NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA CR 71187

Technical Report No. 32-873

Far-Infrared Reflectance of Spacecraft Coatings

D. K. Edwards

W. M. Hall

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

January 31, 1966

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-873

Far-Infrared Reflectance of Spacecraft Coatings

D. K. Edwards
W. M. Hall

C. E. Levoe, Manager
Materials Section

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

January 31, 1966

Prepared Under Contract No. NAS 7-100
National Aeronautics & Space Administration

CONTENTS

I. Introduction 1

II. Apparatus and Procedure 2

III. Theory 3

IV. Results 5

V. Discussion 8

VI. Conclusions 9

References 9

Table 1. Absorption coefficient from transmission data, laminar X-500 resin 5

FIGURES

1. Transmission of laminar X-500 clear film 5
2. Reflectance of laminar X-500 clear film on aluminum substrate 6
3. Transmission of Cat-a-lac clear film 6
4. Reflectance of PV-100 white paint on aluminum substrate 7
5. Reflectance of Cat-a-lac black paint on aluminum substrate 7

PREFACE

This Report was presented at the AIAA Thermophysics Specialist Conference, Monterey, California, September 13–15, 1965, and was published as Paper No. 65-653 by the American Institute of Aeronautics and Astronautics, New York. D. K. Edwards is Associate Professor at the University of California, Los Angeles.

ABSTRACT

19633

Reflectances and transmittances as a function of wavelength are reported for 17 specimens of painted aluminum and paint films. Such measurements were made with a directional integrating-sphere reflectometer in the 0.33- to 2.5-μ region, a directional heated-cavity reflectometer in the 1.5- to 23-μ region, and a far-infrared reciprocal paraboloid reflectometer in the 20- to 61-μ region. The spectral range thus includes 98% of the room-temperature emission spectrum as well as 98% of the extraterrestrial solar spectrum. Coatings of clear resins on aluminum were discovered to have high reflectances in the far-infrared when the film thicknesses were approximately 25 μ or thinner. Reflectance data for the clear-resin-coated aluminum were found to be predictable with some accuracy from the measurements of binormal transmittance (infrared transparency) of resin films together with use of the Fresnel relations. Pigmented paint resins were found to have low reflectances in the far-infrared region investigated even when the film thicknesses on aluminum substrates were as small as 25 μ.

Author

I. INTRODUCTION

In order to predict thermal-radiation transfer between spacecraft elements it is desirable to know, among other things, how much radiation incident from a given direction is absorbed, reflected, or transmitted. For an opaque solid slab in thermodynamic equilibrium, the directional reflectance, which is the ratio of all energy reflected to that incident from a particular direction, serves to describe both the fraction reflected and, by subtraction from unity, the fraction absorbed. Much information on the spectral dependence of the directional reflectance is available for wavelengths up to approximately 25 μ (Refs. 1–8). However, a room-temperature black thermal radiator emits over 17% of the radiation at wavelengths longer than 25 μ (Ref. 9). Uncertainty in the spectral behavior of thermal radiators and receivers beyond 25 μ thus causes a significant uncertainty in spacecraft design heat-transfer calculations.

It is rather difficult to measure spectral directional reflectance directly for an incompletely specular specimen, that is, for one which scatters radiation, because of the need to detect correctly all radiation scattered to the hemisphere above the surface. However, it is even more difficult to make direct spectral absorptance or emittance measurements at room temperature. Fortunately, it is possible to utilize the Helmholtz reciprocity principle, which, in one of its extended forms, states that the directional reflectance is the ratio of the intensity viewed from a slab that is diffusely irradiated to the intensity of the diffuse irradiation (Refs. 10 and 11). A reciprocal paraboloid reflectometer suitable for use in the far-infrared has been designed by application of this principle (Ref. 12). The instrument makes it possible to investigate spacecraft materials at wavelengths several times longer than 25 μ.

It is well known that absorbing films on thick metal substrates lose their absorptance as the wavelength of radiation becomes large compared to the film thickness. This factor has been a cause for concern to the spacecraft designer who employs, for example, painted metal surfaces. There is a weight penalty associated with a very thick coat of paint, but if a thin coat is used, there is a question as to whether or not the spectral reflectance beyond 25 μ becomes large.

Binormal transmittance or transparency measurements of paint or other films are relatively easy to make, even in the far-infrared, because only the nearly undeviated transmitted intensity must be detected. If the designer could be sure that the film does not scatter, he could either use observed transparency, together with an estimate or measurement of refractive index, to predict the behavior of a painted metal by use of the Fresnel relations, or he could use a specular-reflectance measurement technique (Ref. 13) which is nearly as easy as a transparency measurement. Because of inhomogeneities, however, the designer is never certain that scattering or imperfectly diffused reflection is not a significant factor.

It is the purpose of this Report to present spectral measurements of normal reflectance and binormal transmittance of 17 specimens of painted aluminum disks and paint films for a spectral region covering 98% of the infrared spectrum of a room-temperature black body. These measurements are to show at what thickness the paints investigated become transmitting in the far-infrared. Predictions based on the Fresnel relations are to be compared with data for the clear-resin-painted specimens investigated. The change in the reflectance, caused by loading the resin with pigment, is also to be found. Short-wavelength data covering approximately 98% of the extraterrestrial solar spectrum are to be included to show the effect of paint thickness on this region as well.

II. APPARATUS AND PROCEDURE

Directional integrating-sphere apparatus (Ref. 14) was used in the 0.33- to 2.5-μ region, a directional heated-cavity reflectometer (Ref. 15) in the 1.5- to 23-μ region, and a reciprocal paraboloid reflectometer (Ref. 12) in the 20- to 61-μ region. All of these instruments were designed carefully to give an accurate measurement of directional reflectance regardless of the bidirectional reflectance or reflection distribution function of the specimen used. Results are thus correct whether the sample is perfectly specular, perfectly diffuse, or imperfectly diffuse.

The integrating sphere and heated cavity have been described previously and their performance analyzed in detail (Refs. 14–19). The far-infrared paraboloid (Ref. 12) has likewise been subjected to the same type of analysis, and only brief descriptions of the instrumentation are given below.

The directional integrating-sphere reflectometer (Ref. 14) consists of a 20-cm-diameter polished-aluminum sphere coated on the interior by deposition of 3 mm of MgO from burning magnesium with an 8000-v potential between the magnesium ribbon and the sphere. A reflectance specimen is suspended in the center of the sphere and is irradiated through a small port by monochromatic radiation which is obtained from a tungsten ribbon lamp, chopped by a rotating blade, and passed through a Perkin Elmer Model 98 monochromator with a quartz prism. Filters are used to reduce stray radiation at the extremes of the wavelength range. Radiation reflected from the sphere wall is received by a PbS cell or an opal-glass-covered type 1P-28 photomultiplier at a pole of the sphere beneath the reflectance specimen. The reference (100%) reading is obtained by directing the beam onto the sphere wall, which is viewed by the detector; the zero reading is obtained by closing a shutter; and the unknown reflectance reading is obtained by directing the beam onto the specimen, which is not viewed by the detector. For this work, a 20-deg angle of incidence was employed, and the slit width was varied to give a spectral width large enough to encompass 2 to 3% of the area under a Planck curve centered at the wavelength of the measurement. Binormal transmittance was measured simply by inserting a specimen into the optical path when the beam was in the reference position.

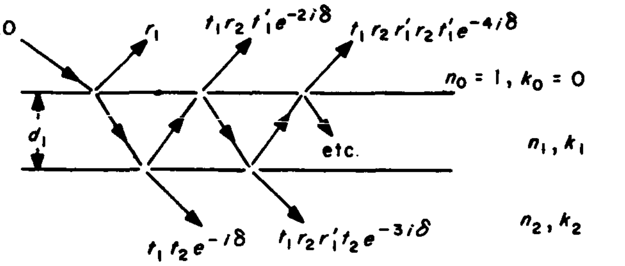
The directional heated-cavity reflectometer (Ref. 15) consists of a right-circular cylinder of 15-cm diameter and height. The 7-mm-thick nickel wall is heated to approximately 1000°K. For this work, a water-cooled reflectance specimen was suspended in the cavity and viewed at 25 deg off-normal through a port in the side of the cylinder. Again a Perkin Elmer Model 98 prism monochromator and associated chopper-rectifier and other standard electronics complete the system. Reflection and transmission filters are used to reduce stray radiation beyond 11 μ. A reference reading is obtained by viewing a platinum fin at the cavity temperature and at an angle of 25 deg off-normal. Slit widths were varied as in the case of the integrating sphere. Binormal transmittance is again measured by inserting the specimen into the optical path while the reference fin is being viewed and observing the decrease in signal.

The paraboloid reflectometer consists of opposed paraboloids: one 41 cm in diameter, on-axis, with a 10-cm focal length; the other 41 cm in projected diameter, 45 deg off-axis, with a 25-cm focal length. The optics are arranged such that a ray incident on the sample at the focus of the on-axis paraboloid comes, via the on-axis mirror and the off-axis mirror, from the off-axis paraboloid focal point, where a 13-cps chopper blade interrupts it. The ray comes to the focal point via a soot-smoked, water-cooled scatter plate from some point on a large, plane, high-emissivity, uniform source at 1000 to 1400°K. The reflected chopped intensity from the sample is viewed through any one of a series of ports (only one port being open at a given time) by a Perkin Elmer Model 98G grating monochromator with Reeder diamond-window vacuum thermocouple and associated electronics. Filters and reststrahlen mirrors are employed in the detection optics to eliminate undesired orders and stray radiation. For the present work, reflectance measurements were made relative to vacuum-evaporated aluminum at a 17-deg off-normal angle and a mechanical slit width of 6 mm.

The specimens consisted of several thicknesses of a flat black and a clear epoxy paint, a clear polyurethane paint, and a white silicone-alkyd paint, all of which have been used on spacecraft. The reflectance specimens were painted on aluminum, and the transmittance specimens were coated on 20-μ-thick transparent polyethylene film and mounted in a fiber frame like that of a 35-mm photographic transparency. Paint film thicknesses ranged from 25 to 750 μ.

III. THEORY

Heavens (Ref. 20) gives a concise summary of the Fresnel relations which implicitly give the reflection and transmission from and through nonscattering films in terms of the complex (containing real and imaginary parts) Fresnel coefficients. He also presents an all-real-number expression for the reflection of an absorbing film on an absorbing substrate. This expression contains eight quantities (A, B, C, D, g_1, g_2, h_1, and h_2 in his nomenclature) related to the basic refractive and absorptive indices. The relation between reflectance and optical constants is consequently rather algebraically intricate. Such an expression can be very easily programmed for machine calculation, but insight into how far-infrared reflectance of nonscattering spacecraft coatings should vary with coating thickness, refractive and absorptive indices, and wavelength is obscured. Since—in the far-infrared—metals are highly reflecting and paint resins have a small absorptive index k and a refractive index n between 1 and 2, it is possible for a simple first-order expression to portray approximately the far-infrared reflectance of a thin coat of clear paint on a metal substrate.



Consider the incident, reflected, and transmitted rays from a film. As the magnitude of r_1 and r'_1 is assumed to be small, and the magnitude of r_2 in what follows is either taken as unity or equal to that of r'_1, only the rays shown are considered. To introduce further simplification, the incident radiation is assumed to be incoherent and normal to the surface, so that polarization may be neglected. In this case, the Fresnel coefficients (Ref. 20) reduce to

$$r_1 = -r_1' = \frac{1-(n_1 - ik_1)}{1+(n_1+ik_1)} \tag{1}$$

$$r_2 = \frac{(n_1 - ik_1)-(n_2 - ik_2)}{(n_1 - ik_1)+(n_2 - ik_2)} \tag{2}$$

$$t_1 = (n_1 - ik_1)\,t_1' = \frac{2}{1+(n_1 - ik_1)} \tag{3}$$

$$t_2 = \frac{2(n_1 - ik_1)}{(n_1 - ik_1)+(n_2 - ik_2)} \tag{4}$$

The phase and amplitude change on traversal of the film is given by

$$e^{-i\delta_1} = e^{-i\frac{2\pi d_1}{\lambda}(n_1 - ik_1)} \tag{5}$$

where i is the unit imaginary number. The fractions of the incident energy reflected and transmitted are, respectively,

$$\rho = RR^* \tag{6}$$

$$\tau = n_2 TT^* \tag{7}$$

where

$$R = r_1 + t_1 r_2 t_1' e^{-2i\delta} + t_1 r_2 r_1' r_2 t_1' e^{-4i\delta} + \cdots \tag{8}$$

$$T = t_1 t_2 e^{-i\delta} + t_1 r_2' r_1' t_2 e^{-3i\delta} + \cdots \tag{9}$$

and the asterisk denotes the complex conjugate.

Equations (1) to (5) may be introduced into Eqs. (8) and (9), which, in turn, are substituted into Eqs. (6) and (7). A simple expression for reflectance results when $n_2 >> n_1 \equiv n < 2$ and $k_1 \equiv k << (n_1 - 1)$.

$$\begin{aligned}\rho_{\text{normal}} = & \left\{\left(\frac{n-1}{n+1}\right)^2\left[1+\frac{16n^2}{(1+n)^4}e^{\frac{-16\pi kd}{\lambda}}\right]+\frac{16n^2}{(1+n)^4}e^{\frac{-8\pi kd}{\lambda}}\right\} \\ & +\left\{\frac{8n}{(1+n)^2}\left(\frac{n-1}{n+1}\right)e^{\frac{-4\pi kd}{\lambda}}\left[1-\frac{4n}{(1+n)^2}e^{\frac{-8\pi kd}{\lambda}}\right]\right\}\cos\frac{4\pi nd}{\lambda} \\ & -\left\{\left(\frac{n-1}{n+1}\right)^2\frac{8n}{(n+1)^2}e^{\frac{-8\pi kd}{\lambda}}\right\}\cos\frac{8\pi nd}{\lambda}\end{aligned} \tag{10}$$

This relation is tailored to describe the reflectance of clear coating on a metal in the far-infrared. A second simple expression results for $n_2 = 1$, $k_2 = 0$, $k_1 \equiv k << (n_1 - 1)$, $n_1 \equiv n < 2$:

$$\tau_{\text{normal}} = \frac{16n^2}{(1+n)^4}e^{\frac{-4\pi kd}{\lambda}}\left\{1-\left[2\left(\frac{n-1}{n+1}\right)^2 e^{\frac{-4\pi kd}{\lambda}}\right]\cos\frac{4\pi nd}{\lambda}\right\} \tag{11}$$

This expression should describe the binormal transmittance of a clear film in the far-infrared.

IV. RESULTS

The polyurethane clear films (Magna Coatings and Chemical Corp., Los Angeles, Calif.) 46 to 260 μ thick indicated increasing transparency in the far-infrared, as shown in Fig. 1. When the clear resin was used to coat aluminum, this transparency manifested itself as an increasing reflectance in the far-infrared which could be predicted by use of Eq. (10) with $n = 1.5$, and k calculated (Table 1) with the first term in Eq. (11) and the transmission data. Such predictions are shown plotted with the reflectance data, for comparison, in Fig. 2.

Increasing transparency in the far-infrared was also shown by the epoxy resin films 43 to 250 μ thick (Fig. 3).

Resins loaded with titanium dioxide and lampblack pigments form the standard commercial white and black paints investigated (PV-100 silicone-alkyd white paint, Vita-Var Co., Newark, N.J., and Cat-a-lac epoxy black paint, Finch Paint and Chemical Co., Torrance, Calif.). Figures 4 and 5 show that for these paints a thickness of 75 μ is sufficient to suppress reflection from a metal substrate for at least 98% of the spectrum emitted by a room-temperature thermal radiator.

Table 1. Absorption coefficient from transmission data, laminar X-500 resin

Wavelength, μ	Absorption coefficient $4\pi k$
15.0	0.52
16.7	0.55
19.0	0.55
20.0	0.44
21.4	0.46
23.0	0.43
24.0	0.41
25.0	0.40
30.0	0.47
35.0	0.45
37.5	0.46
40.0	0.46
45.0	0.44
50.0	0.56
60.0	0.52

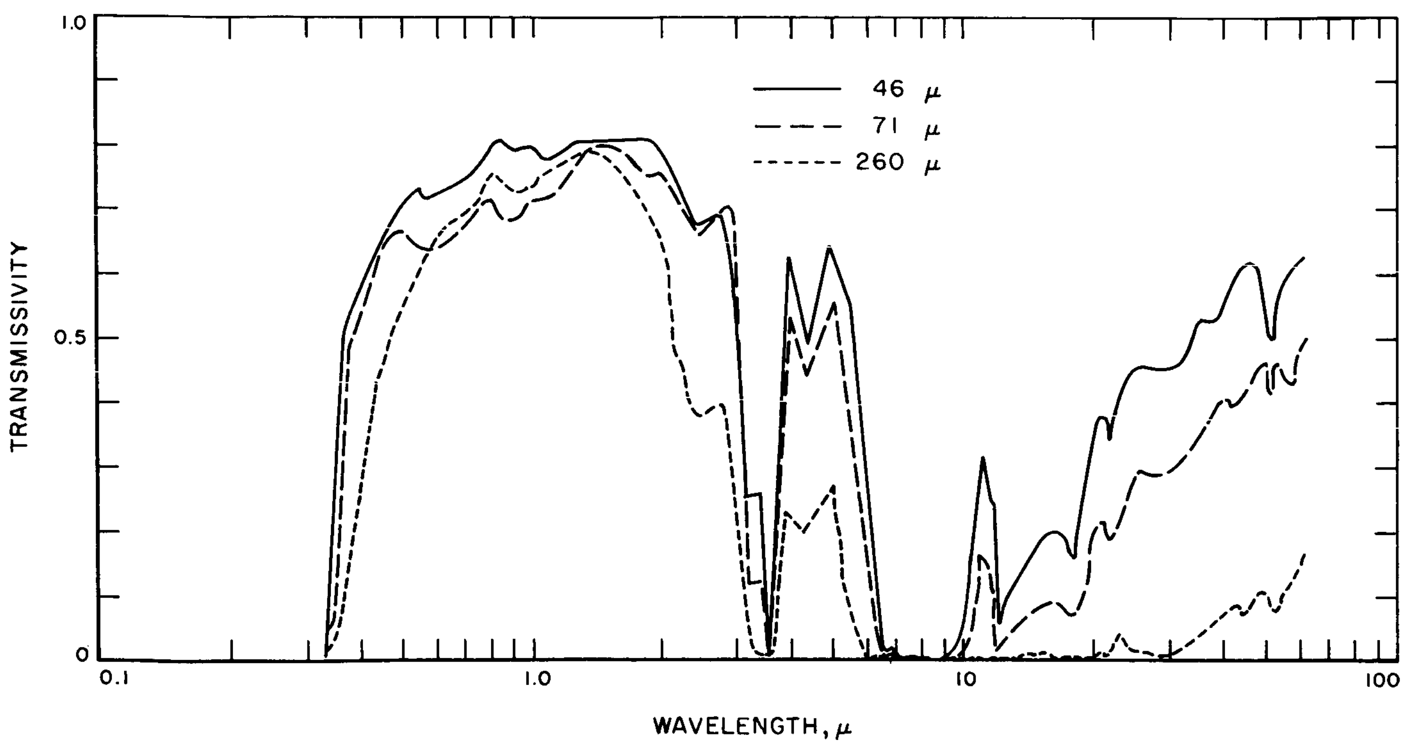


Fig. 1. Transmission of laminar X-500 clear film

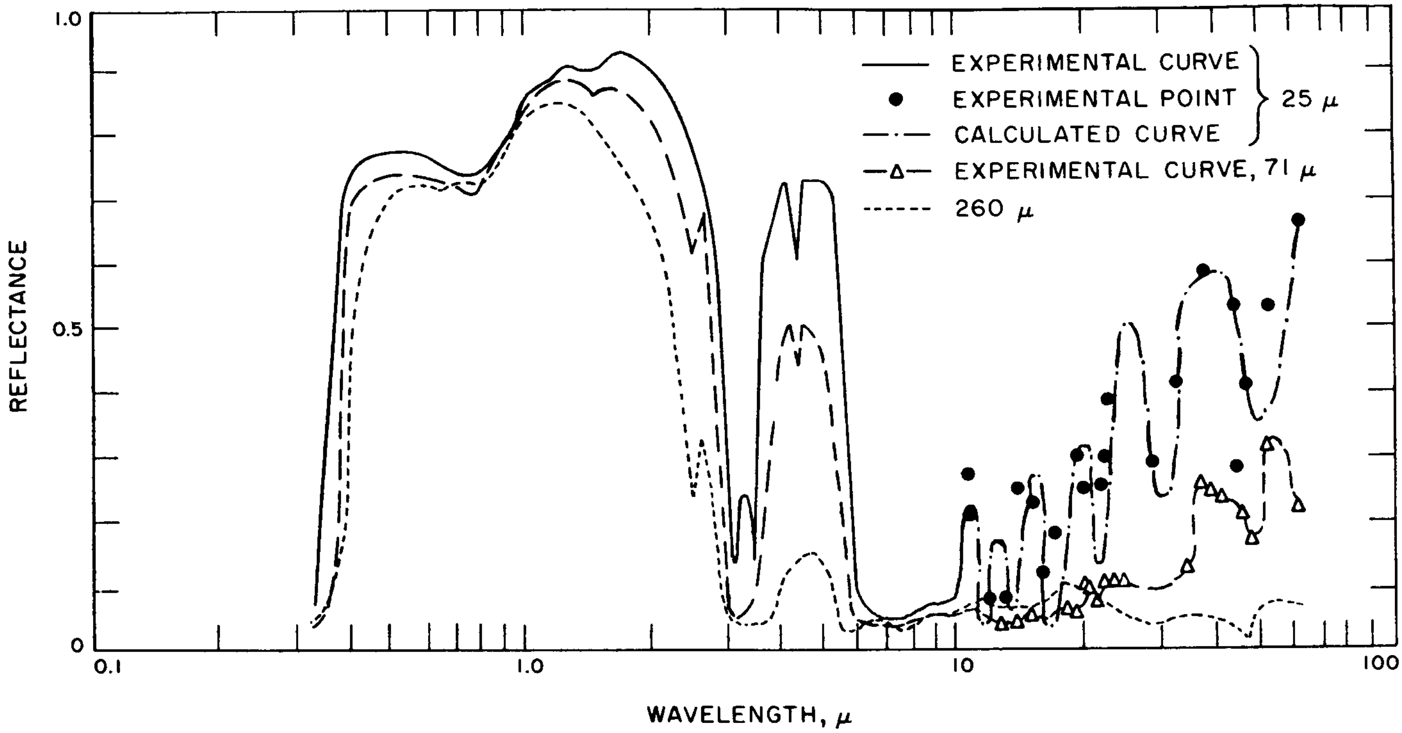


Fig. 2. Reflectance of laminar X-500 clear film on aluminum substrate

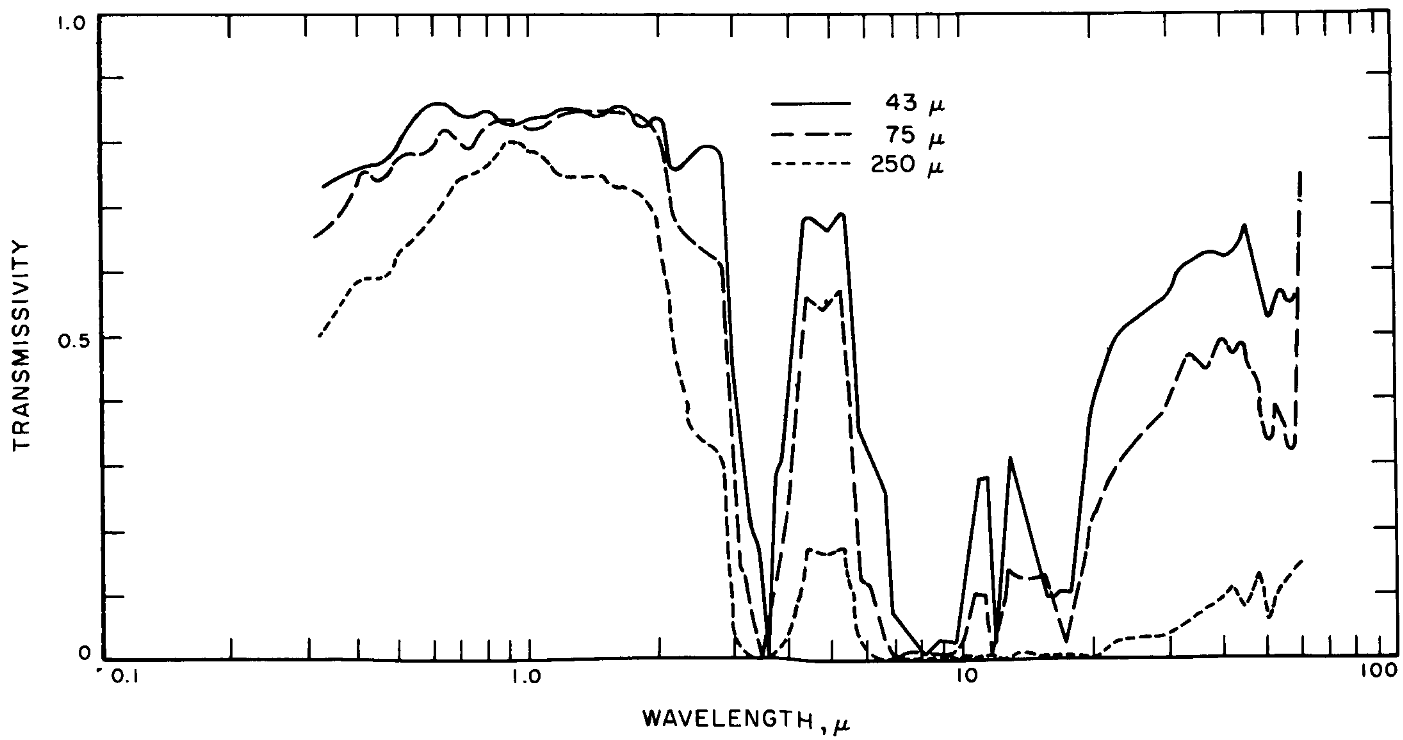


Fig. 3. Transmission of Cat-a-lac clear film

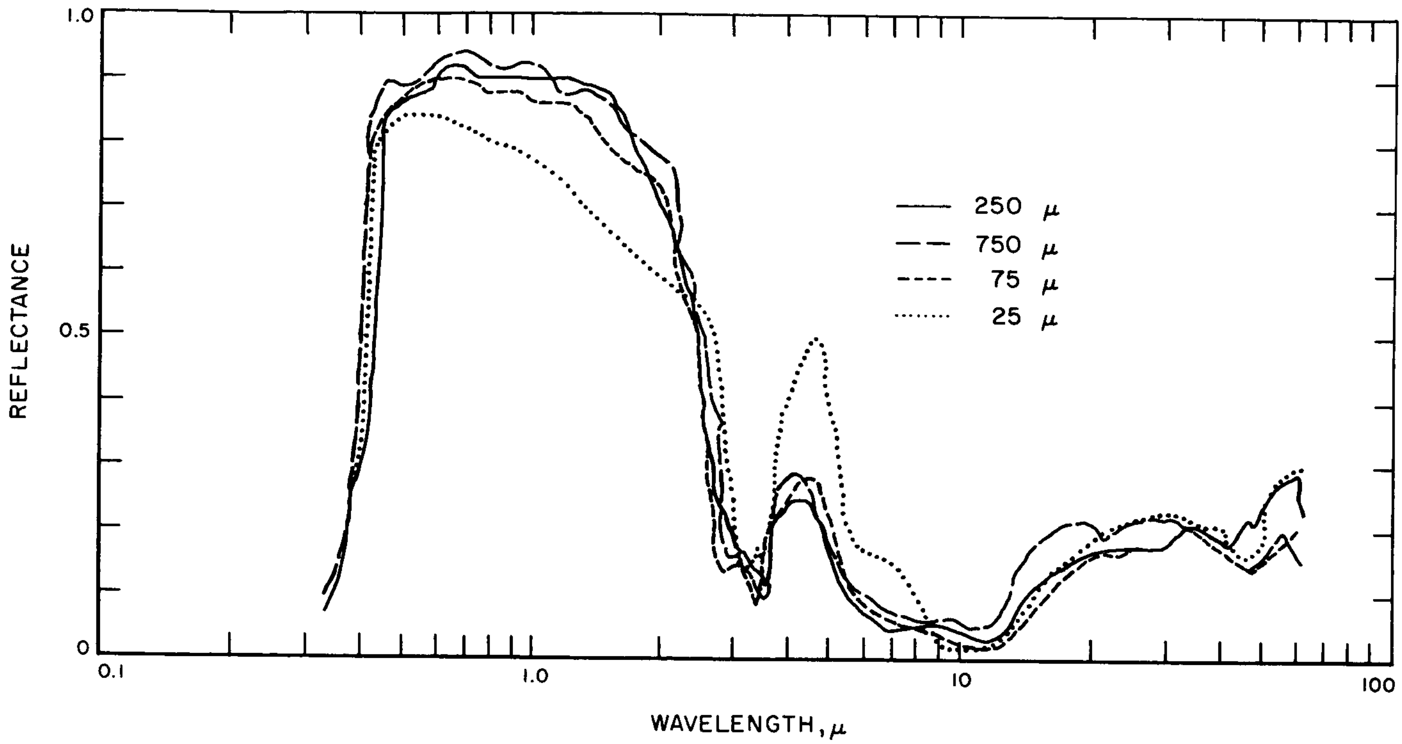


Fig. 4. Reflectance of PV-100 white paint on aluminum substrate

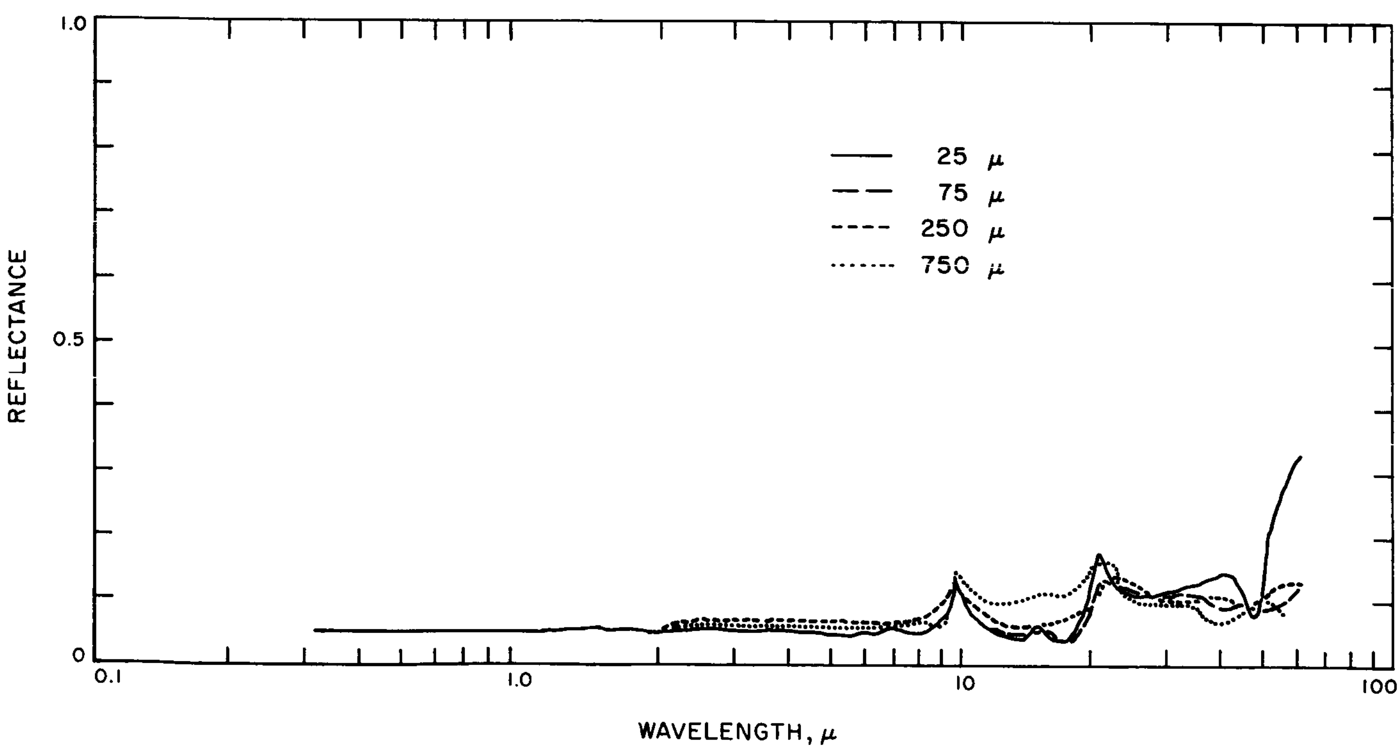


Fig. 5. Reflectance of Cat-a-lac black paint on aluminum substrate

V. DISCUSSION

An interesting feature of the data and theory presented in Fig. 2 is the far-infrared interference structure in the reflectance spectrum of a coat of clear resin on metal. Interference films are, of course, commonly used for reflection and antireflection coatings, usually in the solar region of the spectrum; in this case, however, the higher-order spectra occur in the ultraviolet and are seldom of interest in spacecraft thermal design. Since coatings such as paints or solar-cell cover glasses are usually 75 μ or more in thickness, the interference fluctuations in the spectrum up to 25 μ are usually averaged out in both measurements and calculations.

The oscillations of the spectral reflectance as a function of wavelength (shown plotted in Fig. 2) are a possible source of error in both measurements and calculations; for example, while the data points in the figure agree in the main with the theoretical estimation, they are too few in number to show a complete interference pattern. If a continuously recorded measurement is made instead of a point-by-point taking of data, it would be necessary to employ a low scan rate to avoid shifting and otherwise distorting the spectra. In the calculation of radiant transfer, neglect of such spectral selectivity has been shown to result in significant errors (Ref. 21). When the film is thicker, so that the maxima and minima are less widely separated and small random variations in film thickness would shift them randomly, only the first term in Eq. (10) need be considered.

In order to make the comparison shown in Fig. 2 a value of $n = 1.5$ was assumed. This value was chosen because there was a residual reflectance of 0.04 $\pm$0.01 wherever the films appeared opaque. Another approximation was neglect of interference in the calculation of k from the transmittance spectra. This neglect is justified by the small size of the second term in the large brackets in Eq. (11) compared to unity. In addition, the support film of polyethylene disturbs the interference pattern so that the full Eq. (11) can not be correctly applied to the present data. (It was found in checking the specimen thicknesses again after the radiation-measurement program that the polyethylene film could be removed without apparent damage to the resin film.) Another source of uncertainty is that the film thicknesses were in some cases found to vary locally over the specimens. A reported thickness may be subject to a ± 4-μ deviation. In view of the uncertainties in nd and k, the lack of a perfectly uniform film thickness, and the experimental errors (Ref. 12), the discrepancies between the data points and the curve in Fig. 2 are not surprising.

Anomalies in Figs. 4 and 5 are higher indicated reflectances for the thick paints than for the thin paints. These anomalies are simply a manifestation of the sample emission error to which the heated-cavity reflectometer is subject (Ref. 17). A major advantage of the paraboloid reflectometer (Ref. 12) is that it is not susceptible to this error.

Another interesting feature of the data is that there is little correlation between the short- and long-wavelength spectral regions. In Fig. 4, the thinnest coating has an appreciably lower solar reflectance while having essentially the same infrared reflectance as the thicker coatings. In Fig. 2, large differences in the far-infrared reflectance are evident, but only small differences occur in the near-infrared.

It was not determined in this investigation whether the paint pigments in the specimens whose reflectances appear in Figs. 4 and 5 scatter appreciably in the far-infrared. It must be emphasized that, while Eq. (9) can be used, together with binormal transmissivity measurements, to make reasonable predictions of the reflectance of metals coated with nonscattering films, such a use would not be appropriate for scattering coatings.

VI. CONCLUSIONS

1. Epoxy and polyurethane resins 40 to 260 μ thick were found to have increasing transparency with increasing wavelength in the far-infrared out to 61 μ.

2. When a clear resin was used to coat aluminum, the reflectance was observed to oscillate about an increasing average value as wavelength was increased. A simplified expression from the Fresnel relations, together with refractive and absorptive indices estimated from the transmittance data, was found to indicate an oscillating but increasing reflectance which agreed well with reflectance data. Oscillations are indicated as resulting from interference of the radiation reflected from the first and second interfaces.

3. For the resins loaded with pigment in the form of two particular commercial black and white paints, a thickness of 75 μ was found adequate to suppress reflection from a metal substrate for at least 98% of the room-temperature black-body spectrum. Only the 25-μ-thick black epoxy paint on an aluminum substrate showed a rise in reflectance above 30% at 61 μ.

REFERENCES

1. Bevans, J. T., Gier, J. T., and Dunkle, R. V., "Comparison of Total Emittances with Values Computed from Spectral Measurements," *Transactions of the American Society of Mechanical Engineers,* Vol. 80, 1958, pp. 1405–1416.
2. Shaw, C., Berry, J., and Lee, T., *Spectral and Total Emissivity Apparatus and Measurements of Opaque Solids,* LMSD 48488, Lockheed Aircraft Co., Sunnyvale, California, March 1959.
3. Gubareff, G. G., Janssen, J. E., and Torborg, R. H., *Thermal Radiation Properties Survey,* Chapter 4, Minneapolis-Honeywell Co., Minneapolis, Minnesota, 1960.
4. McKellar, L. A., et al., *Thermophysics Design Handbook,* LMSD 8-55-63-3, Lockheed Aircraft Co., Sunnyvale, California, July 1963.
5. Edwards, D. K., Gier, J. T., Nelson, K. E., and Roddick, R. D., "Spectral and Directional Thermal Radiation Characteristics of Selective Surfaces for Solar Collectors," *Solar Energy,* Vol. 6, No. 1, 1962, pp. 1–8.
6. Edwards, D. K., "Directional Solar Reflectances in Space Vehicle Temperature Control Problem," *American Rocket Society Journal,* Vol. 31, 1961, pp. 1548–1553.
7. Edwards, D. K., and Roddick, R. D., "Spectral and Directional Thermal Radiation Characteristics of Surfaces for Heat Rejection by Radiation," *Progress in Astronautics and Aeronautics: Vol. 11, Power Systems for Space Flight,* Academic Press, New York and London, 1963, pp. 427–446.
8. Edwards, D. K., and Catton, I., "Radiation Characteristics of Rough and Oxidized Metals," *Advances in Thermophysical Properties at Extreme Temperatures and Pressures,* American Society of Mechanical Engineers, New York, 1965, pp. 189–199.
9. Dunkle, R. V., "Thermal Radiation Tables and Application," *Transactions of the American Society of Mechanical Engineers,* Vol. 76, 1954, pp. 549–552.

REFERENCES (Cont'd)

10. McNicholas, H. J., "Absolute Methods in Reflectometry," *National Bureau of Standards, Journal of Research*, Vol. 1, 1928, pp. 29–73.

11. Edwards, D. K., "Measurement of Thermal Radiation Characteristics," *1963 Proceedings, Institute of Environmental Sciences*, Institute of Environmental Sciences, Mt. Prospect, Illinois, pp. 417–424.

12. Neher, R. T., and Edwards, D. K., "Far Infrared Reflectometer for Imperfectly Diffuse Specimens," *Applied Optics*, Vol. 4, 1965, pp. 775–780.

13. Aronson, J. R., and McLinden, H. G., *Far Infrared Spectra of Solids*, Paper No. 3, Symposium on Thermal Radiation of Solids, San Francisco, California, March 4, 1964.

14. Edwards, D. K., Gier, J. T., Nelson, K. E., and Roddick, R. D., "Integrating Sphere for Imperfectly Diffuse Samples," *Journal of the Optical Society of America*, Vol. 51, 1961, pp. 1279–1288.

15. Dunkle, R. V., Edwards, D. K., Gier, J. T., Nelson, K. E., and Roddick, R. D., "Heated Cavity Reflectometer for Angular Reflectance Measurements," *Progress in International Research on Thermodynamic and Transport Properties*, Academic Press, New York and London, 1962, pp. 541–562.

16. Gier, J. T., Dunkle, R. V., and Bevans, J. T., "Measurement of Absolute Spectral Reflectivity from 1.0 to 15 Microns," *Journal of the Optical Society of America*, Vol. 44, 1954, pp. 558–562.

17. Dunkle, R. V., Ehrenburg, F., and Gier, J. T., "Spectral Characteristics of Fabrics from 1 to 23 Microns," *Journal of Heat Transfer*, Vol. 82, 1960, pp. 64–70.

18. Dunkle, R. V., "Spectral Reflectance Measurements," *Surface Effects on Spacecraft Materials*, F. J. Clauss, editor, John Wiley and Sons, Inc., New York, 1960, pp. 117–137.

19. Edwards, D. K., and Bayard de Volo, N., "Useful Approximations for the Spectral and Total Emissivity of Smooth Bare Metals," *Advances in Thermophysical Properties at Extreme Temperatures and Pressures*, American Society of Mechanical Engineers, New York, 1965, pp. 174–188.

20. Heavens, O. S., *Optical Properties of Thin Solid Films*, Chapter 4, Butterworths Scientific Publications, London, 1955.

21. Bevans, J. T., and Dunkle, R. V., "Radiant Interchange Within an Enclosure," *Journal of Heat Transfer*, Vol. 82, 1960, pp. 1–19.

ACKNOWLEDGMENT

Radiation measurements were made in the UCLA Morrin–Martinelli–Gier Heat Transfer Laboratory with financial support from the Jet Propulsion Laboratory. T. Golondzinier aided in the measurements and calculations. Specimens were prepared at JPL.