TABLE OF CONTENTS

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SECTION 4

THERMAL RADIATION

4.1 Introduction. The natural thermal environments, such as solar and sky radiation (thermal radiation) and temperature, can produce undesirable effects on aerospace vehicles while being fabricated, transported, tested, on the pad, or in flight. The ground support system may also be affected. Effects on the vehicles and ground support system include:

a. Unequal heating resulting in stresses of various types.

b. Temperature extremes (high or low) occurring inside or on the vehicle surface which may cause equipment malfunctions or uncomfortable/undesirable conditions for manned missions.

c. Difficulties in alignment of the vehicle parts at interfaces, and calibration of R&D instruments on the vehicle because of variations in size, thermal effects, and/or shape with temperature.

Because of these and other effects, information on the radiation/thermal environment at the Earth's surface and up to 90-km altitude is presented in the following order:

a. Thermal definitions.

b. Extraterrestrial solar radiation over small wavelength intervals that irradiate the atmosphere from approximately 20-km to 90-km altitude.

c. Solar radiation transmitted, absorped, and scattered through a reference atmosphere in small wavelength interval irradiances (direct solar). Data are valid at the Earth’s surface on a very clear day.

d. Diffuse (sky) radiation.

e. Extreme values of total horizontal, diffuse, total normal incident, and total 45∞ surface solar radiation at various times of day at the Earth's surface for various geographic locations.

f. Application of solar radiation in design using solar radiation design curves.

g. Methods of using surface emittance and the effect of wind speed to determine temperatures on surfaces exposed to solar radiation and sky radiation, and the application of solar radiation in design with solar radiation design curves.

h. Extreme and mean values of monthly air temperature at the Earth's surface at various times of day.

i. Extreme temperature changes, surface skin temperatures, and compartment temperature values.

4.2 Definitions. The thermal and radiation terms used in this section are defined as follows:

Absorption bands are those portions of the solar spectrum or other continuous spectra which have lesser intensity because of absorption by gaseous elements or molecules. In general, elements give sharp lines, but molecules, such as water vapor or carbon dioxide, give broad diffuse bands.

Absorptivity for any object is the fraction of the radiant energy falling on an object that is absorbed or transferred into heat. It is the ratio of the radiation absorbed by any substance to that absorbed under the same conditions by a blackbody.

Air mass (atmosphere) is the amount of atmosphere that the solar radiation passes through, considering the vertical path at sea level as unity (i.e., when the Sun is at the zenith, directly overhead). The air mass (atmosphere) will always be greater than 1.0 when the path deviates from the vertical.

Air temperature (surface) is the free or ambient air temperature measured under standard conditions of height, ventilation, and radiation shielding. The air temperature is normally measured with liquid-in-glass thermometers in a louvered wooden shelter, painted white inside and outside, with the base of the shelter normally 1.22 m (4 ft) above a close-cropped grass surface (Ref. 4.1). Unless an exception is stated, surface air temperatures given in this report are temperatures measured under these standard conditions.

Atmospheric transmittance is the ratio between the intensity of the extraterrestrial solar radiation and intensity of the solar radiation after passing through the atmosphere.

Astronomical unit (au) is the mean distance of Earth from the Sun (1.496×10^8 km).

Blackbody is an ideal emitter which radiates energy at the maximum possible rate per unit area at each wavelength for any given temperature and which absorbs all incident radiation at all wavelengths. Its absorptivity is always 1.0.

Diffuse (sky) radiation (I_{dH}) is the solar radiation reaching the Earth's surface after having been scattered from the direct solar beam by molecules and particles in the atmosphere. It is measured at the Earth's surface by subtracting the direct solar radiation from the total horizontal radiation.

Direct normal incident radiation (I_{DN}): see normal incident.

Direct solar radiation is the solar radiation received by an object from on a line directly to the Sun. It does not include diffuse radiation.

Emittance is the ratio of the energy emitted by a body at a specific temperature to the energy which would be emitted by a blackbody at the same temperature. All real bodies will emit energy in different amounts from a blackbody at various wavelengths; i.e., low-temperature bodies emit in the IR not visible spectrum. They are colored because they reflect the colored part of the visible spectrum. In this document, the assumption is made that the absorptivity of an object is numerically equal to the emittance of the object at the same wavelengths. Therefore, the value of the emittance can be used to determine the portion of the energy received by the object which heats (or energy lost which cools) the object. Emittance is always less than 1.0.

Extraterrestrial solar radiation is that solar radiation received outside the Earth's atmosphere at one astronomical unit from the Sun. The term "solar spectral irradiance" is used when the extraterrestrial solar radiation is considered by wavelength intervals.

Fraunhofer lines are the dark absorption lines or bands in the solar spectrum caused by gases in the outer portion of the Sun and Earth's atmosphere. These lines may be of metals (sharp lines) or molecules (broad lines) in the gaseous state.

Horizontal solar radiation is the solar radiation measured on a horizontal surface. This is frequently referred to as "global radiation" or "total horizontal radiation" or “total hemispherical radiation” when solar and diffuse sky radiation are included.

Irradiation is the emitting of energy from an object. In this report the energy is black body radiation.

Normal incident (I_{DN}) solar radiation is the radiation received on a surface, normal to the direction of the Sun, direct from the Sun. A very small amount of diffuse sky radiation in a narrow band around the Sun is normally measured with normal incident measuring instruments.

Radiation temperature is the absolute temperature of a radiating blackbody determined by Wien's displacement law, expressed as

$$T_R = \frac{w}{\lambda \mathrm{max}} \tag{4.1}$$

where T_R is the absolute temperature of the radiating body (K), w is the Wien's displacement constant (0.2880 cm K), and λmax is the wavelength of the maximum radiation intensity for the blackbody.

Sky radiation temperature is the average radiation temperature of the sky when it is assumed to be a blackbody. Sky radiation is the radiation to and through the atmosphere from outer space. While this radiation is normally termed nocturnal radiation, it takes place under clear skies even during daylight hours, and is always much lower than the measured air temperature.

Solar constant is the intensity of solar radiation received outside the Earth's atmosphere on a surface normal to the incident radiation at the Earth's mean distance (1 au) from the Sun. The best value of the solar constant is 1,371±5 W m^{-2} at 1 au (Ref. 4.2, with refs. 4.3, 4.4, and 4.5 providing prior background information).

Total solar radiation: When the word "Total" is used it means the wavelength band covering the entire solar spectrum from the extreme ultraviolet to the far infrared.

4.3 Spectral Distribution of Radiation

4.3.1 Introduction. All objects radiate energy in some portion of the electromagnetic spectrum. The amount and frequency of the radiation distribution is a function of temperature. The higher the temperature, the greater the amount of total energy emitted and the higher the frequency (shorter the wavelength) of the peak energy emission, according to Wien's displacement law,

$$\lambda_{\mathrm{max}} = \frac{w}{T_R} \ . \tag{4.1A}$$

Solar radiation and its transmittance characteristics through the atmosphere are presented in the following subsections.

4.3.2 Solar Radiation. The Sun emits energy in the electromagnetic spectrum from below 10^{-7} to greater than 10^5 µm. This radiation ranges from cosmic rays through the very long wave radio waves. The total amount of radiation from the Sun is nearly constant in intensity with time.

Of the total electromagnetic spectrum of the Sun, only the radiant energy from that portion of the spectrum between 0.22 and 20.0 µm will be considered in this document since it contributes 99.8 percent of the total electromagnetic energy from the Sun. The spectral distribution of this region closely resembles the emission of a black body radiating at 5,762 K (T_{max}). This is the spectral region which causes nearly all of the heating of an object.

Solar radiation, observed at an altitude high enough that the Earth's atmosphere does not absorb the radiation, is distributed in a continuous spectrum with many narrow absorption bands caused by the elements and molecules in the colder solar atmosphere. These absorption bands are the Fraunhofer lines, whose widths are usually very small ($<10^{-4}$ µm in most cases).

The Earth's atmosphere also absorbs a part of the solar radiation. The major portion of the solar radiation reaching the Earth's surface is between about 0.35 and 4.00 µm. The distribution of the solar energy outside the Earth's atmosphere* (extraterrestrial) is as follows:

Region (μm)	Distribution (%)	Solar Intensity* g-cal cm^{-2} (min^{-1})
Ultraviolet below 0.38	7.003	0.136
0.38 to 0.75	44.688	0.867
Infrared above 0.75	48.309	0.937

The first detailed information published for use by engineers on the distribution of solar radiation energy (solar irradiation) wavelengths was that by Parry Moon in 1940 (Ref. 4.6). These data were generally based on theoretical curves but are still used as the basic solar radiation in design by many engineers.†

4.3.3 Solar Radiation Intensity Distribution Table 4.1 presents data on the distribution with wavelength of solar radiation outside the Earth's atmosphere and at the Earth's surface after 1.0 atmosphere absorption on a very clear day. This "clear day" is based on a day where the value of the solar radiation at the surface equals the value of 1.64 g-cal cm^{-2} min^{-1}. It was determined by fitting a spectral curve to give the proper area under the curve from the data as shown in Table 4.1.

In Table 4.1, above a wavelength of 0.290 microns, the table is accurate to within ±30 percent. The smaller wavelength data are up to 5X low in some cases. For more precise data, reference 4.2 gives the recommended data for above the atmosphere, while data for below the atmosphere can be obtained by using LOWTRAN 7 model and computer code (Ref. 4.7).

The solar radiation distribution outside the Earth's atmosphere (solar spectral irradiance) are defined for the average Sun-Earth distance of 1 au. This is based on data obtained from high flying aircraft, high altitude platforms, balloons, and the Mariner-Mars probe. Different types of instruments were used. The instruments were referred to three scales of radiometry, the absolute electrical units scale, the international pyrheliometric scale IPS 56, and the thermodynamic Kelvin temperature scale (Ref. 4.4). The Earth is at 1 au on April 4 and October 5. At other times of the year the Earth is closer to, or farther away, from the Sun making the values increase or decrease by approximately 3.5 percent. Also, the cyclic variation in the solar energy output received from the Sun is about equal to the variation of the Earth's distance from the Sun. Therefore, any adjustment of the solar spectral irradiance would not be feasible.

* At one astronomical unit (au) on a surface normal to the Sun.

† Additional information is provided by: Beckman, W.A., Klein, S.S., and Duffie, J.A.: "Solar Heating Design," John Wiley and Sons, New York, 1967; Daniels, G.E., Smith, O.E., and Greene, W.M.: "Application of Solar

Radiation and Temperature in Design of Aerospace Vehicles," Internal Note IN-ES 42-76-1, NASA Marshall Space Flight Center, April 15, 1976.

TABLE 4.1 Solar Spectral Irradiance (Outside Atmosphere) And Solar Radiation After Absorption By Clear Atmosphere

Wavelength (microns) λ	Solar Spectral Irradiance (W cm^{-2} μ^{-1})	Area Under Solar Spectral Irradiance Curve (W cm^{-2})	Solar Radiation After One Atmosphere Absorption (W cm^{-2} λ^{-1})	Area Under One Atmosphere Solar Radiation Curve (W cm^{-2})	Percentage of Solar Radiation After One Atmosphere Absorption for Wavelengths Shorter Than 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
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

TABLE 4.1 Solar Spectral Irradiance (Outside Atmosphere) And Solar Radiation After Absorption By Clear Atmosphere (Continued).

Wavelength (microns) λ	Solar Spectral Irradiance (W cm^{-2} μ^{-1})	Area Under Solar Spectral Irradiance Curve (W cm^{-2})	Solar Radiation After One Atmosphere Absorption (W cm^{-2} μ^{-1})	Area Under One Atmosphere Solar Radiation Curve (W cm^{-2})	Percentage of Solar Radiation After One Atmosphere Absorption for Wavelengths Shorter Than λ (%)
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
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	44.05
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
2.200	0.0079	0.128300	0.007596	0.109682	98.76
2.300	0.0068	0.129035	0.006538	0.110336	99.34

TABLE 4.1 Solar Spectral Irradiance (Outside Atmosphere) And Solar Radiation After Absorption By Clear Atmosphere (Continued).

Wavelength (microns)λ	Solar Spectral Irradiance (W cm^{-2} μ^{-1})	Area Under Solar Spectral Irradiance Curve (W cm^{-2})	Solar Radiation After One Atmosphere Absorption (W cm^{-2} μ^{-1})	Area Under One Atmosphere Solar Radiation Curve (W cm^{-2})	Percentage of Solar Radiation After One Atmosphere Absorption for Wavelengths Shorter Than λ (%)
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
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
1,000.0	0.000000000	0.13530000	0.000000	0.111063	100.00

The values of solar radiation given in Table 4.1 for a one standard atmosphere absorption are representative of a very clear atmosphere which provides a minimum of atmospheric absorption. This gives a total solar radiation value (area under the spectral curve) equal to the highest values measured at the Earth's surface at sea level in mid-latitudes. These values are for use in solar radiation design when extreme solar radiation effects are desired at the Earth's surface. If data are required for less extreme or average values of solar radiation at the surface and for values for more than one standard atmosphere (air mass), values given in Ref. 4.5, pages 36 through 39. Also Ref. 4.8 or LOWTRAN 7 can be used.

Figure 4.1 shows in graphical form the solar spectral irradiance at 1 au, normal incident solar radiation at sea level on a clear day, and the blackbody spectral irradiance curve at T = 5,762 K.

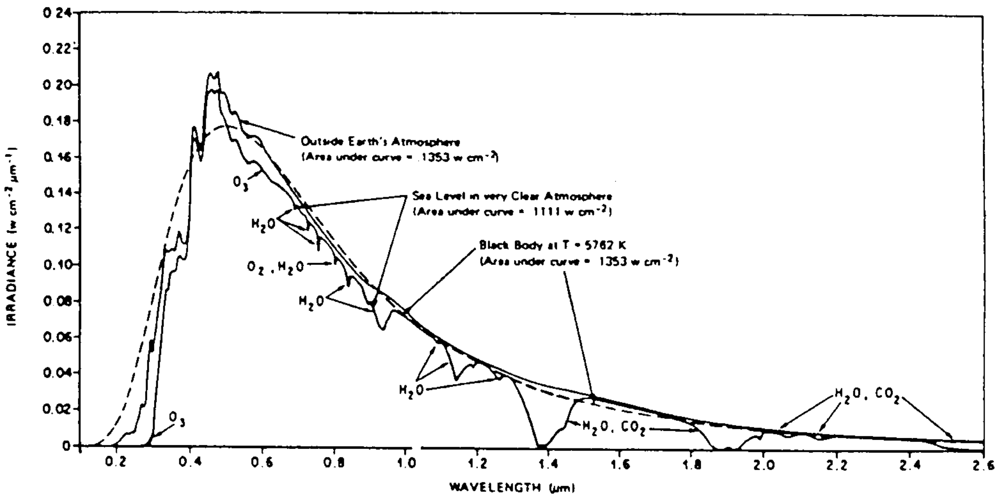


FIGURE 4-1. Normal Incident Solar Radiation At Sea Level on Very Clear Days, Solar Spectral Irradiance Outside The Earth's Atmosphere At 1 au (Ref. 4.4), And Blackbody Spectral Irradiance Curve At T = 5.762 K (Normalized To 1 au).

4.3.4 Atmospheric Transmittance of Solar Radiation. The atmosphere of the Earth is composed of a mixture of gases, aerosols, and dust which absorb, scatter and emit radiation in different amounts at various wavelengths. If the ratio is taken of the solar spectral irradiance I_0 to that of the solar radiation after absorption through one air mass $I_{1.00}$ an atmospheric transmittance factor M can be found (equation (4.2)):

$$M = \frac{I_{1.00}}{I_0} \quad . \tag{4.2}$$

The atmospheric transmittance constant can be used in the following equation for computations of intensities for any other number of air masses:

$$I_N = I_0 \left(M^N\right) \quad , \tag{4.3}$$

where

I_N = intensity of solar radiation for N air mass thickness

N = number of air masses.

Equation (4.3) can also be used to obtain solar radiation intensities versus wavelengths for total normal incident solar radiation intensities (area under curve) by computing new values of atmospheric transmittance as follows:

$$M_N = M \frac{I_{TN}}{0.1111} , \tag{4.4}$$

where I_{TN} = new value of total normal incident solar radiation intensity in W cm^{-2}
M = value for atmospheric transmittance given in Table 4.1
M_N = new value of atmospheric transmittance.

Equations (4.3) and (4.4) are valid only for locations relatively near the Earth's surface (below 5 km altitude). For higher altitudes, corrections are needed for the change of the amount of ozone and water vapor in the atmosphere. Also, equation (4.4) should be used only for values of I_{TN} greater than 0.0767 W cm^{-2} (1.10 g-cal cm^{-2} min^{-1}). Values lower than this would indicate a considerably higher ratio of water vapor to ozone in the atmosphere and require that the curve be adjusted to give more absorption in the infrared water vapor bands at long wavelengths (infrared) and a small increase for the ozone at shorter wavelengths. Tables providing lower solar radiation values are given in refs. 4.5 and 4.8. Caution should be used in any analysis using lower values of solar radiation in areas where smoke (such as from forest fires), dust or sand from high winds, or other types of unusual particulate matter exist, since the shape of the curve with respect to wavelength will be entirely different than the normal curves. These particulate matters and aerosols will also give unusual diffuse radiation values.

4.3.5 Diffuse (Sky) Radiation. When solar radiation, which is a nearly parallel beam of light, enters the atmosphere of the Earth, molecules of air and aerosols such as dust particles and water vapor droplets diffuse and absorb a part of the radiation. The diffuse or scattered radiation then reaches the Earth as nonparallel light from all directions. This is described in the following subsection.

4.3.5.1 Scattered Radiation. Scattered radiation gives the sky its brightness and color. The color is a result of selective scattering at specific wavelengths as a function of the size and type of the molecules and particles. On a clear day, the amount of scattering is very low because there are fewer particles, water vapor, and water droplets present. The clear sky can be as little as 10^{-6} as bright as the surface of the Sun. This sky radiation will be referred to as "diffuse radiation." On a clear day, the total energy contribution from the diffuse radiation from the entire sky hemisphere to a horizontal surface is between 0.0007 and 0.014 W cm^{-2} (0.01 and 0.02 g-cal cm^{-2} min^{-1}). With clouds present, the amount of diffuse radiation can be much greater. The total sky hemisphere during an overcast day may contribute as much as 0.069 W cm^{-2} (1.0 g-cal cm^{-2} min^{-1}) of radiation to a horizontal surface.

Table 4.2 presents expected extremal surface temperatures and the sky radiation values for selected locations of interest to NASA. The surface temperatures are primarily the result of a balance between incoming and outgoing radiative energy along with convection effects. As a black-body radiator, the clear sky is considered equivalent to a cold surface. The radiation temperature of the clear sky is the same during the day as at night. It is the clear sky acting as a cold sink, without the incoming solar radiation heating of the surface, that causes air temperatures to be lower at night than during the day. At night, clouds act as a barrier to the outgoing radiation. Clouds absorb outgoing IR and emit radiation at lower temperature, making the effective atmospheric temperature warmer than the clear sky. Thus the air near the ground will not cool off to as low a temperature on a cloud covered night. Although not a significant factor, atmospheric dust, which is related to wind speed, and pollution aerosols behave in a similar fashion. Therefore, the greatest cooling of the Earth's surface occurs with calm winds (no mixing with warmer air) and clear skies.

TABLE 4.2 Surface Air And Sky Radiation Temperature Extremes.

Area		Surface Air Temperature Extremes[a]				Sky Radiation	
		Maximum Extreme	Maximum 95%[b]	Minimum Extreme	Minimum 95%[b]	Extreme Minimum Equivalent Temperature	Equivalent Radiation (g-cal cm^{-2} min^{-1})
Huntsville, Alabama	°C	40.0	36.7	–23.9	–12.8	–30.0	0.28
	°F	104	98	–11	9	–22	
Kennedy Space Center, Florida[c]	°C	37.2	35.0	–7.2	0.6	–15.0	0.36
	°F	99	95	19	33	5	
Vandenberg AFB, California[c]	°C	37.8	29.4	–3.9	1.1	–15.0	0.36
	°F	100	85	25	34	5	
Edwards AFB, California	°C	45.0	41.7	–15.6	–7.8	–30.0	0.28
	°F	113	107	4	18	–22	
Honolulu, Oahu – Hickam Field	°C	33.9	32.8	11.1	15.6	–15.0	0.36
	°F	93	91	52	60	5	
Guam – Andersen AFB	°C	34.4	31.1	18.9	22.2	–15.0	0.36
	°F	94	88	66	72	5	
Santa Susana, California	°C	42.2	36.1	–2.2	1.7	–15.0	0.36
	°F	108	97	28	35	5	
Thiokol Wasatch Division, Utah[d]	°C	40.0	35.6	–29.4	–16.1	–30.0	0.28
	°F	104	96	–21	3	–22	
New Orleans, Lousiana[e]	°C	38.9	35.0	–10.0	–3.3	–17.8	0.35
	°F	102	95	14	26	0	
Stennis Space Center Mississippi[f]	°C	39.4	35.6	–14.4	–2.2	–17.8	0.35
	°F	103	96	6	28	0	
Continent Transportation (rail, truck, river barge)	°C	47.2	–	–34.4	–	–30.0	0.28
	°F	117	–	–30	–	–22	
Ship Transportation (West Coast, Panama Canal, Gulf of Mexico)	°C	37.8	–	–12.2	–	–15.0	0.36
	°F	100	–	10	–	5	
Johnson Space Center, Texas	°C	40.0	36.7	–9.4	–2.2	–17.8	0.35
	°F	104	98	15	28	0	
GSFC-Wallops Flight Facility, Virginia	°C	38.3	33.3	–20.0	–5.6	–17.8	0.35
	°F	101	92	–4	22	0	
White Sands Missile Range, New Mexico[g]	°C	44.4	38.9	–25.6	–10.0	–30.0	0.28
	°F	112	102	–14	14	–22	

a. The extreme maximum and minimum temperatures will be encountered during periods of wind speeds less than about 1 m/s.

b. Based on daily extreme (maximum or minimum) observations for worst month.

c. Sky temperature limits for shuttle launch at KSC and VAFB as given in NSTS 07700 Appendix 10.10 are 50° F for a design high and –30°F for a design low.

d. Includes extreme temperature observations at Bear River Refuge, UT.

e. Applies for the Michoud Assembly Facility (New Orleans, LA) and the Slidell Computer Complex (Slidell, LA).

f. Includes extreme temperature observations at Picayune, MS.
g. Also applies for Northrup Strip. Includes extreme temperature observations at Alamogordo and Holloman AFB, NM.

Radiation interchange with the sky should be based on the design high and design low effective sky temperatures of 50 ^{o}F and –30 ^{o}F, respectively (Ref. 4.9). These are representative of any global launch site or reentry region.

Maximum values of solar radiation for several locations, as a function of surface wind speed, are given in Table 4.3. These decreased values are primarily the result of additional particulate matter in the atmosphere due to wind speed increases.

TABLE 4.3 Solar Radiation Maximum Values Associated With Extreme Wind Values.

Maximum Solar Radiation (Normal Incident)						
Steady-State Ground Wind Speed at 18-m Height	Huntsville, New Orleans, Stennis, JSC, Gulf Transportation, Eastern Range, Western Range, West Coast Transportation and Wallops Flight Facility			White Sands Missile Range		
(m s^{-1})	(kJm^{-2} s^{-1})	(g-cal cm^{-2} min^{-1})	(Btu ft^{-2} h^{-1})	(kJm^{-2} s^{-1})	(g-cal cm^{-2} min^{-1})	(Btu ft^{-2} h^{-1})
10	0.84	1.20	265	1.05	1.50	322
15	0.56	0.80	177	0.70	1.00	221
≥20	0.35	0.50	111	0.56	0.80	177

4.3.5.2 Absorbed Radiation. The various gases in the atmosphere selectively absorb some of the incoming radiation. The absorbed energy warms the gas and is reradiated at different (typically longer) wavelengths. Absorption by gases is observed in the solar spectrum as bands of various widths. The major gases in the Earth's atmosphere, which show as absorption bands in the solar spectrum, are water vapor, carbon dioxide, ozone, and molecular oxygen.

4.4 Total Solar Radiation at the Earth's Surface

4.4.1 Introduction. This subsection presents a description of the total solar radiation, its definitions, and applications for use in design.

Standard solar radiation sensors measure the intensity of direct solar radiation from the Sun falling on a horizontal surface, plus the diffuse (sky) radiation from the total sky hemisphere at the Earth's surface where the instrument is located. This may not be at sea level. Diffuse radiation is lowest with dry, clean air; it increases with increasing water vapor, water droplets, or dust in the air. With extremely dense clouds or fog, the measured solar radiation will be nearly all diffuse radiation, with the total measured amount being much lower than the solar radiation on a clear day (see 4.3.5.1). The higher (≈95 percentile) values of measured horizontal solar radiation occur under very clear skies or under conditions of scattered fair weather cumulus clouds which reflect additional solar radiation onto the measuring sensor.

4.4.2 Use of Solar Radiation in Design. When radiation data are used in design studies, the direct solar radiation should be applied from one direction as parallel rays, and, at the same time, diffuse radiation must be applied as rays from all directions of a hemisphere (see fig. 4.2).

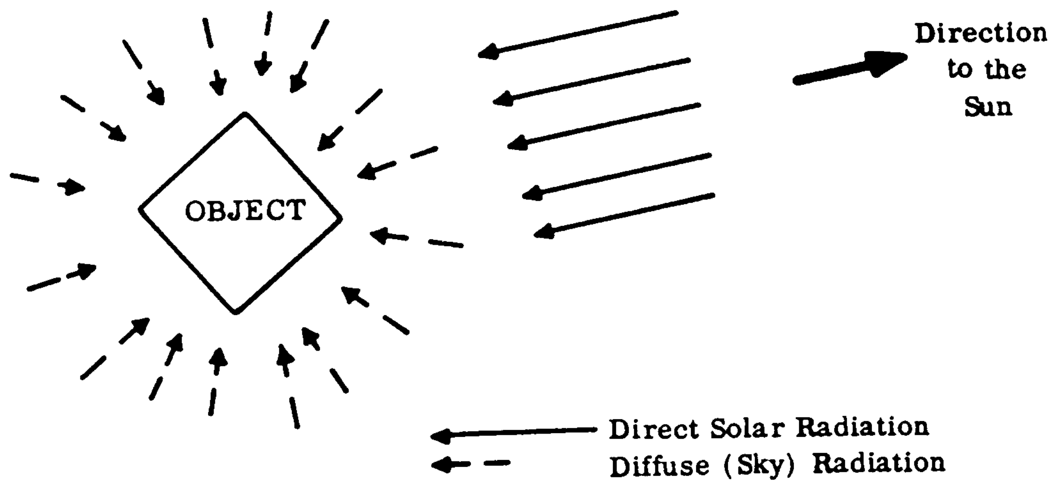


FIGURE 4.2 Method of Applying Radiation for Design.

Because the Sun provides heat (from radiation) from a specific direction, differential heating of an object occurs; i.e., one part is heated more than another. This may result in stress and deformation. As an example, the side of the space shuttle vehicle facing the Sun is heated, while the sky cools the opposite side. This differential heating causes the vehicle to bend away from the Sun sufficiently, at the top, to be a required consideration in the design of platforms surrounding the vehicle. These platforms are used to ready the vehicle on the launch pad and must be designed so as to prevent damage to the vehicle skin from the platform, as the vehicle bends.

4.4.3 Total Solar Radiation Computations and Extreme Conditions. Ten years of total horizontal solar and diffuse (sky) radiation data were selected from measuring stations at two geographic locations for analysis to determine the frequency distribution of solar radiation for use in design. The data analysis was made by the National Oceanic and Atmospheric Administration (NOAA), National Climatic Data Center, under contract to NASA-Marshall Space Flight Center.

4.4.3.1 Computing Total Normal Incident Solar Radiation. The basic data used in computing the normal incident radiation (I_{TN}) were hourly totals of horizontal (direct) solar (I_{TH}) and diffuse (sky) radiation (I_{dH}) for each hour of the day for a 10-year period at each of two locations: Apalachicola, Florida (to represent Kennedy Space Center, Florida) and Santa Maria, California (to represent Vandenberg AFB, California). The hourly totals were divided by 60 to obtain the average solar radiation values per minute for each hour of the day. The units of this data are g-cal cm^{-2} min^{-1}. The average value per minute is numerically equal to intensity. These values were used in the computation of frequency distributions. The diffuse sky radiation intensities (I_{dH}) were empirically estimated for each value based on the amount of total horizontal (direct) solar radiation (I_{TH}) and diffuse (sky) radiation

(I_{dH}) measured and the solar elevation angle, similar to the methods used in Ref. 4.10. After the diffuse sky radiation (I_{dH}) is subtracted from the total horizontal solar and sky radiation, the resultant horizontal radiation (I) can be used to compute the direct normal incident radiation (I_{DN}) by using the following equation (refs. 4.11, 4.12, and 4.13).

$$I_{DN} = \frac{I}{\sin b} \ , \qquad (4.5)$$

where

I_{DN} = direct normal incident solar radiation

I = horizontal solar radiation = $I_{TH} - I_{dH}$

b = solar elevation angle, in degrees (refs. 4.12 and 4.13).

Any of the solar radiation units, such as g-cal cm^{-2} min^{-1}, W cm^{-2}, W m^{-2}, Btu ft^{-2} h^{-1}, or other units may be used in any of the following equations depending on the source of the data (refs. 4.12 and 4.13).

The total normal solar radiation I_{TN} values were found by adding the direct normal incident solar radiation (I_{DN}) and the diffuse sky radiation (I_{dH}) as previously estimated from the contract with NOAA and presented in Tables 4.4 and 4.5; i.e.,

$$I_{TN} = I_{DN} + I_{dH} \ . \qquad (4.6)$$

This method of finding the normal incident solar radiation may result in a slight overestimate of the value for low solar elevation because the sky hemisphere may be intercepted by the ground surface above the normal horizon. This error is insignificant, however, when extreme values are used and would be small for values equal to or greater than the mean plus one standard deviation.

To determine the amount of solar radiation on a south-facing surface, with the normal at some angle X to the horizon, the following equations may be used:

$$I_{D(X)} = I(\sin X \text{ deg} = \cot b \cos a \cos X \text{ deg}) \ , \qquad (4.7)$$

where

$I_{D(X)}$ =intensity of direct solar radiation on a south-facing surface, the normal being X degrees to the horizontal

I = horizontal solar radiation $I_{TH} - I_{dH}$

a = Sun's azimuth measured from the south direction, either east or west in degrees

b = Sun’s elevation angle above the true horizon, in degrees

If we wish to include the diffuse radiation, we can use the following equation:

$$T_{TN} = I_{D(X)} + I_{dH} \quad . \tag{4.8}$$

4.4.3.2 Solar Radiation Extremals. To present the solar radiation data in a simplified form, the month of June was selected to represent the summer and the longest period of daylight, and December was selected for the winter and shortest period of daylight. The June Santa Maria, California, data for normal incident solar radiation (I_{DN}) were measured at the Earth's surface. These data were increased for the period from 1100 to 1900 hours to reflect the higher values which occur early in July (first week) during the afternoon. This was done because of the frequent fog which occurs in June and lasts most of the day.

TABLE 4.4 Extreme Values of Solar Radiation for the Vandenberg AFB, West Coast Transportation, Santa Susana, White Sands Missile Range, Brigham City, and Edwards AFB.

Time of Day (Local Standard Time)	Total Horizontal Solar Radiation g-cal cm^{-2} min^{-1}		Diffuse Radiation* g-cal cm^{-2} min^{-1}		Total Normal Incident Solar Radiation g-cal cm^{-2} min^{-1}		Total 45° Surface Solar Radiation g-cal cm^{-2} min^{-1}	
	June							
	Extreme	95 Percentile	Extreme	95 Percentile	Extreme	95 Percentile	Extreme	95 Percentile
0500	0	0	0	0	0	0	0	0
0600	0.16	0.11	0.02	0.04	1.14	0.78	0.04	0
0700	0.46	0.40	0.05	0.08	1.34	1.08	0.19	0.16
0800	0.82	0.76	0.06	0.09	1.54	1.38	0.34	0.31
0900	1.16	1.11	0.04	0.08	1.74	1.62	0.84	0.77
1000	1.45	1.42	0	0.03	1.79	1.71	1.19	1.12
1100	1.64	1.56	0	0.10	1.79	1.69	1.39	1.31
1200	1.69	1.63	0	0.08	1.74	1.68	1.49	1.38
1300	1.69	1.64	0	0.07	1.74	1.68	1.49	1.40
1400	1.59	1.54	0.06	0.12	1.74	1.68	1.34	1.29
1500	1.45	1.39	0	0.06	1.79	1.70	1.14	1.09
1600	1.21	1.19	0	0.02	1.79	1.71	0.89	0.78
1700	0.87	0.83	0.03	0.05	1.69	1.60	0.34	0.18
1800	0.46	0.42	0.05	0.08	1.39	1.23	0.19	0.13
1900	0.14	0.12	0.02	0.04	1.19	0.93	0.04	0
2000	0	0	0	0	0	0	0	0
	December							
	Extreme	95 Percentile	Extreme	95 Percentile	Extreme	95 Percentile	Extreme	95 Percentile
0800	0	0	0	0	0	0	0	0
0900	0.35	0.32	0.04	0.05	1.59	1.39	0.99	0.85
1000	0.65	0.60	0.03	0.05	1.64	1.53	1.29	1.21
1100	0.86	0.80	0	0.04	1.84	1.64	1.64	1.49
1200	0.96	0.89	0.02	0.06	1.79	1.69	1.74	1.63
1300	0.99	0.89	0	0.06	1.84	1.70	1.79	1.64
1400	0.85	0.80	0.01	0.04	1.79	1.64	1.59	1.49
1500	0.66	0.60	0.02	0.05	1.69	1.54	1.34	1.21
1600	0.38	0.31	0.02	0.05	1.64	1.38	1.04	0.87
1700	0	0	0	0	0	0	0	0

*Diffuse radiation, associated with total horizontal solar radiation extremes.

TABLE 4.5 Extreme values of solar radiation for Eastern Range (KSC), Stennis Space Center, JSC, New Orleans, Gulf Transportation, and Huntsville.

Time of Day (Local Standard Time)	Total Horizontal Solar Radiation g-cal cm^{-2} min^{-1}		Diffuse Radiation* g-cal cm^{-2} min^{-1}		Total Normal Incident Solar Radiation g-cal cm^{-2} min^{-1}		Total 45° Surface Solar Radiation g-cal cm^{-2} min^{-1}	
	June							
	Extreme	95 Percentile	Extreme	95 Percentile	Extreme	95 Percentile	Extreme	95 Percentile
0500	0	0	0	0	0	0	0	0
0600	0.12	0.07	0	0	1.09	1.00	0	0
0700	0.42	0.36	0.05	0.07	1.29	1.04	0.19	0.16
0800	0.82	0.71	0.04	0.10	1.59	1.30	0.34	0.27
0900	1.23	1.02	0	0.10	1.59	1.48	0.49	0.41
1000	1.35	1.30	0.02	0.06	1.59	1.54	0.99	0.95
1100	1.52	1.45	0.03	0.09	1.59	1.54	1.19	1.14
1200	1.58	1.53	0.10	0.16	1.64	1.55	1.29	1.24
1300	1.58	1.50	0.10	0.20	1.64	1.53	1.29	1.24
1400	1.50	1.44	0.05	0.12	1.59	1.52	1.19	1.09
1500	1.35	1.30	0.02	0.06	1.59	1.52	1.04	0.95
1600	1.10	1.01	0.05	0.12	1.54	1.44	0.54	0.44
1700	0.77	0.72	0.05	0.09	1.49	1.33	0.34	0.30
1800	0.48	0.40	0.03	0.06	1.44	1.14	0.19	0.18
1900	0.11	0.08	0	0	1.14	1.00	0.14	0.03
2000	0	0	0	0	0	0	0	0
	December							
	Extreme	95 Percentile	Extreme	95 Percentile	Extreme	95 Percentile	Extreme	95 Percentile
0700	0	0	0	0	0	0	0	0
0800	0.16	0.10	0	0	1.34	1.12	0.64	0.50
0900	0.46	0.42	0.04	0.06	1.44	1.36	0.94	0.89
1000	0.79	0.71	0.01	0.07	1.69	1.60	1.39	1.29
1100	0.95	0.92	0.02	0.04	1.79	1.68	1.64	1.56
1200	1.09	1.02	0	0.03	1.79	1.70	1.74	1.66
1300	1.05	1.02	0	0.03	1.79	1.78	1.74	1.66
1400	0.94	0.89	0.02	0.05	1.74	1.67	1.59	1.63
1500	0.79	0.70	0	0.03	1.74	1.57	1.39	1.27
1600	0.46	0.41	0.04	0.06	1.54	1.40	0.99	0.91
1700	0.16	0.10	0	0	1.34	1.12	0.64	0.50
1800	0	0	0	0	0	0	0	0

*Diffuse radiation, associated with total horizontal solar radiation extremes.

Tables 4.4 and 4.5 give the frequency distributions for the extreme* values and the 95 percentile values for the different types of solar radiation as a function of hours of the day. The values given for diffuse radiation are the values which occurred in association with the extremes and the 95th percentiles of the other solar radiations given. Direct sunlight with surrounding cumulus clouds may give significantly higher values of radiation. Since the diffuse sky radiation decreases with increasing total horizontal solar radiation, the values given in Tables 4.4 and 4.5 are lower than the highest values of diffuse radiation which occurred during the period of record. They should be used with the other extreme values. Tables 4.4 and 4.5 both present the total solar radiation intensities received on a south-facing surface, with the normal to the surface at 45□ to the horizon, as dictated by equation (4.7). Solar radiation data recommended for use in design are given in Table 4.6 and figure 4.3 versus time of day. The design high curve presents clear day direct incident solar radiation to a horizontal surface. The actual radiation absorbed by a surface would be a function of the surface optical properties and the surface geometry relative to the Sun vector. The design low curve presents cloudy day diffuse solar radiation which would apply to all surfaces. The actual radiation absorbed by these surfaces would also be a function of surface optical properties. These data should be used in conjunction with the sky temperature defined in section 4.3.5.1..

4.4.3.3 Variation With Altitude. Solar radiation intensity on a surface will increase with altitude above the Earth's surface, with clear skies, according to the following equation (the LOWTRAN 7 code can be used to calculate I_H):

$$I_H = I_{DN} + (1.94 - I_{DN}\left(1 - \frac{\rho_H}{\rho_S}\right) , \qquad (4.9)$$

where

I_H = intensity of solar radiation normal to surface at required height

I_{DN} = intensity of solar radiation normal to surface at the Earth's surface assuming clear skies ($I_{DN} = I_{TN} - I_{dH}$)

ρ_H = atmospheric density at required height (from U.S. Standard Atmospheres, U.S. Standard Supplemental Atmospheres, or this document) (kg m^{-3})

ρ_S = atmospheric density at sea level (from U.S. Standard Atmospheres, U.S. Standard .... Supplemental Atmospheres, or this document) (kg m^{-3})

S = solar constant (in g-cal cm^{-2}).

The diffuse radiation I_{dH} decreases with altitude above the Earth's surface, with clear skies. A good estimate of the value can be obtained from the following equation:†

$$I_{dH} = 0.7500 - 0.4076\, I_H \ , \qquad (4.10)$$

where

I_{dH} = intensity of diffuse radiation

I_H = intensity of solar radiation normal to surface.

Equation (4.10) is valid for values of I_H from equation (4.9) up to 1.84 g-cal cm^{-2}. For values of I_H greater than 1.84 g-cal cm^{-2}, $I_{dH} = 0$.

4.4.3.4 Solar Radiation During Extreme Wind Conditions. When ground winds occur exceeding the 95, 99, or 99.9 percentile design winds given in section 2 of this document, the associated weather normally is such that clouds, rain, or dust is generally present; therefore, the intensity of the incoming solar radiation will be less than the maximum values given in Tables 4.4 and 4.5. Maximum values of solar radiation intensity to use with corresponding wind speeds are given in Table 4.3.

* Extreme as used in this section is the highest measured value of record.

† Equation (4.10) is based on a cloudless and dust-free atmosphere.

TABLE 4.6 Recommended Design High And Design Low Solar Radiation (Ref. 4.9).

Local Time of Day	Design High Solar Radiation		Local Time of Day	Design Low Solar Radiation	
Hour	Btu/ft^2/h	g-cal/cm^2/min	Hour	Btu/ft^2/h	g-cal/cm^2/min
0500	0	0.00	0655	0	0.00
1100	363	1.64	1100	70	0.32
1400	363	1.64	1300	80	0.36
2000	0	0.00	1710	0	0.00

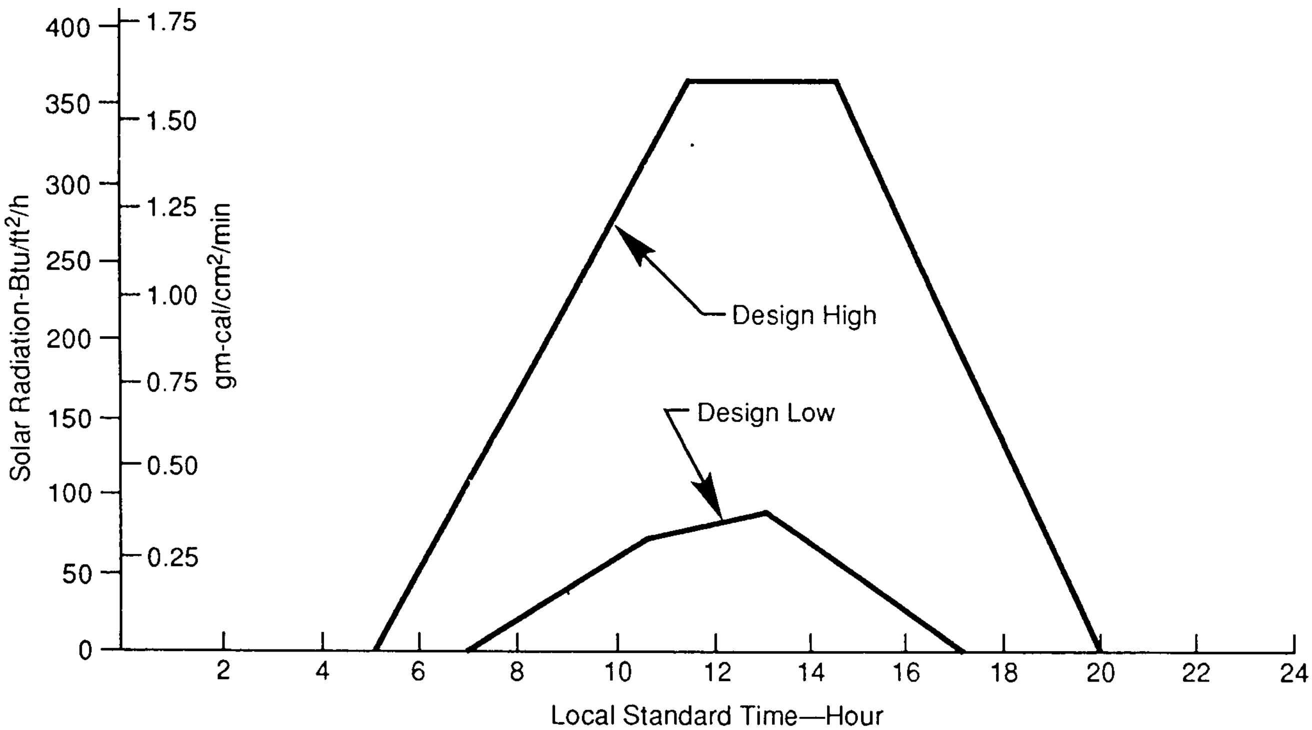


FIGURE 4.3 Recommended Design Solar Radiation at Ground Level (Ref. 4.9).

NOTE: Design high is direct incident solar radiation to a horizontal surface. Design low is diffuse incident radiation to any surface.

4.5 Reradiation and Temperature Effects. Objects receiving solar or other radiation absorb some of the energy and reradiate energy in the infrared band. The exchange of energy will heat or cool an object and may also affect surrounding objects.

4.5.1 Average Emittance of Objects. In thermal engineering studies, the color of a surface, especially when painted, is not important for low-temperature radiation (i.e., below about 0 °C for most painted surfaces). At such low temperatures, the absorptivity is about the same in the visible spectrum. The word "emittance" (or emissivity) is used to describe such data. Emittance is the ratio of the actual measured value to the emittance of a black body (considered “1.00”) (ratio is always less than one). The emittance of some substances is essentially the same at all wavelengths. Such radiators are referred to as "gray" bodies. However, in most real substances the emittance varies as a function of wavelength and the temperature of the object. Colored surfaces may differ in absorptivity as was shown in tests with thermisters having different spectral responses when used on radiosondes at Marshall Space Flight Center (Ref. 4.14) and also at Goddard Space Flight Center (Ref. 4.15). A list of values of emissivity and absorptivity for various surfaces and different colors of paint exposed to solar radiation is presented in reference 4.11. Similar data are available in other publications. These give either a range of values for different wavelengths or mean values for each type of surface. Nearly all paints have very high emittances in the infrared region of the spectrum, yet most metals have lower emittance in the infrared. The change of temperature of an object (above or below the air temperature), which is the amount of heating or cooling, is proportional to the emittance or absorptivity. Therefore, the accuracy of determining the temperature of a surface exposed to radiation is related to the accuracy of the values of emittance and absorptivity available. Spectral distribution curves of emittance are available (or can be determined) for many surfaces. Knowing the emittance curve, the average emittance of any surface can be computed by the following method:

a. Divide the spectral emittance curve (i.e., that given in Figure 4.4) into small intervals that have small or no change of emittance within the interval.

b. Using the same intervals from the spectral distribution of radiation (i.e., from Table 4.1), multiply each value of emittance over the selected interval by the percentage of radient power over the interval.

c. Sum the resultant products to give the average emittance.

Table 4.7 and figure 4.4 give an example of such emittance computations for a white surface with data from figure 4.1 and Table 4.1 being used. Similar computations can be accomplished for other sources of radiation such as the night sky or from cloudy skies.

4.5.2 Computation of Surface Temperature From One Radiation Source. Note: In the following computations, except in equation (4.13), degrees Kelvin must be used. In equation (4.13), any unit of temperature may be used. Units of solar radiation must be in the same unit system as the Stefan-Boltzmann constant.

The extreme value of temperature which a surface may reach when exposed to daytime (solar) or nighttime (night sky) radiation with no wind (calm), assuming it has no mass or heat transfer within the object, is

$$T_S = T_A + \mathrm{E}\,(\Delta T_{BS}) \;, \qquad (4.11)$$

where

T_S = surface temperature (K)

T_A = air temperature (K)

E = emittance of surface

TABLE 4.7 Computation of Emittance of White Paint ($BaSO_4$ And MgO) Exposed to Direct Solar Radiation at the Earth's Surface.

Wavelength (μ)	Emittance (Ratio)	Average Emittance (Ratio)	Solar Radiation, 1 Atmosphere (%)	Solar Radiation Over Interval (%)	Product of Average Emittance and Percent Solar Radiation Over Interval Divided by 100
0.300	0.73		0.03		
0.330	0.45	0.590	1.25	1.22	0.0072
0.350	0.37	0.410	2.80	1.55	0.0063
0.500	0.36	0.365	23.80	21.00	0.0766
0.580	0.29	0.325	35.57	11.77	0.0382
0.700	0.23	0.260	51.11	15.54	0.0404
0.800	0.22	0.225	61.48	10.37	0.0233
0.900	0.30	0.260	69.36	7.88	0.0205
1.000	0.44	0.370	76.07	6.71	0.0248
1.200	0.60	0.520	85.39	9.32	0.0485
1.400	0.70	0.650	88.83	3.44	0.0224
1.600	0.79	0.745	93.40	4.57	0.0340
1.900	0.83	0.810	96.41	3.01	0.0244
50.000	0.83	0.830	100.0	3.59	0.0298
Sum = average emittance = 0.396					

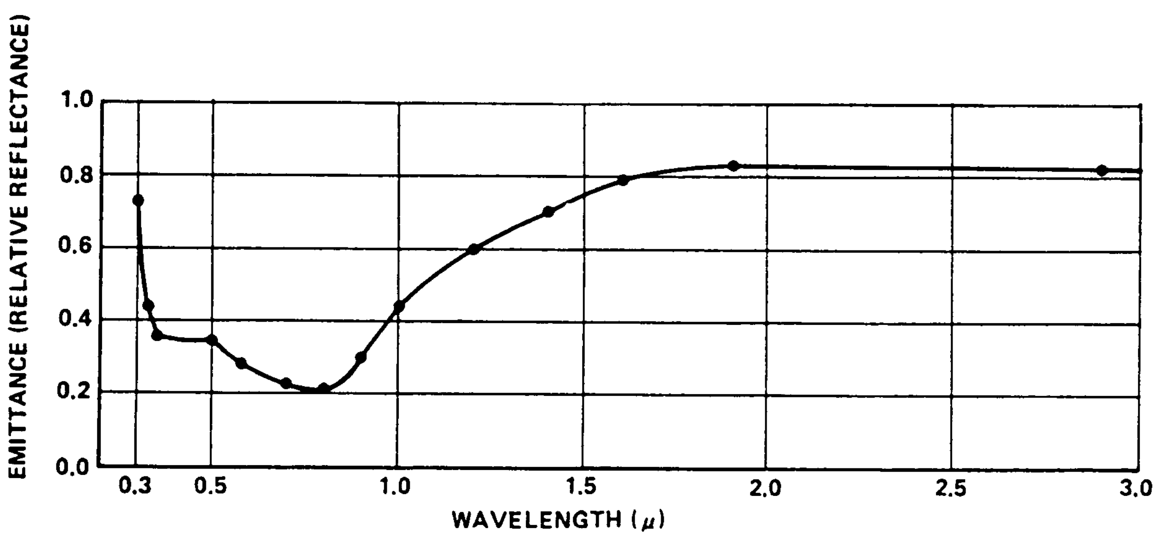


FIGURE 4.4 Plot of Measured Emittance of Barium Sulfate and Magnesium Oxide (White Paint) Versus Wavelength When Exposed to the Solar Spectrum.

ΔT_{BS} = Surface temperature differential resulting in an increase in blackbody temperature (K) from daytime solar radiation (plus); or a decrease in blackbody temperature (K) from day or nighttime sky radiation (minus), calculated from

$$\Delta T_{BS} = \left(\frac{I_{TS}}{\sigma}\right)^{1/4} - T_A \ . \qquad (4.12)$$

Equation (4.12) gives the surface radiative balance, i.e., absorbed radiation = emitted radiation.

Extreme values of ΔT_{BS} can be obtained from figure 4.5A or Table 4.8, where

I_{TS} = total radiation (solar by day) (sky for night) received at surface. These values can be extremes from Tables 4.4, 4.5, or 4.2 from this report.

σ = Stefan-Boltzmann constant

= 8.312×10^{-11} g-cal cm^{-2} K^{-4}

= 5.6697×10^{-12} W cm^{-2} K^{-4}.

The term $(I_{TS}/\sigma)^{1/4}$ is equal to the extreme blackbody surface temperature.

If a correction for wind speed is desired, equation (4.11) can be used as follows:

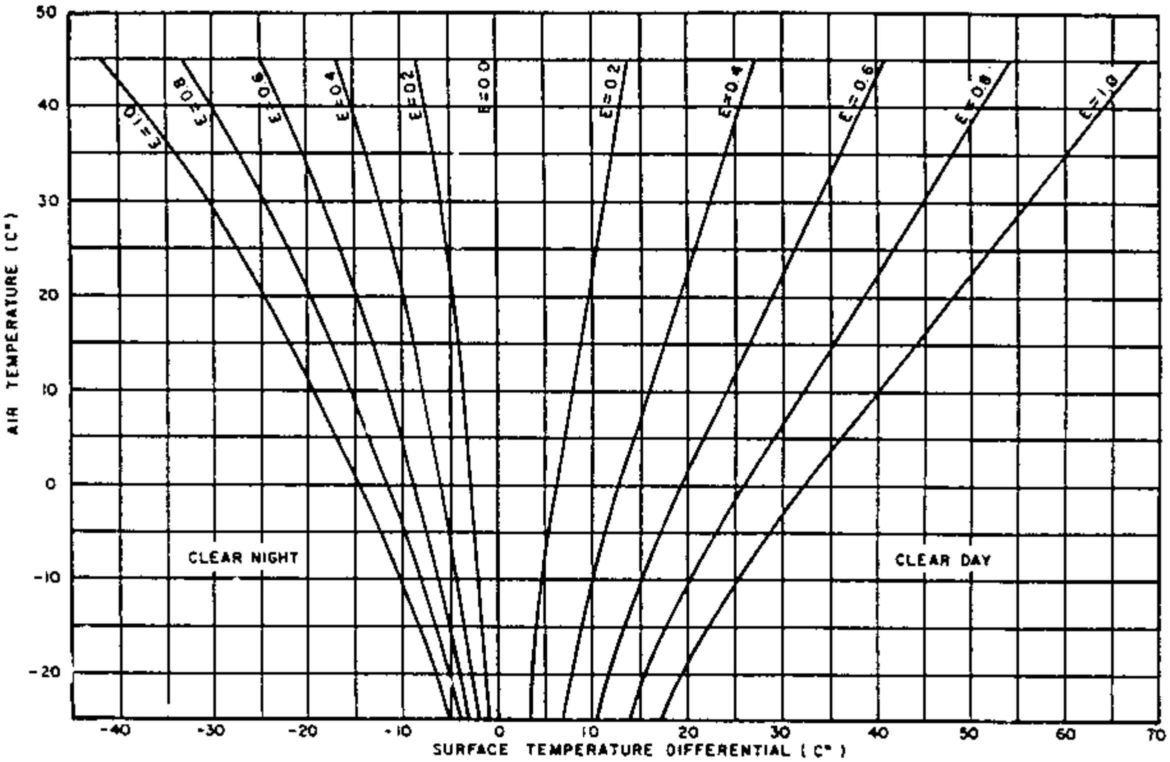
$$T_S = T_A + E(\Delta T_{BS})\frac{f_w}{100} \ , \qquad (4.13)$$

where f_w is the correction for wind speed in percent from figure 4.5B. Equations (4.11), (4.12), and (4.13) are only for computing the effect of one source of radiation on a surface. When more than one radiation source is received by an object, then a more complex method must be used, as given in subsection 4.5.3. The value of f_w is for sea level (1.0 atmosphere pressure). For values at higher altitudes the value of

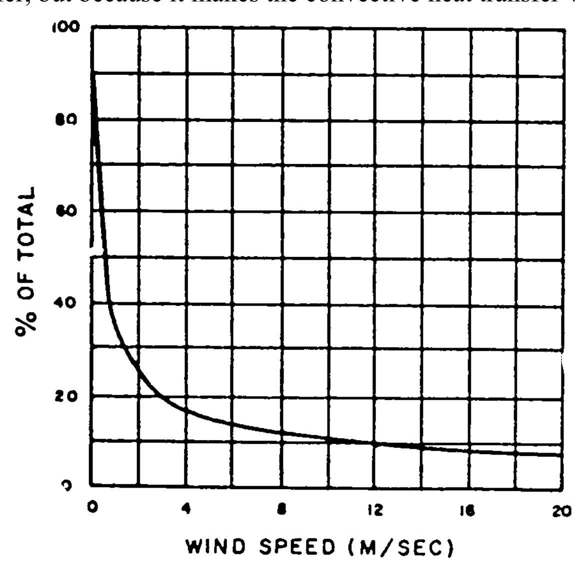
$$f_{w_{alt}} = f_w\,(\rho_{alt}/\rho_{sea\ level}) \ . \qquad (4.13A)$$

4.5.3 Computation of Surface Temperature From Several Simultaneous Radiation Sources. If we have a blackbody with several radiation sources and no forced or natural convection (calm wind), then the total radiation balance (I) can be computed from the Stefan-Boltzmann law:

$$\sigma T^4 = \sum_{i}^{n} I_i \qquad i = 1, 2, 3, \ldots, n \ . \qquad (4.14)$$



A. Surface temperature differential (ΔT_{BS}) with respect to air temperature for surface with emittance between 0.0 and 1.0 for a calm wind. The temperature difference, after correction for wind speed, is added or subtracted to the air temperature to give the surface (skin) temperature. Wind speed has a great effect, not because it changes the radiation part of the heat transfer, but because it makes the convective heat transfer very significant.



B. Correction (*fw*) for wind speed to the surface temperature difference (obtained from graph A). Valid only for a pressure of one atmosphere.

FIGURE 4.5 Extreme Surface (Skin) Temperature of an Object Near the Earth's Surface (0 To 300 M) for Clear Sky.

TABLE 4.8 Extreme surface (skin) temperature above or below air temperature of an object near the Earth's surface.

Air Temperature (°C)	Surface Temperature Differential (°C)									
	Clear Night					Clear Day				
	Wind Speed (m s^{-1})					Wind Speed (m s^{-1})				
	0	2	4	10	20	0	2	4	10	20
	Correction Factor					Correction Factor				
	1.00	0.25	0.17	0.11	0.08	1.00	0.25	0.17	0.11	0.08
–25	–5.0	–1.2	–0.8	–0.6	–0.4	16.9	4.2	2.9	1.9	1.4
–20	–6.5	–1.6	–1.1	–0.7	–0.5	19.2	4.8	3.3	2.1	1.5
–15	–8.2	–2.0	–1.4	–0.9	–0.6	22.0	5.5	3.7	2.4	1.8
–10	–10.2	–2.6	–1.7	–1.1	–0.8	25.1	6.3	4.3	2.8	2.0
–5	–12.2	–3.0	–2.1	–1.3	–1.0	28.5	7.1	4.8	3.1	2.3
0	–14.5	–3.6	–2.5	–1.6	–1.2	32.0	8.0	5.4	3.5	2.6
5	–16.9	–4.2	–2.9	–1.9	–1.4	36.0	9.0	6.1	4.0	2.9
10	–19.4	–4.8	–3.3	–2.1	–1.6	40.0	10.0	6.8	4.4	3.2
15	–21.9	–5.5	–3.7	–2.4	–1.8	44.0	11.0	7.5	4.8	3.5
20	–24.6	–6.2	–4.2	–2.7	–2.0	48.0	12.0	8.2	5.3	3.8
25	–27.4	–6.8	–4.6	–3.0	–2.2	52.0	13.0	8.8	5.7	4.2
30	–30.5	–7.6	–5.2	–3.4	–2.4	56.0	14.0	9.5	6.2	4.5
35	–34.0	–8.5	–5.8	–3.7	–2.7	60.0	15.0	10.2	6.6	4.8
40	–37.7	–9.4	–6.4	–4.1	–3.0	64.0	16.0	10.9	7.0	5.1
45	–41.7	–10.4	–7.1	–4.6	–3.3	68.0	17.0	11.6	7.5	5.4

NOTE: Values are given for solar absorbtivity and an emittance value of 1.0, i.e., black body. Temperature differences for other emittance can be determined by multiplying tabular value by the appropriate emittance.

Then

$$T - T_A = \Delta T_{BS} = \left(\frac{\sum_{1}^{n} I_{i_1}}{\sigma} \right) - T_A \ , \qquad (4.15)$$

where T_A is the air temperature.

For any object exposed to any type of radiation in the Earth's atmosphere, the following function may be used.

$$\Delta T_{BS} = f_w \left(\frac{\sum_{1}^{n} E_i I_i}{\sigma} \right)^{1/4} - T_A \ , \qquad (4.16)$$

where

E_i = emittance of object for corresponding radiation source I_i

$$\Delta T_{BS} = T - T_A \qquad (4.17)$$

f_w = wind effect (convection)

$$f_w = \frac{0.325}{\sqrt{w}} \ , \qquad (4.18)$$

w = wind speed (m/s).

4.6 Temperature. Several types of temperatures at the Earth's boundary layer must be considered in design. These are as follows:

a. Air temperatures at surface level (normally measured at a height of 1.22 m (4 ft) above a grass surface in special shelter) (see section 4.6.1). Temperatures at various altitudes above the surface are given in the Reference Atmosphere tables of section 3.

b. Changes of air temperature with changes in solar radiation intensity (usually the rapid changes which occur in less than 24 hours) are given in section 4.6.2.

c. Measurement of surface or skin temperature of a surface exposed to radiation is presented in section 4.6.3.

d. Temperatures within a closed compartment. See section 4.6.4.

All of the above will be discussed in the following Subsections.

4.6.1 Extreme Air Temperature Near the Surface. Surface air temperature extremes (maximum, minimum, and 95-percentile values) and the extreme minimum sky radiation (equal to the out-going radiation) are given in Table 4.2 for various geographical areas. Maximum and minimum temperature values should be expected to last only a few hours during a daily period.* Generally, the maximum temperature is reached after 12 noon and before 5 p.m., while the minimum temperature is reached just before sunrise. Table 4.9 shows the maximum and minimum design air temperatures for each hour at Kennedy Space Center. These curves represent a cold and hot extreme day. The method of sampling the day (frequency of occurrence of observations) will result in the same extreme values if the same period of time for the data is used, but the 95-percentile values will be different for hourly, daily, and monthly data reference periods. Selection of the reference period depends on engineering application. Table 4.10 gives monthly mean temperatures, standard deviations, and 2.5 and 97.5 percentiles of temperature values for Kennedy Space Center, Florida, and Vandenberg AFB, California. United States and worldwide temperature extremes are given in section 5.

4.6.2 Extreme Air Temperature Change Over Time.

a. For all areas the design values of extreme air temperature changes (thermal shock) are:

(1) An increase of air temperature of 10 °C (18 °F) with a simultaneous increase of solar radiation (measured on a normal surface) from 0.50 g-cal cm^{-2} min^{-1} (110 Btu ft^{-2} h^{-1}) to 1.85 g-cal cm^{-2} min^{1} (410 Btu ft^{-2} h^{-1}) may occur in a 1-hour period. Likewise, the reverse change of the same magnitude may occur for decreasing air temperature and solar radiation.

(2) A 24-hour change may occur with an increase of 27.7 °C (50 °F) in air temperature in a 5-hour period, followed by 4 hours of constant air temperature, then a decrease of 27.7 °C (50 °F) in a 5-hour period, followed by 10 hours of constant air temperature.

* The equivalent radiation values given here were computed from the equivalent temperature minimum extremes by using the Stefan-Boltzmann law (σT^4).

TABLE 4.9 Maximum and Minimum Design Surface Air Temperatures at Each Hour For KSC [a]

Time (LST)	Annual Maximum Temperature		Annual Minimum Temperature b, c	
Hours	°C	°F	°C	°F
1 a.m.	28.9	84	–3.3	26
2	28.9	84	–3.9	25
3	29.4	85	–4.4	24
4	28.3	83	–4.4	24
5	28.9	84	–5.0	23
6	29.4	85	–5.6	22
7	30.6	87	–6.1	21
8	31.1	88	–5.6	22
9	33.3	92	–3.9	25
10	34.4	94	–2.2	28
11	35.0	95	–1.7	29
12 noon	36.1	97	–0.6	31
1 p.m.	37.2	99	0.0	32
2	36.1	97	+2.8 (+3.3)	37 (38)
3	36.7	98	+2.8 (+3.9)	37 (39)
4	36.1	97	+2.2 (+4.4)	36 (40)
5	36.1	97	+1.1 (+4.4)	34 (40)
6	35.0	95	0.0 (+1.7)	32 (35)
7	33.3	92	–0.6	31
8	31.7	89	–1.1	30
9	31.1	88	–1.7 (–1.1)	29 (30)
10	30.0	86	–2.2 (–1.7)	28 (29)
11	30.0	86	–2.2	28
12 mid	30.0	86	–2.2	28

a. Data based on Patrick Air Force Base and Kennedy Space Center records.

b. Many KSC minimum temperatures are representative of the January 21–22, 1985, cold spell. This cold spell altered most minimum temperature values. These values given represent annual extreme conditions, but can also be used in a continuous 24-hour cycle of extreme KSC cold temperature conditions starting at 9 a.m. January 21 (25 °F) through 8 a.m. January 22 (22 °F). The minimum values given for 2, 3, 4, 5, 6, 9, and 10 p.m. are not representative of the January 1985 cold spell. Cold spell values for these hours in January 21, 1985, are presented in brackets to the right. Note that the maximum values cannot be used in a continuous time cycle.

c. Note that the minimum temperature of record for this location, as given in Tables 3.4 and 4.2, is –7.2 °C (19 °F).

TABLE 4.10 Monthly Mean, Standard Deviations (STD), and 2.5 and 97.5 Percentile Values of Temperature for Kennedy Space Center, Florida and Vandenberg AFB, California.

	Kennedy Space Center				Vandenberg AFB			
			Percentiles				Percentiles	
Month	Monthly Mean or 50 Percentile (°F)	Standard Deviation 30-Day Average	30-Day 2.5%[a] (°F)	Average 97.5%[a] (°F)	Monthly Mean or 50 Percentile (°F)	Standard Deviation 30-Day Average	30-Day 2.5%[a] (°F)	Average 97.5%[a] (°F)
January	59.9	3.5	53.1	66.7	50.9	1.7	47.6	54.2
February	59.8	4.8	50.4	69.2	51.1	2.0	47.1	55.1
March	64.4	3.1	58.3	70.5	51.6	1.8	48.1	55.1
April	70.1	1.3	67.6	72.6	52.4	1.6	49.3	55.5
May	74.5	0.9	72.8	76.2	53.2	1.1	51.2	55.7
June	77.8	1.3	75.3	80.3	55.6	1.7	52.2	59.0
July	79.2	1.2	76.8	81.6	56.9	1.7	53.0	59.5
August	78.9	0.7	77.6	80.2	58.3	1.7	55.0	61.6
September	78.5	1.1	76.3	80.6	59.2	2.0	55.3	63.1
October	73.9	1.7	70.3	77.1	58.6	1.8	55.0	62.2
November	67.0	2.8	61.3	72.4	54.7	2.1	50.5	58.9
December	60.6	3.0	54.8	66.4	51.0	2.7	45.7	56.3

a. Recommended for use in solid rocket motor propellant bulk temperature predictions for design analyses. See (Ref. 14.9) Natural Environment Design Requirements – Appendix 10.10 of NSTS 07700, Volume X.

b. For Eastern Range (Kennedy Space Center), the 99.9-percentile air temperature changes are as follows:

(1) An increase of air temperature of 5.6 °C (11 °F) with a simultaneous increase of solar radiation (measured on a normal surface) from 0.50 g-cal cm^{-2} min^{-1} (110 Btu ft^{-2} h^{-1}) to 1.60 g-cal cm^{-2} min^{-1} (354 Btu ft^{-2} hr^{-1}), or a decrease of air temperature of 9.4 °C (17 °F) with a simultaneous decrease of solar radiation from 1.60 g-cal cm^{-2} min^{-1} (354 Btu ft^{-2} h^{-1}) to 0.50 g-cal cm^{-2} min^{-1} (110 Btu ft^{-2} h^{-1}) may occur in a 1-hour period.

(2) A 24-hour temperature change may occur as follows: An increase of 16.1 °C (29 °F) in air temperature (wind speed under 5 m/s) in an 8-hour period, followed by 2 hours of constant air temperature (wind speed under 5 m/s), then a decrease of 21.7 °C (39 °F) in air temperature (wind speed between 7 and 10 m/s) in a 14-hour period.

4.6.3 Surface (Skin) Temperature. The temperature of the surface of an object exposed to radiation (solar, day sky, or night sky) is usually different from the air temperature (refs. 4.16 and 4.17). The amount of the extreme difference in temperature between a black body object and the surrounding air temperature is given in Table 4.8 and figure 4.5A for exposure to a clear night (or day)* sky or to the Sun on a clear day with calm winds. A change in the flow of air across an object will change the balance between the heat transfer, resulting from radiation and convection-conduction. The difference in the temperature between air and the object will decrease with increasing wind speed (Ref. 4.18). Part B of figure 4.5 provides information for making the correction for wind speed. These values are also given in Table 4.8 for different wind speeds.

4.6.4 Compartment Temperatures

4.6.4.1 Introduction. A cover of material enclosing an air space will conduct heat to (or remove heat from) the inside air when the cover is heated by solar radiation (or cooled by the night sky). This results in the compartment air space being frequently considerably hotter or cooler than the surrounding air. The temperature reached in a compartment is dependent on the location of the air space with respect to the heated surface, the type, thickness, and optical properties of the surface material, the type of construction, and the insulating value of the material. Adding more layers of material with high insulating value on the inside surface of the compartment will greatly reduce the heating or cooling of the air in the compartment space (refs. 4.20 and 4.21).

4.6.4.2 Compartment High Temperature Extreme. A compartment probable extreme average high temperature of 87.8 °C (190 °F) for a period of 1 hour and an average high temperature of 65.6 °C (150 °F) for a period of 6 hours must be considered at all geographic locations while aircraft or other transportation equipment is stationary on the ground without air conditioning in the compartment. These extremes will be found at the top and center of the compartment (refs. 4.20 and 4.21).

4.7 Data on Air Temperature Distribution With Altitude. Data on air temperature distribution with altitude are given in section 3.

* Without the Sun's rays striking, the daytime sky is about as cold as the nighttime sky.

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