SPECTRAL AND DIRECTIONAL THERMAL RADIATION CHARACTERISTICS OF SURFACES FOR HEAT REJECTION BY RADIATION

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Abstract

Surface systems suitable for waste heat radiators are examined, and spectral and directional reflectances of actual high-emittance materials are presented. Evaluation of the emittance of merit for these materials is made.

Introduction

A vital part of any heat-power conversion system, using solar energy or not, is the waste heat rejector. If waste heat is rejected by radiation, as it must be in space, or if the rejector is exposed to thermal radiation from the surrounds, including the sun, the thermal radiation characteristics of the rejector influence the optimization of the power conversion system.

Similarly, the radiation characteristics of components of thermal environment control systems influence performance when radiant energy transfer is important. Important components of such control systems may well be heat radiators.

When heat is rejected by radiation, the optimum surface for a radiator is one with an emittance of merit

$$\epsilon_r' = \epsilon_r - \left(\alpha_s G_s / \sigma T_r^4\right) \tag{1}$$

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as high as possible, assuming that differences in costs of surface coatings are negligible. The quantity $\epsilon_r \sigma T_r^4$ represents the net power rejected per unit area of the surface. In this equation ϵ_r is the total hemispherical emittance of the radiator at temperature T_r,

$$\epsilon_r = \frac{\int_0^\infty \int_0^{2\pi} \int_0^{\pi/2} \alpha_{\lambda r}(\theta, \phi) E_{b\lambda}(T_r) \sin\theta \cos\theta d\theta d\phi d\lambda}{\sigma T_r^4} \tag{2}$$

α_s is the absorptance of radiator for irradiation from the surrounds,

$$\alpha_s = \frac{\int_0^\infty \int_0^{2\pi} \int_0^{\pi/2} \alpha_{\lambda r}(\theta, \phi) I_{\lambda s}(\theta, \phi) \sin\theta \cos\theta \, d\theta d\phi d\lambda}{\int_0^\infty \int_0^{2\pi} \int_0^{\pi/2} I_{\lambda s}(\theta, \phi) \sin\theta \cos\theta \, d\theta d\phi d\lambda} \tag{3}$$

and G_s is the total irradiation from the surrounds of intensity $I_{\lambda s}(\theta, \phi)$,

$$G_s = \int_0^\infty \int_0^{2\pi} \int_0^{\pi/2} I_{\lambda s}(\theta, \phi) \sin\theta \cos\theta \, d\theta d\phi d\lambda \tag{4}$$

The quantity $\alpha_{\lambda r}(\theta, \phi)$ is the directional spectral absorptance for wavelength λ and polar and azimuthal angles of incidence θ and ϕ, respectively.

It is obvious from Eq. (1) that it is desirable to place the radiator so that the irradiation from the surrounds is as small as possible. In space it may be possible to place the radiator parallel to the direction to the sun or to locate it in the shade of some portion of the vehicle. If G_s is zero, then ϵ_r is simply ϵ_r and a blackbody radiator is desirable.

If for some reason the radiator is exposed to sunlight, as might be the case for an unoriented space vehicle or a satellite oriented with respect to a planetary body, it is desirable to use a selective surface with a high ϵ_r and a low α_s. Such a surface is obtained with a spectral absorptance low at wavelengths less than 2 or 3μ and high at greater wavelengths.

In what follows, some classes of surface systems suitable for radiators are surveyed. Specific materials then are investigated.

Surface Systems for Radiators

Isotropic Perfectly Plane Slab

The normal emittance of an opaque perfectly plane slab is

$$\epsilon_n = 1 - \rho_n \tag{5}$$

where the normal reflectance ρ_n of a dielectric is given by Fresnel's law as

$$\rho_n = (n - 1)^2/(n + 1)^2 \tag{6}$$

Thus the normal emittance is

$$\epsilon_n = 4n/(n + 1)^2 \tag{7}$$

The index of refraction n should be less than 2 in order for ϵ_n to be greater than 0.9. However, the hemispherical emittance ϵ is less than the normal emittance for a dielectric with low n. Jakob[5] presents the correction for this effect. The result is that, when $\epsilon_n = 0.9$, ϵ is only 0.84, and n must be less than about 1.6 for ϵ to be greater than 0.9.

Since the index of refraction must be low in the infrared, use of metals can be ruled out, and only dielectrics can be considered. Both the absorption coefficient and thermal conductivity of the dielectric must be sufficiently high so that the thickness of coating does not introduce a deleterious thermal resistance on the radiator surface.

In order for ϵ or α to be small in the solar region of the spectrum, the index of refraction of an isotropic slab would have to increase greatly with decreasing wavelength. This behavior would be unusual.

Metallic Substrate with Dielectric Thick Film

The low reflectance of dielectrics in the long wavelengths may be coupled with the high reflectance of some metals in the solar region of the spectrum by use of a metallic substrate having a thick dielectric film that is highly absorbing in the infrared and transparent in the solar region. Such a surface system may be created, for example, by evaporating a metal on a dielectric slab, fusing a dielectric on a metal, coating a metal with a liquid that dries or sets to leave a dielectric film, or forming a dielectric compound of the metal surface itself by oxidizing or anodizing. A second surface mirror, lacquered aluminum, and anodized aluminum are explicit examples.

Suspension of Scattering and/or Absorbing Particles in a Selectively Transparent Resin

A suspension of particles with a high index of refraction in a resin of low index of refraction has a high reflectance when both the scattering particles and resin are little absorbing.[6] If the resin and/or particles are absorbing in the long wavelength region, a selective surface is obtained. White paints, milk glass, and white enamel may be classified under this category. Black paint would be a nonselective surface.

A powder or porous material of scattering particles behaves much as the foregoing, except that selectivity in the long wavelengths would depend only on the particles themselves, since no resin is present. Smoked or flame-sprayed materials may be grouped in this category.

Surface Roughness

Inter-reflections brought about by cavities in the surface leads to an increased emittance based on the projected area. This method would be especially useful to increase the directional emittance at high angles from the surface normal, thus increasing the hemispherical emittance. For example, machined surface grooves[3] of 22.5° to 30° half angles result in an increase of 0.04 in the normal emittance of painted surfaces which would otherwise have a normal emittance of about 0.90. The increase in the hemispherical emittance brought about by grooving would probably exceed the 0.04 increase in the normal emittance.

Measured Characteristics of Materials for Radiators

Figures 1-12 show measured near-normal spectral reflectances of a few specific materials with high emittance. Data in Figs. 1-6, 10, and 11 were extracted from the compiled data of R. V. Dunkle and J. T. Gier, corrected for consistent errors in the short wavelength region, and smoothed in regions of overlap of measurements. The original data had been obtained with a General Electric spectrophotometer in the 0.4 to 1.0μ range, a Beckman DK 2 spectrophotometer in the 0.25 to 2.5μ range, and a Gier-Dunkle heated cavity absolute reflectometer[4] in the

1.0 to 25μ range. Data in Figs. 7-9 and 12 were obtained with a directional heated cavity reflectometer[1] in the 1.5 to 25μ range and with an integrating sphere[2] in the 0.33 to 2.5μ region.

Figures 13-17 show measured directional characteristics of a selected few of the surfaces in Figs. 1-12. These data were obtained with a directional heated cavity reflectometer.[1]

In Figs. 1-12, which give the near-normal spectral data, both selective and nonselective surfaces are illustrated. In Figs. 13-17, the directional reflectance is seen to increase markedly with increasing angle from the normal in the characteristic manner of dielectrics.

Evaluation of Materials for Radiators

Equation (1) may be used to evaluate the emittance of merit ϵ_r. In order to show the effect of selectivity as a function of temperature when materials are exposed to solar radiation, temperatures of $T_r = 450°$ and 1000°R and a solar irradiation of $G_s = 100$ Btu/hr-ft^2 are chosen. The value of G_s is representative of the average solar irradiation on a cylindrical or spherical radiator exposed to the sun. The lower temperature is representative of a low-internal-power space vehicle that uses a low temperature exterior skin for temperature control purposes, and the higher temperature is representative of a radiator of waste heat from a space heat-power converter.

Table 1 shows ϵ_r' for several real materials calculated under the assumption that the hemispherical and normal emittance are identical. That this assumption is not strictly valid is discussed immediately below. It may be noted in Table 1 that at the lower temperature nonselective surfaces will not function as indicated by negative values of ϵ_r'. The titanium oxide powder, white paint, second-surface mirrors, fused silica, and alumina are among the best surfaces. At the higher temperature, however, selectivity is of little importance, and the black paints and hard anodized aluminum are desirable, depending upon their stability in space.

As was remarked in the text following Eq. (7), the hemispherical emittance is lower than the normal emittance of a low-refractive-index dielectric. For a perfectly plane homogeneous material with no long wavelength spectral selectivity, the correction given by Jakob[5] easily is applicable. In the case of rough and/or inhomogeneous surface systems or for materials containing restrahlen bands such as glass, direct measurements of the type shown in Figs. 2, 4, 9, and 14 are necessary. These measurements are used to estimate the hemispherical emittance.

The total hemispherical emittance

$$\epsilon = \int_0^\infty \int_0^{2\pi} \int_0^{\pi/2} [1-\rho_\lambda(\theta,\phi)] \sin\theta\cos\theta\, d\theta d\phi\, (I_{b\lambda}/\sigma T_r^5) d(\lambda T_r) \qquad (8)$$

may be estimated by approximating the integrals by finite sums as follows for little ϕ dependency:

$$\epsilon = 1 - \sum_{j=1}^{N} \int_0^{\pi/2} \frac{\rho_{\lambda j}(\theta)}{\rho_{\lambda j}(0)} d(\sin^2\theta) \sum_{i=1}^{M_j} \rho_{\lambda j}(0) \int_{\lambda_{i-1}T_r}^{\lambda_i T_r} \frac{\pi I_{b\lambda}}{\sigma T^5} d(\lambda T_r) \qquad (9)$$

The spectrum is divided into N large intervals, of which the jth contains a value of $\rho(\theta)/\rho(\theta=0)$ which is insensitive to wavelength in the region and contains M_j subintervals, of which the ith contains a value of $\rho(\theta=0)$ which is insensitive to wavelength in this subregion.

Table 2 shows a comparison of the normal emittance ϵ_n with the hemispherical emittance ϵ calculated from Eq. (9) and estimated from Jacob.[5] The differences between ϵ and ϵ_n range up to 12%. The actual values of ϵ are only slightly higher than those predicted from ϵ_n by use of the Fresnel relations as given by Jakob[5] except for the flame-sprayed alumina at 1000°R.

From the foregoing comparison of ϵ_n with ϵ, it is seen that the performance of a radiator as measured by ϵ_r' would be affected significantly by variation of the emittance with direction. Thus, when comparing radiator materials and especially when predicting their performance, it is necessary for the designer to take into account the directional as well as the spectral characteristics of each material.

Summary and Conclusions

1) Black paints appear desirable for high temperature (1000°R) radiators, since spectral selectivity is of little consequence at high temperatures.

2) Anodized metals may be preferable to the forementioned surfaces, since they have an emittance of merit only about 10% less and are durable and easily produced.

3) For low radiator temperatures (450°R), selective surfaces such as white paints, white ceramics, or second-surface mirrors must be used.

References

[1] Dunkle, R.V., Edwards, D.K., Gier, J.T., Nelson, K.E., and Roddick, R.D., "Heated cavity for angular reflectance measurements," Progress in International Research on Thermodynamic and Transport Properties, pp. 541-562 (Academic Press, New York, January 1962).

[2] Edwards, D.K., Gier, J.T., Nelson, K.E., and Roddick, R.D., "Integrating sphere for imperfectly diffuse samples," J. Opt. Soc. Am. 51, 1279-1288.

[3] Gier, J.T., Dunkle, R.V., and Bevans, J.T., "Final progress report, snow characteristics project," Contract DA-11-190-Eng. 3, Inst. Eng. Research (August 31, 1955).

[4] Gier, J.T., Dunkle, R.V., and Bevans, J.T., "Measurement of absolute spectral reflectivity from 1.0 to 15 microns," J. Opt. Soc. Am. 44, 558-562 (1954).

[5] Jakob, M., Heat Transfer (John Wiley and Sons, New York, 1949), Vol. 1, Chap. 4.

[6] Moore, L.E., Prastein, M., Tomkins, E.H., and Van Ostenburg, D.O., "Evaluation of the mechanisms which affect the performance of thermal radiation resistant coatings," Armour Research Foundation Contract AF 33(616)-3595 (1957); also Wright Air Dev. Center Rept. 57-334.

Table 1 Evaluation of materials for heat rejection by radiation (irradiated by 100 Btu/hr ft^2 of extraterrestrial solar energy)

Material	T = 450°R				T = 1000°R		
	α_s	ϵ_{rn}	α_s/ϵ_{rn}	ϵ'_{rn}	ϵ_{rn}	α_s/ϵ_{rn}	ϵ'_{rn}
1) Black epoxy paint (cat-a-lac flat black, Finch Paint and Chem. Co. no. 463-1-8 on aluminum)	0.95	0.89	1.07	-0.46	0.92	1.03	0.87
2) Black silicone paint (National Lead Co. 46H47 high heat black paint baked at 350°F for 20 min)	0.94	0.94	1.00	-0.40	0.92	1.02	0.87
3) Parson's optical black (3 coats on 1 coat of Parson's primer on cold rolled steel)	0.975	0.95	1.03	-0.44	0.96	1.02	0.90
4) Graphite on sodium silicate (crushed carbon electrodes 16 mils thick on sodium silicate on polished aluminum)	0.96	0.91	1.06	-0.45	0.93	1.03	0.87
5) Oxidized inconel X (oxidized 4 hr at 1825°F in air followed by 10 hr at 1300°F in air)	0.90	0.71	1.26	-0.57	0.81	1.11	0.76

Table 1 (Continued)

Material	T = 450°R				T = 1000°R		
	α_s	ϵ_{rn}	α_s/ϵ_{rn}	ϵ'_{rn}	ϵ_{rn}	α_s/ϵ_{rn}	ϵ'_{rn}
6) Oxidized stainless steel (Armco black oxide on type-301 stainless steel)	0.89	0.75	1.19	-0.51	0.76	1.18	0.70
7) Hard-anodized aluminum (6061-T6 aluminum anodized 1 mil thick with 35 amps/ft^2 at 45 v in a 20°F sulfuric acid solution)	0.92	0.84	1.10	-0.47	0.85	1.09	0.82
8) Anodized titanium	0.51	0.87	0.59	0.13	0.83	0.62	0.80
9) Soft-anodized aluminum	0.23	0.79	0.30	0.046	0.44	0.52	0.43
10) Glass on evap. aluminum	0.13	0.83	0.16	0.65	0.82	0.16	0.81
11) Glass on evap. silver	0.13	0.83	0.16	0.65	0.82	0.16	0.81
12) Titanium dioxide powder (Titanox RA 2 mils thick on black paint)	0.15	0.88	0.17	0.67	0.90	0.17	0.89

Table 1 (Continued)

Material	T = 450°R			T = 1000°R			
	α_s	ϵ_{rn}	α_s/ϵ_{rn}	ϵ_{rn}	ϵ_{rn}	α_s/ϵ_{rn}	ϵ_{rn}
13) Flame-sprayed alumina (deposited on 410 stainless steel and heated for 1 min up to 1300°F in air and held for 30 additional sec at 1300°F)	0.28	0.80	0.34	0.41	0.79	0.35	0.77
14) Fused silica, sintered	0.08	0.84	0.095	0.73	0.85	0.095	0.84
15) White epoxy paint (cat-a-lac flat white, Finch Paint and Chem. Co. no. 463-1-8 on aluminum)	0.25	0.88	0.28	0.53	0.91	0.27	0.90

Table 2 Comparison of normal with hemispherical emittance

	T = 450°R			T = 1000°R		
	Normal emittance	Hemispherical emittance		Normal emittance	Hemispherical emittance	
Material		Calc. Eq.(9)	From Jakob		Calc. Eq.(9)	From Jakob
1) Black silicone paint	0.94	0.92	0.89	0.92	0.87	0.86
2) Parson's black	0.95	0.92	0.90	0.96	0.94	0.92
3) Hard-anodized aluminum	0.84	0.80	0.79	0.84	0.83	0.79
4) Soft-anodized aluminum	0.79	0.75	0.75	0.44	0.42	0.46
5) Glass on evap. aluminum	0.83	0.79	0.78	0.82	0.78	0.77
6) Glass on evap. silver	0.83	0.79	0.78	0.82	0.78	0.77
7) Flame-sprayed alumina	0.80	0.77	0.76	0.79	0.69	0.75
8) Fused silica	0.84	0.77	0.79	0.85	0.78	0.80

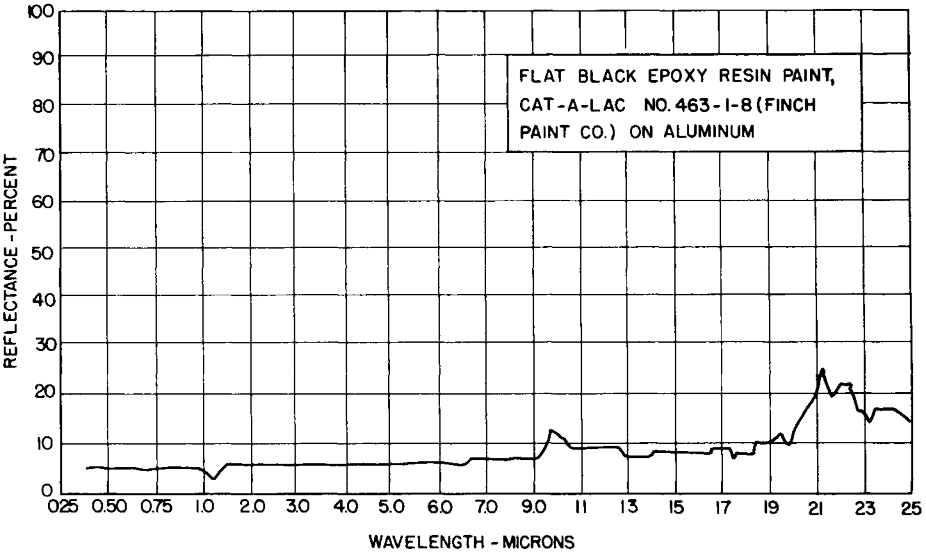

Fig. 1 Near-normal spectral reflectance of black epoxy resin paint

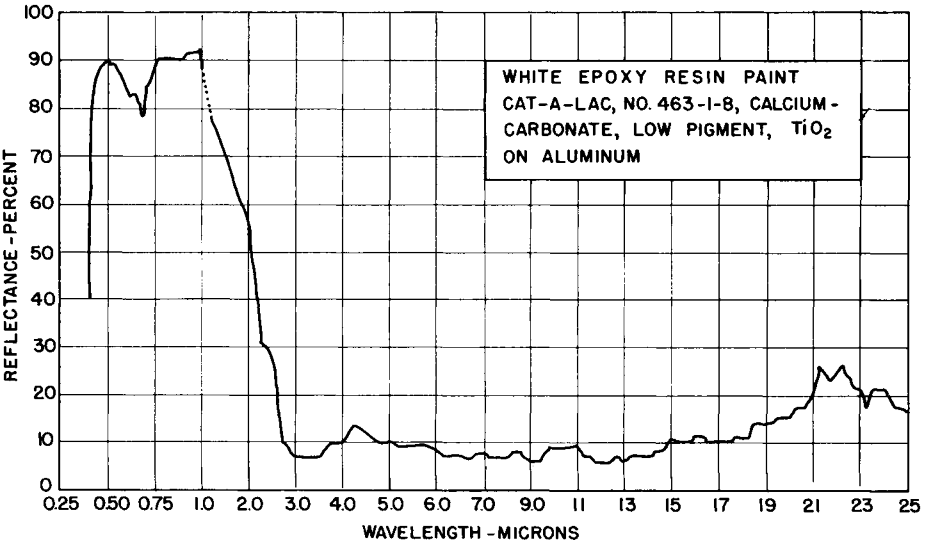

Fig. 1a Near-normal spectral reflectance of white epoxy resin paint

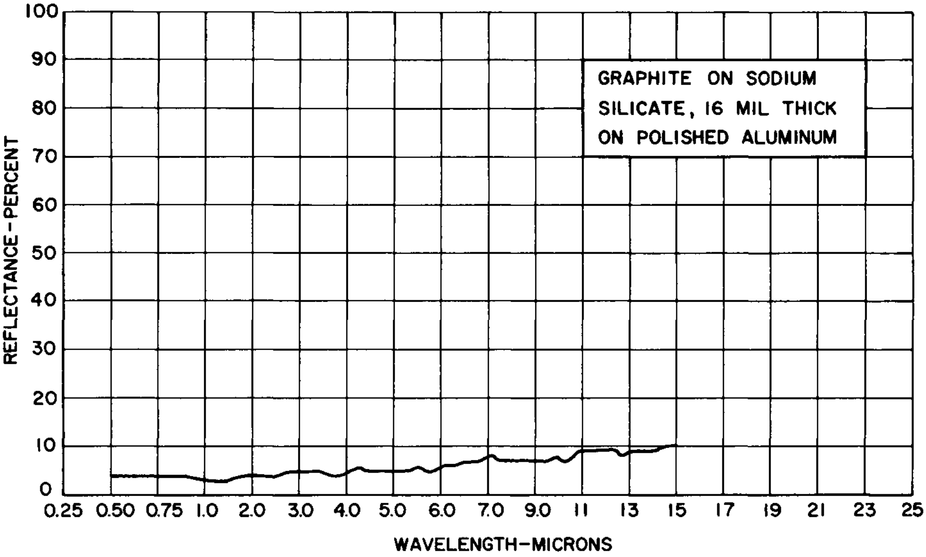

Fig. 2 Near-normal spectral reflectance of graphite on sodium silicate

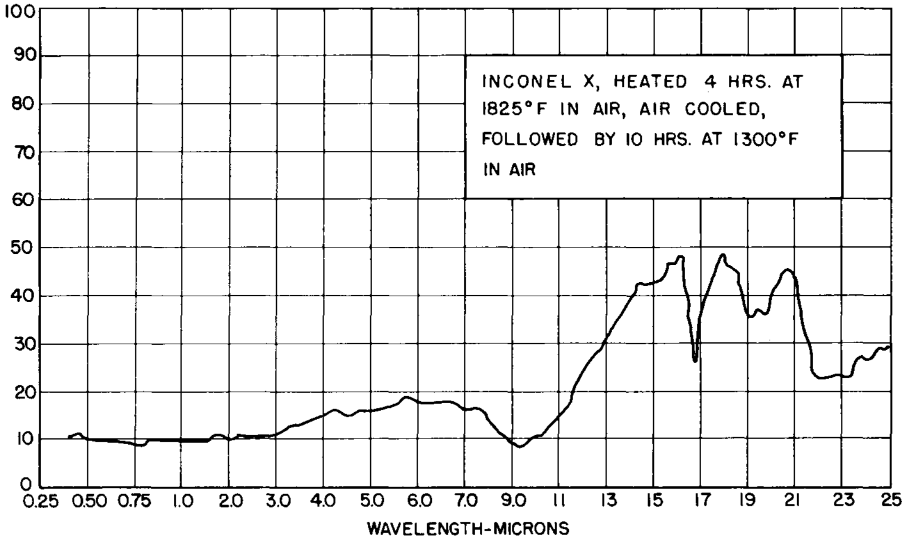

Fig. 3 Near-normal spectral reflectance of oxidized Inconel X

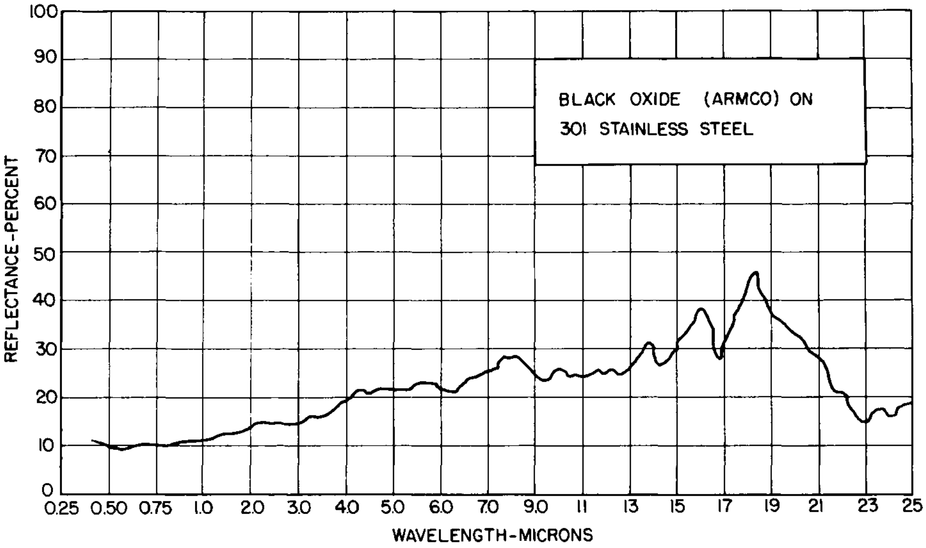

Fig. 4 Near-normal spectral reflectance of oxidized stainless steel

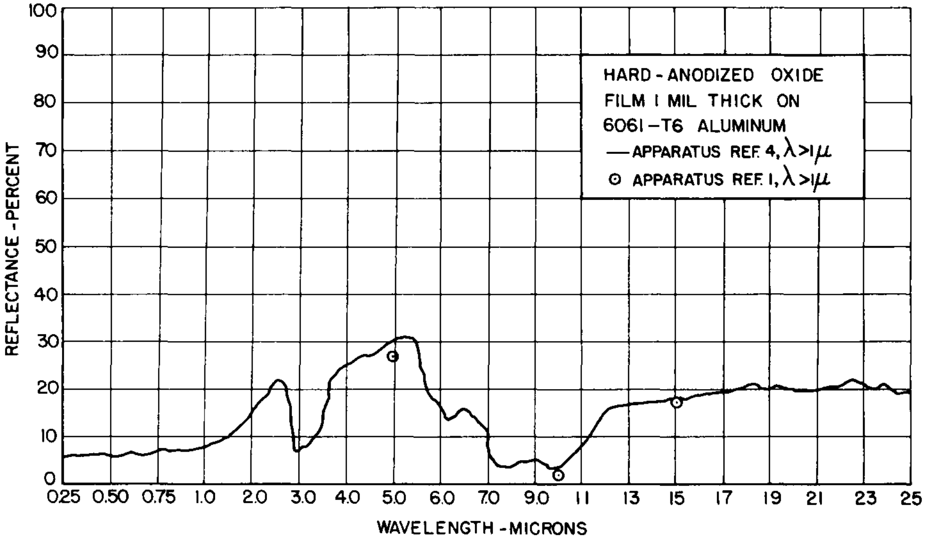

Fig. 5 Near-normal spectral reflectance of hard-anodized aluminum

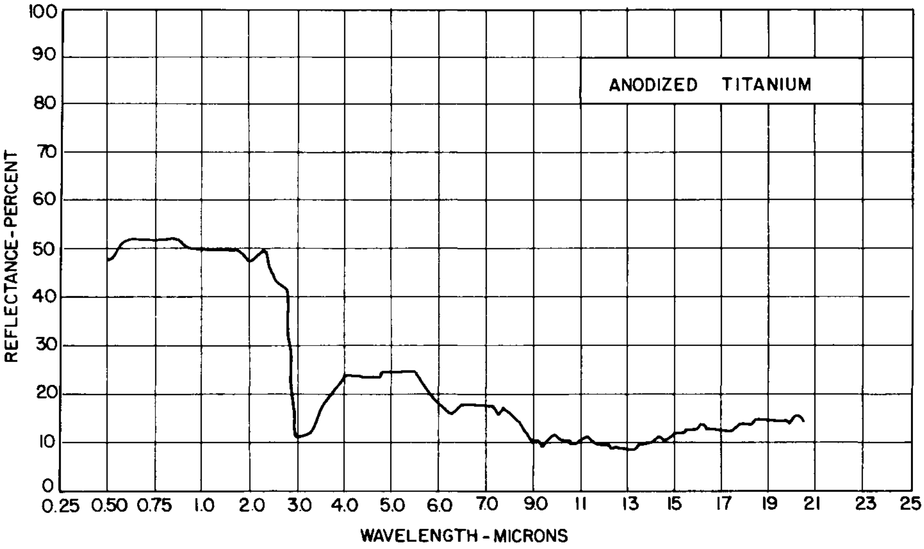

Fig. 6 Near-normal spectral reflectance of anodized titanium

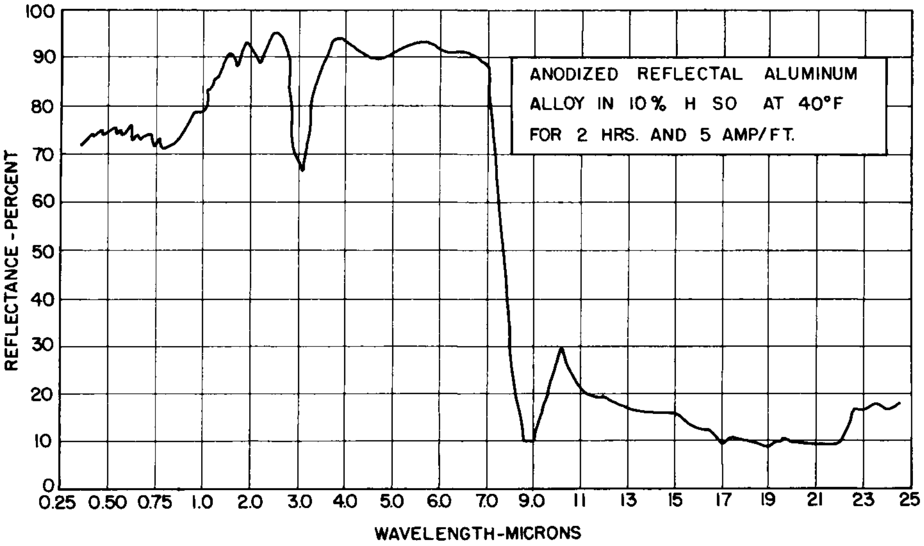

Fig. 7 Near-normal spectral reflectance of soft-anodized aluminum

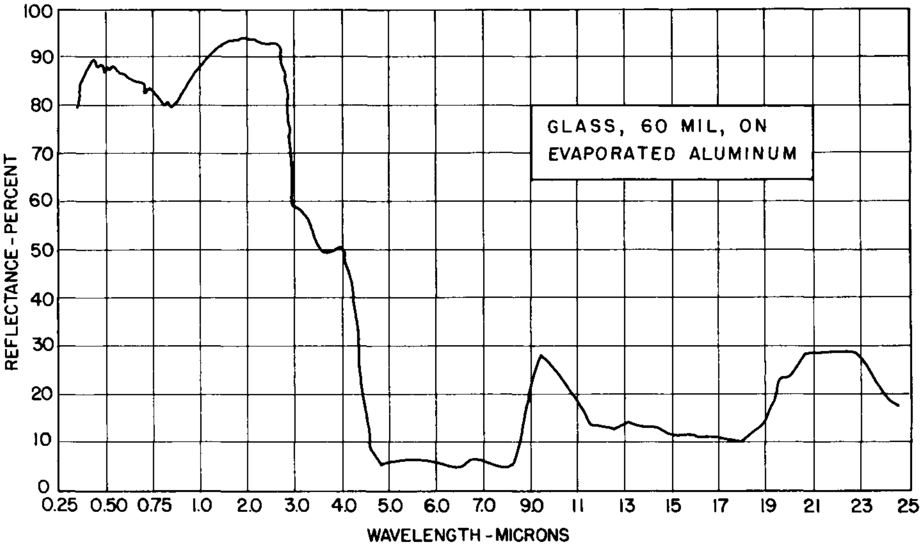

Fig. 8 Near-normal spectral reflectance of glass on evaporated aluminum

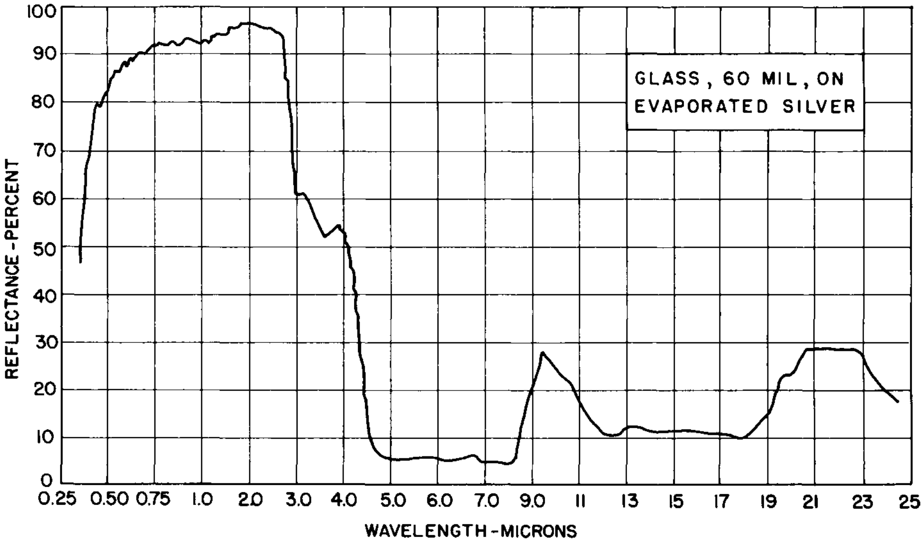

Fig. 9 Near-normal spectral reflectance of glass on evaporated silver

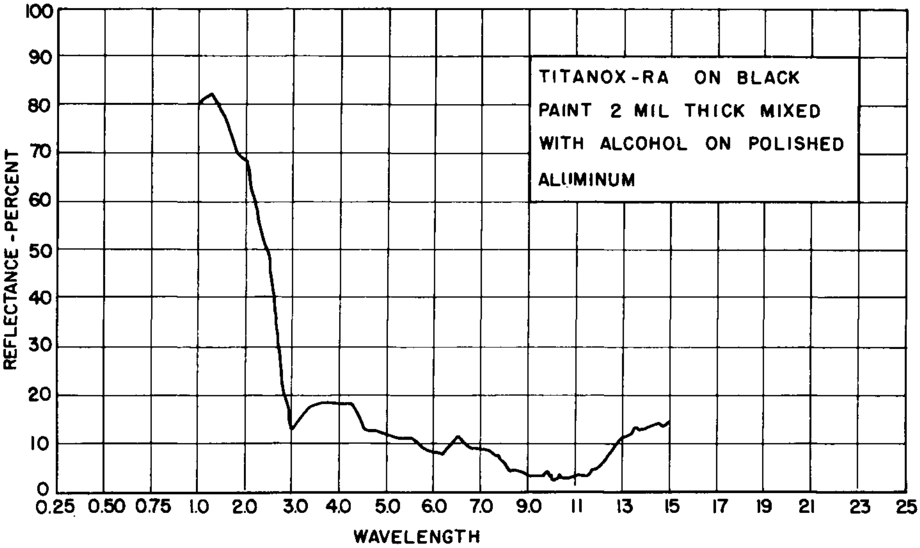

Fig. 10 Near-normal spectral reflectance of titanium dioxide powder

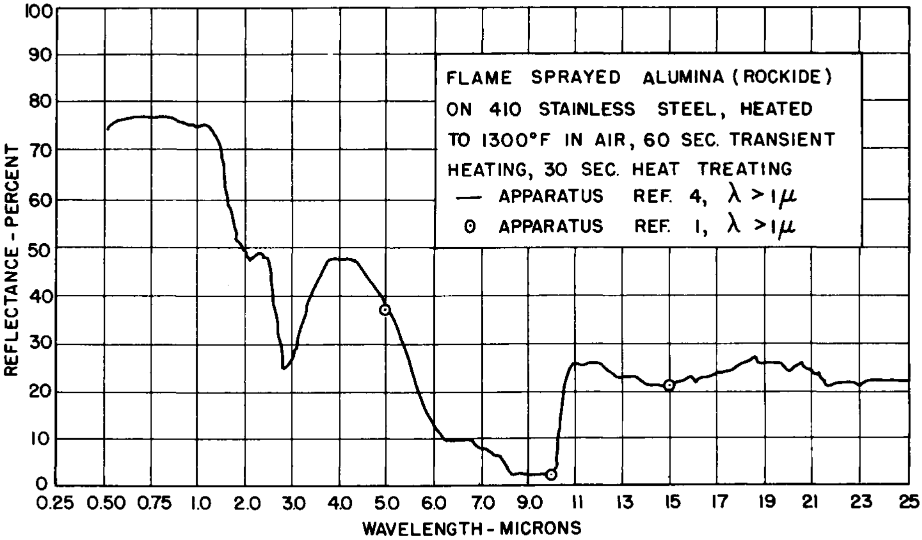

Fig. 11 Near-normal spectral reflectance of flame-sprayed alumina

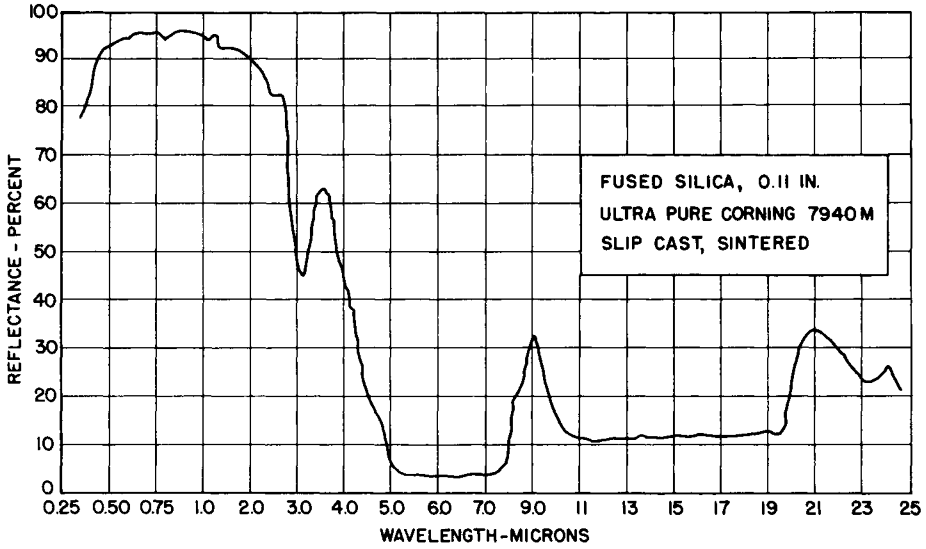

Fig. 12 Near-normal spectral reflectance of fused silica

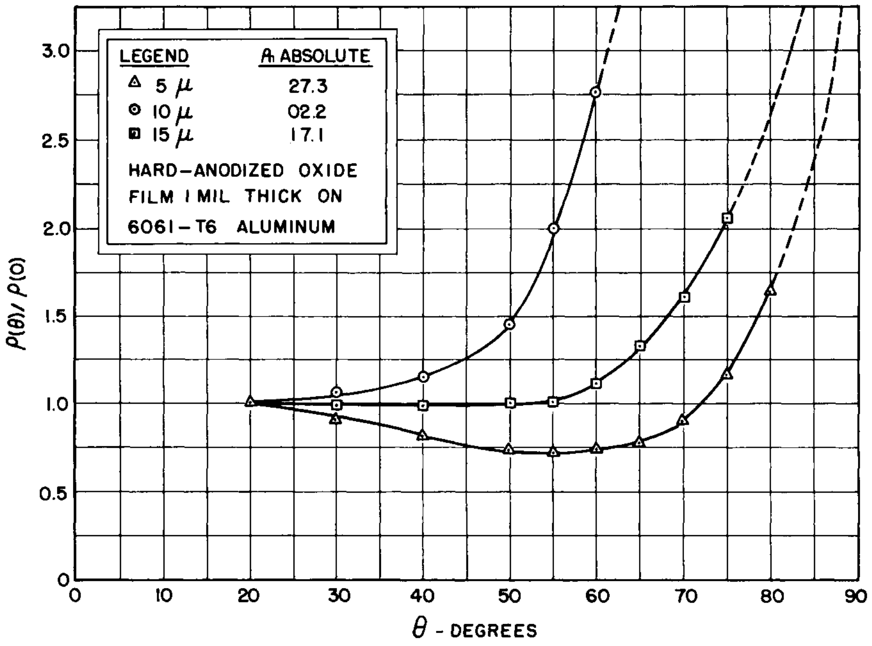

Fig. 13 Normalized directional reflectance of hard-anodized aluminum

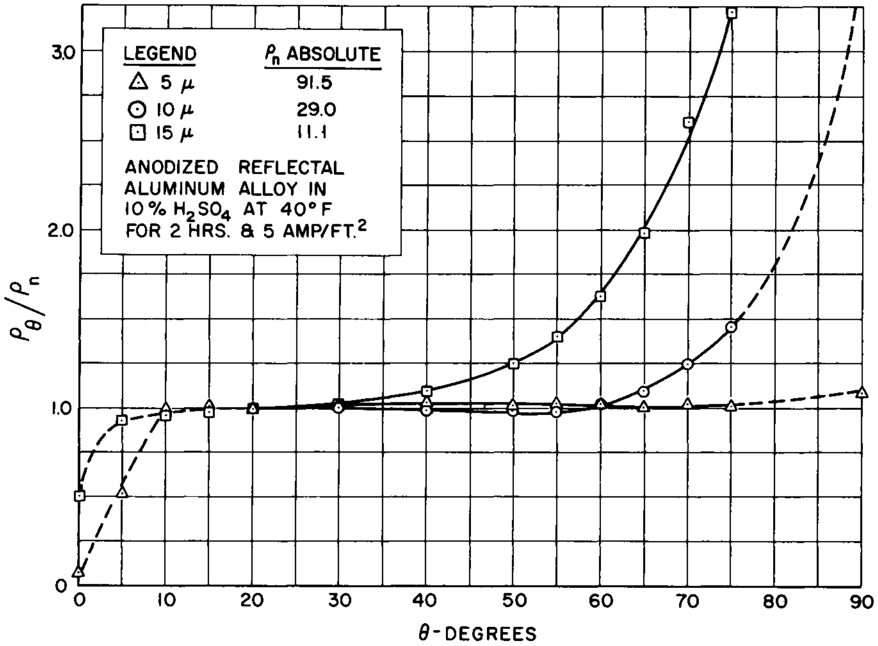

Fig. 14 Normalized directional reflectance of soft-anodized aluminum

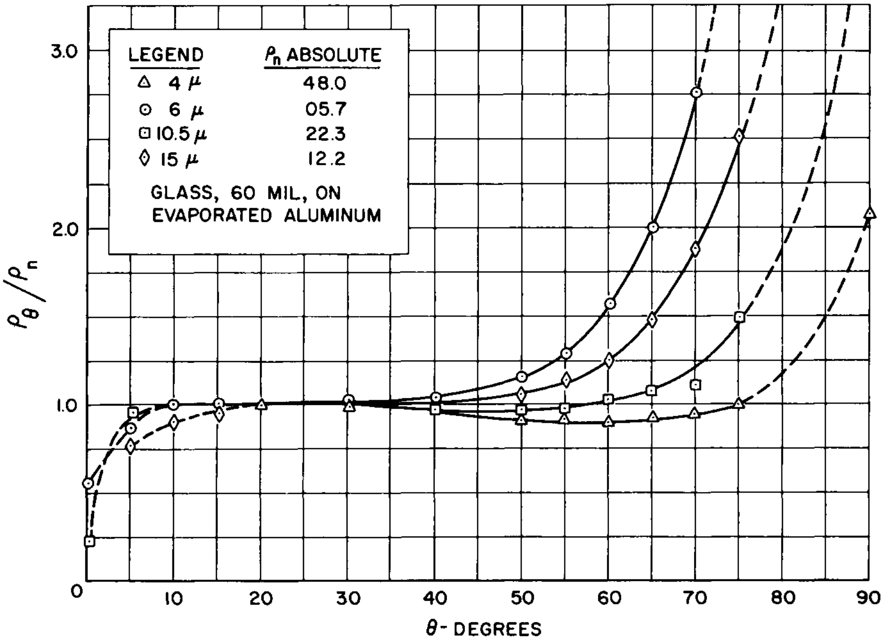

Fig. 15 Normalized directional reflectance of glass on evaporated aluminum

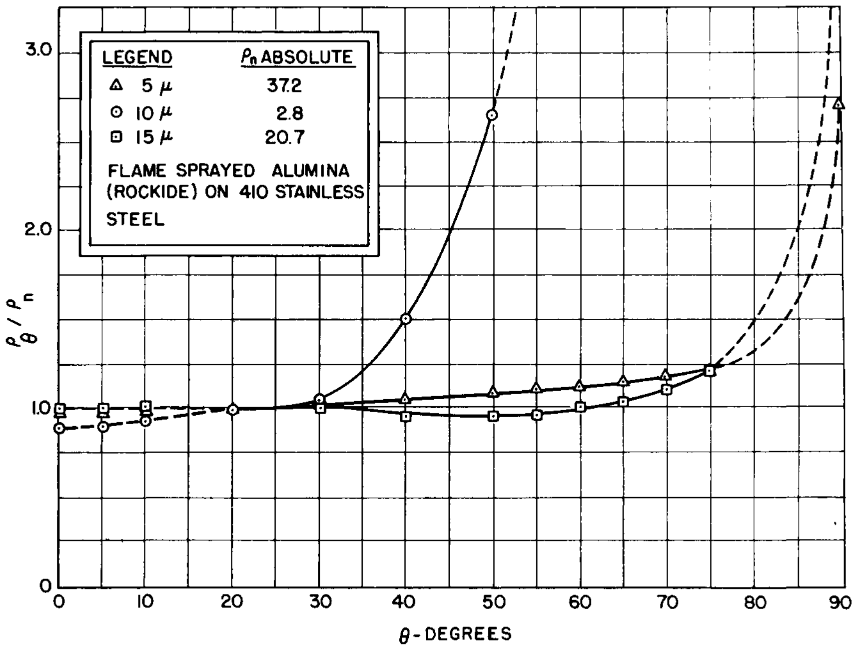

Fig. 16 Normalized directional reflectance of flame-sprayed alumina

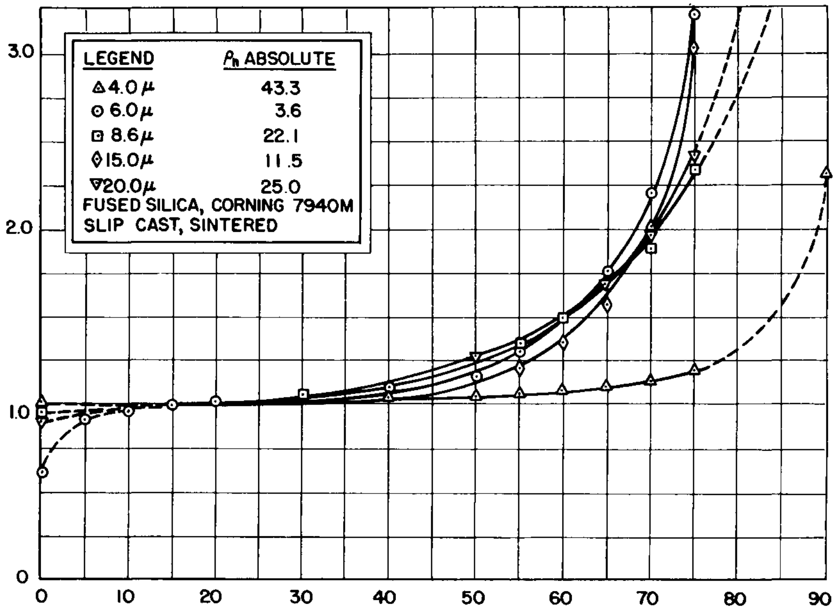

Fig. 17 Normalized directional reflectance of fused silica