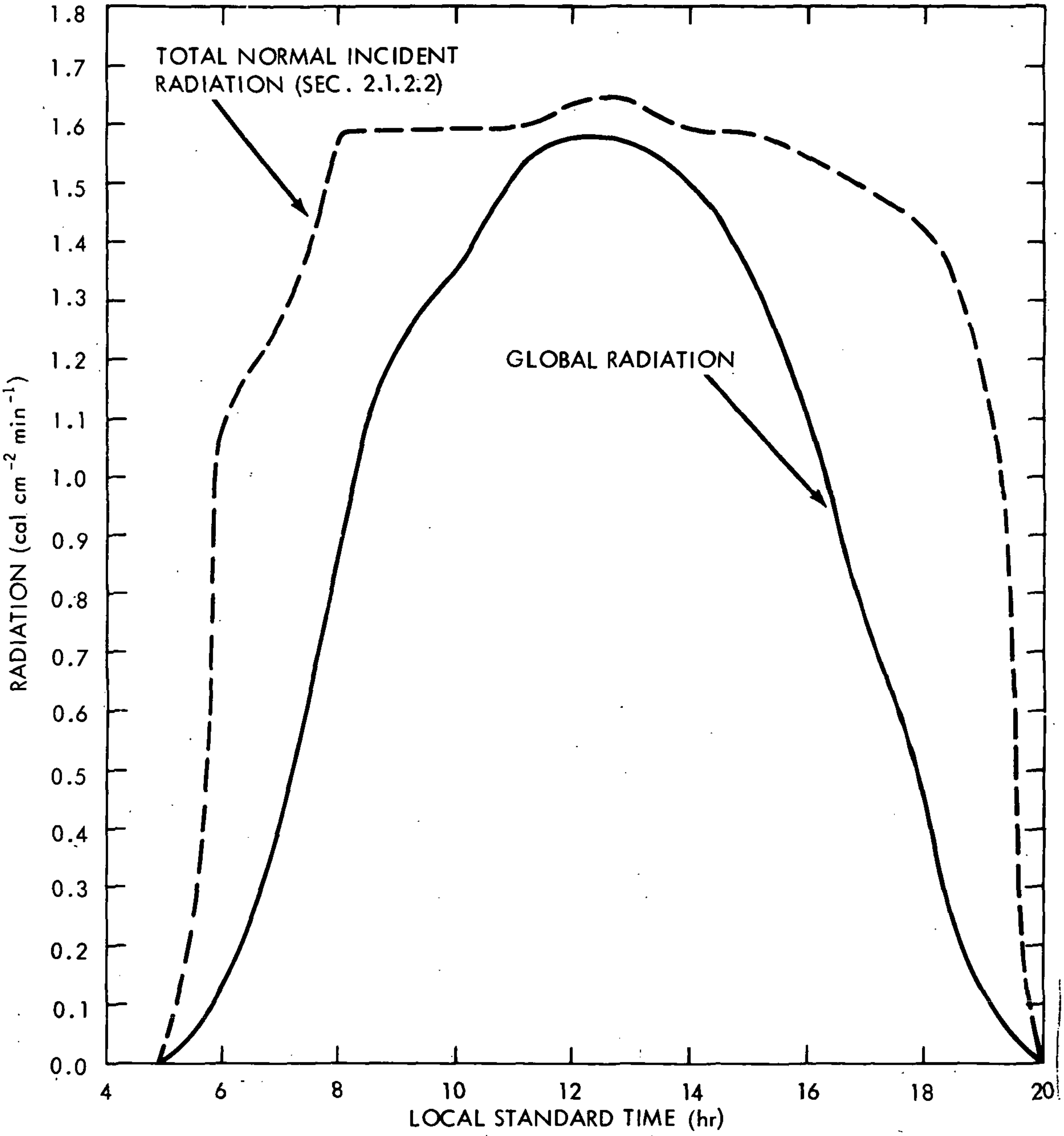


Figure 6. June extreme values of solar radiation for Kennedy Space Center, New Orleans, Gulf Transportation, and Huntsville (ref. 2).

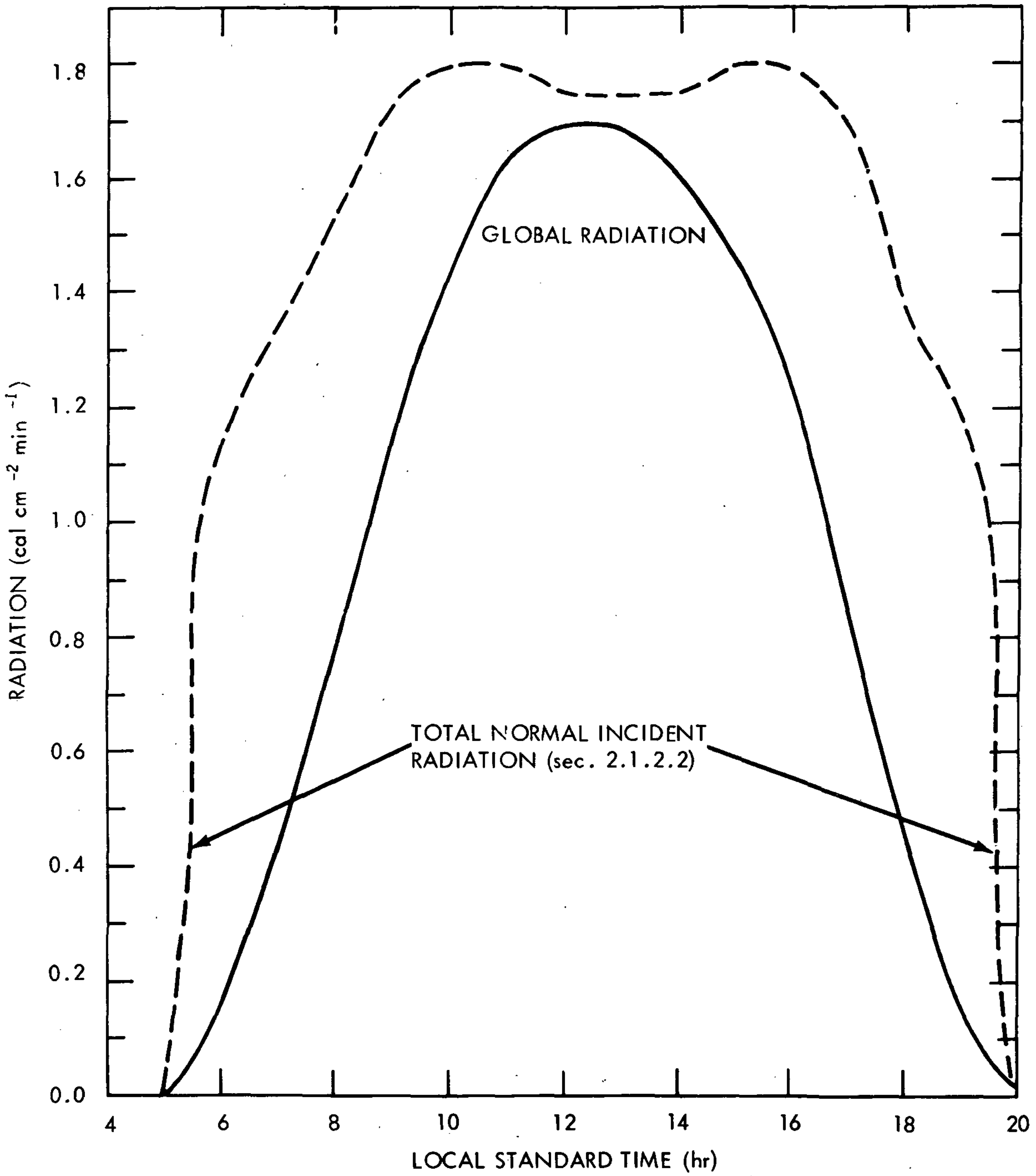


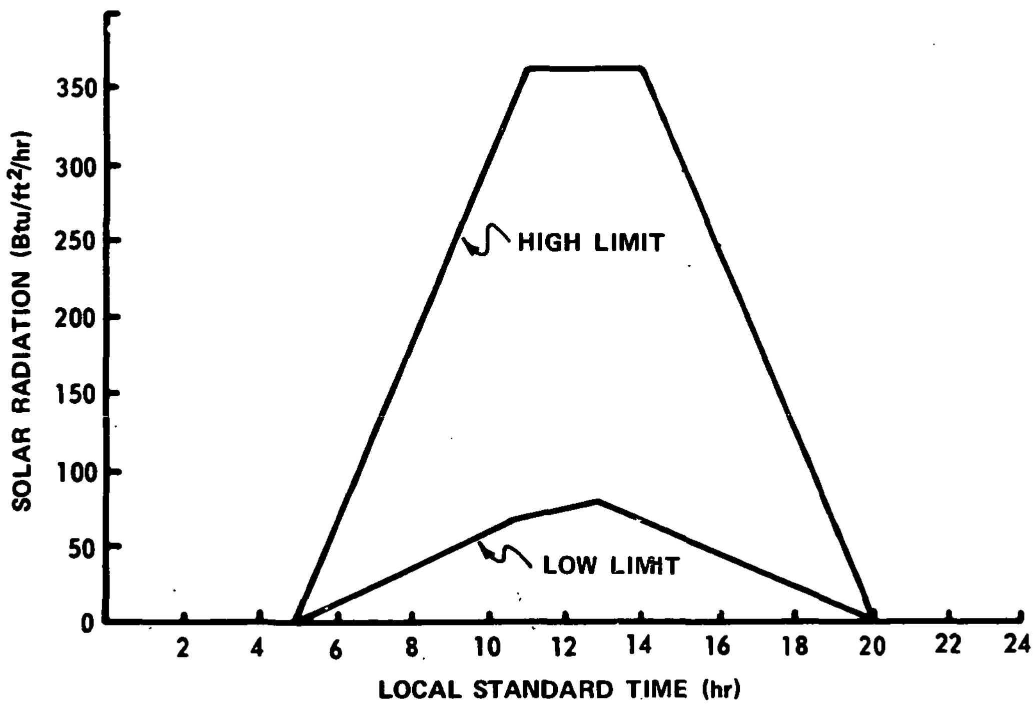
Figure 7. June extreme values of solar radiation for Space and Missile Test Center (at Vandenberg AFB), West Coast Transportation, Sacramento, and White Sands Missile Range (ref. 2).

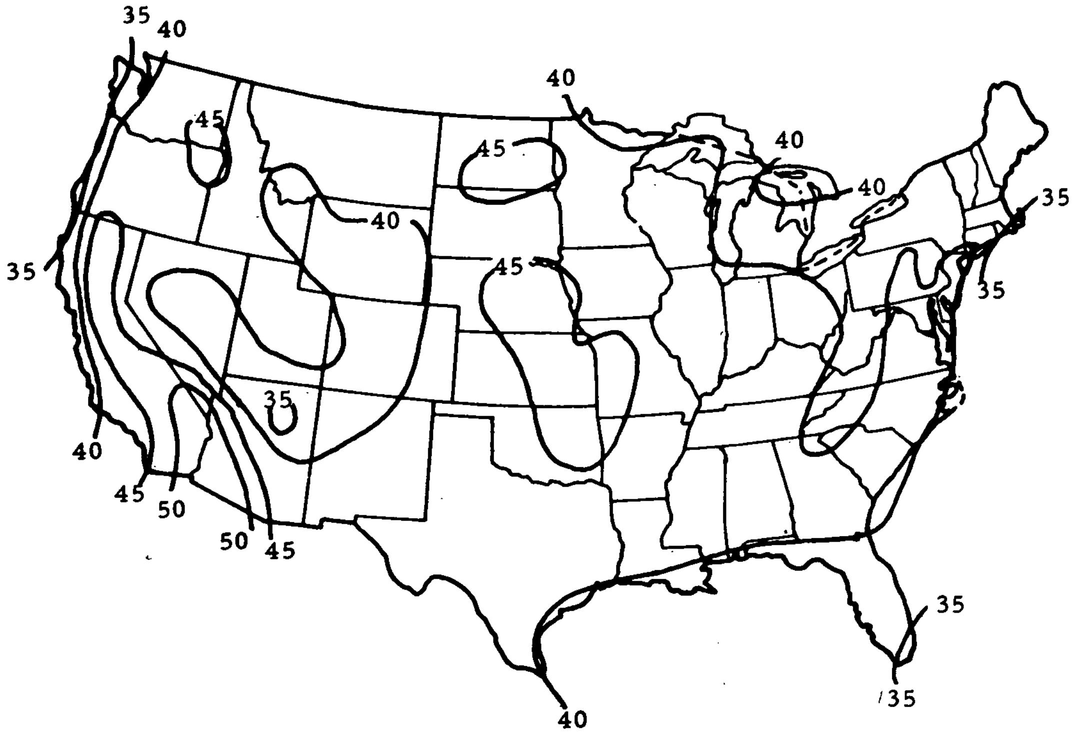
Table II

SOLAR RADIATION EXTREMES FOR ALL AREAS

Time of Day	High Limit		Low Limit	
hr	BTU/ft²/hr	g-cal/cm²/min	BTU/ft²/hr	g-cal/cm²/min
0500	0	0.00	0	0.00
1100	363	1.64	70	0.32
1300	—	—	80	0.36
1400	363	1.64	—	—
2000	0	0.00	0	0.00

Diagram of Table II Data





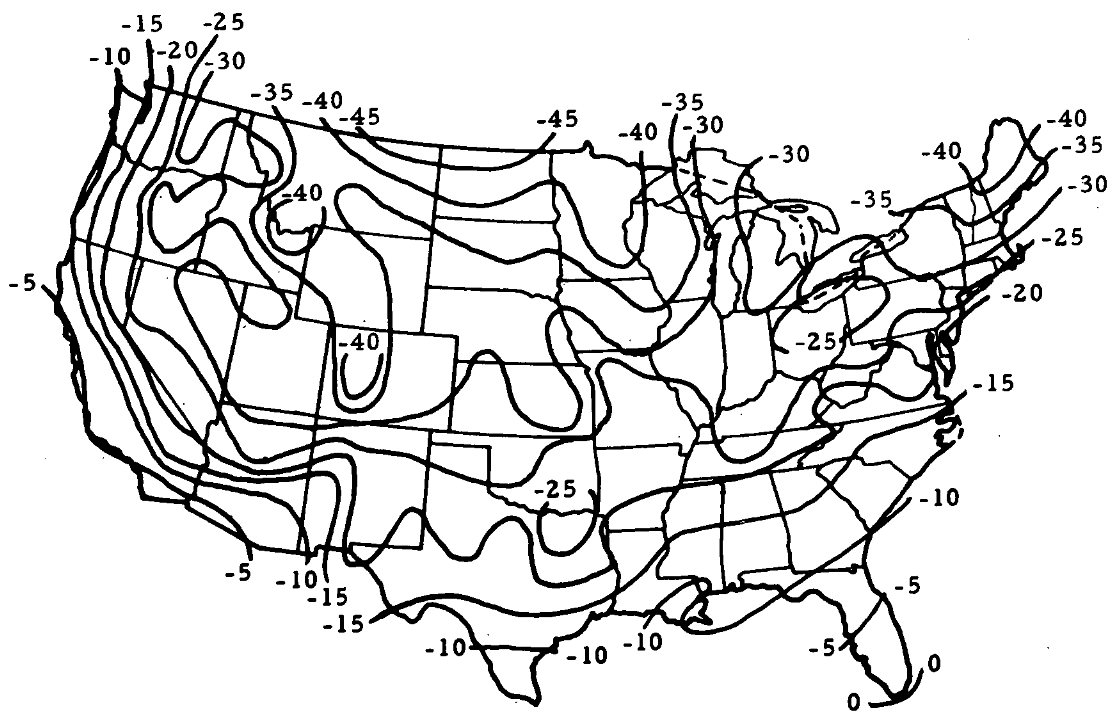


Figure 8. Extreme surface temperatures (°C) in the United States (ref. 2).

Table III

SURFACE AIR AND SKY RADIATION TEMPERATURE EXTREMES

Area		Air Temperature Extremes (occur with winds < 1 m sec^{-1})				Diffuse Sky Radiation	
		Maximum		Minimum		Equivalent Temperature Minimum Extreme	Equivalent Radiation (cal cm^{-2} min^{-1})
		Extreme	95%	Extreme	95%		
Huntsville*	°C	43.9	41.7	-23.3	-21.7	-30.0	0.28
	°F	111	107	-10	-7	-22	
River Transportation**	°C	43.9		-30.6		-37.2	0.25
	°F	111		-23		-35	
New Orleans***	°C	37.8	31.7	-12.8	7.8	-17.8	0.35
	°F	100	89	9	46	0	
Gulf Transportation**	°C	40.6		-12.8		-17.8	0.35
	°F	105		9		0	
Kennedy Space Center***	°C	37.2	30.0	-3.9	12.2	-15.0	0.36
	°F	99	86	25	54	5	
Kennedy Space Center****	°C	37.2	31.7	-3.9	6.7	-15.0	0.36
	°F	99	89	25	44	5	
Panama Canal Transportation**	°C	41.7		-12.8		15.0	0.36
	°F	107		9		5	
Space and Missile Test Center (Vandenberg AFB, Calif.)****	°C	37.2	28.3	-1.1	0.0	-15.0	0.36
	°F	99	83	30	32	5	
West Coast Transportation**	°C	46.1		-6.1		-17.8	0.35
	°F	115		21		0	
Sacramento***	°C	46.1	36.7	-6.1	1.1	-17.8	0.35
	°F	115	98	21	34	0	
White Sands Missile Range***	°C	41.1	37.2	-21.1	-5.6	-30.0	0.28
	°F	106	99	-6	22	-22	
Wallops Island***	°C	39.4	33.3	-11.7	-3.3	-17.8	0.35
	°F	103	92	11	26	0	
Edwards AFB****	°C	43.3	39.4	-15.0	-7.8	-30.0	0.28
	°F	110	103	5	18	-22	

*Percentiles based on the extreme maximum and minimum readings during each of past 60 years.
**Use extreme values for 95 percentile.
***Percentiles based on hourly readings.
****Percentiles based on daily extreme readings.

3.1.2.2 Duration of Extremes

Duration of high temperatures within 4°C of the maximum can be expected to be five hours. In temperate climates at latitudes below 65°, minimum temperatures will behave similarly (ref. 18). At higher latitudes, the duration of minimum temperatures may be several days or longer.

3.1.2.3 Detailed Data for Kennedy and Vandenberg

Table IV gives mean temperatures, standard deviations, and 2.5 and 97.5 percentile temperatures for each month at Kennedy Space Center and Space and Missile Test Center at Vandenberg AFB.

3.1.2.4 Design Temperatures Based on Percentiles

Figure 9 gives the mean temperature values and standard deviations for January; figure 10 gives the same information for July (ref. 59).

The 5th percentile value (level below which temperature will not go 5 percent of January days) is recommended for cold day design. The 95th percentile value (temperature which will not be exceeded 95 percent of July days) is recommended for hot day design ambient temperatures over finished surfaces.

Various percentile values can be obtained by using figures 9 and 10 in conjunction with the following procedures:

1. Find the mean temperature $\bar{T}$ and standard deviation S_T from figure 7 or 8 with interpolation as necessary.

2. Select the value for Y_S from the following tables to correspond with the desired percentile.

COLD TEMPERATURES

Percentile	Y_S
20	-0.84
10	-1.28
5	-1.65
2.5	-1.96
1	-2.33

HOT TEMPERATURES

Percentile	Y_S
80	+0.84
90	+1.28
95	+1.65
97.5	+1.96
99	+2.33

3. To obtain the temperature $\hat{T}$ in °F that applies to the selected percentile, substitute $\bar{\bar{T}}$, S_T, and Y_S in the following equation

$$\hat{T} = \bar{\bar{T}} + S_T \ (Y_S)$$

3.1.2.5 Extreme Air Temperature Change

The following table gives extreme changes in air temperature during one hour and the associated changes in solar radiation for Kennedy Space Center, Wallops Island, White Sands Missile Range, and Edwards Air Force Base.

Temperature Change, °C (°F)	Associated Radiation Changes on Normal Surface, cal cm^{-2} min^{-1} (Btu ft^{-2} hr^{-1})
Increase of 10°C (18°F)	From 0.50 (110) to 1.85 (410)
Decrease of 10°C (18°F)	From 1.85 (410) to 0.50 (110)

The 24-hour temperature change cycle that should be considered in design for Kennedy Space Center, Wallops Island, Space and Missile Test Center*, White Sands Missile Range, River Transportation, and Edwards Air Force Base are as follows:

- Increase of 27.7°C (50°F) in air temperature during a five-hour period.
- Constant air temperature during a four-hour period.
- Decrease of 27.7°C (50°F) in air temperature during a five-hour period.
- Constant air temperature for a ten-hour period.

*At Vandenberg Air Force Base, California.

Table IV

MONTHLY MEAN WITH STANDARD DEVIATIONS (STD) AND 2.5 AND 97.5 PERCENTILE VALUES OF TEMPERATURE

Month	Kennedy Space Center				Space and Missile Test Center*			
	Monthly Mean or 50 Percentile (°F)	Standard Deviation (30-day average)	Percentiles 30-Day Average		Monthly Mean or 50 Percentile (°F)	Standard Deviation (30-day average)	Percentiles 30-Day Average	
			2.5% (°F)	97.5% (°F)			2.5% (°F)	97.5% (°F)
Jan.	60.3	2.9	54.6	66.0	52.2	2.0	48.3	56.1
Feb.	61.7	4.0	53.9	69.4	52.6	1.9	48.9	56.3
Mar.	65.3	3.3	58.8	71.8	52.3	1.8	48.8	55.8
Apr.	70.0	2.6	64.9	75.1	54.2	1.7	50.9	57.5
May	74.8	2.2	70.5	79.1	53.9	1.5	51.0	56.8
June	79.2	1.6	76.1	82.3	56.8	1.5	53.9	59.7
July	80.7	0.5	79.7	81.7	58.4	1.4	55.7	61.1
Aug.	80.9	0.8	79.3	82.5	59.8	1.5	56.9	62.7
Sept.	80.0	1.2	77.7	82.4	60.2	1.8	56.7	63.7
Oct.	75.2	2.3	70.7	79.7	60.1	1.9	56.4	63.8
Nov.	68.0	3.5	61.1	74.9	55.8	2.0	51.9	59.7
Dec.	61.7	4.0	53.9	69.5	53.1	2.5	48.2	58.0

*At Vandenberg Air Force Base.

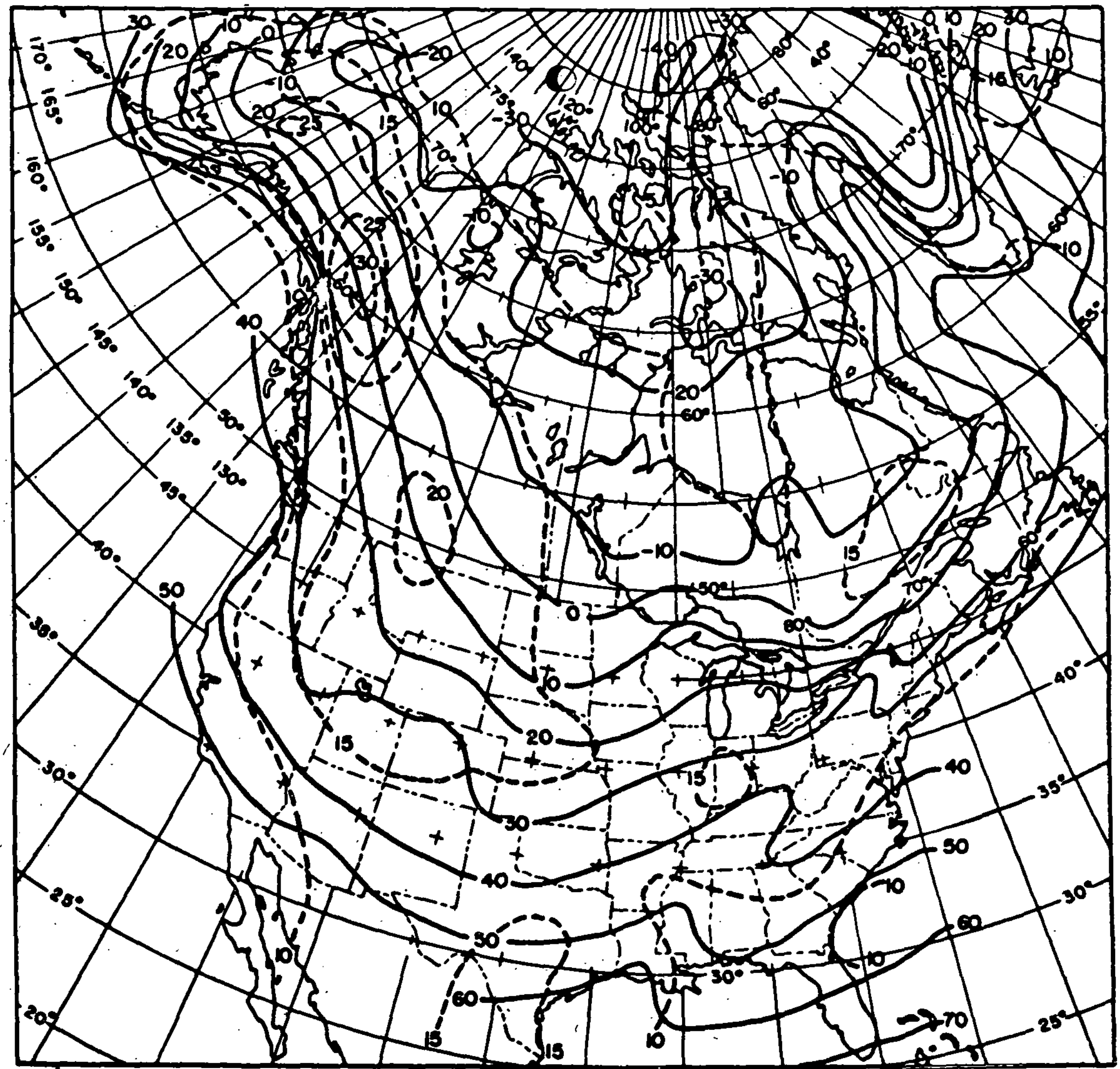


Figure 9. Isotherms of January hourly surface temperatures. Approximate mean values (°F) are shown by solid lines, standard deviation values by broken lines. The approximations were made to give best estimates of lower (1 to 20 percentile) values by normal distribution (taken from ref. 59).

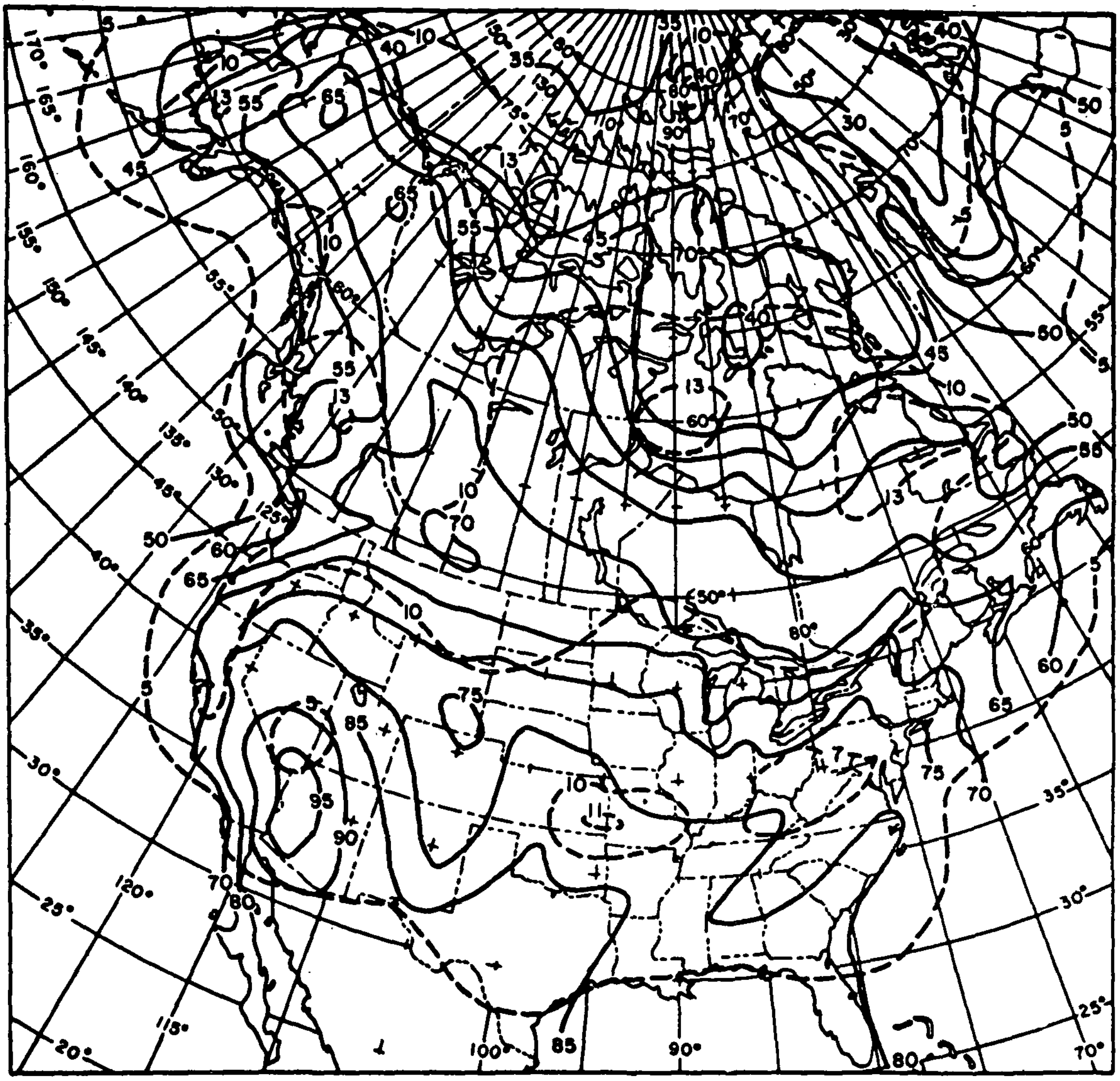


Figure 10. Isotherms of July hourly surface temperatures. Approximate mean values (°F) are shown by solid lines, standard deviation values by broken lines. The approximations were made to yield the best estimates of upper (80 to 99 percentile) values by normal distribution (taken from ref. 59).

3.1.2.6 Surface (Skin) Temperature of Object

The skin temperature of an object is usually different from the air temperature. Figure 11 gives curves of air temperature versus skin temperature for a clear day and clear night.

3.1.2.7 Compartment Temperatures

The following compartment temperatures should be used for design of equipment on the ground without air conditioning.

$\geq$87.8°C (190°F) for a period of one hour.

$\geq$65.6°C (150°F) for a period of 6 hours.

3.2 Humidity

3.2.1 High Vapor Concentration

Figures 12 through 14 depict 24-hour relative humidity cycles with extreme high vapor concentration that should be considered in design because such conditions favor fungal and bacterial growth as well as corrosion (ref. 2). The associated wind speed is assumed to be less than 5 $msec^{-1}$. In addition to humidity, the vapor concentration, air temperature, and saturation temperature cycles are shown.

Expected duration and ranges of humidity and associated temperature are given in table V for all locations except White Sands. High vapor concentration is less of a problem in the White Sands area where the mean annual rainfall is 10 inches, and the low levels of humidity generally prevail that are typical for southwest United States.

3.2.2 Low Vapor Concentration

Table VI provides information on the duration and range of temperature and humidity associated with low vapor concentrations. The tables show data for high humidity-low temperature conditions and also for low humidity-high temperature conditions. For example, at Wallops Island during low humidity conditions, a vapor concentration of 4.5 g m^{-3} (2.0 grain ft^{-3}) at a temperature of 28.9°C (84°F) and relative humidity of 15 percent must be considered for 6 hours of each 24-hour period. For the remaining 18 hours, a maximum relative humidity of 34 percent at an air temperature of 15.6°C (60°F) must be considered. These conditions could exist for as long as ten days.

3.2.3 Compartment Vapor Concentration

Figure 15 shows a typical cycle of humidity and vapor concentration extremes for compartments.

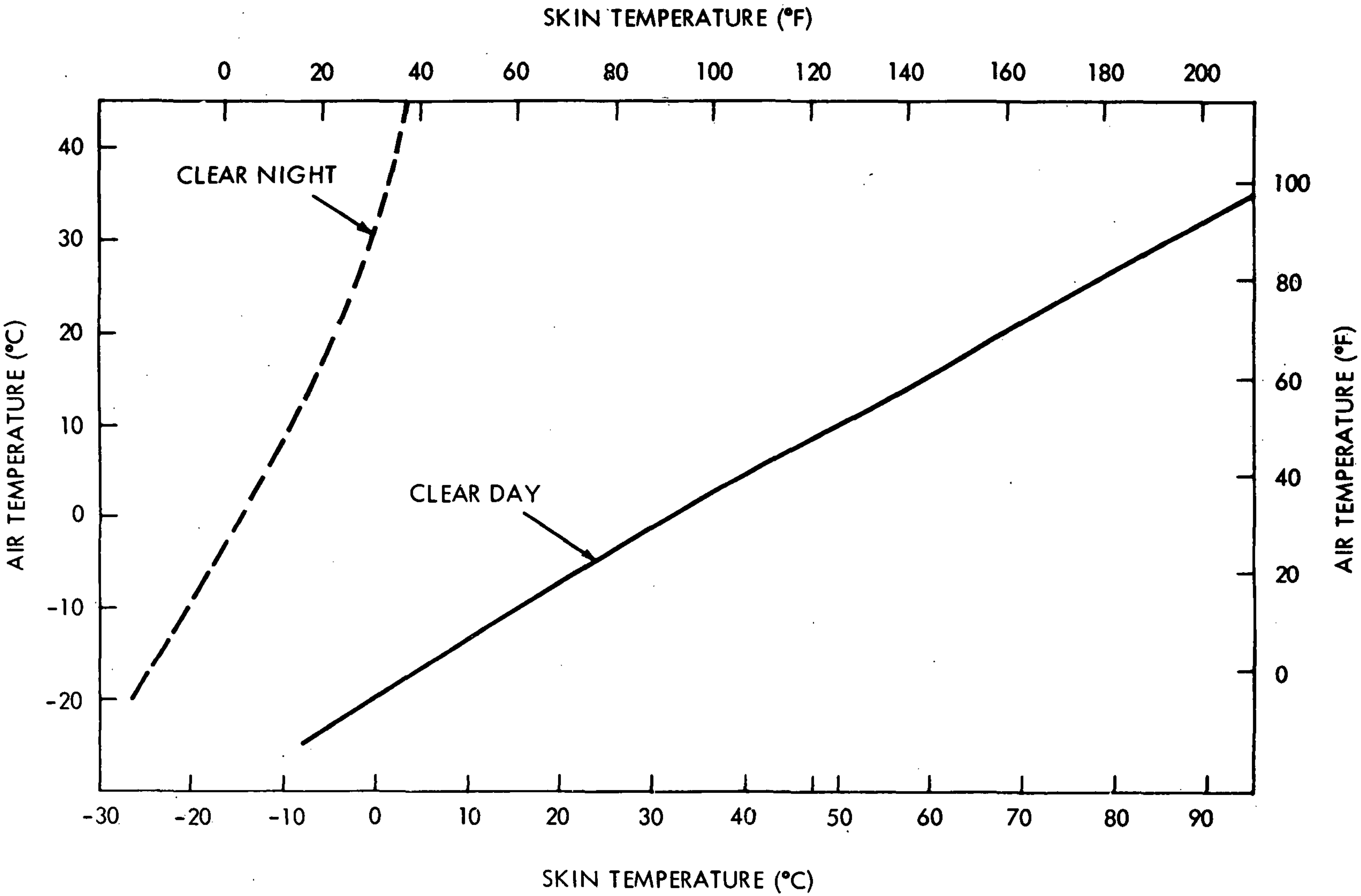


Figure 11. Air temperature vs skin temperature with calm wind and emissivity equal to 1.0 (ref. 2).

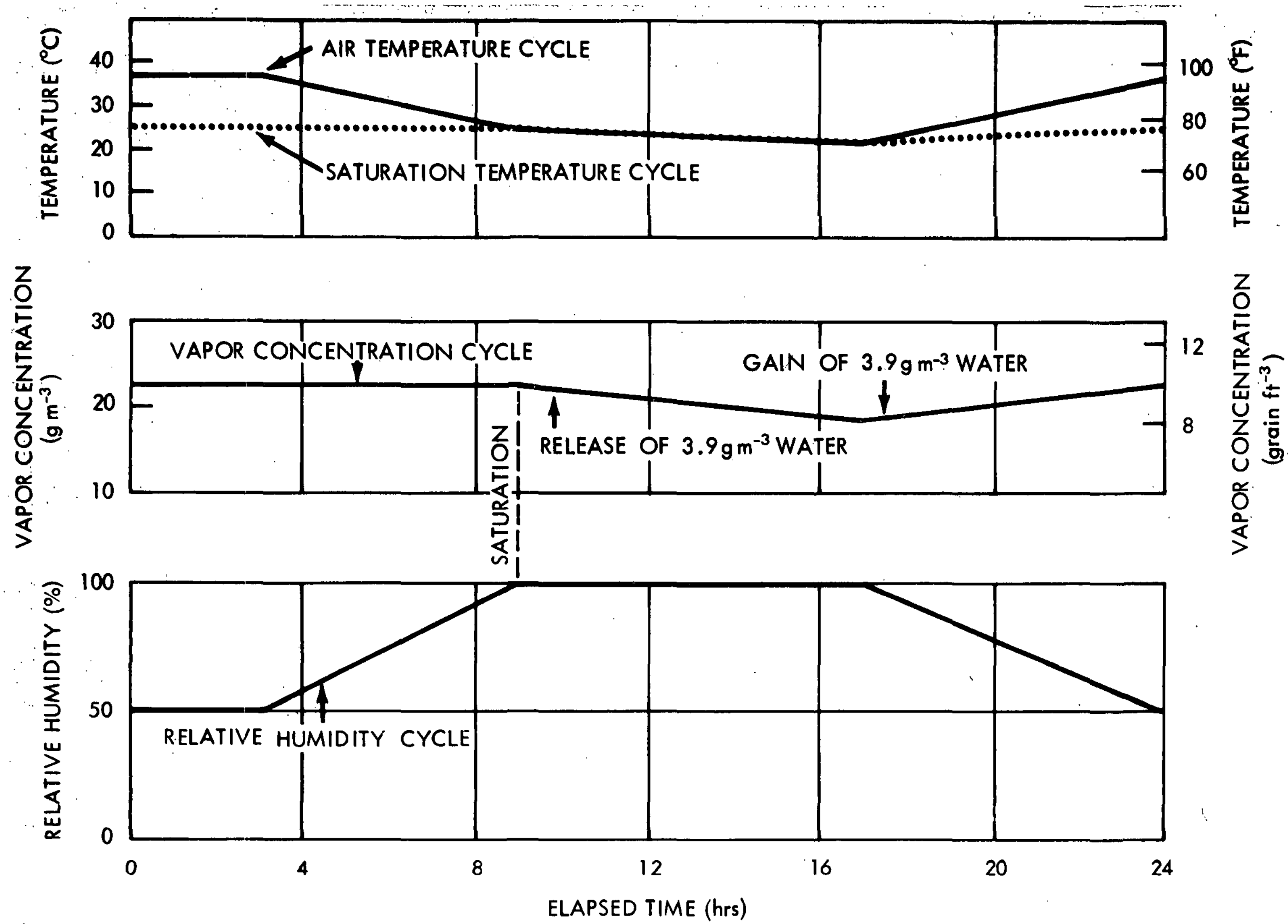


Figure 12. Extreme high vapor concentration cycle with assumed wind <5m sec^{-1} for Huntsville, River Transportation, New Orleans, Gulf Transportation, Kennedy Space Center, and Wallops Island (ref. 2).

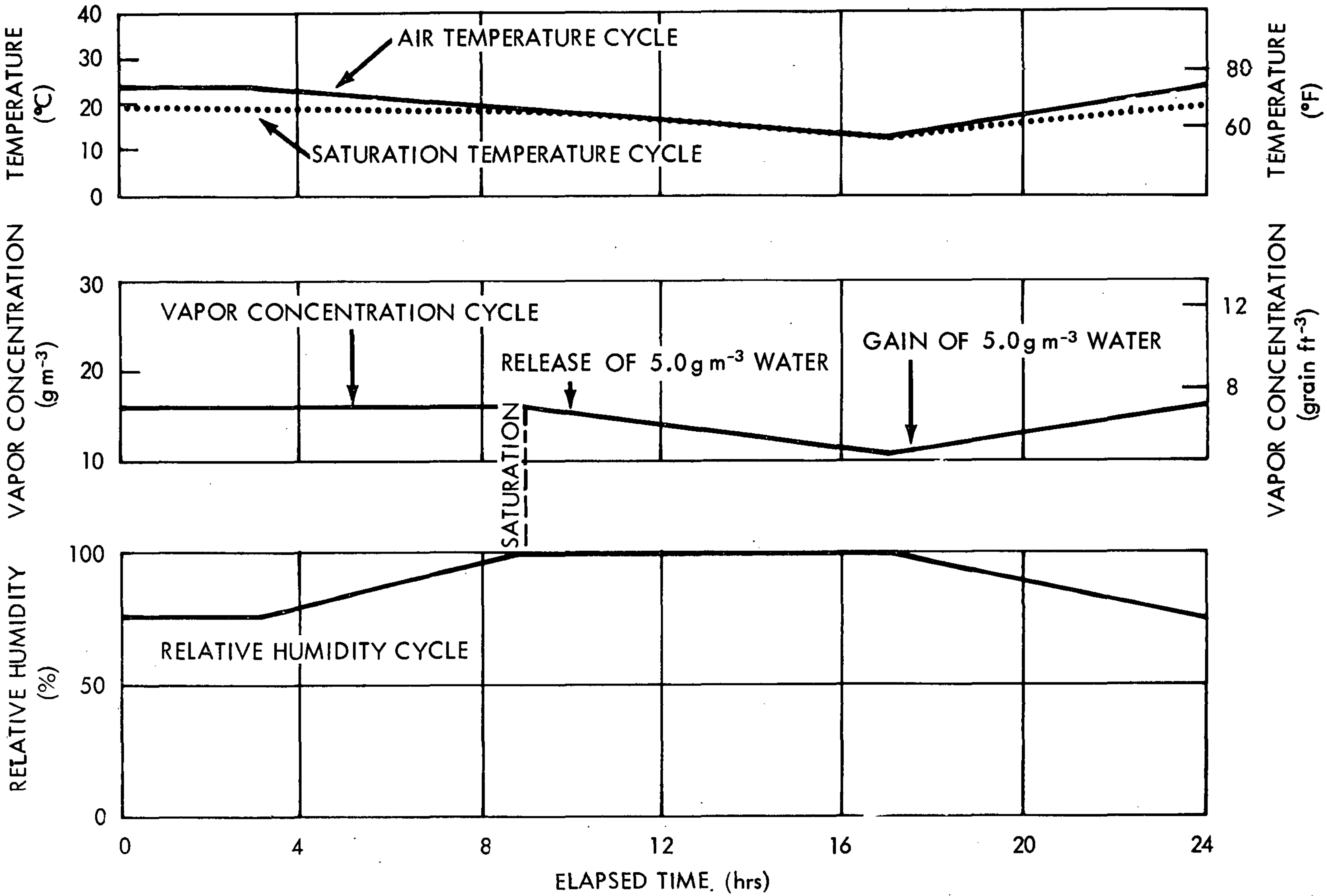


Figure 13. Extreme high vapor concentration cycle with assumed wind of 5m sec^{-1} for Space and Missile Test Center (at Vandenberg AFB) and West Coast Transportation (ref. 2).

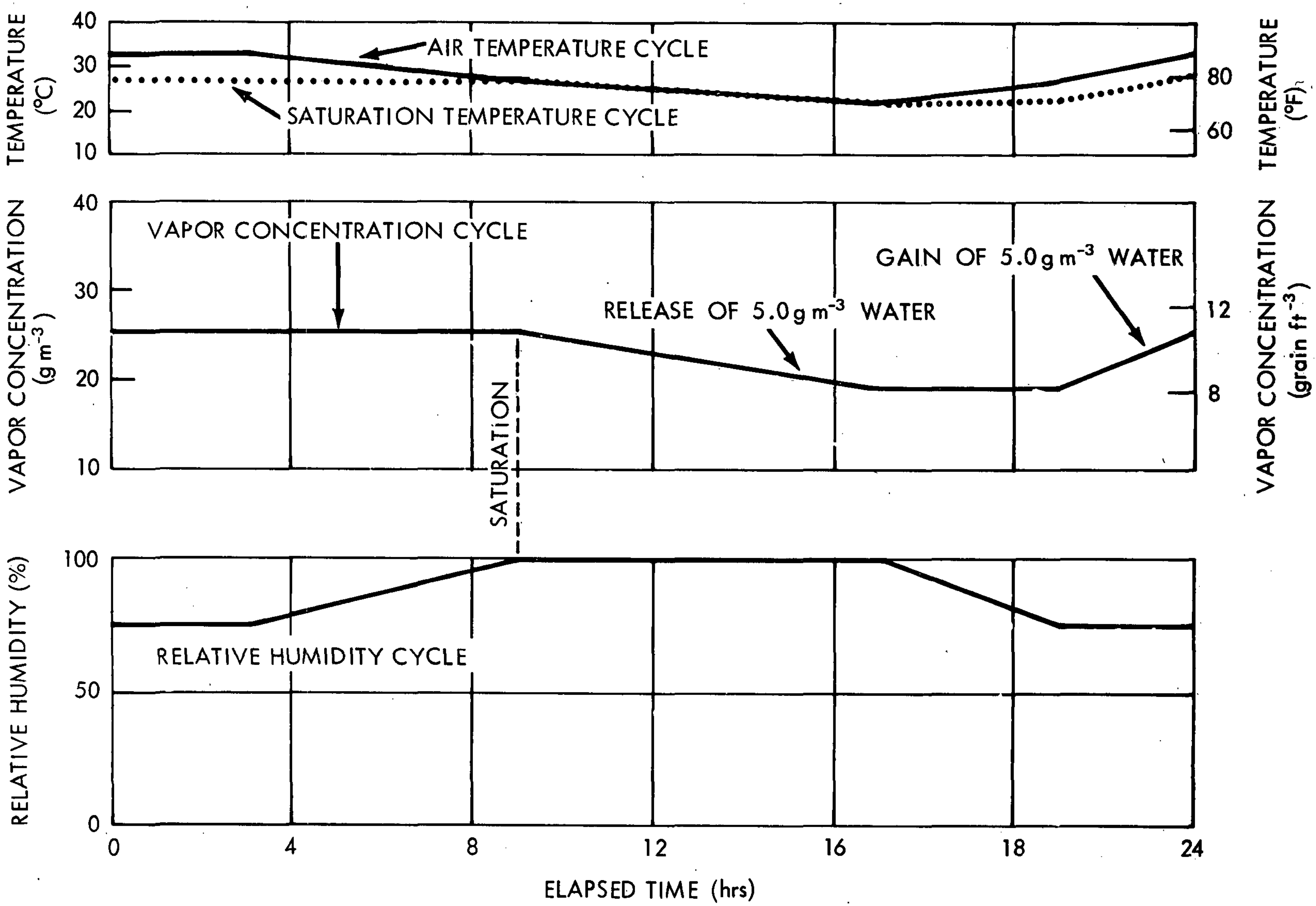


Figure 14. Extreme high vapor concentration cycle with assumed wind of 5m sec^{-1} for Panama Canal transportation (ref. 2).

Table V

EXPECTED CONDITIONS FAVORING CORROSION, BACTERIAL, OR FUNGAL GROWTH* (ref. 2)

Location	Daily Relative Humidity Range (%)	Daily Air Temperature Range, °C (°F)	Consecutive Days
Huntsville, River & Gulf Transportations, Kennedy Space Center, Wallops Island, New Orleans	75-100	22.8-27.8 (73-82)	15
Panama Canal Transportation	85-100	23.9-26.1 (75-79)	30
Space and Missile Test Center, West Coast Transportation, Sacramento**	75-100	18.3-23.3 (65-74)	15

*100% relative humidity expected during 1/4 of each day (6 hrs) at the lower temperature. Any loss of water vapor from the air by condensation is replaced from outside sources to maintain at least the lower relative humidity at the higher temperature.
**Corrosion only; because of low temperatures, bacteria and fungi are not significant.

3.3 Precipitation

Table VII gives altitudes and characteristics of different forms of precipitation (hydrometeors). Raindrops that fall on the surface may originate at higher altitudes as ice or snow.

3.3.1 Rain

3.3.1.1 Rates and Drop Sizes

Tables VIII through XI give ranges of rainfall rates and drop sizes for specified areas.

3.3.1.2 Probabilities for Amounts

Tables XII through XVI give the probabilities of rain not exceeding a specific amount in a single day of a specified month for various areas.

3.3.1.3 Rate Probabilities

Table XVII gives rainfall rates for 50, 95, and 99 percentile values on a day of rain in August at Kennedy Space Center.

3.3.1.4 Ice Formation

The type of ice that forms on the exposed surfaces of cryogenic tanks in general depends on the temperature of the tank surface, precipitation rate, drop size and wind velocity. Table XVIII gives ice types for various tank wall temperatures with moderate precipitation (over 10mm/hr).

In general higher tank surface temperatures, higher rates of precipitation, and higher wind speeds quicken the buildup of ice. If the ambient temperature and wind speed are too high, the tank may be warmed sufficiently to melt ice that had been previously formed.

Table VI

HUMIDITY DATA FOR LOW VAPOR CONCENTRATIONS (ref. 2)

Location*	High Rel. Humidity (Ice or Water Formation)					Low Rel. Humidity (Drying and Splitting)					
	Time Interval (hr)	Air Temperature °C	(°F)	Relative Humidity (%)	Vapor Conc. g m^{-3} (grain ft^{-3})	Time Interval (hr)	Air Temperature °C	(°F)	Relative Humidity (%)	Vapor Conc. g m^{-3} (grain ft^{-3})	Consecutive Days
A	24	-11.7	(11)	98-100	2.1	6	28.9	(84)	15	4.5	10
					(0.9)	18	15.6	(60)	Max of 34	(2.0)	
B	24	-2.2	(28)	98-100	4.2	8	22.2	(72)	29	5.6	10
					(1.8)	16	15.6	(60)	Max of 42	(2.4)	
C	24	-2.2	(28)	98-100	4.2	4	37.8	(100)	11	4.8	10
					(1.8)	20	21.1	(70)	Max of 26	(2.1)	
D	24	-6.1	(21)	98-100	3.1	4	37.8	(100)	22	10.1	10
					(1.4)	20	21.1	(70)	Max of 55	(4.4)	

*Key to locations:
A Huntsville, River Transportation, Wallops Island, White Sands Missile Range
B New Orleans, Gulf Transportation, Panama Canal Transportation, Kennedy Space Center
C Space and Missile Test Center (Vandenberg AFB, Calif.)
D West Coast Transportation and Sacramento

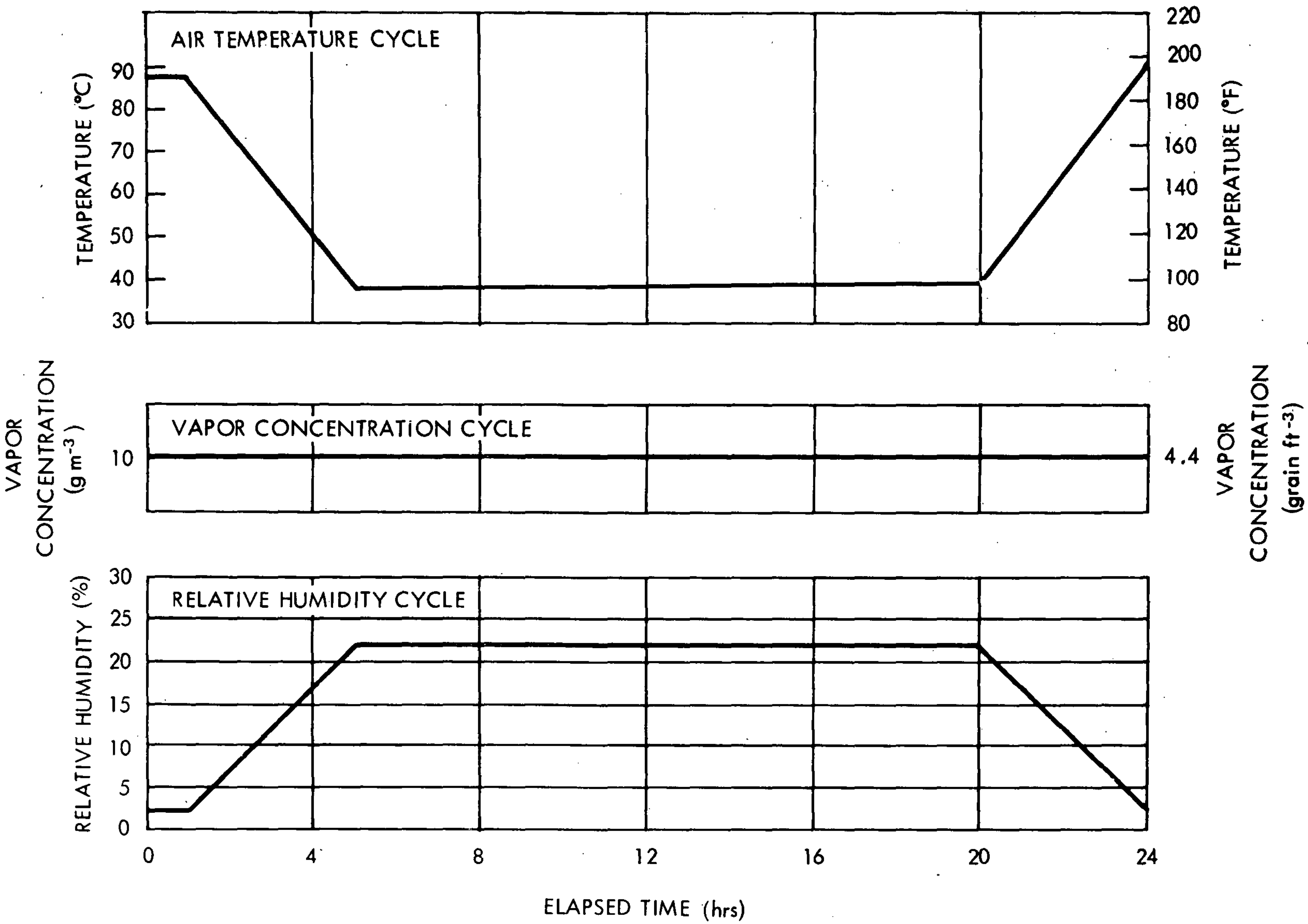


Figure 15. Moisture cycle for compartments (ref. 2).

Table VII

ALTITUDES AND CHARACTERISTICS OF PRECIPITANTS (HYDROMETEORS) (ref. 60)

Location or Type of Hydrometeor	Altitude (km)	Drop Diameter (μm)		Concentration per Unit Volume		Liquid Water Content Per Unit Volume (g/m^3)		Ambient Temperature (°C)
		Range	Rep.*	Range	Rep.*	Range	Rep.*	Range ≈
Layer Clouds	0-1.5	<1-40	11	<10-10 000 cm^3	500 cm^3	<0.1-1	0.2	+30 to -15
Layer Clouds	2.5-7.5	<1-50	12	<20-1000 cm^3	100 cm^3	<0.1-1	0.2	+20 to -25
Layer Clouds (ice crystals)	7.5-15.0	<10-10 000	100	<0.1-10 cm^3	0.2 cm^3	<0.01-0.1	0.02	-10 to -55
Convective Clouds -								
Fair Weather Cumulus	0.5-8.0	<1-75	12	<10-10 000 cm^3	300 cm^3	<0.1-1	0.5	+20 to -30
Cumulus Congestus	0.5-13.0	<1-200	25	<10-10 000 cm^3	150 cm^3	<1-10	4.0	+20 to -55
Continuous Rain	0-6.0	<500-3000	1000	<50-3000 m^3	500 m^3	<0.05-0.7	0.1	+30 to -15
Shower Rain	0-13.0	<500-7000	2000	<10-3000 m^3	500 m^3	<0.1-30	1.0	+30 to -55
Coalescence (Warm) Rain	0-5.0	<100-1000	500	<500-50 000 m^3	3000 m^3	<0.05-0.1	0.1	+30 to 0
Hail	0-13.0	<0.01-13 cm	0.8	<0.5-1000 m^3	50 m^3	<0.1-0.9**	0.8**	+15 to -55
Ice and Snow Crystals	0-13.0	<100-20 000	5000	<1-1000 m^3	100 m^3	<0.001-0.7***	0.07***	+5 to -55

*Representative value or value most frequently encountered
**Density of particles (g/cm^3)
***Mass of crystals (mg)

Table VIII

RAINFALL RATES AND DROP SIZES AT KENNEDY SPACE CENTER, HUNTSVILLE, AND WALLOPS ISLAND

Duration	Rainfall Rate		Total Accumulation		Raindrop Size Average	Raindrop Size Largest	Average Rate of Fall
	mm/hr	in./hr	mm	in.	mm	mm	m/s
1 min	492	19.4	8	0.3	2.0	6.0	6.5
5 min	220	8.7	18	0.7	2.0	5.8	6.5
15 min	127	5.0	32	1.25	2.0	5.7	6.5
1 hr	64	2.5	64	2.5	2.0	5.0	6.5
6 hr	26	1.0	156	6.1	1.8	5.0	6.5
12 hr	18	0.7	220	8.7	1.6	4.5	6.5
24 hr	13	0.5	311	12.2	1.5	4.5	6.5

Table IX

RAINFALL RATES AND DROP SIZES AT NEW ORLEANS

Duration	Rainfall Rate		Total Accumulation		Raindrop Size Average	Raindrop Size Largest	Average Rate of Fall
	mm/hr	in./hr	mm	in.	mm	mm	m/s
1 min	787	31.0	13	0.5	2.1	6.0	6.5
5 min	352	13.9	29	1.2	2.0	6.0	6.5
15 min	203	8.0	51	2.0	2.0	5.7	6.5
1 hr	102	4.0	102	4.0	2.0	5.5	6.5
6 hr	41	1.6	249	9.8	1.9	5.0	6.5
12 hr	29	1.2	352	13.9	1.8	5.0	6.5
24 hr	21	0.8	498	19.6	1.6	5.0	6.5

Table X

RAINFALL RATES AND DROP SIZES AT MISSILE AND SPACE TEST CENTER, EDWARDS AFB, AND WHITE SANDS MISSILE RANGE

Duration	Rainfall Rate		Total Accumulation		Raindrop Size Average	Raindrop Size Largest	Average Rate of Fall
	mm/hr	in./hr	mm	in.	mm	mm	m/s
1 min	197	7.7	3	0.1	2.0	5.6	6.5
5 min	88	3.5	7	0.3	2.0	5.3	6.5
15 min	51	2.0	13	0.5	2.0	5.0	6.5
1 hr	25	1.0	25	1.0	1.8	5.0	6.5
6 hr	10	0.4	62	2.4	1.5	4.6	6.0
12 hr	7	0.3	88	3.5	1.3	4.3	5.8
24 hr	5	0.2	124	4.9	1.3	4.0	5.5

*At Vandenberg Air Force Base

Table XI

RAINFALL RATES AND DROP SIZES (WORLDWIDE EXTREMES)

Duration	Rainfall Rate		Total Accumulation		Raindrop Size Average	Raindrop Size Largest	Average Rate of Fall
	mm/hr	in./hr	mm	in.	mm	mm	m/s
1 min	2813	110.8	47	1.8	2.5	6.0	6.5
5 min	1258	49.5	105	4.1	2.2	6.0	6.5
15 min	726	28.6	182	7.1	2.1	6.0	6.5
1 hr	363	14.3	363	14.3	2.0	6.0	6.5
6 hr	148	5.8	890	35.3	2.0	5.8	6.5
12 hr	105	4.1	1258	49.5	2.0	5.5	6.5
24 hr	74	2.9	1779	70.1	2.0	5.2	6.5

Table XII

PROBABILITY THAT PRECIPITATION WILL NOT EXCEED A SPECIFIC AMOUNT IN ANY ONE DAY AT KENNEDY SPACE CENTER*

Amount		Jan.	Feb.	Mar.	Apr.	May	June
(in.)	(mm)	(%)	(%)	(%)	(%)	(%)	(%)
0.00	0.00	68.1	60.8	62.2	70.6	64.2	54.7
Trace	Trace	77.1	71.4	71.3	80.0	76.2	65.7
0.01	0.25	79.0	74.3	72.5	82.7	79.4	68.4
0.05	1.27	84.8	79.4	77.5	86.6	84.7	74.1
0.10	2.54	87.1	82.3	81.6	89.3	89.4	75.8
0.25	6.35	90.0	85.8	87.8	93.5	92.9	82.8
0.50	12.70	93.9	91.6	91.6	95.9	96.4	90.8
1.00	25.40	97.1	96.1	96.3	98.0	99.3	97.1
2.50	63.50	99.4	100.0	99.5	99.5	100.0	99.8
5.00	127.00	100.0	100.0	99.8	99.8	100.0	100.0

Amount		July	Aug.	Sept.	Oct.	Nov.	Dec.
(in.)	(mm)	(%)	(%)	(%)	(%)	(%)	(%)
0.00	0.00	56.8	52.6	40.0	47.4	62.1	64.2
Trace	Trace	65.8	63.9	53.9	61.6	74.2	78.1
0.01	0.25	68.4	66.2	57.5	63.9	77.2	81.0
0.05	1.27	73.2	69.4	62.7	72.0	83.9	86.8
0.10	2.54	75.8	74.9	67.9	76.8	86.9	89.4
0.25	6.35	83.5	80.7	75.8	85.5	90.8	93.3
0.50	12.70	88.3	88.4	83.7	91.3	92.6	96.5
1.00	25.40	93.8	93.6	92.2	95.5	96.2	99.1
2.50	63.50	99.6	99.7	97.4	99.4	99.2	100.0
5.00	127.00	99.6	100.0	99.8	99.7	99.5	100.0

*The 100% values in the table indicate no chance of exceeding certain amounts of precipitation during most of the months; however, it should be realized that the length of available data records is not long and that there is always a chance of any meteorological extreme of record being exceeded.

Table XIII

PROBABILITY THAT PRECIPITATION WILL NOT EXCEED A SPECIFIC AMOUNT IN ANY ONE DAY AT EDWARDS AFB*

Amount		Jan.	Feb.	Mar.	Apr.	May	June
(in.)	(mm)	(%)	(%)	(%)	(%)	(%)	(%)
0.00	0.00	81.7	81.8	82.6	86.7	95.1	98.8
Trace	Trace	88.0	88.9	89.6	93.8	98.6	99.5
0.01	0.25	88.9	89.5	91.3	94.8	99.0	99.5
0.05	1.27	91.7	92.1	93.8	96.4	99.1	99.5
0.10	2.54	93.5	93.5	95.5	97.6	99.4	99.5
0.25	6.35	96.9	95.6	98.0	99.0	100.0	99.9
0.50	12.70	98.8	98.3	99.1	99.6	100.0	100.0
1.00	25.40	99.8	99.6	99.8	100.0	100.0	100.0
2.50	63.50	100.0	100.0	99.9	100.0	100.0	100.0
5.00	127.00	100.0	100.0	100.0	100.0	100.0	100.0

Amount		July	Aug.	Sept.	Oct.	Nov.	Dec.
(in.)	(mm)	(%)	(%)	(%)	(%)	(%)	(%)
0.00	0.00	94.7	95.2	94.6	93.0	89.8	85.2
Trace	Trace	99.0	98.1	97.8	95.8	94.2	90.8
0.01	0.25	99.3	98.1	98.2	96.1	94.4	91.4
0.05	1.27	99.7	98.9	98.9	97.2	96.4	93.7
0.10	2.54	99.7	99.3	98.9	98.2	97.0	94.9
0.25	6.35	100.0	99.6	99.2	99.2	98.4	96.7
0.50	12.70	100.0	99.9	99.8	99.6	99.3	99.0
1.00	25.40	100.0	100.0	99.9	99.7	100.0	99.9
2.50	63.50	100.0	100.0	100.0	100.0	100.0	100.0
5.00	127.00	100.0	100.0	100.0	100.0	100.0	100.0

*The 100% values in the table indicate no chance of exceeding certain amounts of precipitation during most of the months; however, it should be realized that the length of available data records is not long and that there is always a chance of any meteorological extreme of record being exceeded.

Table XIV*

PROBABILITY THAT PRECIPITATION WILL NOT EXCEED A SPECIFIC AMOUNT IN ANY ONE DAY AT SPACE AND MISSILE TEST CENTER**

Amount		Jan.	Feb.	Mar.	Apr.	May	June
(in.)	(mm)	(%)	(%)	(%)	(%)	(%)	(%)
0.00	0.00	69.4	70.4	61.7	70.4	71.8	70.0
Trace	Trace	79.1	75.9	72.2	80.4	94.0	94.8
0.01	0.25	81.1	76.9	74.6	82.5	96.8	97.7
0.05	1.27	83.5	81.4	83.9	87.9	98.0	100.0
0.10	2.54	88.3	84.4	85.9	90.8	98.8	100.0
0.25	6.35	91.5	90.4	91.5	95.4	99.6	100.0
0.50	12.70	95.1	94.4	96.3	97.5	100.0	100.0
1.00	25.40	98.3	96.9	98.7	99.2	100.0	100.0
2.50	63.50	99.9	99.9	99.5	100.0	100.0	100.0
5.00	127.00	100.0	100.0	99.9	100.0	100.0	100.0

Amount		July	Aug.	Sept.	Oct.	Nov.	Dec.
(in.)	(mm)	(%)	(%)	(%)	(%)	(%)	(%)
0.00	0.00	62.4	63.4	77.9	79.4	73.3	73.8
Trace	Trace	98.2	94.9	95.4	95.1	82.6	80.6
0.01	0.25	98.9	98.1	95.8	95.5	83.3	83.1
0.05	1.27	100.0	98.8	97.5	95.9	85.9	87.4
0.10	2.54	100.0	99.5	97.9	96.7	87.4	89.2
0.25	6.35	100.0	99.9	98.7	97.5	90.0	93.5
0.50	12.70	100.0	100.0	99.9	98.7	94.4	97.1
1.00	25.40	100.0	100.0	100.0	99.5	98.8	99.6
2.50	63.50	100.0	100.0	100.0	99.9	99.9	100.0
5.00	127.00	100.0	100.0	100.0	100.0	100.0	100.0

*The 100% values in the table indicate no chance of exceeding certain amounts of precipitation during most of the months; however, it should be realized that the length of available data records is not long and that there is always a chance of any meteorological extreme of record being exceeded.

**At Vandenberg Air Force Base

Table XV

PROBABILITY THAT PRECIPITATION WILL NOT EXCEED A SPECIFIC AMOUNT IN ANY ONE DAY AT NEW ORLEANS*

Amount		Jan.	Feb.	Mar.	Apr.	May	June
(in.)	(mm)	(%)	(%)	(%)	(%)	(%)	(%)
0.00	0.00	77.1	70.2	73.6	79.7	75.9	72.2
0.01	0.25	77.7	71.1	74.1	79.9	76.4	72.6
0.05	1.27	80.9	74.5	78.1	81.9	78.0	77.7
0.10	2.54	85.7	76.4	81.0	83.6	82.9	82.3
0.20	5.08	89.1	80.4	82.8	87.0	86.5	85.3
0.50	12.70	94.0	88.8	88.6	91.2	92.2	90.3
1.00	25.40	97.4	93.8	92.9	95.3	95.6	93.8
2.00	50.8	98.9	97.8	97.9	97.8	99.0	98.8
5.00	127.00	99.7	99.7	99.7	100.0	100.0	100.0
10.00	254.00	100.0	100.0	100.0	100.0	100.0	100.0

Amount		July	Aug.	Sept.	Oct.	Nov.	Dec.
(in.)	(mm)	(%)	(%)	(%)	(%)	(%)	(%)
0.00	0.00	54.5	70.1	69.2	84.4	83.4	77.6
0.01	0.25	55.8	71.3	71.1	85.6	84.7	78.2
0.05	1.27	61.4	74.4	76.3	88.2	85.7	80.7
0.10	2.54	67.4	79.3	79.2	90.5	87.4	83.2
0.20	5.08	73.3	83.5	84.4	93.4	89.4	85.2
0.50	12.70	81.5	92.4	90.3	96.0	94.0	91.9
1.00	25.40	91.5	95.7	94.5	98.0	97.3	95.2
2.00	50.80	96.7	98.2	98.0	99.7	98.3	99.4
5.00	127.00	100.0	100.0	99.0	100.0	99.7	99.7
10.00	254.00	100.0	100.0	100.0	100.0	100.0	100.0

*The 100% values in the table indicate no chance of exceeding certain amounts of precipitation during most of the months; however, it should be realized that the length of available data records is not long and that there is always a chance of any meteorological extreme of record being exceeded.

Table XVI*

PROBABILITY THAT PRECIPITATION WILL NOT EXCEED A SPECIFIC AMOUNT IN ANY ONE DAY AT WALLOPS ISLAND**

Amount		Jan.	Feb.	Mar.	Apr.	May	June
(in.)	(mm)	(%)	(%)	(%)	(%)	(%)	(%)
0.00	0.00	54.2	51.4	50.0	51.7	54.2	54.0
Trace	Trace	68.8	66.8	65.5	70.1	69.3	70.0
0.01	0.25	71.2	69.0	68.7	72.4	71.4	71.2
0.05	1.27	75.9	74.3	74.2	78.8	76.1	76.0
0.10	2.54	80.5	78.0	78.9	82.4	79.4	79.5
0.25	6.35	87.7	84.3	86.3	89.2	86.6	87.2
0.50	12.70	93.3	90.2	92.5	94.5	92.8	92.9
1.00	25.40	98.0	97.7	97.7	97.7	97.5	97.4
2.50	63.50	99.0	100.0	99.8	100.0	99.5	99.5
5.00	127.00	100.0	100.0	100.0	100.0	100.0	99.8
10.00	254.00	100.0	100.0	100.0	100.0	100.0	99.9

Amount		July	Aug.	Sept.	Oct.	Nov.	Dec.
(in.)	(mm)	(%)	(%)	(%)	(%)	(%)	(%)
0.00	0.00	52.6	55.2	62.8	64.0	58.1	59.4
Trace	Trace	68.0	69.0	75.4	76.5	71.0	72.6
0.01	0.25	70.1	72.5	77.8	78.0	73.2	74.5
0.05	1.27	74.2	77.7	81.5	81.8	78.7	79.1
0.10	2.54	78.2	79.8	84.7	85.6	82.8	83.2
0.25	6.35	84.0	85.3	88.0	90.2	88.3	88.2
0.50	12.70	90.6	90.5	91.6	93.4	93.2	93.1
1.00	25.40	94.9	94.8	96.3	96.9	97.6	98.6
2.50	63.50	99.2	98.8	99.2	99.6	99.8	99.9
5.00	127.00	100.0	99.9	99.8	99.8	100.0	100.0

*The 100% values in the table indicate no chance of exceeding certain amounts of precipitation during most of the months; however, it should be realized that the length of available data records is not long and that there is always a chance of any meteorological extreme of record being exceeded.

**Based on Langley Air Force Base data.

Table XVII

HIGHEST RAINFALL RATE VERSUS DURATION FOR VARIOUS PROBABILITIES, GIVEN A DAY WITH RAIN FOR THE HIGHEST RAIN MONTH KENNEDY SPACE CENTER

Duration	50 Percentile				95 Percentile				99 Percentile			
	Accumulation		Rate		Accumulation		Rate		Accumulation		Rate	
	(in.)	(mm)	(in./hr)	(mm/hr)	(in.)	(mm)	(in./hr)	(mm/hr)	(in.)	(mm)	(in./hr)	(mm/hr)
5 min	0.22	5.6	2.6	66.0	0.72	18.0	8.7	221.0	1.00	25.0	12.0	305.0
15 min	0.23	5.8	0.93	24.0	0.88	22.0	3.5	89.0	1.30	33.0	5.2	132.0
1 hr	0.25	6.4	0.25	6.4	1.17	30.0	1.17	30.0	1.93	49.0	1.93	49.0
6 hr	0.28	7.1	0.05	1.3	1.55	39.0	0.26	6.6	3.18	81.0	0.53	13.0
24 hr	0.43	10.9	0.02	0.5	2.62	67.0	0.11	2.8	5.00	127.0	0.21	5.3

Table XVIII

ICE TYPES AS A FUNCTION OF TANK WALL TEMPERATURES

Temperature of Tank Wall		Type of Ice	Density Range	
°F	°C		lb/ft³	g/cm³
23 to 32	-5 to 0	Clear ice (hard, dense)	60	0.69
0 to 23	-18 to -5	milky ice or clear ice with air bubbles	43-53	0.69-0.85
below 15	below -9	Rime ice (frosty, crumbly)	18-25	0.29-0.40

3.3.2 Snow

3.3.2.1 Loads

The maximum snow load on horizontal surfaces at Huntsville, Wallops Island, and River Transportation Areas ranges from 25 kg m^{-2} (5.1 lb ft^{-2}) in a 24 hour period (equivalent to a 10 inch snowfall) to a maximum of 50 kg m^{-2} (10.2 lb ft^{-2}) in a 72 hour period.

At New Orleans, Edwards Air Force Base, White Sands Missile Range, and Sacramento the maximum snow load on horizontal surfaces is 10 kg m^{-2} (2.0 lb ft^{-2}) in a 24 hour period.

3.3.2.2 Particle Size

The following table gives expected particle sizes of snow at areas of interest.

Launch/Transportation Areas	Particle Diameter		Associated Parameters			
	(mm)	(in.)	Wind Speed (m sec^{-1})	Wind Speed (ft sec^{-1})	Air Temperature (°C)	Air Temperature (°F)
Huntsville, Wallops Island, River Transportation Areas	0.1 to 5	0.0039 to 0.20	10	19	-17.8	0
New Orleans, West Coast Transportation Area, White Sands Missile Range, Sacramento	0.5 to 5	0.020 to 0.20	10	33	-5.0	23

3.3.3 Hail

3.3.3.1 Density, Loads, and Wind Speed

Although hail has a higher density than snow, 0.80 g cm^{-3} (50 lb ft^{-3}) as compared to 0.24 g cm^{-3} (15 lb ft^{-3}) for snow, the extreme load from hail will not exceed the extreme snow load at the areas specified in section 3.3.2.1. Therefore, the snow load design will adequately cover any hail loads expected. Likewise, the wind speed associated with snow (10 m sec^{-1} or 33 ft sec^{-1}) should be used for hail. Hail occurs in about one out of 400 thunderstorms.

3.3.3.2 Expected Occurrence at Various Areas

The maximum hailstone size is 50 mm (2 in.) in diameter with an occurrence probability of one time in 15 years.

Damaging hailstorms occur most frequently between 3 p.m. and 9 p.m. from March through September. April is the month of highest frequency-of-occurrence of hailstorms for Huntsville, River Transportation, and Gulf Transportation. March is the month of highest frequency-of-occurrence of hailstorms for Edwards Air Force Base and White Sands Missile Range, and May is the month of the highest frequency-of-occurrence of hailstorms for Wallops Island.

The period of large hail (over 25 mm in diameter) will not be expected to last more than 15 minutes and should have a maximum total accumulation of 50 mm (2 in.) for depth of hailstones on horizontal surfaces.

Velocity of fall equals 30.5 m sec^{-1} (100 ft sec^{-1}) for each stone.

3.3.3.3 Kennedy Space Center

A maximum hailstone size of 25.4 mm (1 in.) in diameter once in 30 years may be expected.

Damaging hailstones occur most frequently between 3 p.m. and 9 p.m. during April through June. May is the month of highest frequency for hailstorms.

The period of large hail will not be expected to last more than 15 minutes and should have a maximum total accumulation of 12.5 mm (0.5 in.) for depth of hailstones on horizontal surfaces. Velocity of fall equals 20 m sec^{-1} (66 ft sec^{-1}).

3.4 Surface Pressure

Table XIX gives extreme values of surface pressure for the locations of interest.

Figure 16 shows distributions of station pressure extremes for the contiguous United States.

Table XIX

SURFACE PRESSURE EXTREMES

Area	Pressure				Station Elevation	
	Units	Maximum	Mean	Minimum	Units	Value
Huntsville	N m^{-2}	102 080	99 543	97 210	m	196
	mb	1020.8	995.4	972.1		
	lb in.$^{-2}$	14.8	14.4	14.1	ft	644
New Orleans	N m^{-2}	104 000	101 600	99 700	m	9
	mb	1040.0	1016.0	997.0		
	lb in.$^{-2}$	15.1	14.7	14.5	ft	30
Wallops Island	N m^{-2}	105 000	101 325	90 000	m	88
	mb	1050	1013.25	900		
	lb in.$^{-2}$	15.2	14.7	13.1	ft	289
Kennedy Space Center	N m^{-2}	103 690	101 701	10 000	m	5
	mb	1036.9	1017.0	1000.0		
	lb in.$^{-2}$	15.0	14.8	14.5	ft	16
Space and Missile Test Center*	N m^{-2}	102 000	100 250	99 010	m	115
	mb	1020.0	1002.5	990.1		
	lb in.$^{-2}$	14.8	14.5	14.4	ft	378
White Sands Missile Range	N m^{-2}	89 010	87 130	85 200	m	1292
	mb	890.1	871.3	852.0		
	lb in.$^{-2}$	12.9	12.6	12.4	ft	4239
Edwards Air Force Base	N m^{-2}	95 560	93 430	92 030	m	706
	mb	955.6	934.3	920.3		
	lb in.$^{-2}$	13.9	13.6	13.3	ft	2316

*At Vandenberg Air Force Base

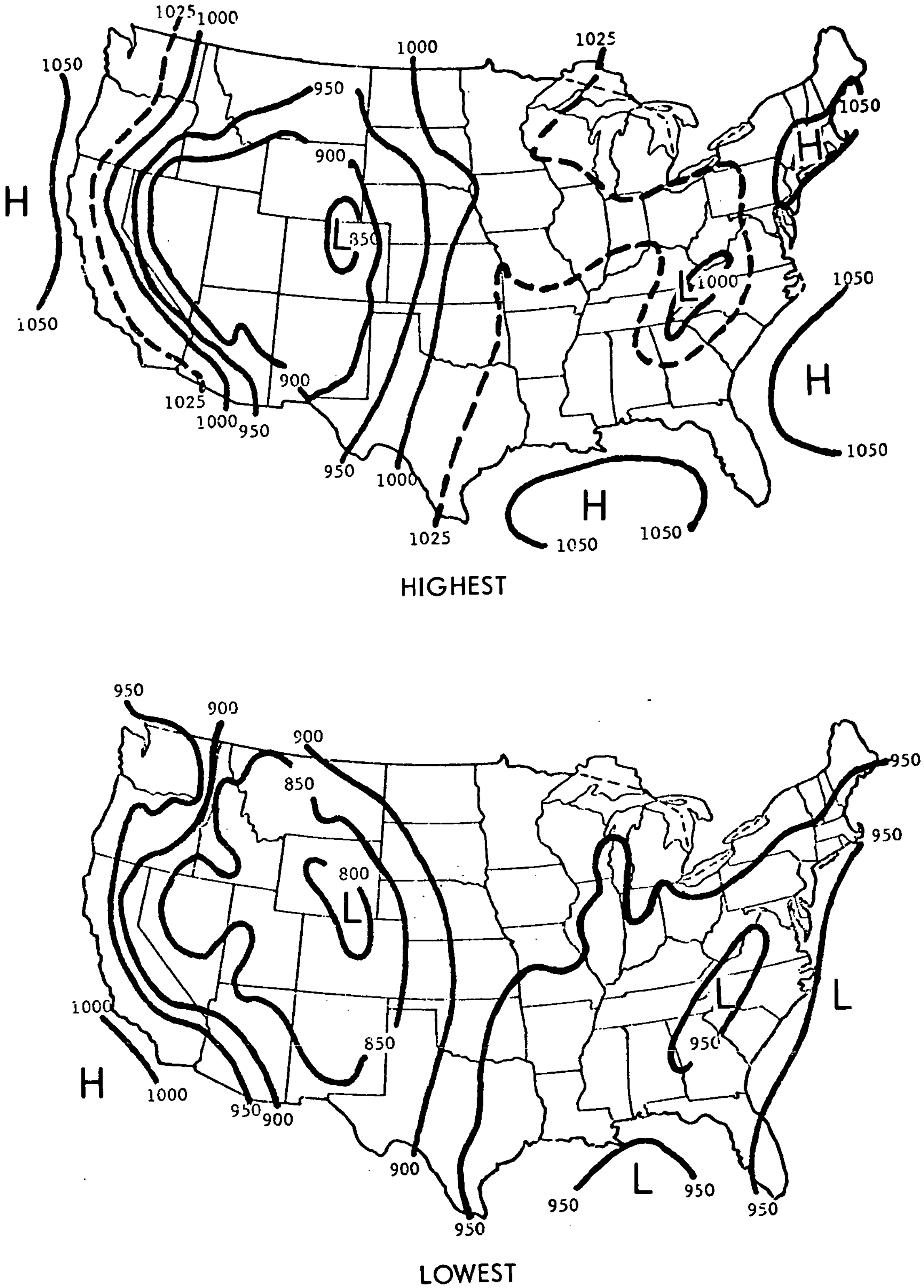


Figure 16. Extreme station pressures in the United States mb (10^{-2} newton m^{-2}) (ref. 28).

Figures 17 through 20 are graphs of extreme station pressure versus elevation above mean sea level. Inserts show the geographical areas to which the curves apply. Based on the available past record of extreme pressures, the graphs indicate the extreme pressures that can be expected at a given elevation above mean sea level. Hurricane effects are also indicated in figures 18 and 20 for those regions where they are significant. Central pressure in tornadoes may be even lower than that in hurricanes, but such data are not included herein.

3.5 Atmospheric Electricity

3.5.1 Fair-Weather Atmospheric Potential Gradient

A value of 300 volts m^{-1} can be used at all locations to approximate the fair-weather atmospheric potential gradient at the surface of the Earth.

3.5.2 Atmospheric Potential Gradient

3.5.2.1 Normal Variations

The normal variations in electrical fields are caused by smoke, haze and fog, clouds, precipitation, and traveling air masses. These variations range from +2000 to -2000 volts m^{-1} at the Earth's surface, and can change polarity rapidly. Higher in the atmosphere, the variations are much greater.

3.5.2.2 Major Disturbances (Thunderstorms)

(a) Frequency Variation with Location - The number of days per year on which thunder is heard is called the isoceraunic level. When multiplied by 0.23 the isoceraunic level gives an indication of the number of lightning flashes which reach the Earth per square mile per year (ref. 42). Table XX gives the isoceraunic level for specific locations and seasonal variation. The likelihood of thunderstorms also varies with time of day with afternoon hours having greater chance for thunderstorms at every location of interest except on West Coast.

(b) Frequency Variation With Height of Structure - The probability of direct lightning strikes to buildings and other structures depends not only on the isoceraunic level but also on the height of the structure. The following table shows the number of strikes at different heights for Kennedy Space Center (ref. 42). Variation with height for other areas would change approximately in proportion to the change in isoceraunic levels.

Height	(m)	30.5	61.0	91.4	121.9	152.4	182.9	213.4
	(ft)	100	200	300	400	500	600	700
(Average Annual) Number of Strikes		0.4	1.1	2.3	3.5	4.4	5.3	5.8

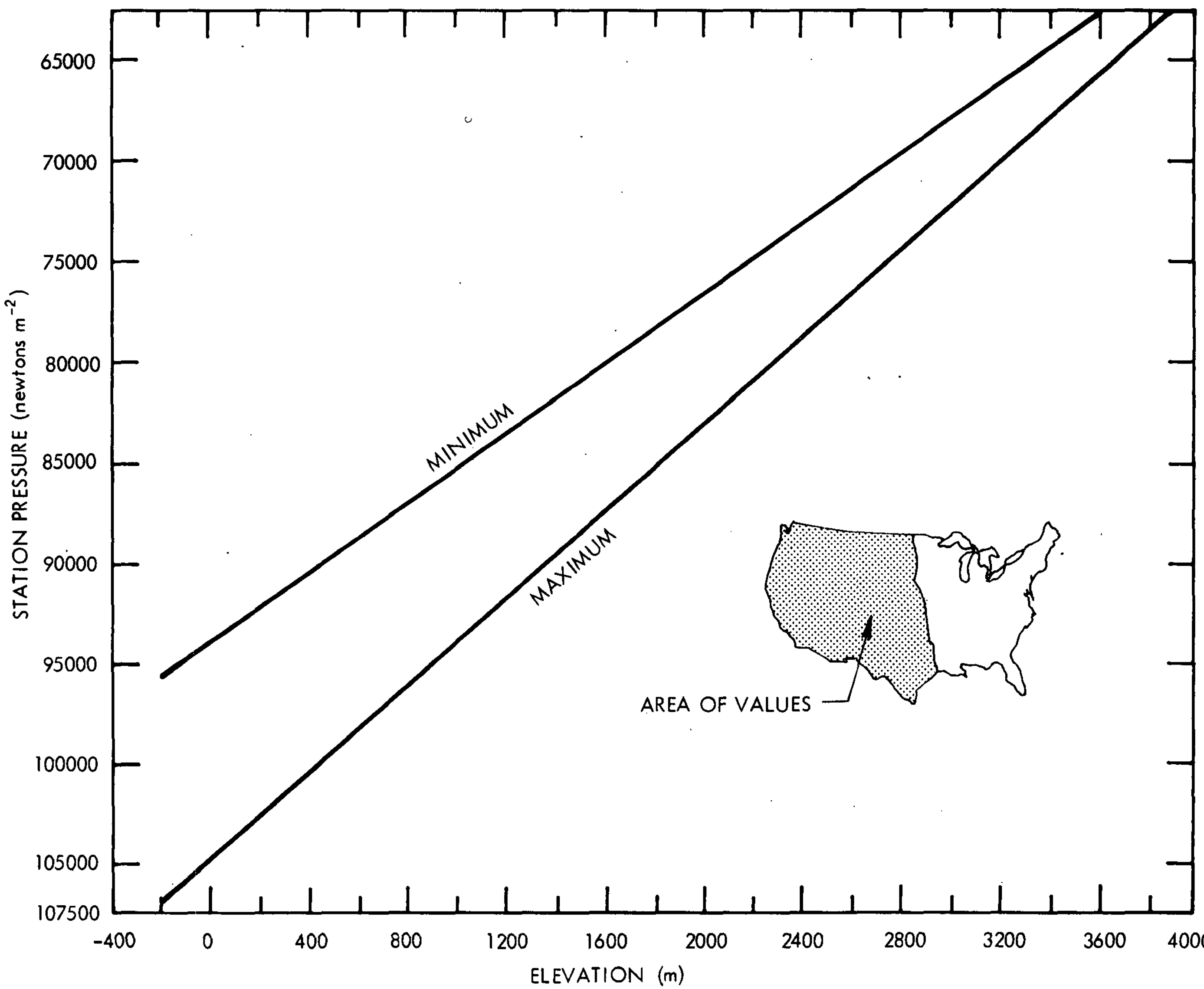


Figure 17. Extreme pressure values versus elevation above mean sea level for Western United States (ref. 2).

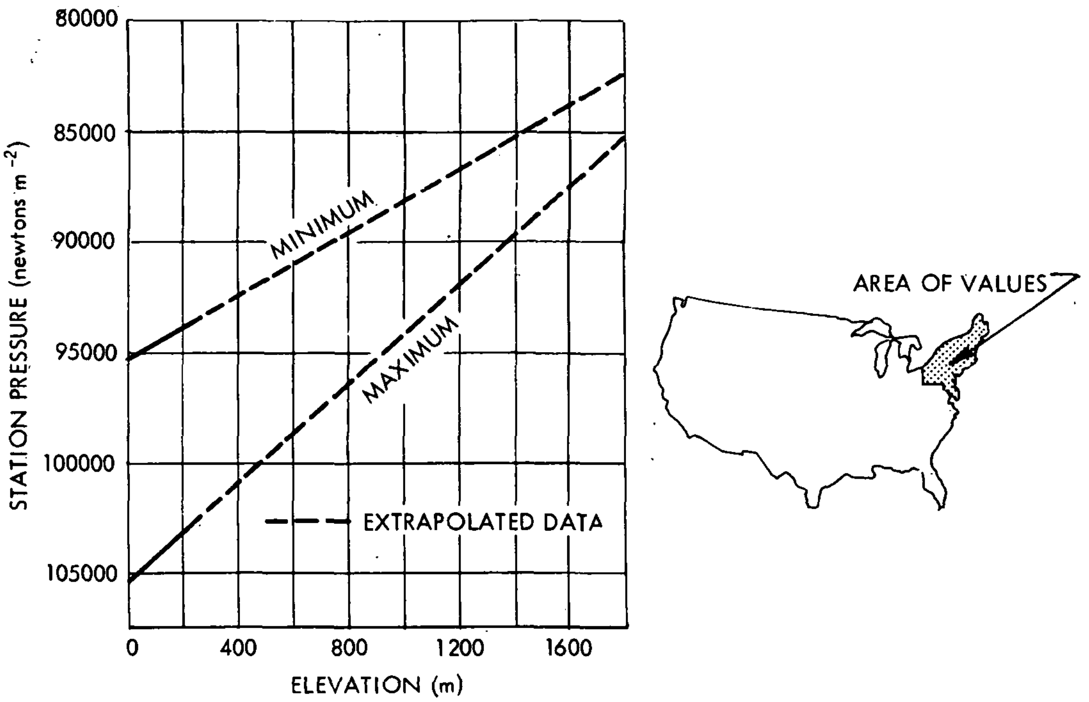


Figure 18. Extreme pressure values versus elevation above mean sea level for Northeastern United States (ref. 2).

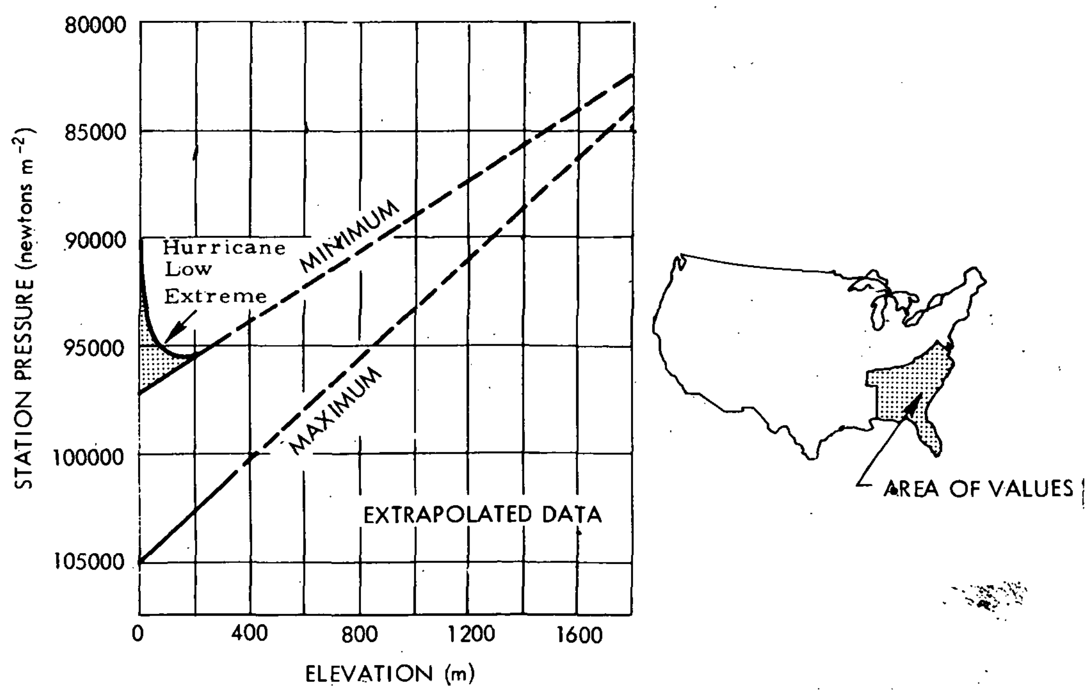


Figure 19. Extreme pressure values versus elevation above mean sea level for Southeastern United States (ref. 2).

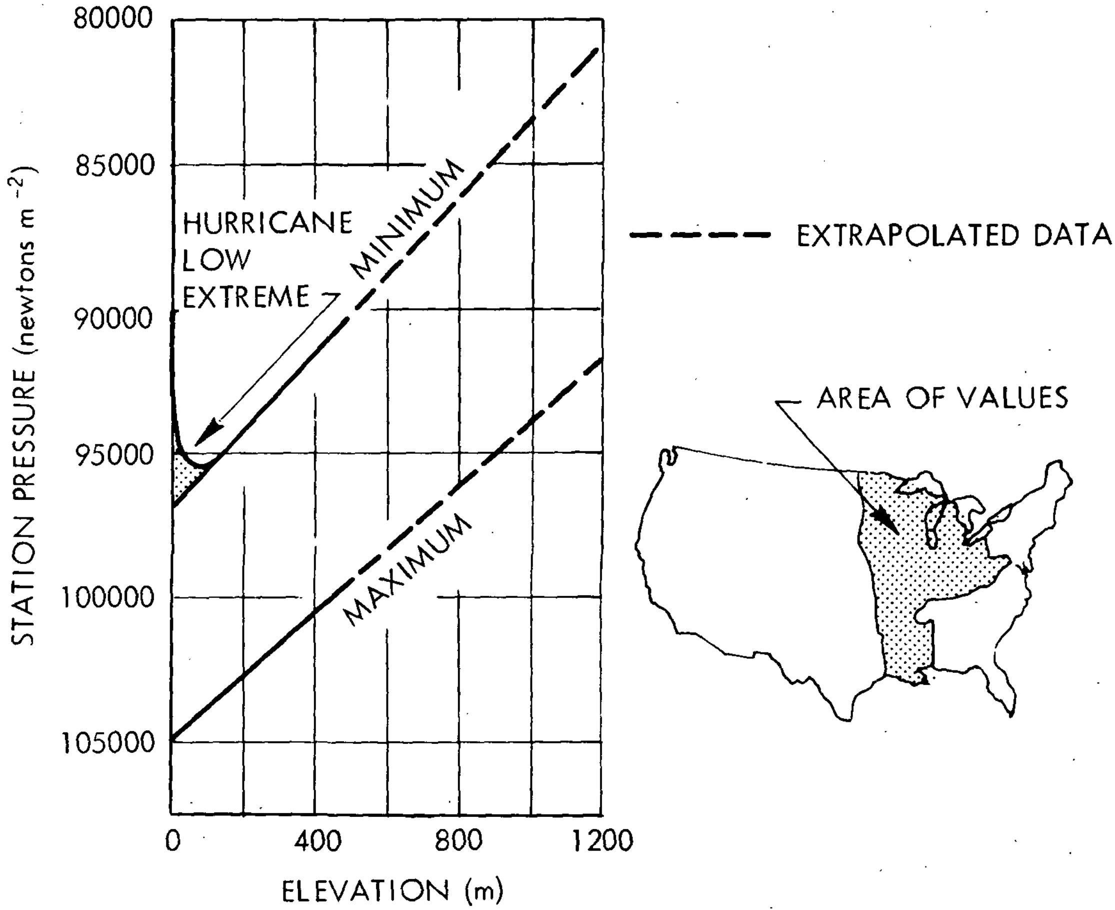


Figure 20. Extreme pressure values versus elevation above mean sea level for Central United States (ref. 2).

Table XX

FREQUENCY OF THUNDERSTORM DAYS (ISOCERAUNIC LEVEL) (ref. 2)

Location	Mean Number of Thunderstorm Days Per Year	Units	Thunderstorm Days (Number) and Percent of Annual Total (%)											
			Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Huntsville	70	% days	1 0.70	3 2.	6 4.20	8 5.60	11 7.70	19 13.30	22 15.40	18 12.60	9 6.30	1 0.70	1 0.70	1 0.70
River Transportation Areas and New Orleans	75	% days	3 2.25	3 2.25	5 3.75	5 3.75	8 6.0	16 12.0	21 15.75	20 15.0	10 7.5	3 2.25	3 2.25	3 2.25
Gulf Transportation Area	90	% days	1 0.90	1 0.90	4 3.60	2 1.80	9 8.10	18 16.20	24 21.60	23 20.70	12 10.80	4 3.60	1 0.90	1 0.90
Kennedy Space Center	70.09	% days	0.77 0.54	1.94 1.36	4.28 3.00	4.02 2.82	9.73 6.82	18.55 13.00	21.27 14.91	20.23 14.18	13.22 9.27	3.89 2.73	1.18 0.82	0.92 0.64
Panama Canal	100	% days	1 1.0	1 1.0	4 4.0	2 2.0	9 9.0	18 18.0	24 24.0	23 23.0	12 12.0	4 4.0	1 1.0	1 1.0
West Coast Transportation	6	% days	9 0.54	11 0.66	19 1.14	13 0.78	7 0.42	4 0.24	3 0.18	7 0.42	8 0.48	8 0.48	3 0.24	8 0.48
Space and Missile Test Center*	2	% days	5 0.1	15 0.3	15 0.3	5 0.1	2 0.04	1.5 0.03	10 0.2	10 0.2	25 0.5	1.5 0.03	5 0.1	5 0.1
Sacramento	4	% days	6 0.24	16 0.64	12 0.48	15 0.60	9 0.54	6 0.24	3 0.12	3 0.12	10 0.40	12 0.48	5 0.20	3 0.12
Wallops Island**	40.6	% days	0.5 0.2	1.2 0.5	5.2 2.1	8.4 3.4	12.6 5.1	17.2 7.0	21.7 8.8	20.4 8.3	7.9 3.2	3.2 1.3	1.0 0.4	0.7 0.3
White Sands Missile Range***	38.1	% days	0.8 0.3	0.1 0.05	1.8 0.7	4.7 1.8	7.6 2.9	15.2 5.8	30.5 11.6	23.9 9.1	8.7 3.3	5.2 2.0	0.5 0.2	1.0 0.4
Edwards AFB, Calif.	4.3	% days	2.3 0.1	2.3 0.1	2.3 0.1	7.0 0.3	4.7 0.2	2.3 0.1	23.3 1.0	25.6 1.1	20.9 0.9	7.0 0.3	2.3 0.1	0 0

*At Vandenberg Air Force Base, California
**Data from Norfolk, Virginia
***Data from Holloman Air Force Base, New Mexico

3.5.3 Lightning

3.5.3.1 Models

Figure 21 and table XXI provide a lightning model for a very severe discharge (Model 1).

Figure 22 and table XXII provide a lightning model that has a 98 percentile peak current (Model 2). The intermediate and continuing currents exceed 98 percentile values to represent associated burning that may occur.

Figure 23 and table XXIII provide an average peak current lightning model (Model 3).

3.5.3.2 In-Flight Design Objectives

The space vehicle in flight should be designed to withstand an electrical discharge from triggered lightning equal to Model 3 (fig. 23).

More extreme lightning currents than specified by Model 3 can cause serious damage to solid and liquid rocket engines that are burning. Therefore, launches should not be undertaken when severe lightning discharges are possible.

Table XXI

TABULATION OF A VERY SEVERE LIGHTNING MODEL (MODEL 1)

Stage	Key Points		Rate of Current Change	Charge Passing
1. First Return Stroke Surge	t = 0	i = 0	Linear Rise - 100 kA/ μs	0.2 C
	t = 2 μs	i = 200 kA	Linear Fall - 193 kA in 98 μs	~ 10.2 C
	t = 100 μs	i = 7 kA		
2. First Stroke Intermediate Current	t = 100 μs	i = 7 kA	Linear Fall - 6 kA in 4.9 ms	19.6 C
	t = 5 ms	i = 1 kA		
3. Continuing Current— First Phase	t = 5 ms	i = 1 kA	Linear Fall - 600 A in 50 ms	35.0 C
	t = 55 ms	i = 400 A		
4. Continuing Current— Second Phase	t = 55 ms	i - 400 A	Steady Current	120.0 C
	t = 355 ms	i = 400 A		
5. Second Return Stroke Surge	t = 355 ms	i = 400 A	Linear Rise ~ 50 kA/ μs	~ 0.1 C
	t = 355.002 ms	i = 100 kA	Linear Fall - 96.5 kA in 98 μs	~ 5.1 C
	t = 355.1 ms	i = 3.5 kA		
6. Second Stroke Intermediate Current	t = 355.1 ms	i = 3.5 kA	Linear Fall - 3 kA in 4.9 ms	9.8 C
	t = 360 ms	i = 500 A		

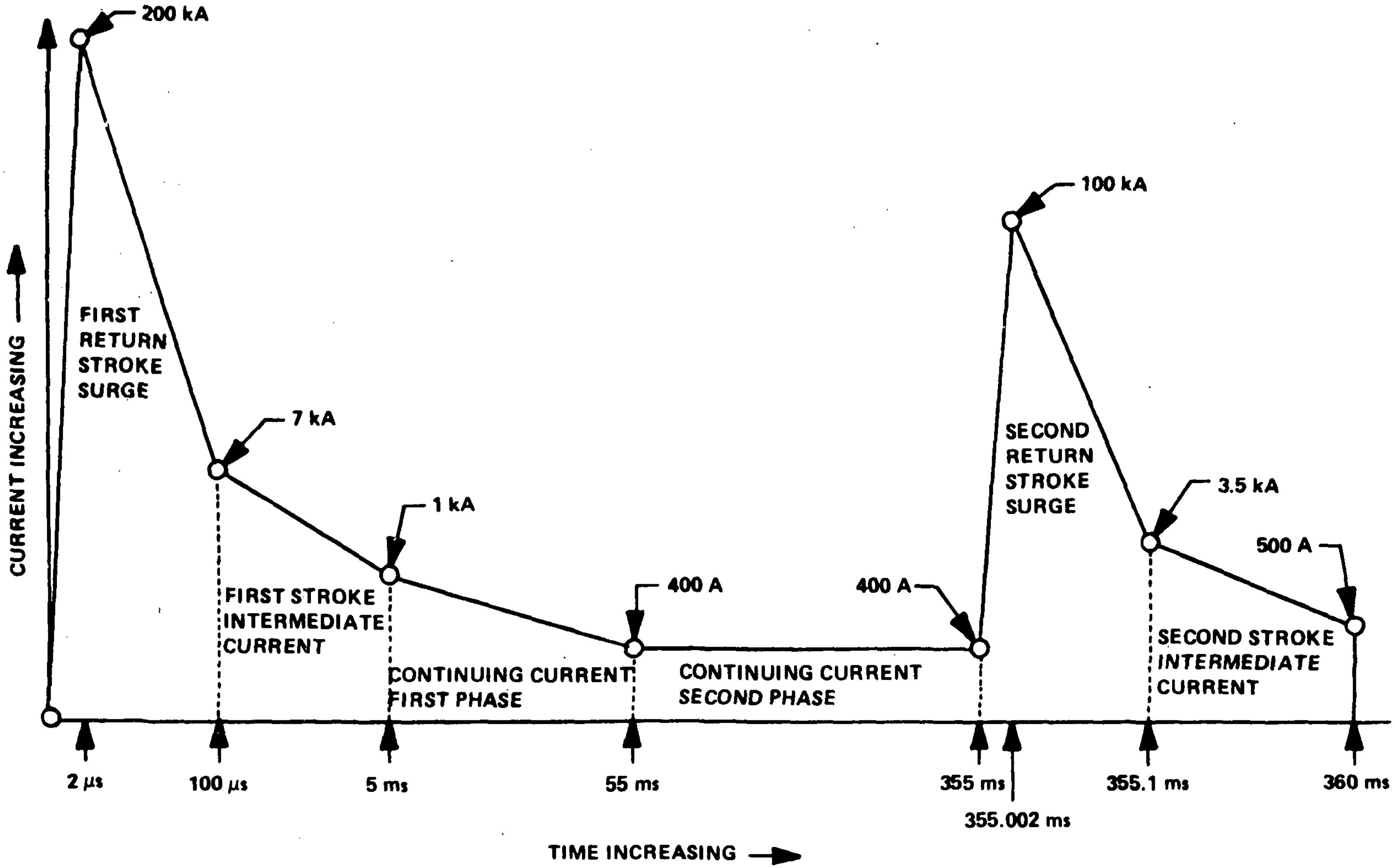


Figure 21. Diagrammatic representation of a very severe lightning stroke (Model 1).

Table XXII

TABULATION OF A 98 PERCENTILE PEAK CURRENT LIGHTNING STROKE (MODEL 2)

Stage	Key Points		Rate of Current Change	Charge Passing
1. First Return Stroke Surge	t = 0	i = 0	Linear Rise - 20 kA/μs	0.3 C
	t = 5 μs	i = 100 kA	Linear Fall - 96.5 kA in 95 μs	~ 4.9 C
	t = 100 μs	i = 3.5 kA		
2. First Stroke Intermediate Current	t = 100 μs	i = 3.5 kA	Linear Fall - 3 kA in 4.9 ms	9.8 C
	t = 5 ms	i = 500 A		
3. Continuing Current— First Phase	t = 5 ms	i = 500 A	Linear Fall - 300 A in 50 ms	17.5 C
	t = 55 ms	i = 200 A		
4. Continuing Current— Second Phase	t = 55 ms	i = 200 A	Steady Current	60 C
	t = 355 ms	i = 200 A		

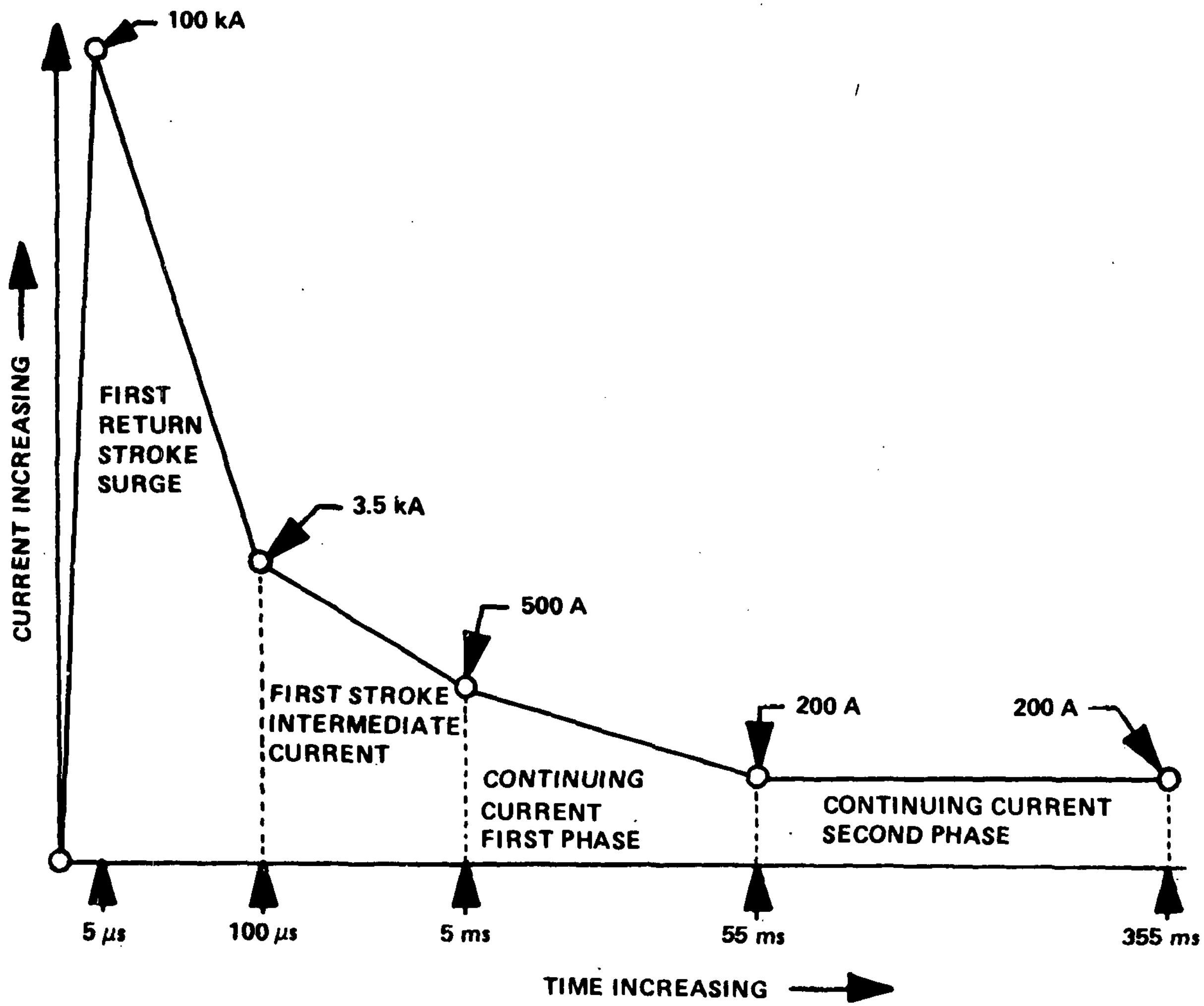


Figure 22. Diagrammatic representation of a 98 percentile peak current lightning stroke (Model 2).

Table XXIII

TABULATION OF AN AVERAGE LIGHTNING STROKE (MODEL 3)

Stage	Key Points		Rate of Current Change	Charge Passing
1. First Return Stroke Surge	t = 0	i = 0	Linear Rise - 4 kA/μs	0.1 C
	t = 5 μs	i = 20 kA	Linear Fall - 18 kA in 95 μs	~ 1.0 C
	t = 100 μs	i = 2 kA		
2. First Stroke Intermediate Current	t = 100 μs	i = 2 kA	Linear Fall - 1.7 kA in 4.9 ms	5.6 C
	t = 5 ms	i = 300 A		
3. Continuing Current— First Phase	t = 5 ms	i = 300 A	Linear Fall - 200 A in 50 ms	10.0 C
	t = 55 ms	i = 100 A		
4. Continuing Current— Second Phase	t = 55 ms	i = 100 A	Steady Current	30.0 C
	t = 355 ms	i = 100 A		

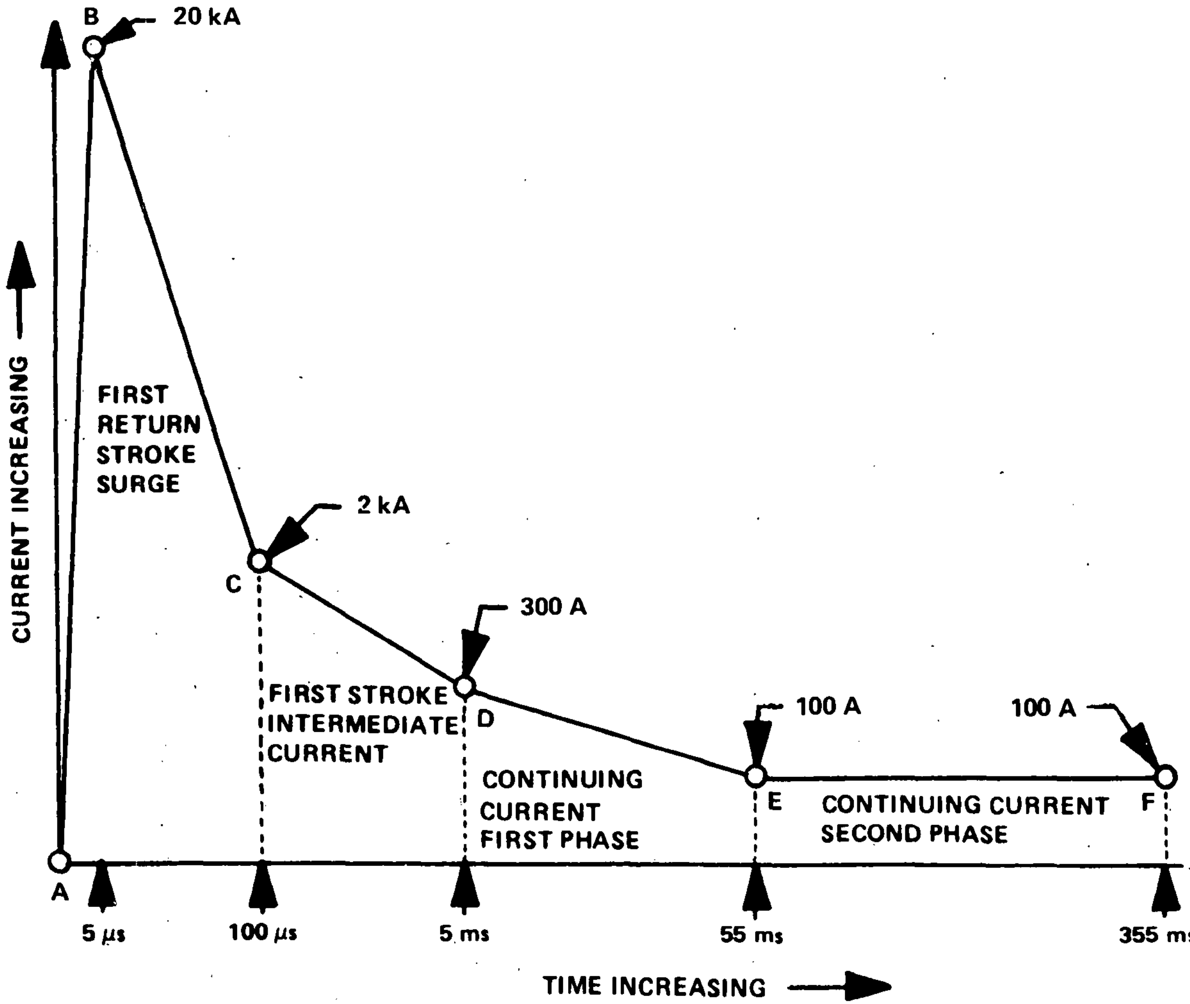


Figure 23. Diagrammatic representation of an average lightning stroke (Model 3).

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APPENDIX A
GLOSSARY*

Absorptivity – The ratio of the amount of radiant energy absorbed by a substance to the total amount incident upon that substance. By Kirchoff's law the absorptivity of any surface is equal to its emissivity when each is taken with reference to the same wavelength and surface temperature.

Air Mass – The amount of atmosphere that the solar radiation passes through. When the Sun is at the zenith and the observer is at sea level at normal atmospheric pressure, the solar radiation passes through one air mass.

Atmospheric Electric Field – The electrical force exerted on a unit positive charge at a given point in the atmosphere, usually expressed in terms of volts per unit length.

Black Body – An object which absorbs all incident radiation in all wavelengths. It also emits radiation at all wavelengths, and does so with maximum possible intensity for any given temperature.

Diffuse Sky Radiation – The solar radiation reaching the Earth's surface after having been scattered from the direct solar beam by molecules or suspensoids in the atmosphere. It is measured on a surface after the direct solar radiation is subtracted from the total radiation received on a horizontal surface.

Direct Solar Radiation – Radiation received on a surface directly from the Sun, and does not include diffuse sky radiation.

Diurnal – Pertaining to actions which are completed within 24 hours, and which recur every 24 hours.

Emissivity – The ratio of the emittance of a given surface at a specified wavelength and temperature to the emittance of an ideal black body at the same wavelength and temperature.

Emittance – A measure of the total radiant energy emitted per unit time per unit area of emitting surface.

Isoceraunic Level – The number of thunderstorm days per year.

Isotherm – A line of equal or constant temperature.

Lightning Flash – The total observed luminous phenomenon which is usually composed of several lightning strokes.

Lightning Stroke – Any one of the leader-return stroke phases in a lightning flash.

Negative Current Lightning Stroke – A lightning stroke that occurs between the normal configuration of negatively charged cloud and positively charged ground. This term is used without respect to direction of the stroke as, in either case, the charge transferred to ground is negative.

*Reference 61 was used extensively and other references to a lesser degree for the definitions given here.

Percentile – The percentage of time that a variable does not exceed a given magnitude.

Positive Current Lightning Stroke – A lightning stroke between ground and cloud that occurs between the less frequent configuration of a positive cloud and negative ground. This term is used without respect to direction of the stroke as, in either case, the charge transferred to ground is positive.

Pyranometer – An instrument which measures the combined intensity of incoming direct solar radiation and diffuse sky radiation. Different models exist, but in principle they generally consist of a thermopile type of sensor, either with a single blackened receiver or a differential arrangement of two receivers one being black and the other white. The emf generated in the thermopile circuit is closely proportional to the incident radiation.

Relative Humidity – The ratio of the fraction of water vapor in a given volume of air to the fraction that the same volume of air at the same temperature would hold if saturated.

Return Lightning Stroke – The intensely luminous streamer of high current that follows the leader process but in the opposite direction.

Solar Constant – The rate at which solar radiation is received outside the Earth's atmosphere on a surface normal to the incident radiation, and at the Earth's mean distance from the Sun.

Spectral – A term used to describe the distribution of energy, e.g., solar energy, arranged according to wavelength or frequency.

Stepped Leader – The initial streamer of a lightning flash. A faint luminous process with current of the order of a few hundred amperes which establishes a channel for subsequent strokes.

Vapor Concentration – Synonomous with absolute humidity. The mass of water vapor present in a unit volume, i.e., the density of the water vapor content.

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ENVIRONMENT

SP-8005	Solar Electromagnetic Radiation, revised May 1971
SP-8010	Models of Mars Atmosphere (1967), May 1968
SP-8011	Models of Venus Atmosphere (1972), revised September 1972
SP-8013	Meteoroid Environment Model–1969 (Near Earth to Lunar Surface), March 1969
SP-8017	Magnetic Fields–Earth and Extraterrestrial, March 1969
SP-8020	Mars Surface Models (1968), May 1969
SP-8021	Models of Earth's Atmosphere (90 to 2500 km), revised March 1973
SP-8023	Lunar Surface Models, May 1969
SP-8037	Assessment and Control of Spacecraft Magnetic Fields, September 1970
SP-8038	Meteoroid Environment Model–1970 (Interplanetary and Planetary), October 1970
SP-8049	The Earth's Ionosphere, March 1971
SP-8067	Earth Albedo and Emitted Radiation, July 1971
SP-8069	The Planet Jupiter (1970), December 1971
SP-8084	Surface Atmospheric Extremes (Launch and Transportation Areas), revised June 1974
SP-8085	The Planet Mercury (1971), March 1972
SP-8091	The Planet Saturn (1970), June 1972
SP-8092	Assessment and Control of Spacecraft Electromagnetic Interference, June 1972
SP-8103	The Planets Uranus, Neptune, and Pluto (1971), November 1972
SP-8105	Spacecraft Thermal Control, May 1973

SP-8111	Assessment and Control of Electrostatic Charges, May 1974

STRUCTURES

SP-8001	Buffeting During Atmospheric Ascent, revised November 1970
SP-8002	Flight-Loads Measurements During Launch and Exit, revised June 1972
SP-8003	Flutter, Buzz, and Divergence, July 1964
SP-8004	Panel Flutter, revised June 1972
SP-8006	Local Steady Aerodynamic Loads During Launch and Exit, May 1965
SP-8007	Buckling of Thin-Walled Circular Cylinders, revised August 1968
SP-8008	Prelaunch Ground Wind Loads, November 1965
SP-8009	Propellant Slosh Loads, August 1968
SP-8012	Natural Vibration Modal Analysis, September 1968
SP-8014	Entry Thermal Protection, August 1968
SP-8019	Buckling of Thin-Walled Truncated Cones, September 1968
SP-8022	Staging Loads, February 1969
SP-8029	Aerodynamic and Rocket-Exhaust Heating During Launch and Ascent, May 1969
SP-8031	Slosh Suppression, May 1969
SP-8032	Buckling of Thin-Walled Doubly Curved Shells, August 1969
SP-8035	Wind Loads During Ascent, June 1970
SP-8040	Fracture Control of Metallic Pressure Vessels, May 1970
SP-8042	Meteoroid Damage Assessment, May 1970
SP-8043	Design–Development testing, May 1970
SP-8044	Qualification testing, May 1970
SP-8045	Acceptance testing, April 1970

SP-8046	Landing Impact Attenuation for Non-Surface-Planing Landers, April 1970
SP-8050	Structural Vibration Prediction, June 1970
SP-8053	Nuclear and Space Radiation Effects on Materials, June 1970
SP-8054	Space Radiation Protection, June 1970
SP-8055	Prevention of Coupled Structure-Propulsion Instability (Pogo), October 1970
SP-8056	Flight Separation Mechanisms, October 1970
SP-8057	Structural Design Criteria Applicable to a Space Shuttle, revised March 1972
SP-8060	Compartment Venting, November 1970
SP-8061	Interaction with Umbilicals and Launch Stand, August 1970
SP-8062	Entry Gasdynamic Heating, January 1971
SP-8063	Lubrication, Friction, and Wear, June 1971
SP-8066	Deployable Aerodynamic Deceleration Systems, June 1971
SP-8068	Buckling Strength of Structural Plates, June 1971
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SP-8079	Structural Interaction with Control Systems, November 1971
SP-8082	Stress-Corrosion Cracking in Metals, August 1971
SP-8083	Discontinuity in Metallic Pressure Vessels, November 1971
SP-8095	Preliminary Criteria for the Fracture Control of Space Shuttle Structures, June 1971
SP-8099	Combining Ascent Loads, May 1972
SP-8104	Structural Interaction with Transportation and Handling Systems, January 1973

GUIDANCE AND CONTROL

SP-8015	Guidance and Navigation for Entry Vehicles, November 1968
SP-8016	Effects of Structural Flexibility on Spacecraft Control Systems, April 1969
SP-8018	Spacecraft Magnetic Torques, March 1969
SP-8024	Spacecraft Gravitational Torques, May 1969
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SP-8065	Tubular Spacecraft Booms (Extendible, Reel Stored), February 1971
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SP-8074	Spacecraft Solar Cell Arrays, May 1971
SP-8078	Spaceborne Electronic Imaging Systems, June 1971
SP-8086	Space Vehicle Displays Design Criteria, March 1972
SP-8096	Space Vehicle Gyroscope Sensor Applications, October 1972
SP-8098	Effects of Structural Flexibility on Entry Vehicle Control Systems, June 1972
SP-8102	Space Vehicle Accelerometer Applications, December 1972

CHEMICAL PROPULSION

SP-8025	Solid Rocket Motor Metal Cases, April 1970
SP-8039	Solid Rocket Motor Performance Analysis and Prediction, May 1971
SP-8041	Captive-Fired Testing of Solid Rocket Motors, March 1971
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SP-8051	Solid Rocket Motor Igniters, March 1971
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SP-8064	Solid Propellant Selection and Characterization, June 1971
SP-8075	Solid Propellant Processing Factors in Rocket Motor Design, October 1971
SP-8076	Solid Propellant Grain Design and Internal Ballistics, March 1972
SP-8080	Liquid Rocket Pressure Regulators, Relief Valves, Check Valves, Burst Disks, and Explosive Valves, March 1973
SP-8081	Liquid Propellant Gas Generators, March 1972
SP-8087	Liquid Rocket Engine Fluid-Cooled Combustion Chambers, April 1972
SP-8090	Liquid Rocket Actuators and Operators, May 1973
SP-8101	Liquid Rocket Engine Turbopump Shafts and Couplings, September 1972