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A NUMERICAL INTEGRATION SCHEME TO DETERMINE HEMISPHERIC EMITTANCE, SOLAR ABSORPTANCE AND EARTH INFRARED ABSORPTANCE FROM SPECTRAL REFLECTANCE DATA

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ABSTRACT

A numerical method for computing hemispheric emittance, solar absorptance, and earth infrared absorptance from experimentally measured values for the spectral reflectance of a coating is discussed.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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RESEARCH AND DEVELOPMENT OPERATIONS

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A NUMERICAL INTEGRATION SCHEME TO DETERMINE HEMISPHERIC EMITTANCE, SOLAR ABSORPTANCE AND EARTH INFRARED ABSORPTANCE FROM SPECTRAL REFLECTANCE DATA

INTRODUCTION

The total hemispheric emittance (ϵ_T), solar absorptance (α_S), and earth infrared absorptance (α_{IR}) of a selected coating are three of the quantities required to completely specify the optical condition of a surface that is to be used in a space application. This paper describes a numerical method of computing these required quantities from experimentally measured values for the spectral reflectance of a coating.

The result of this method is a numerical integration scheme to calculate ϵ_T, α_S, and α_{IR} that can easily be programmed on a computer. The inputs to the computer program are the spectral reflectance and transmittance or the spectral absorptance and transmittance. The output of this program for several thermal control coatings is given in Appendix A.

TOTAL EMITTANCE

The total emittance of a surface is defined as

$$\epsilon_T = \frac{\text{Energy total emitted by surface at temperature, T}}{\text{Energy total emitted by a black body at same temperature}} ;$$

thus,

$$\epsilon_T = \frac{\int_0^\infty \alpha_\lambda S_T(\lambda)\, d\lambda}{\int_0^\infty S_T(\lambda)\, d\lambda} \quad , \qquad (1)$$

where

α_λ = spectral absorptance of the surface,

$S_T(\lambda)$ = spectral energy distribution emitted by a black body at temperature T, and

λ = wavelength.

Since the input data to this equation are experimental, the integration must be numerical, so the equation for total emittance becomes

$$\epsilon_T = \frac{1}{E_T} \sum_{\lambda=0}^{\infty} \alpha_\lambda S_T(\lambda)\, \Delta\lambda \ , \qquad (2)$$

where $E_T = \int_0^\infty S_T(\lambda)\, d\lambda$ = total black body energy at temperature T.

The method of "weighted ordinates" to calculate the total emittance was described by Atkins [1]. In this method, equal values of $\Delta\lambda$ are used in equation (2).

The method described here is the "100 selected ordinates" which reduces equation (2) to a simpler form.

If the α_λ are picked such that each increment $\Delta\lambda$ contains one percent of the total black body energy, E_T, then the sum becomes

$$\sum_{\lambda=0}^{\infty} \alpha_\lambda S_T(\lambda)\, \Delta\lambda \quad \sum_{\lambda=0}^{\infty} \alpha_\lambda \frac{E_T}{100} \quad , \qquad (3)$$

but, since E_T is independent of λ

$$\sum_{\lambda=0}^{\infty} \alpha_\lambda E_T(\lambda) \Delta\lambda = \frac{E_T}{100} \sum_{\lambda=0}^{\infty} \alpha_\lambda \quad , \qquad \text{Equa. } 4$$

The total emittance equation now becomes

$$\epsilon_T = \frac{1}{100} \sum_{\lambda=0}^{\infty} \alpha_\lambda \quad . \qquad (5)$$

There is an α_λ for each E_λ; therefore, there are 100 independent α_λ's. Thus,

$$\epsilon_T = \frac{1}{100} \sum_{m=1}^{100} \alpha_m \quad . \qquad (6)$$

The equation for total emittance has now been reduced to a sum of the spectral absorptances taken in a special way.

Since the absorptivity is spectrally dependent, the wavelength of the α_m's must be found.

In the typical black body curve seen in Figure 1, one percent of the energy is between the lines A and C. However, the α_m that will be selected to represent this energy segment will not be at λ_A or λ_B, but, at the mid-point, λ_C or at the 0.5 percent interval. Therefore, the desired wavelengths will fall at 0.5 percent, 1.5 percent, etc.

Black body curves vary with the temperature, but they are similar in that

$$\lambda_i T = k_i \qquad (i = 1, 2, 3 \ldots.) \; , \qquad (7)$$

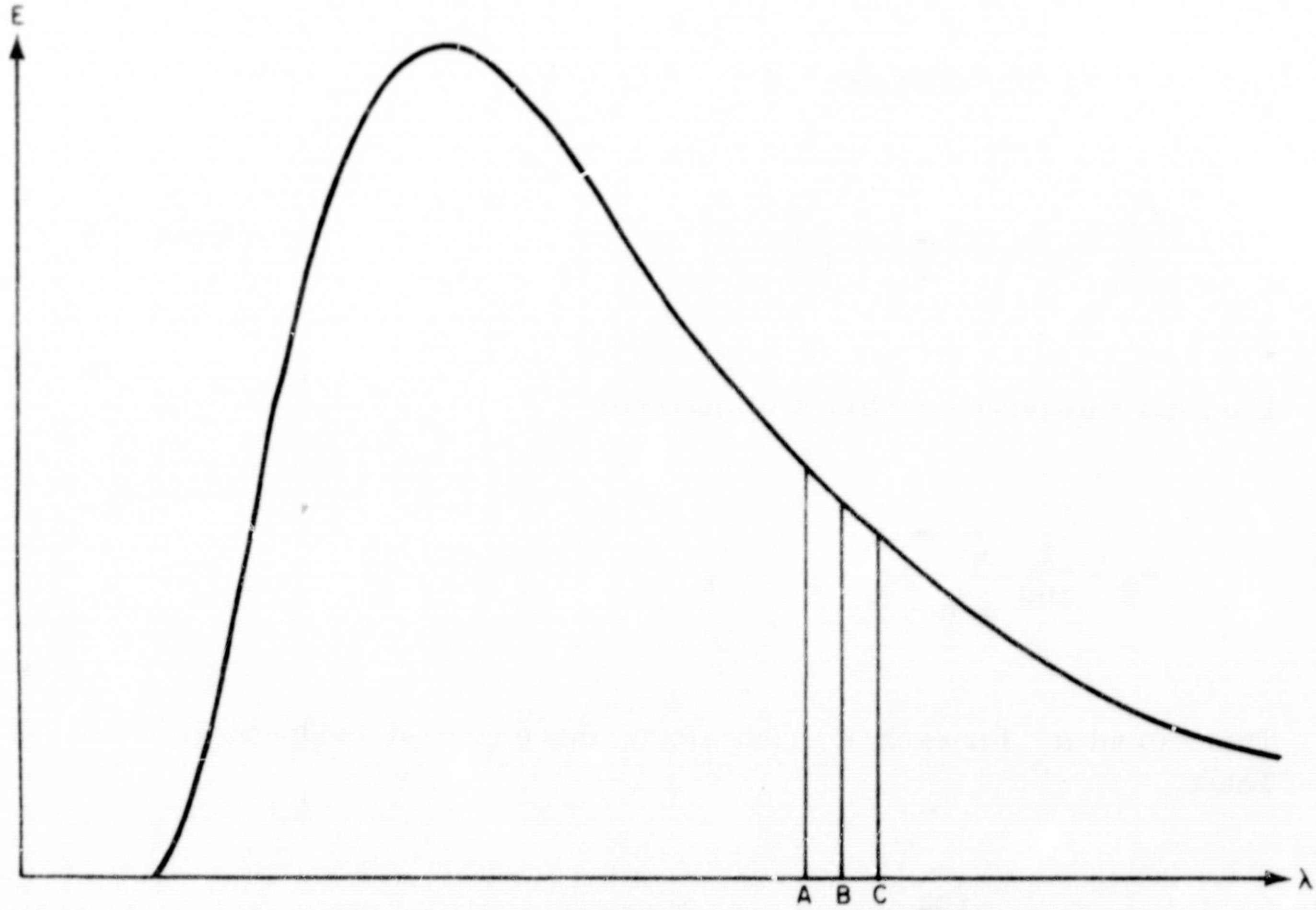

FIGURE 1. TYPICAL BLACK BODY CURVE

where

λ_i = wavelength

T = black body temperature

k_i = constant

The k_i's for the 100 energy points 0.5 percent, 1.5 percent, 2.5 percent, etc., have been computed and are listed in Appendix B. Thus, for a given black body temperature, the wavelengths for the desired absorptances may be easily calculated.

The experimental points for absorptance will seldom fall on the wavelengths given by equation (7); therefore, a linear interpolation between the data points is used to find the α_m's.

The spectral absorptance data that can be obtained with the equipment used does not cover the entire range of the black body curve, so the linear interpolation scheme did not give all the α_m's.

Three techniques were used to obtain the α_m's beyond the endpoints. The first of these is called "no extrapolation." In this method the limits on the integration in equation (1) are reduced to the range covered by the experimental data.

Then, for this case, equation (1) is changed to

$$\epsilon_T = \frac{\sum\limits_{\lambda=\lambda_1}^{\lambda_2} \alpha_\lambda \, S_T(\lambda) \, \Delta\lambda}{\sum\limits_{\lambda=\lambda_1}^{\lambda_2} S_T(\lambda) \, \Delta\lambda} = \frac{1}{100A} \sum_{\lambda_2}^{\lambda_2} \alpha_\lambda \quad ,$$

where λ_1 and λ_2 are the endpoints of the data and

$$A = \frac{\sum\limits_{\lambda_1}^{\lambda_2} S_T(\lambda) \, \Delta\lambda}{E_T} \quad .$$

In the output of this program A represents the percent of the black body curve covered by the data. The complement of A (in percent) is printed by the computer program along with the emittance values under the heading "percent not covered."

In the second method, called "straight extrapolation," the value of α_m beyond the endpoints is taken to be the value of α_m at the endpoint (Fig. 2).

The last method, called the "curved extrapolation," fits a parabola to the last three points at each end of the data (Fig. 3) and uses this curve for choosing α_m in this region. In this method, the value of α_m is forced to stay between 0 and 1 since these values are the minimum and maximum for absorptance.

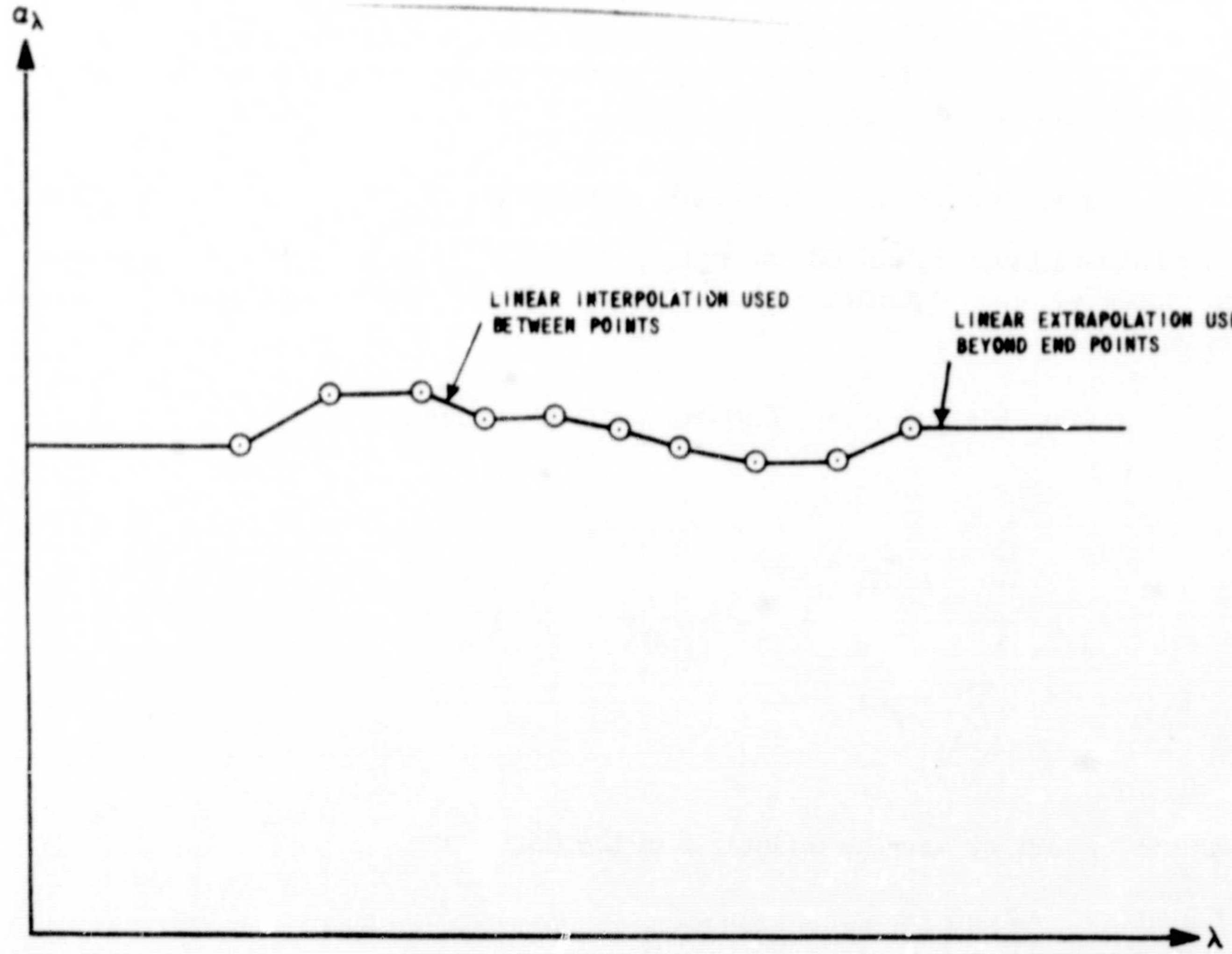

FIGURE 2. "STRAIGHT EXTRAPOLATION" SCHEME

When all the α_m's are found and summed from K = 1 to 100 in equation (6) for all three endpoint cases, the results obtained will be three values of the total emittance. A comparison of the three values will yield a range of values for ϵ_T, but the "no extrapolation" case will usually provide a more useful value for the total emittance.

SOLAR ABSORPTANCE

The total solar absorptance of a surface is calculated the same way as the total emittance, since

$$\alpha_s = \frac{1}{E_s} \int_0^\infty \alpha_\lambda S_s(\lambda)\, d\lambda \approx \frac{1}{E_s} \sum_{\lambda=0}^{\infty} \alpha_\lambda S_s(\lambda)\, \Delta\lambda \quad .$$

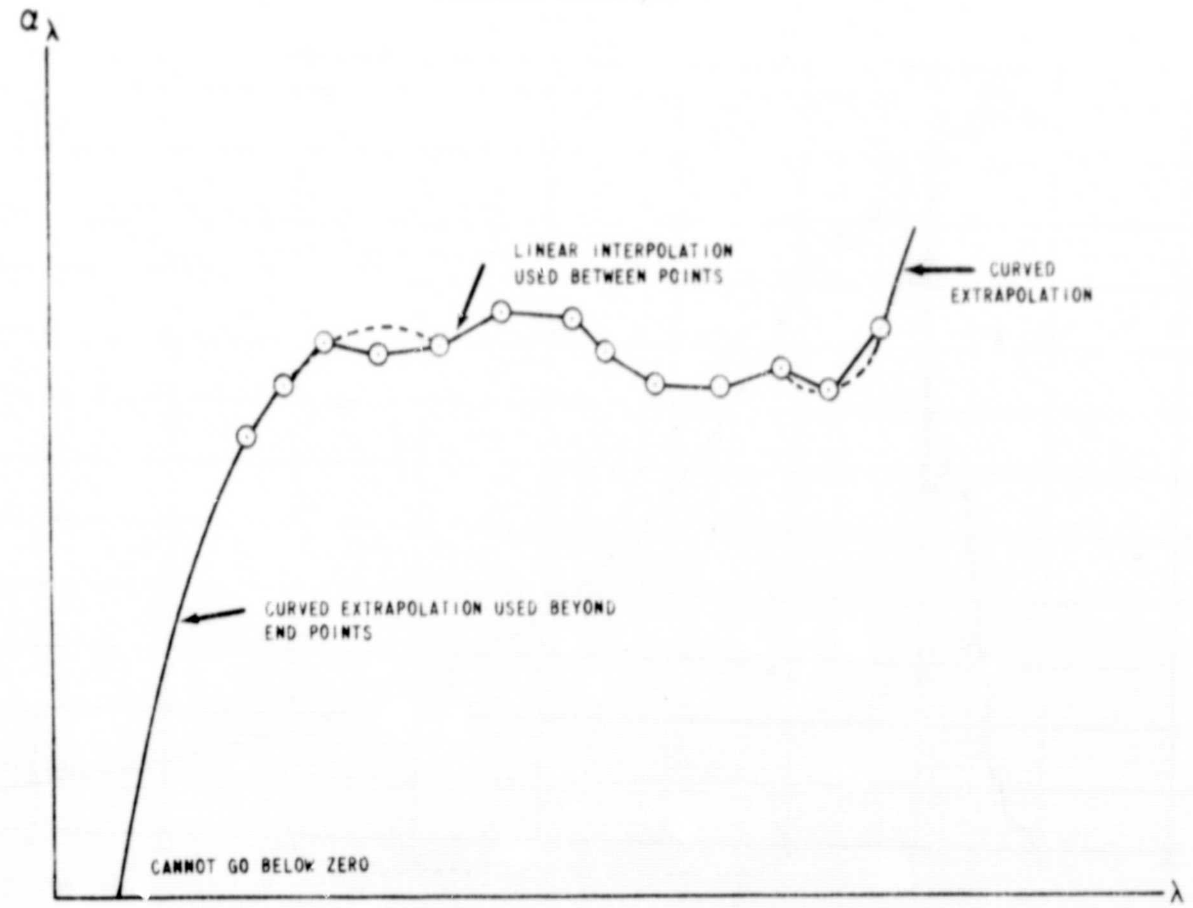

FIGURE 3. "CURVED EXTRAPOLATION" SCHEME

where

α_s = total solar absorptance

α_λ = spectral absorptance of the sample

$S_s(\lambda)$ = spectral solar energy distribution

E_s = integrated solar energy

Thus, if Johnson's solar irradiance curve [2] (Fig. 4) is divided into 100 equal energy bands (Appendix B) , as in the total emittance case, and the α_m's determined as before, the total solar absorptance is

$$\alpha_s = \frac{1}{100} \sum_{m=1}^{100} \alpha_m \quad .$$

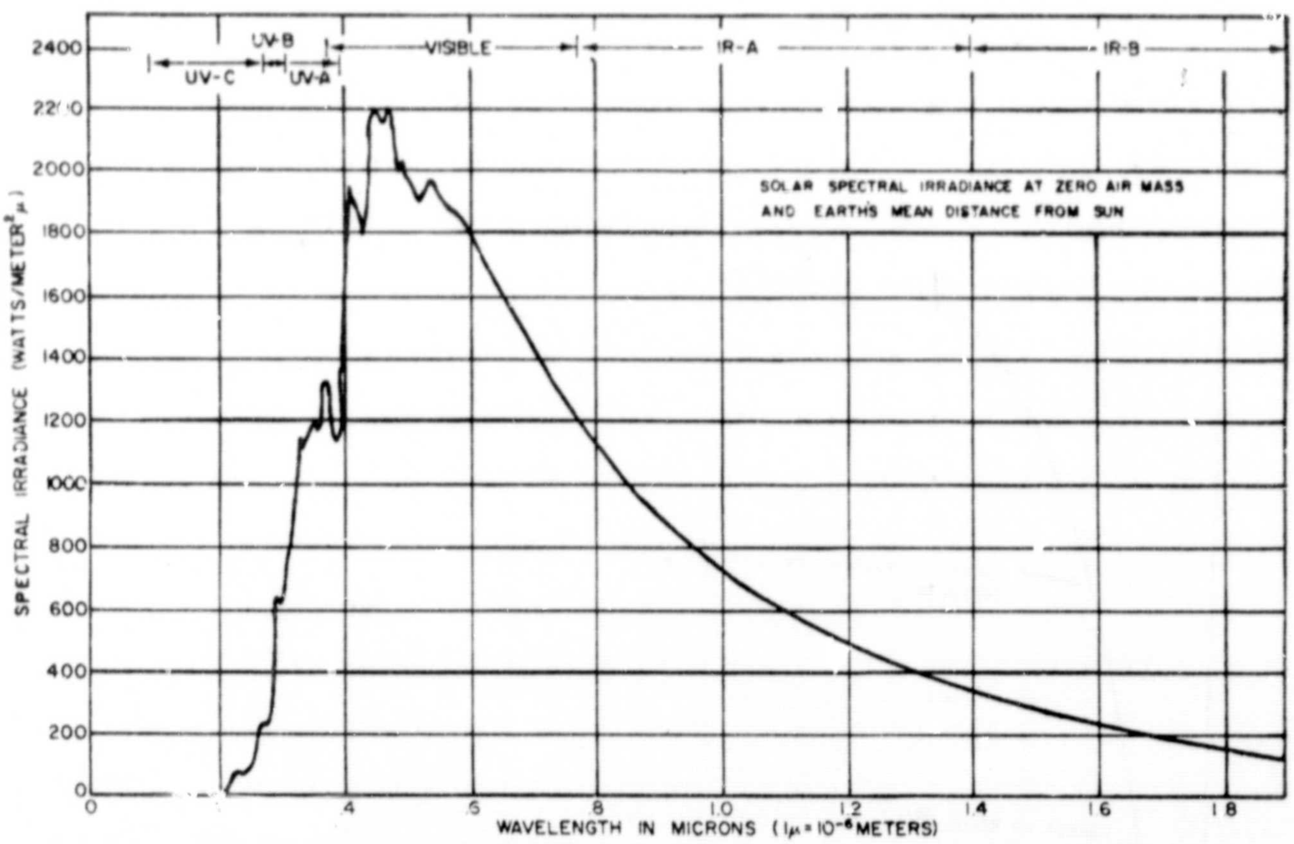

FIGURE 4. JOHNSON'S SOLAR IRRADIANCE CURVE [2]

EARTH INFRARED ABSORPTANCE

The earth IR absorptance, as in the solar case, is defined by the equation

$$\alpha_{IR} = \frac{1}{E} \int_0^\infty \alpha_\lambda S_{IR} \, d\lambda \approx \frac{1}{E} \sum_{\lambda=0}^{\infty} \alpha_\lambda S_{IR}$$

where

α_λ = spectral absorptance

S_{IR} = spectral earth IR emittance distribution

E = integrated earth IR emittance

If the energy under Johnson's earth infrared emission curve (Fig. 5) is divided into one percent energy segments (Appendix B), and an absorptance α_m determined for each one percent energy segment, then the expression for total earth infrared absorptance becomes

$$\alpha_{IR} = \frac{1}{100} \sum_{m=1}^{100} \alpha_m \quad .$$

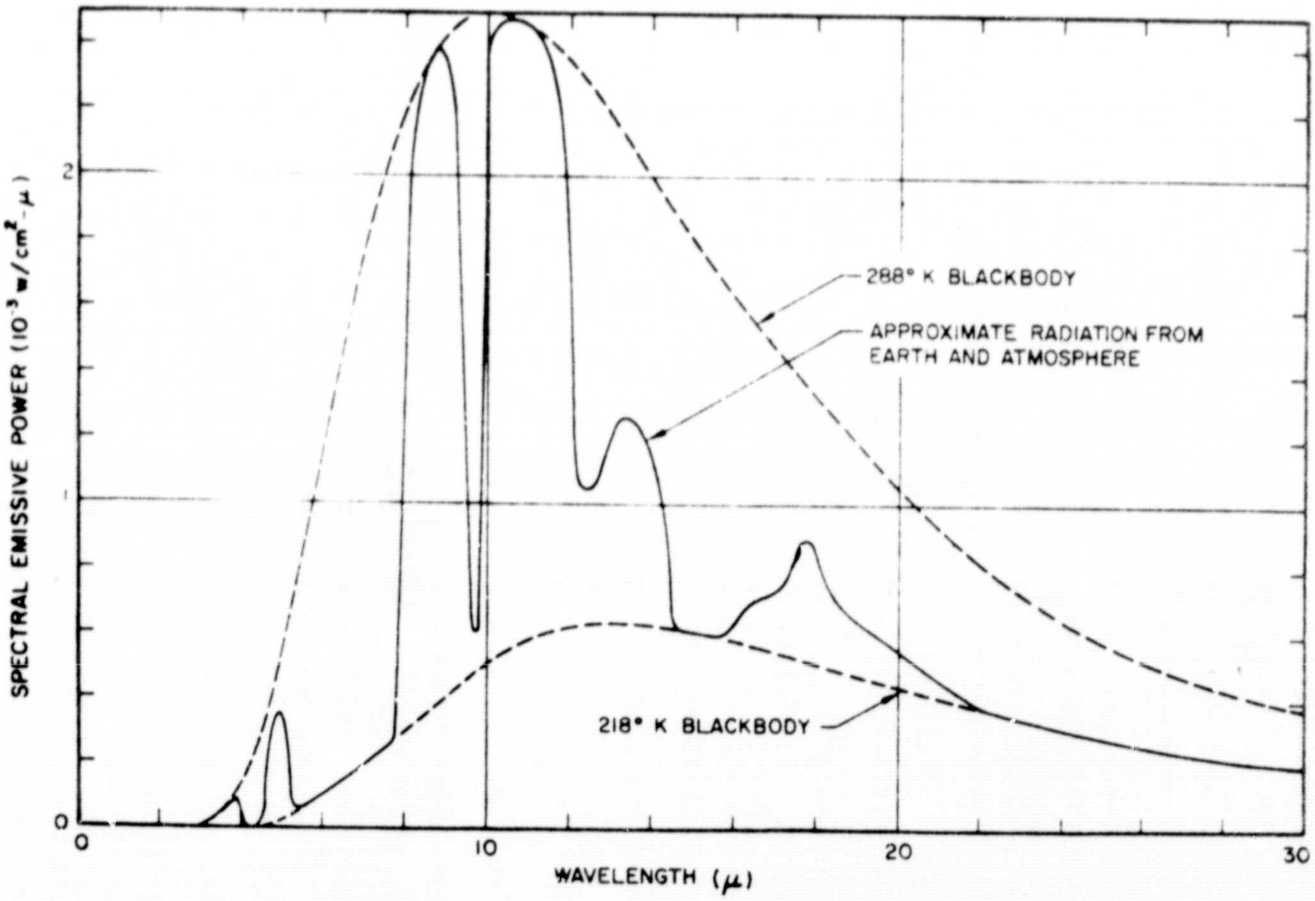

FIGURE 5. JOHNSON'S EARTH INFRARED EMISSION CURVE [2]

APPLICATION TO SPECTRAL DATA

The spectral data used as input to these equations are taken on two different spectrometers. The first is an integrating sphere which provides total hemispherical reflectance measurements from 0.295 microns to 2.6 microns. This range covers all but four percent of the solar spectrum;

therefore, integrating sphere measurements are sufficient to calculate solar absorptance, but not total emittance or earth IR absorptance. These require measurements in the longer wavelength region; therefore, a second spectrometer, a heated Hohlraum (cavity), is used to make total hemispherical measurements in the range from 2.0 microns to 25 microns. This range is sufficient to cover the majority of the energy under the earth infrared curve and the black body curves (black body temperatures from approximately 200 to 500° K).

CONCLUSION

Therefore, for all three cases (ϵ_T, α_s, α_{IR}), the equations reduce to

$$X_i = \frac{1}{100} \sum_{m=1}^{100} \alpha_m \quad ,$$

where $X_i = \epsilon_T$, α_s or α_{IR} with the α_m and $\Delta\lambda$ chosen in a special way. This enables easy programming of the problem on a computer with the required constants to find the λ_m's stored as permanent data. This program will then require only spectral data and black body temperatures to compute ϵ_T, α_s, α_{IR}.

APPENDIX A

SPECTRAL DATA AND COMPUTER RESULTS

Alodine Coating

WAVE LENGTH	EMITTANCE	REFLECTANCE
2.000	.190	.810
2.100	.196	.804
2.200	.190	.810
2.300	.170	.830
2.400	.146	.854
2.500	.150	.850
2.650	.152	.848
2.800	.165	.835
2.950	.170	.830
3.100	.165	.835
3.250	.170	.830
3.400	.265	.735
3.550	.685	.315
3.700	.877	.123
3.850	.880	.120
4.000	.822	.178
4.200	.740	.260
4.400	.645	.355
4.600	.564	.436
4.800	.450	.550
5.000	.375	.625
5.250	.335	.665
5.500	.280	.720
5.750	.265	.735
6.000	.285	.715
6.250	.360	.640
6.500	.483	.517
6.750	.410	.590
7.000	.405	.595
7.400	.485	.515
7.800	.410	.590
8.200	.515	.485
8.600	.675	.325
9.000	.820	.180
9.400	.900	.100
9.800	.940	.060
10.200	.932	.068
10.600	.885	.115
11.000	.870	.130
11.500	.845	.155
12.000	.720	.280
12.500	.640	.360
13.000	.475	.525

Alodine Coating (Cont'd):

13.500	.430	.570
14.000	.395	.605
14.500	.380	.620
15.000	.394	.606
15.500	.425	.575
16.000	.450	.550
16.500	.465	.535
17.000	.475	.525
17.500	.490	.510
18.000	.485	.515
18.500	.485	.515
19.000	.482	.518
19.500	.480	.520
20.000	.460	.540
20.500	.440	.560
21.000	.415	.585
21.500	.400	.600
22.000	.375	.625
22.500	.365	.635
23.000	.340	.660
23.500	.320	.680
24.000	.305	.695
24.500	.285	.715
25.000	.275	.725

Total Emittance

Black body Temp.	STRAIGHT EXTRAPOLATION	CURVED EXTRAPOLATION	NO EXTRAPOLATION	PCT. BLACK BODY NOT COVERED
170.	.38	.18	.48	48
300.	.51	.46	.56	17
370.	.53	.50	.55	9

Total Earth IR Absorptance

	.55	.54	.62	10

Alodine Coating (Cont'd)

WAVE LENGTH	EMITTANCE	REFLECTANCE
.295	.740	.260
.330	.650	.350
.354	.617	.383
.377	.627	.373
.398	.683	.317
.415	.708	.292
.430	.723	.277
.444	.722	.278
.457	.710	.290
.470	.689	.311
.483	.658	.342
.497	.629	.371
.511	.613	.387
.525	.609	.391
.540	.619	.381
.554	.638	.362
.569	.659	.341
.584	.675	.325
.599	.687	.313
.614	.692	.308
.630	.685	.315
.647	.675	.325
.665	.755	.245
.682	.645	.355
.701	.618	.382
.721	.601	.399
.743	.578	.422
.764	.564	.436
.788	.545	.455
.812	.550	.450
.840	.538	.462
.868	.519	.481
.898	.488	.512
.929	.450	.550
.966	.408	.592
1.003	.377	.623
1.043	.348	.652
1.085	.328	.572
1.130	.300	.700
1.180	.277	.723
1.240	.258	.742
1.300	.250	.750
1.380	.228	.772
1.470	.205	.795
1.580	.197	.803
1.710	.193	.807
1.900	.165	.835
2.160	.161	.839
2.620	.175	.825

Total Solar Absorptance

STRAIGHT EXTRAPOLATION	CURVED EXTRAPOLATION	NO EXTRAPOLATION	PCT. BLACK BODY NOT COVERED
.51	.51	.51	4

NOTE: The transmittance value is zero.

Z-93 Coating

WAVE LENGTH	EMITTANCE	REFLECTANCE.
2.000	.150	.850
2.100	.160	.840
2.200	.160	.840
2.300	.175	.825
2.400	.205	.795
2.500	.230	.770
2.650	.260	.740
2.800	.275	.725
2.950	.295	.705
3.100	.335	.665
3.250	.375	.625
3.400	.465	.535
3.550	.620	.380
3.700	.705	.295
3.850	.740	.260
4.000	.765	.235
4.200	.766	.234
4.400	.755	.245
4.600	.745	.255
4.800	.755	.245
5.000	.770	.230
5.250	.760	.240
5.500	.782	.218
5.750	.790	.210
6.000	.810	.190
6.250	.815	.185
6.500	.835	.165
6.750	.840	.160
7.000	.815	.185
7.400	.845	.155
7.800	.825	.175
8.200	.830	.170
8.600	.865	.135
9.000	.855	.145
9.400	.850	.150
9.800	.840	.160
10.200	.835	.165

Z-93 Coating (Cont'd)

10.500	.827	.173
11.000	.790	.210
11.500	.804	.196
12.000	.814	.186
12.500	.820	.180
13.000	.935	.065
13.500	.935	.065
14.000	.935	.065
14.500	.932	.068
15.000	.932	.068
15.500	.937	.063
16.000	.940	.060
16.500	.940	.060
17.000	.940	.060
17.500	.925	.075
18.000	.910	.090
18.500	.900	.100
19.000	.890	.110
19.500	.885	.115
20.000	.880	.120
20.500	.880	.120
21.000	.875	.125
21.500	.870	.130
22.000	.865	.135
22.500	.860	.140
23.000	.850	.150
23.500	.850	.150
24.000	.860	.140
24.500	.840	.160
25.000	.850	.150

Total Emittance

Black Body Temp.	STRAIGHT EXTRAPOLATION	CURVED EXTRAPOLATION	NO EXTRAPOLATION	PCT. BLACK BODY NOT COVERED
170.	.85	1.06	.88	48
300.	.86	.91	.86	17
370.	.84	.87	.84	9

Total Earth IR Absorptance

	.86	.87	.86	19

Z-93 Coating

WAVE LENGTH	EMITTANCE	REFLECTANCE
.295	.670	.330
.330	.920	.080
.354	.940	.060
.377	.820	.180
.398	.350	.650
.415	.230	.770
.430	.135	.865
.444	.130	.870
.457	.120	.880
.470	.105	.895
.483	.095	.905
.497	.092	.908
.511	.085	.915
.525	.082	.918
.540	.075	.925
.554	.072	.928
.569	.070	.930
.584	.078	.922
.599	.075	.925
.614	.058	.942
.630	.058	.942
.647	.060	.940
.665	.060	.940
.682	.055	.945
.701	.058	.942
.721	.055	.945
.743	.054	.946
.764	.060	.940
.788	.060	.940
.812	.059	.941
.840	.057	.943
.868	.065	.935
.898	.062	.938
.929	.062	.938
.966	.063	.937
1.003	.067	.933
1.043	.070	.930
1.085	.067	.933
1.130	.072	.928
1.180	.070	.930
1.240	.073	.927
1.300	.078	.922
1.380	.091	.909
1.470	.095	.905
1.580	.109	.891
1.710	.134	.866
1.900	.202	.798
2.160	.245	.755
2.620	.360	.640

Total Solar Absorptance

STRAIGHT EXTRAPOLATION	CURVED EXTRAPOLATION	NO EXTRAPOLATION	PCT. BLACK BODY NOT COVERED
.16	.17	.15	4

NOTE: The transmittance value is zero.

Lowe Bros. Black

WAVE LENGTH	EMITTANCE	REFLECTANCE
2.000	.940	.060
2.100	.940	.060
2.200	.940	.060
2.300	.940	.060
2.400	.940	.060
2.500	.940	.060
2.650	.940	.060
2.800	.940	.060
2.950	.942	.058
3.100	.940	.060
3.350	.936	.064
3.400	.936	.064
3.550	.940	.060
3.700	.936	.064
3.850	.935	.065
4.000	.936	.064
4.200	.940	.060
4.400	.940	.060
4.600	.940	.060
4.800	.928	.072
5.000	.940	.060
5.250	.940	.060
5.500	.940	.060
5.750	.940	.060
6.000	.937	.063
6.250	.928	.072
6.500	.937	.063
6.750	.930	.070
7.000	.915	.085
7.400	.926	.074
7.800	.937	.063
8.200	.955	.045
8.600	.950	.050
9.000	.954	.046
9.400	.935	.065
9.800	.928	.072
10.200	.926	.074

Lowe Bros. Black

10.000	.942	.058
11.000	.946	.054
11.500	.920	.080
12.000	.935	.065
12.500	.932	.068
13.000	.918	.082
13.500	.915	.085
14.000	.912	.088
14.500	.910	.090
15.000	.905	.095
15.500	.905	.095
16.000	.905	.095
16.500	.905	.095
17.000	.905	.095
17.500	.905	.095
18.000	.905	.095
18.500	.905	.095
19.000	.902	.098
19.500	.900	.100
20.000	.888	.112
20.500	.900	.100
21.000	.895	.105
21.500	.890	.110
22.000	.850	.150
22.500	.838	.162
23.000	.820	.180
23.500	.825	.175
24.000	.830	.170
24.500	.850	.150
25.000	.860	.140

Total Emittance

Black Body Temp.	STRAIGHT EXTRAPOLATION	CURVED EXTRAPOLATION	NO EXTRAPOLATION	PCT. BLACK BODY NOT COVERED
170.	.87	1.07	.89	48
300.	.90	.95	.91	17
370.	.91	.94	.92	9
Total Earth IR Absorptance				
	.90	.92	.92	19

Lowe Bros. Black

WAVE LENGTH	EMITTANCE	REFLECTANCE
[illegible]	.946	.054
.330	.950	.050
.354	.950	.050
.377	.952	.048
.398	.950	.050
.416	.953	.047
.430	.953	.047
.444	.954	.046
.457	.954	.046
.470	.955	.045
.483	.954	.046
.497	.955	.045
.511	.954	.046
.525	.956	.044
.540	.953	.047
.554	.955	.045
.569	.953	.047
.584	.955	.045
.599	.953	.047
.614	.955	.045
.630	.952	.048
.647	.954	.046
.665	.953	.047
.682	.953	.047
.701	.953	.047
.721	.953	.047
.743	.952	.048
.764	.953	.047
.788	.953	.047
.812	.950	.050
.840	.950	.050
.868	.950	.050
.898	.950	.050
.929	.950	.050
.966	.950	.050
1.003	.950	.050
1.043	.950	.050
1.085	.950	.050
1.130	.942	.058
1.180	.950	.050
1.240	.950	.050
1.300	.947	.053
1.380	.950	.050
1.470	.955	.045
1.580	.953	.047
1.710	.955	.045
1.900	.950	.050
2.160	.950	.050
2.620	.952	.048

Total Solar Absorptance

STRAIGHT EXTRAPOLATION	CURVED EXTRAPOLATION	NO EXTRAPOLATION	PCT. BLACK BODY NOT COVERED
.95	.95	.95	4

NOTE: The transmittance value is zero.

S-13 Coating

WAVE LENGTH	EMITTANCE	REFLECTANCE
2.000	.365	.635
2.100	.346	.654
2.200	.383	.617
2.300	.390	.610
2.400	.460	.540
2.500	.615	.385
2.650	.605	.395
2.800	.550	.450
2.950	.590	.410
3.100	.700	.300
3.250	.763	.237
3.400	.850	.150
3.550	.906	.094
3.700	.944	.056
3.850	.955	.045
4.000	.956	.044
4.200	.850	.150
4.400	.790	.210
4.600	.760	.240
4.800	.745	.255
5.000	.740	.260
5.250	.700	.300
5.500	.700	.300
5.750	.695	.305
6.000	.690	.310
6.250	.710	.290
6.500	.840	.160
6.750	.770	.230
7.000	.680	.320
7.400	.810	.190
7.800	.820	.180
8.200	.920	.080
8.600	.947	.053
9.000	.965	.035
9.400	.962	.038
9.800	.964	.036
10.200	.943	.057

S-13 Coating

10.500	.950	.050
11.000	.960	.040
11.500	.960	.040
12.000	.953	.047
12.500	.930	.070
13.000	.890	.110
13.500	.840	.160
14.000	.795	.205
14.500	.770	.230
15.000	.745	.255
15.500	.735	.265
16.000	.725	.275
16.500	.725	.275
17.000	.725	.275
17.500	.722	.278
18.000	.715	.285
18.500	.705	.295
19.000	.705	.295
19.500	.700	.300
20.000	.685	.315
20.500	.700	.300
21.000	.700	.300
21.500	.705	.295
22.000	.705	.295
22.500	.725	.275
23.000	.720	.280
23.500	.705	.295
24.000	.670	.330
24.500	.650	.350
25.000	.630	.370

Total Emittance

Black Body Temp.	STRAIGHT EXTRAPOLATION	CURVED EXTRAPOLATION	NO EXTRAPOLATION	PCT. BLACK BODY NOT COVERED
170.	.70	.30	.76	48
300.	.79	.68	.82	17
370.	.80	.74	.82	9

Total Earth IR Absorptance

	.81	.78	.85	19

S-13 Coating

WAVE LENGTH	EMITTANCE	REFLECTANCE
.295	.550	.450
.330	.907	.093
.354	.929	.071
.377	.754	.246
.398	.250	.750
.415	.160	.840
.430	.113	.887
.444	.120	.880
.457	.110	.890
.470	.105	.895
.483	.100	.900
.497	.097	.903
.511	.100	.900
.525	.100	.900
.540	.100	.900
.554	.100	.900
.569	.100	.900
.584	.104	.896
.599	.110	.890
.614	.096	.904
.630	.096	.904
.647	.102	.898
.665	.104	.896
.682	.104	.896
.701	.106	.894
.721	.106	.894
.743	.112	.888
.764	.115	.885
.788	.120	.880
.812	.130	.870
.840	.128	.872
.868	.135	.865
.898	.144	.856
.929	.144	.856
.966	.154	.846
1.003	.157	.843
1.043	.166	.834
1.085	.170	.830
1.130	.180	.820
1.180	.196	.804
1.240	.200	.800
1.300	.210	.790
1.380	.223	.777
1.470	.227	.773
1.580	.244	.756
1.710	.300	.700
1.900	.274	.726
2.160	.359	.641
2.620	.565	.435

Total Solar Absorptance

STRAIGHT EXTRAPOLATION	CURVED EXTRAPOLATION	NO EXTRAPOLATION	PCT. BLACK BODY NOT COVERED
.21	.23	.20	4

NOTE: The transmittance value is zero.

Rutile (TiO_2) Coating

WAVE LENGTH	EMITTANCE	REFLECTANCE
2.000	.185	.815
2.100	.195	.805
2.200	.280	.720
2.300	.290	.710
2.400	.245	.755
2.500	.230	.770
2.650	.230	.770
2.800	.275	.725
2.950	.460	.540
3.100	.540	.460
3.250	.528	.472
3.400	.715	.285
3.550	.740	.260
3.700	.753	.247
3.850	.835	.165
4.000	.915	.085
4.200	.680	.320
4.400	.500	.500
4.600	.430	.570
4.800	.410	.590
5.000	.498	.502
5.250	.530	.470
5.500	.715	.285
5.750	.660	.340
6.000	.745	.255
6.250	.800	.200
6.500	.890	.110
6.750	.895	.105
7.000	.862	.138
7.400	.945	.055
7.800	.930	.070
8.200	.952	.048
8.600	.970	.030
9.000	.982	.018
9.400	.944	.056
9.800	.934	.066
10.200	.922	.078

Rutile (TiO_2) Coating

10.500	.944	.056
11.000	.950	.050
11.500	.967	.033
12.000	.963	.037
12.500	.920	.080
13.000	.960	.040
13.500	.920	.080
14.000	.920	.080
14.500	.890	.110
15.000	.880	.120
15.500	.820	.180
16.000	.780	.220
16.500	.740	.260
17.000	.735	.265
17.500	.715	.285
18.000	.722	.278
18.500	.750	.250
19.000	.750	.250
19.500	.744	.256
20.000	.670	.330
20.500	.745	.255
21.000	.655	.345
21.500	.720	.280
22.000	.575	.425
22.500	.635	.365
23.000	.600	.400
23.500	.660	.340
24.000	.640	.360
24.500	.700	.300
25.000	.600	.400

Total Emittance

Black Body Temp.	STRAIGHT EXTRAPOLATION	CURVED EXTRAPOLATION	NO EXTRAPOLATION	PCT. BLACK BODY NOT COVERED
170.	.69	-1.30	.78	48
300.	.80	.29	.85	17
370.	.82	.53	.84	9

Total Earth IR Absorptance

	.82	.66	.87	19

Rutile (TiO_2) Coating

WAVE LENGTH	EMITTANCE	REFLECTANCE
.295	.900	.100
.330	.867	.133
.354	.875	.125
.377	.838	.162
.398	.470	.530
.415	.265	.735
.430	.148	.852
.444	.148	.852
.457	.140	.860
.470	.132	.868
.4[illegible]3	.130	.870
.497	.122	.878
.511	.120	.880
.525	.114	.886
.540	.118	.882
.554	.113	.887
.569	.113	.887
.584	.113	.887
.599	.115	.885
.614	.115	.885
.630	.112	.888
.647	.115	.885
.665	.115	.885
.682	.115	.885
.701	.115	.885
.721	.120	.880
.743	.125	.875
.764	.130	.870
.788	.130	.870
.812	.133	.867
.840	.138	.862
.868	.142	.858
.898	.150	.850
.929	.155	.845
.966	.160	.840
1.003	.168	.832
1.043	.165	.835
1.085	.182	.818
1.130	.195	.805
1.180	.203	.797
1.240	.210	.790
1.300	.222	.778
1.380	.245	.755
1.470	.258	.742
1.580	.286	.714
1.710	.322	.678
1.900	.325	.675
2.160	.425	.575
2.620	.555	.445

Total Solar Absorptance

STRAIGHT EXTRAPOLATION	CURVED EXTRAPOLATION	NO EXTRAPOLATION	PCT. BLACK BODY NOT COVERED
.24	.25	.22	4

NOTE: The transmittance value is zero.

APPENDIX B

ONE-PERCENT ENERGY BANDS

TABLE I. ONE PERCENT ENERGY BANDS FOR JOHNSON'S SOLAR CURVE

%E	λ	%E	λ
.5	.2793	30.5	.5500
1.5	.3053	31.5	.5575
2.5	.3235	32.5	.5650
3.5	.3355	33.5	.5721
4.5	.3484	34.5	.5800
5.5	.3603	35.5	.5871
6.5	.3714	36.5	.5950
7.5	.3824	37.5	.6025
8.5	.3945	38.5	.6108
9.5	.4038	39.5	.6185
10.5	.4110	40.5	.6267
11.5	.4186	41.5	.6305
12.5	.4258	42.5	.6433
13.5	.4336	43.5	.6417
14.5	.4407	44.5	.6600
15.5	.4475	45.5	.6691
16.5	.4573	46.5	.6782
17.5	.4600	47.5	.6873
18.5	.4669	48.5	.6970
19.5	.4731	49.5	.7070
20.5	.4794	50.5	.7170
21.5	.4864	51.5	.7270
22.5	.4931	52.5	.7378
23.5	.5000	53.5	.7980
24.5	.5071	54.5	.7595
25.5	.5143	55.5	.7714
26.5	.5217	56.5	.7833
27.5	.5293	57.5	.7952
28.5	.5364	58.5	.8079
29.5	.5431	59.5	.8210

TABLE I (Concluded)

%E	λ	%E	λ
60.5	.8342	80.5	1.1974
61.5	.8474	81.5	1.2273
62.5	.8618	82.5	1.2576
63.5	.8765	83.5	1.2879
64.5	.8912	84.5	1.3231
65.5	.9100	85.5	1.3615
66.5	.9233	86.5	1.4000
67.5	.9400	87.5	1.5476
68.5	.9571	88.5	1.5952
69.5	.9750	89.5	1.6500
70.5	.9929	90.5	1.7070
71.5	1.0125	91.5	1.7769
72.5	1.0333	92.5	1.8535
73.5	1.0542	93.5	1.9565
74.5	1.0750	94.5	2.0887
75.5	1.0958	95.5	2.2588
76.5	1.1205	96.5	2.4820
77.5	1.1461	97.5	2.8136
78.5	1.1718	98.5	2.3846
79.5	1.1718	99.5	4.9667

TABLE II. ONE PERCENT ENERGY BANDS FOR JOHNSON'S EARTH IR CURVE

%E	λ_i	%E	λ_i
.5	4.92700	11.5	8.83400
1.5	6.53800	12.5	8.92600
2.5	7.61900	13.5	9.02000
3.5	8.02300	14.5	9.11400
4.5	8.16400	15.5	9.21000
5.5	8.27100	16.5	9.31700
6.5	8.37000	17.5	9.44300
7.5	8.46600	18.5	9.60300
8.5	8.55800	19.5	9.85600
9.5	8.65100	20.5	10.01100
10.5	8.74300	21.5	10.11200

TABLE II (Continued)

%E	λ_i	%E	λ_i
22.5	10.20200	54.5	14.29800
23.5	10.29200	55.5	14.57200
24.5	10.38100	56.5	14.92500
25.5	10.46900	57.5	15.28200
26.5	10.55800	58.5	15.64500
27.5	10.64600	59.5	16.00900
28.5	10.73500	60.6	16.34400
29.5	10.82300	61.5	16.65500
30.5	10.91100	62.5	16.95700
31.5	11.00000	63.5	17.24800
32.5	11.08800	64.5	17.51700
33.5	11.17700	65.5	17.76800
34.5	11.26700	66.5	18.01500
35.5	11.35700	67.5	18.27800
36.5	11.44700	68.5	18.58200
37.5	11.53800	69.5	18.90500
38.5	11.62900	70.5	19.24700
39.5	11.72400	71.5	19.60800
40.5	11.82200	72.5	19.98900
41.5	11.92800	73.5	20.39600
42.5	12.04700	74.5	20.83300
43.5	12.20700	75.5	21.30900
44.5	12.41100	76.5	21.83600
45.5	12.61800	77.5	22.41500
46.5	12.82100	78.5	23.05000
47.5	13.01100	79.5	23.72400
48.5	13.19100	80.5	24.44000
49.5	13.36600	81.5	25.20500
50.5	13.54000	82.5	26.02900
51.5	13.71600	83.5	27.81400
52.5	13.89800	84.5	28.78300
53.5	14.09000		

For a black body emission curve of temperature T

$$\lambda_i T = K_i \ .$$

The following table is a listing of the K_i's at the 0.5%, 1.5%, 2.5%..... 99.5% points on the curve making it possible to determine the λ_i's at the desired energy points for any temperature T.

TABLE III. BLACK BODY CONSTANTS

%	K_i	%	K_i
.5	1322.	31.5	3186.
1.5	1534.	32.5	3231.
2.5	1662.	33.5	3277.
3.5	1762.	34.5	3323.
4.5	1846.	35.5	3369.
5.5	1920.	36.5	3415.
6.5	1989.	37.5	3462.
7.5	2050.	38.5	3510.
8.5	2111.	39.5	3558.
9.5	2168.	40.5	3607.
10.5	2222.	41.5	3656.
11.5	2274.	42.5	3706.
12.5	2325.	43.5	3757.
13.5	2374.	44.5	3809.
14.5	2423.	45.5	3861.
15.5	2470.	46.5	3914.
16.5	2517.	47.5	3968.
17.5	2563.	48.5	4023.
18.5	2609.	49.5	4079.
19.5	2654.	50.5	4136.
20.5	2698.	51.5	4194.
21.5	2743.	52.5	4254.
22.5	2787.	53.5	4314.
23.5	2831.	54.5	4377.
24.5	2876.	55.5	4440.
25.5	2920.	56.5	4505.
26.5	2964.	57.5	4572.
27.5	3008.	58.5	4640.
28.5	3052.	59.5	4710.
29.5	3097.	60.5	4782.
30.5	3141.	61.5	4856.

TABLE III (Concluded)

%	K_i
62.5	4932.
63.5	5010.
64.5	5091.
65.5	5175.
66.5	5262.
67.5	5351.
68.5	5444.
69.5	5541.
70.5	5641.
71.5	5745.
72.5	5854.
73.5	5968.
74.5	6087.
75.5	6212.
76.5	6343.
77.5	6482.
78.5	6628.
79.5	6783.
80.5	6948.
81.5	7123.
82.5	7311.
83.5	7514.
84.5	7732.
85.5	7969.
86.5	8228.
87.5	8513.
88.5	8829.
89.5	9183.
90.5	9153.
91.5	10042.
92.5	10577.
93.5	11215.
94.5	11996.
95.5	12990.
96.5	14327.
97.5	19724.
98.5	29372.
99.5	16295.

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APPROVAL

IN-SSL-T-68-10

A NUMERICAL INTEGRATION SCHEME TO DETERMINE HEMISPHERIC EMITTANCE, SOLAR ABSORPTANCE AND EARTH INFRARED ABSORPTANCE FROM SPECTRAL REFLECTANCE DATA

By Donald R. Wilkes

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

Gerhard B. Heller

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