

NASA TECHNICAL NOTE



NASA TN D-3115

c 1

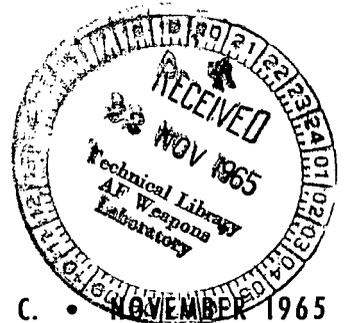
NASA TN D-3115

LOAN COPY: RETU  
AFWL (WLIL-2  
KIRTLAND AFB, N



# SPECTRAL EMITTANCE OF ALUMINUM OXIDE AND ZINC OXIDE ON OPAQUE SUBSTRATES

*by Curt H. Liebert*  
*Lewis Research Center*  
*Cleveland, Ohio*



TECH LIBRARY KAFB, NM



0079843

NASA TN D-3115

SPECTRAL EMITTANCE OF ALUMINUM OXIDE AND  
ZINC OXIDE ON OPAQUE SUBSTRATES

By Curt H. Liebert

Lewis Research Center  
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

---

For sale by the Clearinghouse for Federal Scientific and Technical Information  
Springfield, Virginia 22151 - Price \$1.00

# SPECTRAL EMITTANCE OF ALUMINUM OXIDE AND ZINC OXIDE ON OPAQUE SUBSTRATES

by Curt H. Liebert

Lewis Research Center

## SUMMARY

An experimental study was conducted to examine the normal spectral emittance of composites of powdered zinc oxide (ZnO) and aluminum oxide ( $\text{Al}_2\text{O}_3$ ) and flame-sprayed  $\text{Al}_2\text{O}_3$  when applied in various thicknesses to substrates of different radiative properties. The emittance measurements were made in air over the wavelength range 1.2 to 14.1 microns at a surface temperature of  $880 \pm 8^\circ \text{K}$ . Coating thicknesses from 0.05 to 0.41 millimeter (0.002 to 0.016 in.) were applied to substrates having widely different spectral emittances. In addition, some normal spectral reflectances at wavelengths of 0.37 to 2 microns and normal transmittance data from 2 to 15 microns were obtained at room temperature for the ZnO coating on a flat sodium chloride window.

Normal spectral emittance of composites made from coatings of powdered ZnO and  $\text{Al}_2\text{O}_3$  changed appreciably with coating thickness and substrate emittance. For instance, the emittance at wavelengths from 2 to 3 microns of composites of ZnO powder can be reduced by almost one-half when coating thickness changes from 0.05 to 0.41 millimeter (0.002 to 0.016 in.) when applied to a substrate having an emittance of 0.9. The variations of spectral emittance are due, in part, to the high translucence of the ZnO coating. While a theoretical interpretation of the experimental results has not been developed at this time, the data indicate a linear logarithmic relation between the composite emittance and the coating thicknesses for the composites of powdered ZnO and  $\text{Al}_2\text{O}_3$ .

## INTRODUCTION

The performance of many space systems is dependent on the absorptance and emittance, or the ratio of absorptance to emittance, of the vehicle surface. This ratio is particularly important in those systems where there is little or no internal heat source or sink. For example, the temperature of space vehicles and the performance of

well-insulated propellant tanks are strongly influenced by the external-surface  $\alpha_s/\epsilon_{t,h}$  where  $\alpha_s$  is the total normal absorptance of a surface to solar radiation and  $\epsilon_{t,h}$  is its total hemispherical emittance (ref. 1).

Values of  $\alpha_s/\epsilon_{t,h}$  for surfaces vary widely, but in general, for metals  $\alpha_s/\epsilon_{t,h}$  is greater than 1 and for nonconductors  $\alpha_s/\epsilon_{t,h}$  is less than 1. Therefore, it should be possible to tailor the surface of a vehicle to the desired values of  $\alpha_s/\epsilon_{t,h}$ . However, nonconductors usually do not have the mechanical properties that are required for structural materials. Therefore, surfaces having  $\alpha_s/\epsilon_{t,h}$  less than 1 can be obtained only by covering metallic structures with nonconducting coatings. This is commonly accomplished by applying paints pigmented with metal oxides. Such paints, when applied in practical thicknesses, may be somewhat translucent and the radiative properties of the painted, composite surface depend on both the properties and the thickness of the coating and on the radiative properties of the substrate (ref. 2). Because the pigment is a basic constituent of the coating, an experimental study was conducted to examine in more detail the radiative performance of two commonly used pigments, zinc oxide (ZnO) and aluminum oxide (Al<sub>2</sub>O<sub>3</sub>), when applied in different thicknesses to substrates of different radiative properties. Some emittance measurements were also made with an adherent flame-sprayed Al<sub>2</sub>O<sub>3</sub> because of its widespread use as a heat-resistant coating.

Spectral-emittance measurements were made in air over the wavelength range 1.2 to 14.1 microns and at a surface temperature of 880<sup>0</sup>±8<sup>0</sup> K. The pigments varied in thickness from 0.05 to 0.41 millimeter (0.002 to 0.016 in.) on four substrates having widely different spectral emittances. Some spectral reflectances at wavelengths of 0.37 to 2 microns and transmittance data from 4.5 to 14.9 microns were obtained at room temperature for the coating on a transparent substrate. All data were obtained with nearly normal viewing.

The results presented herein show the importance of both coating and substrate characteristics in the overall radiative performance of coated, composite surfaces. While a theoretical interpretation of the experimental results has not been developed at this time, data indicate a linear logarithmic relation between the composite emittance and the coating thickness for the composites of powdered ZnO and Al<sub>2</sub>O<sub>3</sub> coatings.

## SYMBOLS

$b_1$	constant in eqs. (2) and (3), $1.2864 \times 10^{-15} \text{ W}/(\text{cm}^2)(\mu)(^\circ\text{K}^3)$
$r_\lambda$	spectral reflectance
$T_s$	surface temperature
$W_\lambda$	spectral intensity of blackbody

$W_{\lambda, m}$	maximum spectral radiant intensity of blackbody
$\alpha_s$	total normal solar absorptance
$\epsilon_{t, h}$	total hemispherical emittance
$\epsilon_{t, n}$	total normal emittance
$\epsilon_{\lambda}$	spectral normal emittance
$\lambda$	wavelength, $\mu$
$\sigma$	Stefan-Boltzmann constant, $5.669 \times 10^{-12} \text{ W}/(\text{cm}^2)(^{\circ}\text{K}^4)$

## APPARATUS AND PROCEDURE

### Spectroscopic Equipment

A Perkin-Elmer Model 13 recording infrared spectrophotometer with an emittance-reflectance attachment was used to measure the normal spectral emittance of specimens heated to  $880^{\circ} \pm 8^{\circ} \text{ K}$  in air. Data were taken in the double beam mode on a strip-chart recorder over the wavelength range 1.2 to 14.1 microns. A Perkin-Elmer Model 350 spectrophotometer with a total reflectance accessory was used to determine emittance indirectly by measurement in air of the normal spectral reflectance at room temperature in the wavelength range 0.37 to 2 microns.

### Substrate Preparation

Four types of substrates differing in the values of their spectral emittance were used in these experiments. Substrates with nearly constant spectral emittances of 0.9 (type A) were achieved by immersing roughened specimens of stainless steel 304 in a solution of sodium dichromate and then baking them at  $670^{\circ} \text{ K}$  for 1/2 hour. Specimens of roughened stainless steel 304 (type B) and roughened aluminum 1100-0 (type C) when oxidized in air achieved nearly constant emittances of 0.7 and 0.5, respectively. Roughness in all three cases was accomplished by sandblasting. Substrates with the lowest spectral emittances from about 0.1 to 0.5 (type D) were made by polishing a disk of aluminum 1100-0, scoring a crosshatched pattern 0.05 millimeter (0.002 in.) deep in the surface, and oxidizing the specimen in air at about  $880^{\circ} \text{ K}$ . All oxidation treatments were accomplished within 1 hour, and thereafter, the emittance did not vary more than 1 percent over a 12-hour period.

The substrates were 23-millimeter (0.090-in.) diameter disks, 1.6 millimeters (0.0625 in.) thick. Three Chromel-Alumel thermocouples fabricated from 0.13-millimeter (0.005-in.) diameter wire were mounted in small grooves machined in the back of each disk. The balls of the thermocouples were spot-welded or peened in the center of the disk and about 3.8 millimeter (0.15-in.) on each side of the center along the groove. The thermocouple wires were held in the grooves with a high-temperature cement. This attachment procedure minimized the heat conduction through the wires. Variations among the three thermocouple readings were not more than  $\pm 1^{\circ}$  K at  $880^{\circ}$  K.

## Pigments

Powders of ZnO and  $\text{Al}_2\text{O}_3$  were applied to the four types of substrates. The  $\text{Al}_2\text{O}_3$  and ZnO were obtained from the Fisher Scientific Company (catalog nos. A-542 and Z-52, respectively). The particle size of the  $\text{Al}_2\text{O}_3$  varied from about 3 to 10 microns. The particle size of the ZnO powder was measured with an electron microscope and found to be about 0.5 micron.

## Composite Preparations

The composites of powdered ZnO and  $\text{Al}_2\text{O}_3$  were formed by spreading and pressing the powders into a smooth compact mass onto the substrates with a glass microscope slide. The measured density of the compacted ZnO powder was 1 gram per cubic centimeter. The powder thickness above the filled substrate was measured with a micrometer caliper by first measuring the combined thickness of substrate and glass and then measuring the increased thickness of the substrate, powder, and glass.

A filled substrate was achieved by spreading the powders into the roughened substrate until the valleys of roughness were totally filled. The peak-to-valley roughness of the sandblasted substrates (types A, B, and C) was about 0.075 millimeter (0.003-in.). If the fraction of voids in this roughened volume is assumed to be two-thirds (the fraction of voids in pyramids with closely packed bases and equal heights), the volume of voids per unit substrate area is 0.05 cubic millimeter per square millimeter. Thus, it requires 0.05 cubic millimeter of powder per square millimeter of substrate just to fill the roughened surface level to the top of the substrate peaks. In a typical experiment, approximately 0.06 cubic millimeter of ZnO per square millimeter of area was applied to the roughened surface to leave only an occasional substrate peak exposed. Visual examination showed that much more than 90 percent of the substrate was covered, while

the thickness of the ZnO over the remainder of the surface varied from 0 to about 0.08 millimeter (0.003-in.)

Approximately 10 percent of the polished surface of substrate D was crosshatched. In a typical experiment, 0.012 cubic millimeter of ZnO per square millimeter of area was required to fill the grooves and leave a layer of powder estimated to be about 0.01 millimeter (0.0004-in.) above the polished surface.

The flame-sprayed alumina composites were made by spraying Norton Rokide A from a rod-type gun onto the substrates (ref. 3). The same type of coating roughness on all substrates was obtained by holding the gun about 6 inches from the substrate.

### Repeatability and Accuracy

The uncertainty associated with the type of emittance measurements presented in this report has been discussed at length by many authors. A good discussion covering most of the possible errors is given in reference 4. One such error arises from the difference between the specimen temperature and the hohlraum temperature. The hohlraum used in these experiments possessed a nonuniform temperature. Figure 1 presents a schematic drawing of the hohlraum and emission furnace. The variations in hohlraum temperature are shown to be within  $13^{\circ}$  K. This reasonably small gradient was achieved by inserting a ceramic plug into the hole normally occupied by the hohlraum samples holder (fig. 1).

Alumina, flame-sprayed to a thickness of 0.4 millimeter (0.016-in.) on oxidized, roughened aluminum 1100-0, was used as a standard to achieve a proper temperature match for this system. Voluminous experiments by others measuring normal spectral reflectance and emittance agree that  $Al_2O_3$  either in powdered, flame-sprayed, or sintered form has an emittance of 0.95 to 0.99 at 8.5 microns over a range of temperature from room temperature to  $1323^{\circ}$  K and over a wide range of surface roughness and thickness. In these experiments a spectral emittance of 0.98 at 8.5 microns for this standard was achieved with the hohlraum temperatures shown in figure 1 and an indicated specimen temperature of  $874^{\circ} \pm 1^{\circ}$  K. The lower indicated specimen temperatures compared with the hohlraum temperatures were due to heat conductance through the thermocouples and a calculated and experimentally determined temperature

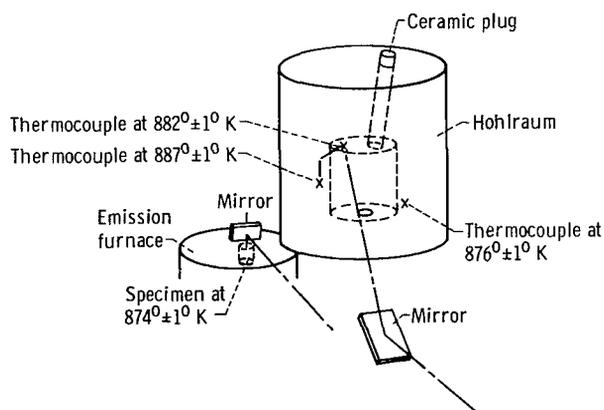


Figure 1. - Schematic drawing of hohlraum and emission furnace.

temperature from room temperature to  $1323^{\circ}$  K and over a wide range of surface roughness and thickness. In these experiments a spectral emittance of 0.98 at 8.5 microns for this standard was achieved with the hohlraum temperatures shown in figure 1 and an indicated specimen temperature of  $874^{\circ} \pm 1^{\circ}$  K. The lower indicated specimen temperatures compared with the hohlraum temperatures were due to heat conductance through the thermocouples and a calculated and experimentally determined temperature

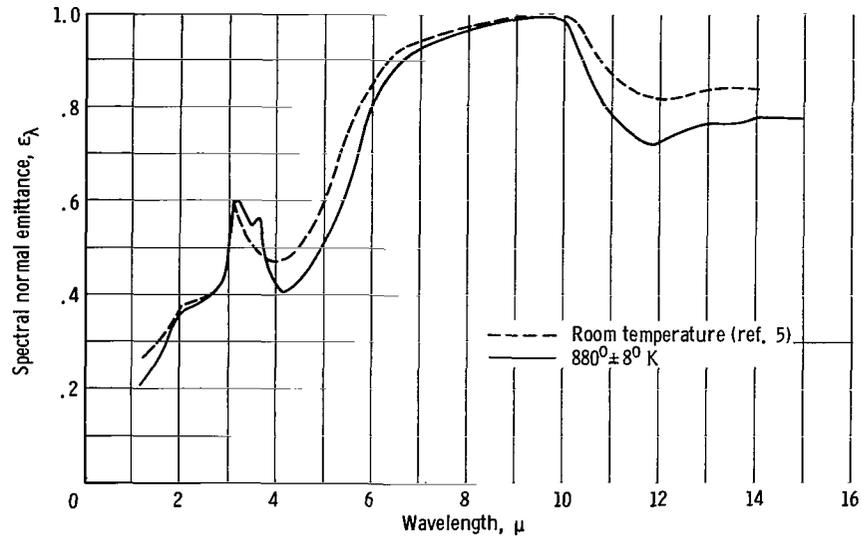
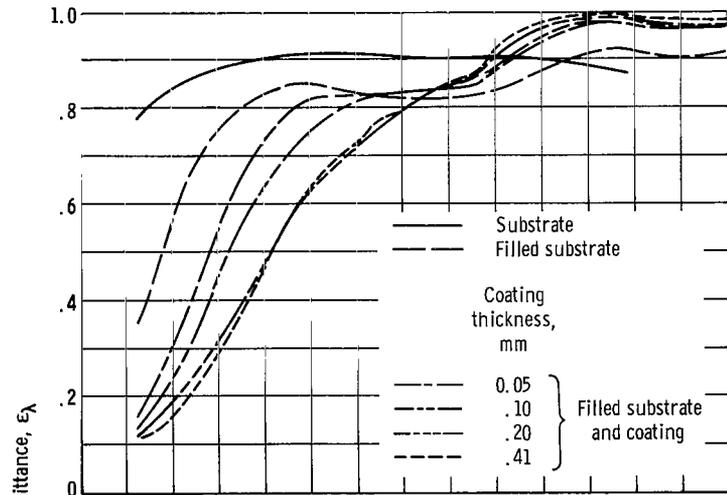


Figure 2. - Spectral emittance of flame-sprayed alumina.

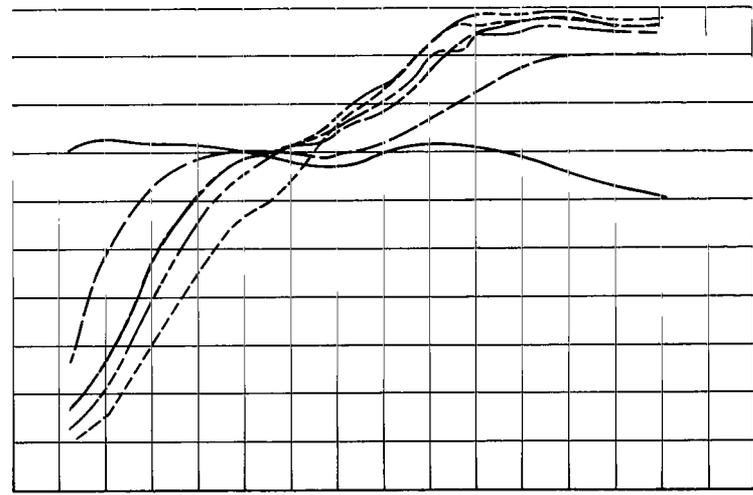
gradient through the standard of about  $2^{\circ}$  K. The temperature gradient through the composites was also calculated to be about  $2^{\circ}$  K. Thus, the actual specimen temperature was considered to be  $880^{\circ} \pm 8^{\circ}$  K.

Figure 2 shows the spectral normal emittance of the standard from 1.2 to 14 microns at the temperature settings indicated previously. These temperature settings were maintained at  $\pm 1^{\circ}$  K for all measured values of composite emittance. For the temperature variation of  $\pm 1^{\circ}$  K, the measured emittance of the composites varied  $\pm 0.03$  at 1.2 microns and  $\pm 0.01$  at 14 microns. Also shown in figure 2 is the normal room-temperature emittance as computed in reference 5 from experimental room-temperature reflectance measurements made by J. C. Richmond. The emittance data at elevated temperature are in fair agreement with the room-temperature data. At 2 microns the elevated-temperature emittances were within 0.02 of the room-temperature emittance. The largest discrepancy is at 11.8 microns, where the emittance difference is 0.1. Comparison of emittance measurements is of questionable value unless the specimens are prepared from the same material, by the same processing, and with the same surface finish (ref. 6). Factors such as grain size, porosity, and impurities can have a large effect on the spectral emittance. As explained later, emittance also appears to vary only slightly with surface temperature at infrared wavelengths. The total experimental error in the emittance measurements at the temperature shown in figure 1 is believed to be  $\pm 0.03$  or less.

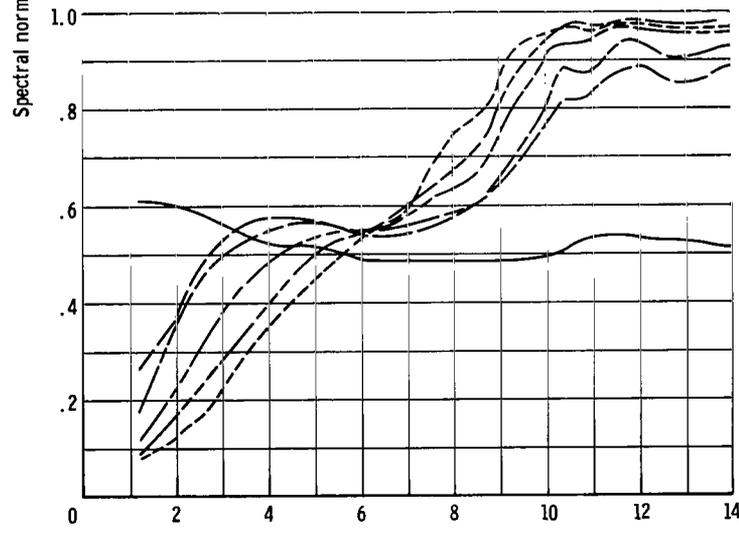
At the shorter wavelengths, where the spectral emittance was estimated from reflectance data, the advertised experimental error for the Perkin-Elmer Model 350 spectrophotometer is  $\pm 2$  percent over most of the wavelength range of the instrument.



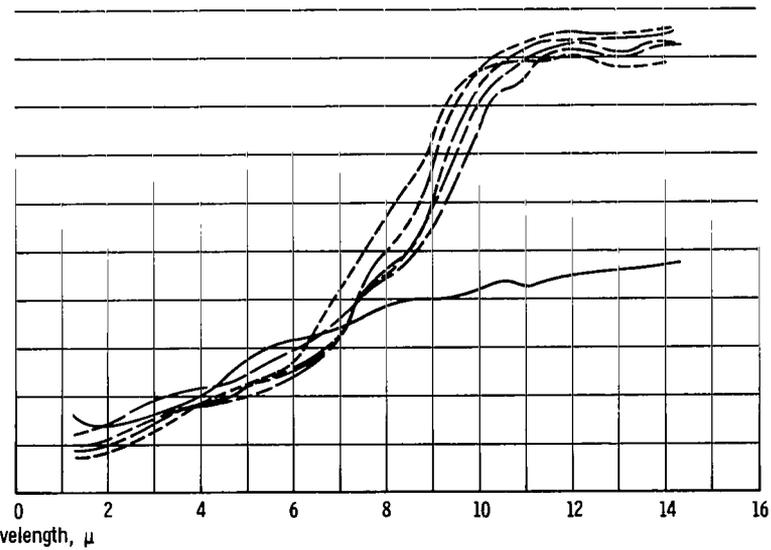
(a) Type A substrate.



(b) Type B substrate.



(c) Type C substrate.



(d) Type D substrate.

Figure 3. - Spectral emittance of powdered zinc oxide on four substrates. Surface temperature,  $880 \pm 8^\circ \text{K}$ .

## RESULTS AND DISCUSSION

### Zinc Oxide

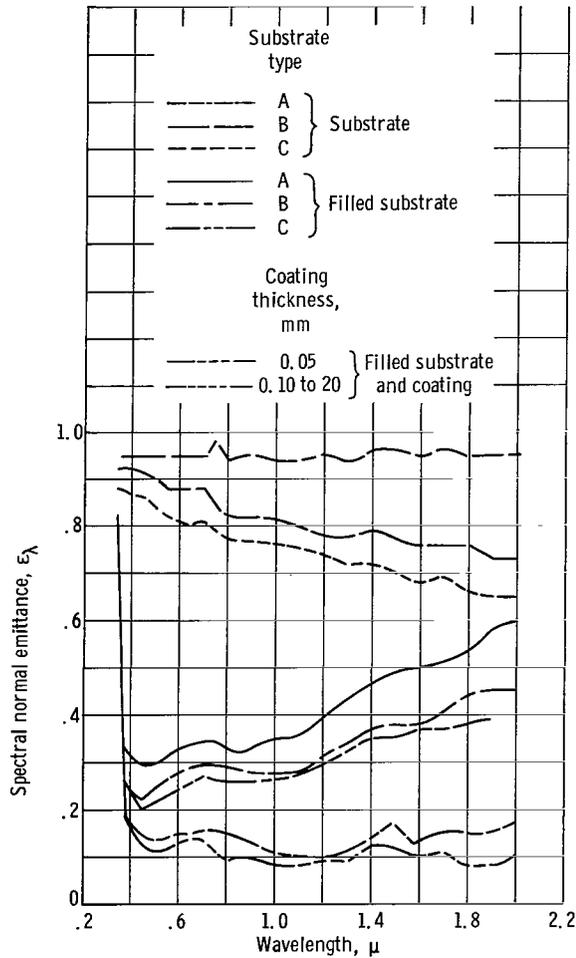


Figure 4. - Room-temperature spectral emittance of zinc oxide composites and substrates.

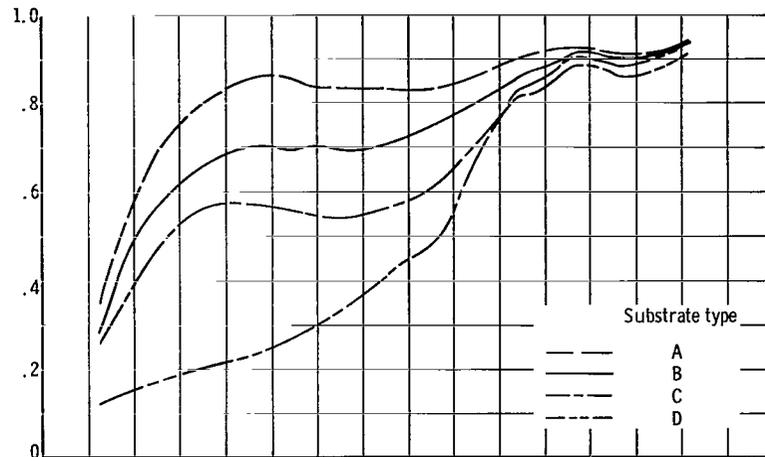
Composite spectral emittance. - Figure 3, presents the change in spectral normal emittance with ZnO powder thickness as the parameter on a given substrate and the substrate spectral emittance as measured at a surface temperature of  $880^{\circ} \pm 8^{\circ}$  K. The data for the ZnO coating on the substrate of highest emittance (fig. 3(a)) show the largest decrease in spectral normal emittance with increasing coating thickness at wavelengths of about 1.2 to 6 microns. This variation continues to be large in figure 3(b) and (c), but is much less for composites made with the substrate of lowest emittance (fig. (d)).

Composite emittance from 0.37 to 2 microns. - The extent of the changes in composite emittance with ZnO powder thickness at wavelengths of 0.37 to 2 microns is shown in figure 4. In this case, the spectral reflectance  $r_{\lambda}$  was measured at room temperature, and the emittance was determined from the relation

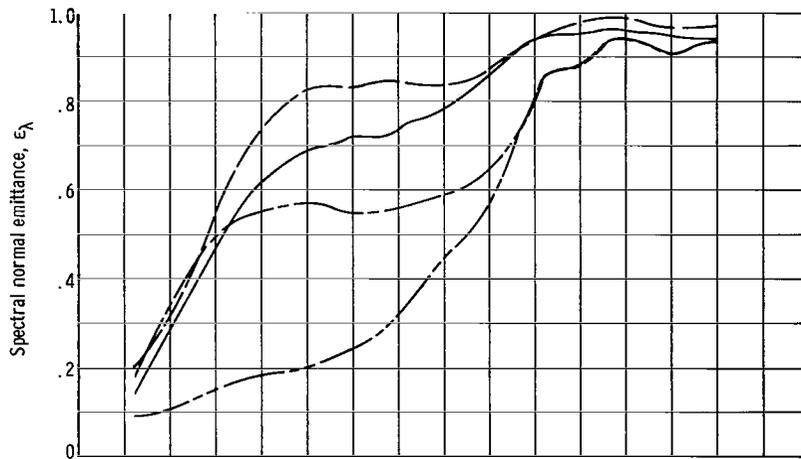
$$\epsilon_{\lambda} = 1 - r_{\lambda} \quad (1)$$

where  $\epsilon_{\lambda}$  is the spectral normal emittance. In general, ZnO composites with coating thicknesses above the filled substrate of 0.05 millimeter (0.002 in.) or greater show little variation of emittance with thickness or wavelength. The values of emittance are about 0.1 to 0.15 for the wavelength range 0.4 to 2 microns. The spectral emittance of the filled substrate surface is greater than that of the other composites. Also, the composite emittance of the filled substrates varies with substrate emittance. The rapid rise of emittance at about 0.4 micron is known as the absorption edge of zinc oxide.

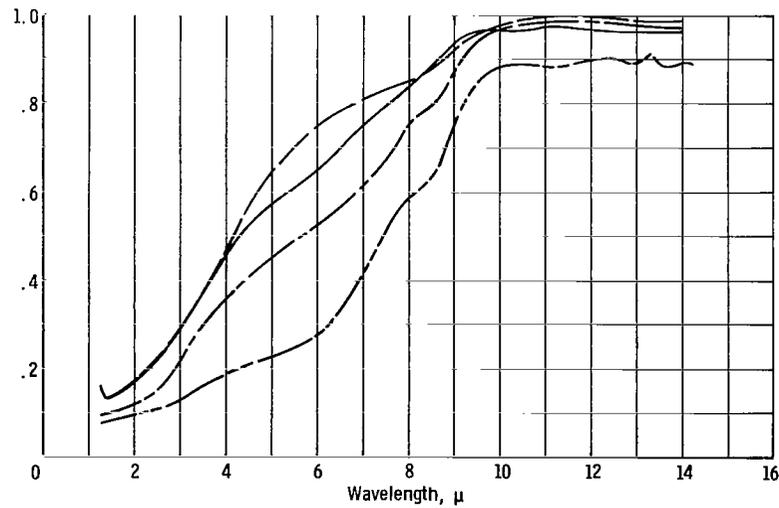
Zinc oxide powder translucence. - The effect of varying substrate on the composite emittance with three levels of ZnO coverage is shown in figure 5. These curves were



(a) Zinc oxide filled substrate.



(b) Zinc oxide 0.05 millimeter above filled substrate.



(c) Zinc oxide 0.4 millimeter above filled substrate.

Figure 5. - Variation of spectral normal emittance of zinc oxide and four substrates.  
Surface temperature,  $880^{\circ} \pm 8^{\circ}$  K.

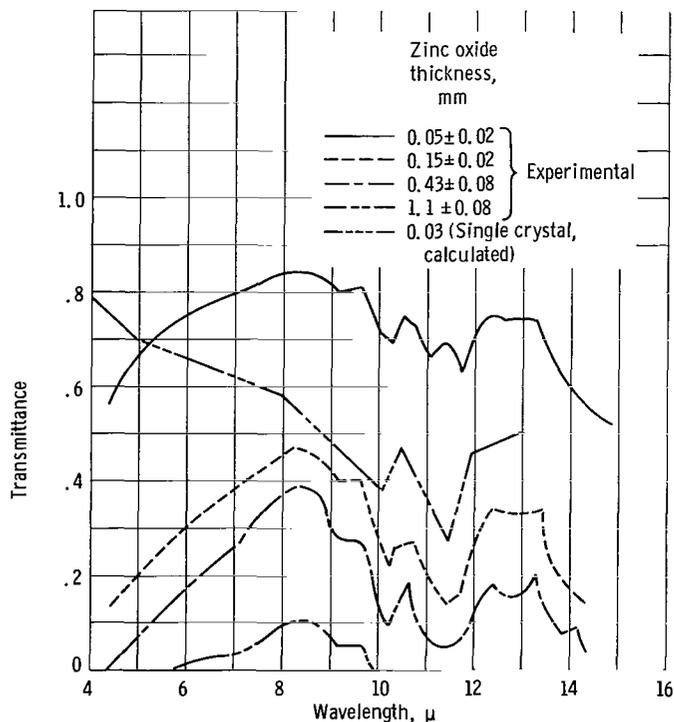


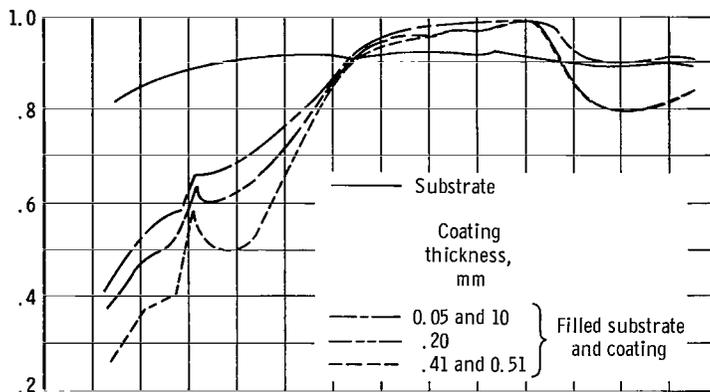
Figure 6. - Calculated transmittance of single crystal of zinc oxide and experimental transmittance of composites of zinc oxide and sodium chloride.

obtained by replotting the data presented in figure 3 (p. 7). The variation of composite emittance may be attributed to radiant energy transmission through the translucent ZnO powder from the substrates of varying emittances. This conclusion is logical because variations of coating emittance, reflectance, and transmittance at a given thickness are probably small.

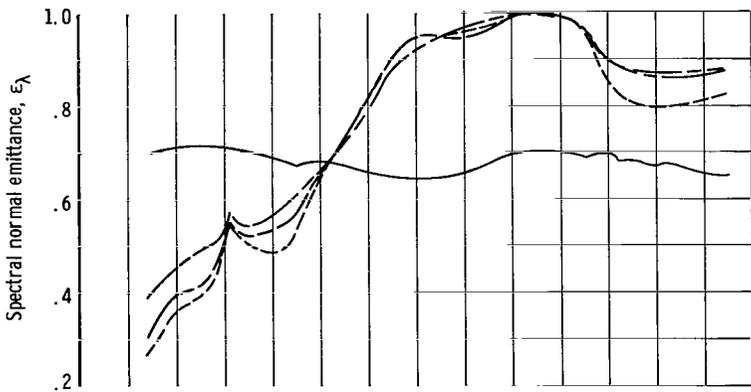
To confirm further that the ZnO powder is translucent as indicated by the emittance data, different thicknesses of ZnO powder were placed on a sodium chloride window. The external transmittance data (reflectance included) of the powder plus the window were obtained and are shown in figure 6. The window transmittance (not shown in fig. 6)

was found to vary from 0.85 to 0.90 in the wavelength range 4.5 to 15 microns. The data indicate that ZnO coatings 0.05 millimeter (0.002-in.) thick are very translucent at these wavelengths. Negligible transmittance was found for powder thicknesses of 1.1 millimeter (0.044 in.).

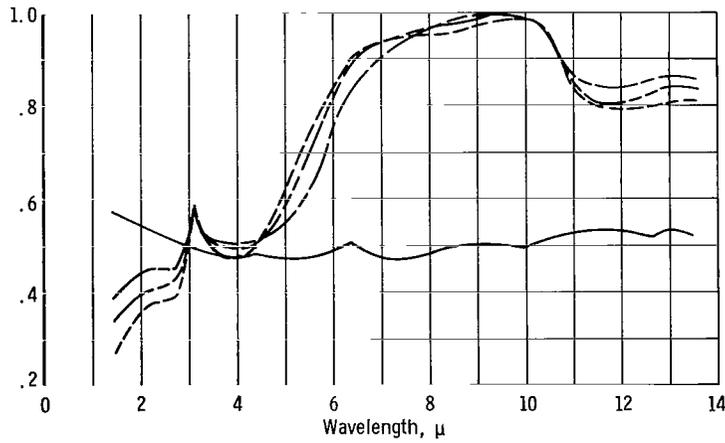
For comparison purposes, figure 6 also shows the internal transmittance (reflectance not included) which was calculated from the absorption coefficient data of reference 7 for a crystal of ZnO 0.03 millimeter thick. This calculated transmittance may be compared to the transmittance of 0.15-millimeter-thick ZnO powder since the density of the powder is about one-fifth that of the crystal; the comparison is then on the basis of equal mass per unit area or equal numbers of ZnO molecules in the optical path. The transmittance of the powder in the 8- to 13-micron region is about the same as that for the single crystal at equal mass per unit area, but the powder transmittance is much less at shorter wavelengths. Usually, comparison of powder external and crystal internal transmittance will show little powder transmittance relative to crystal transmittance because the finely packed, closely divided powder particles usually scatter most of the incident light. Therefore, the transmittance of the ZnO is surprisingly high.



(a) Type A substrate.



(b) Type B substrate.



(c) Type C substrate.

Figure 7. - Spectral emittance of flame-sprayed alumina. Surface temperature,  $880^{\circ} \pm 8^{\circ}$  K.

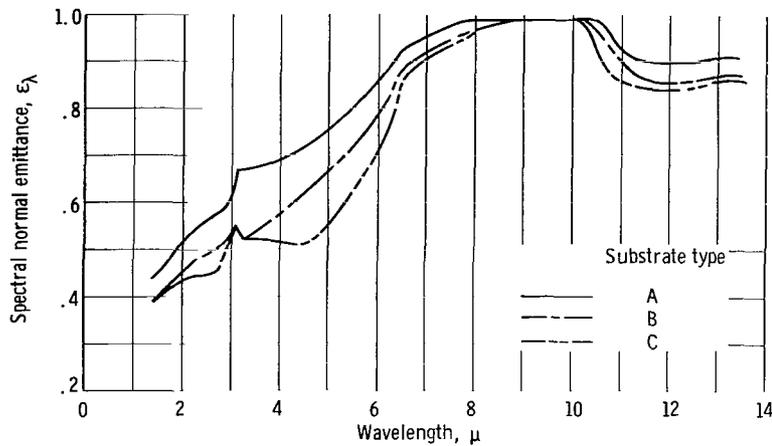


Figure 8. - Variation of spectral composite emittance of 0.05- and 0.10-millimeter, flame-sprayed alumina above filled substrate on three substrates. Surface temperature,  $880^{\circ} \pm 8^{\circ}$  K.

### Flame-Sprayed Alumina Composite Emittance

Figure 7 shows the variation of spectral normal emittance with flame-sprayed  $\text{Al}_2\text{O}_3$  coating thickness on three substrates. The data indicate some changes in composite emittance with thickness, the largest changes occurring for the coating on the substrate of the highest emittance. A comparison of the figures indicates that the spectral normal emittance is invariant with substrate emittance when the coating thickness is about 0.4 millimeter (0.016 in.).

Figure 8 presents data replotted from figure 7. Figure 8 indicates that the spectral normal emittance variation at coating thicknesses of 0.05 and 0.1 millimeter (0.002 and 0.004 in.) is due to at least some coating transmittance.

### Powdered Aluminum Oxide Composite Emittance

Figure 9 presents the variation of spectral normal emittance with  $\text{Al}_2\text{O}_3$  powder thickness as the parameter on four substrates. Figure 10 (p. 14) presents the variations in room temperature spectral normal emittance with  $\text{Al}_2\text{O}_3$  powder thickness as the parameter on three substrates. The composites of coating thickness above the filled substrate exceeding 0.05 millimeter (0.002 in.) show almost the same emittance as the ZnO composites in the spectral region from 0.4 to 2 microns. Figure 11 (p. 15) gives data replotted from figure 9 and shows the variation in composite spectral emittance of  $\text{Al}_2\text{O}_3$  spread on the four substrates at two given values of the coating thickness,

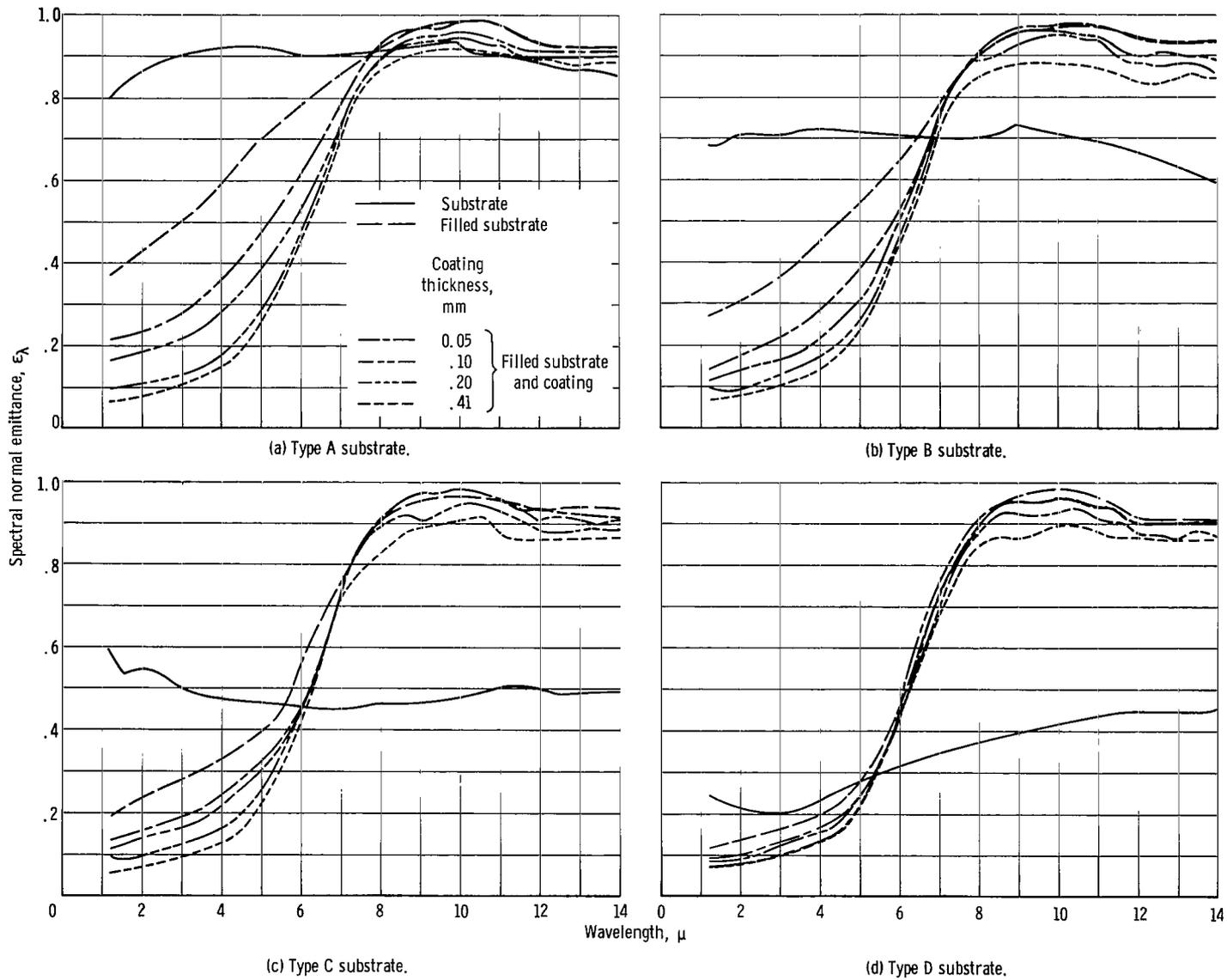


Figure 9. - Spectral emittance of powdered alumina on four substrates. Surface temperature,  $880^{\circ} \pm 8^{\circ}$  K.

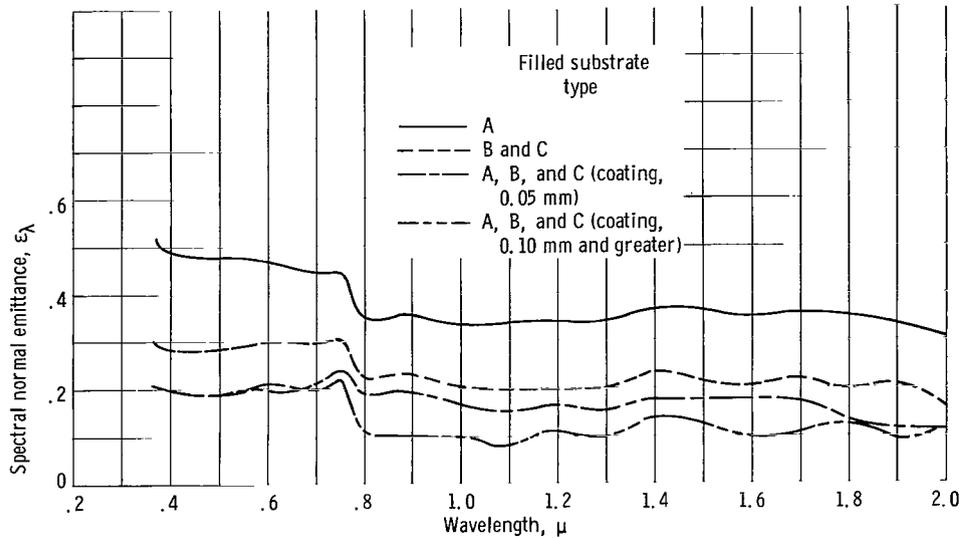


Figure 10. - Spectral emittance at room temperature of powdered alumina composites. (Substrate emittances are identical to those shown in fig. 4.)

0.05 and 0.20 millimeter, (0.002 and 0.008 in.) above the filled substrate. Comparison of figure 11(a) with figure 5(b) shows that generally the  $\text{Al}_2\text{O}_3$  powder is less translucent than the ZnO powder. Figure 11(b) indicates that the powder is opaque at a thickness of about 0.2 millimeter (0.008 in.). This opaqueness was also verified from transmittance measurements of the type discussed in the section Zinc Oxide (p. 8).

### Total Normal and Hemispherical Emittance

Zinc oxide. - Data from all the composites (fig. 3, p. 7) show that substantial variations in the normal emittance with wavelength occur from 1.2 to 6 microns. Also, as discussed previously, the spectral normal emittance varies appreciably with coating thickness and substrate emittance. Therefore, the total normal and hemispherical emittance will vary with surface temperature, coating thickness, and substrate emittance. The extent of these variations is shown in table I (p. 16). The values of total normal emittance given in table I were calculated from the spectral data of figures 3 and 4 and the following equation (ref. 8):

$$\epsilon_{t, n} = \frac{b_1 T_s}{\sigma} \int_0^{\infty} \epsilon_{\lambda} \frac{W_{\lambda}}{W_{\lambda m}} d\lambda \quad (2)$$

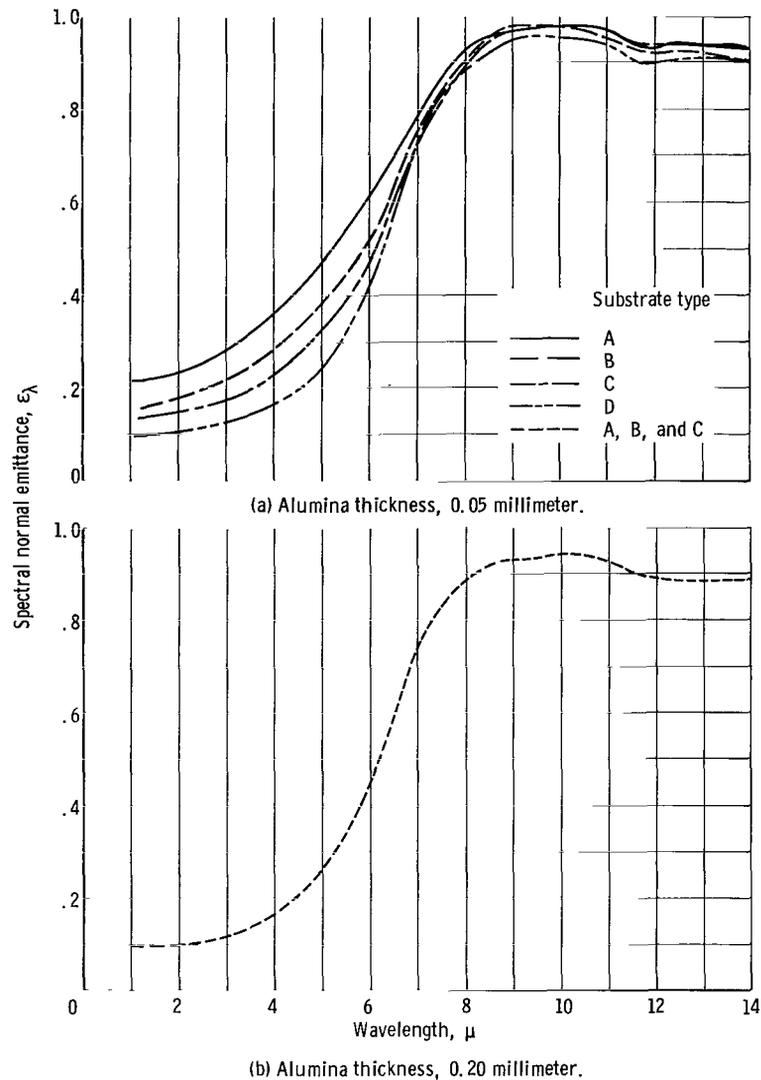


Figure 11. - Spectral composite emittance of powdered alumina above filled substrates.

The values of total hemispherical emittance  $\epsilon_{t,h}$  in table I were obtained by correcting  $\epsilon_{t,n}$  according to the theory of reference 10, which presents equations and curves for estimating hemispherical properties from values measured normal to the surface. For this estimation the composites were considered to be dielectrics.

It was assumed that the infrared spectral emittance of the ZnO composites was invariant with surface temperature. This assumption was reasonably substantiated from other measurements of the spectral emittance of a composite of ZnO made at surface temperatures of  $598^{0\pm 8}$  K and  $1076^{0\pm 19}$  K. The composites in this case were 0.05 millimeter (0.002 in.) of ZnO above filled substrates of types A and D. The results showed the emittance at the lower surface temperature to be about 0.03 less than

TABLE I. - EMITTANCE OF ZINC OXIDE COATINGS

Substrate type	Coating thickness, mm	Surface temperature, $T_s$ , °K					
		350	880	1400	350	880	1400
		Total normal emittance, $\epsilon_{t,n}$			Total hemispherical emittance, $\epsilon_{t,h}$		
A	Filled	0.88	0.80	0.71	0.83	0.76	0.69
	0.05	.92	.71	.52	.87	.69	.53
	.41	.91	.57	.37	.86	.57	.40
B	Filled	0.82	0.66	0.58	0.78	0.65	0.58
	0.05	.87	.63	.44	.82	.62	.46
	.41	.88	.54	.35	.83	.55	.38
C	Filled	0.76	0.57	0.49	0.73	0.57	0.50
	0.05	.79	.56	.42	.75	.56	.44
	.41	.85	.46	.29	.80	.48	.32
D	Filled	0.70	----	0.21	0.68	----	0.24
	0.41	.73	----	.19	.70	----	.22

the emittance of the higher temperature surface over most of the wavelength region from 2 to 14 microns. At shorter wavelengths, however, this will not be true.

At visible wavelengths it is known that pure crystalline or powdered ZnO turns from a white color at room temperature to a light yellow and finally to orange with increasing temperature. The original white color is restored upon cooling to room temperature (ref. 7). This effect was also observed in these experiments. This coloration is produced by a shift of the absorption edge. The wavelengths at which the absorption edge occurs vary from about 0.38 micron at 293° K to about 0.54 micron at 1363° K. However, less than 1 percent of the radiation from a 1400° K blackbody is emitted at wavelengths shorter than 1.0 micron. Therefore this shift of the absorption edge at even shorter wavelengths has a negligible effect on the total emittance of the surface at temperatures of 1400° K and below.

The total normal emittance calculations are largely based on the data presented in figure 3 (p. 7). The spectral emittance data calculated from room temperature reflectance (fig. 4, p. 8) were used only for the 1400° K case to estimate the small (<3 percent) contribution at wavelengths shorter than 1.2 microns. The total emittance evaluated at 350° K was calculated by assuming the composite spectral emittance at 14 microns to be the same constant value to 50 microns.

Table I shows that, for any given substrate and coating thickness, the total composite emittance (both normal and hemispherical) increases as surface temperature decreases. This is caused by the spectral selectivity of the composites which, as figure 3 shows, have low emittance at the short wavelengths, which would be more

TABLE II. - EMITTANCE OF POWDERED ALUMINA COATINGS

Substrate type	Coating thickness, mm	Surface temperature, $T_s$ , °K						Surface absorptance, $\alpha_s$	Surface temperature, $T_s$ , °K		
		350	880	1400	350	880	1400		350	880	1400
		Total normal emittance, $\epsilon_{t,n}$			Total hemispherical emittance, $\epsilon_{t,h}$				Ratio of solar absorptance to total hemispherical emittance, $\alpha_s/\epsilon_{t,h}$		
A	Filled	0.89	0.61	0.53	0.84	0.66	0.54	0.40	0.48	0.61	0.74
	0.05	.81	.55	.35	.82	.56	.38	.21	.26	.38	.55
	.41	.78	.36	.19	.74	.39	.22	.14	.19	.36	.64
B	Filled	0.88	0.56	0.40	0.83	0.56	0.42	0.25	0.30	0.45	0.60
	0.05	.86	.46	.30	.81	.48	.33	.18	.22	.38	.54
	.41	.78	.35	.19	.74	.38	.22	.14	.19	.37	.64
C	Filled	0.85	0.49	0.34	0.80	0.50	0.37	0.25	0.31	0.50	0.68
	0.05	.83	----	.28	.79	----	.31	.16	.20	----	.52
	.41	.78	.34	.19	.74	.37	.22	.14	.19	.38	.64
D	Filled	0.84	0.41	0.24	0.79	0.43	0.27	----	----	----	----
	0.05	.82	----	.22	.78	----	.25	----	----	----	----
	.41	.78	.34	.19	.74	.37	.22	----	----	----	----

important at the higher surface temperatures, and high emittance at the longer wavelengths, which would be more important at the lower surface temperatures.

Table I also indicates that the total composite emittance with a given substrate decreases as coating thickness increases at the higher surface temperature. The emittance increases slightly as coating thickness increases at a surface temperature of 350° K. These effects may be attributed partly to the decrease in coating transmittance with increased thickness which allows the composite emittance to be less affected by substrate emittance.

Powdered aluminum oxide. - The extent of the composite emittance variations with surface temperature, coating thickness, and type of substrate is given in table II. Wherever applicable, both total normal and total hemispherical emittance were calculated from the data presented in figure 9 (p. 13) and equation (2). The data in figure 10 (p. 14) were used only to extend the calculation to wavelengths less than 1.2 microns. The spectral emittance was considered invariant with temperature.

A comparison of the data in tables I and II reveals that the total emittance evaluated at 873° and 1400° K for the ZnO composites produced with substrates of type A, B, and C is greater than the corresponding Al<sub>2</sub>O<sub>3</sub> composite emittance. This effect may be attributed mostly to the larger translucence of the ZnO coating relative to the Al<sub>2</sub>O<sub>3</sub> coating. The greater translucence allows more substrate energy to be emitted through the coating

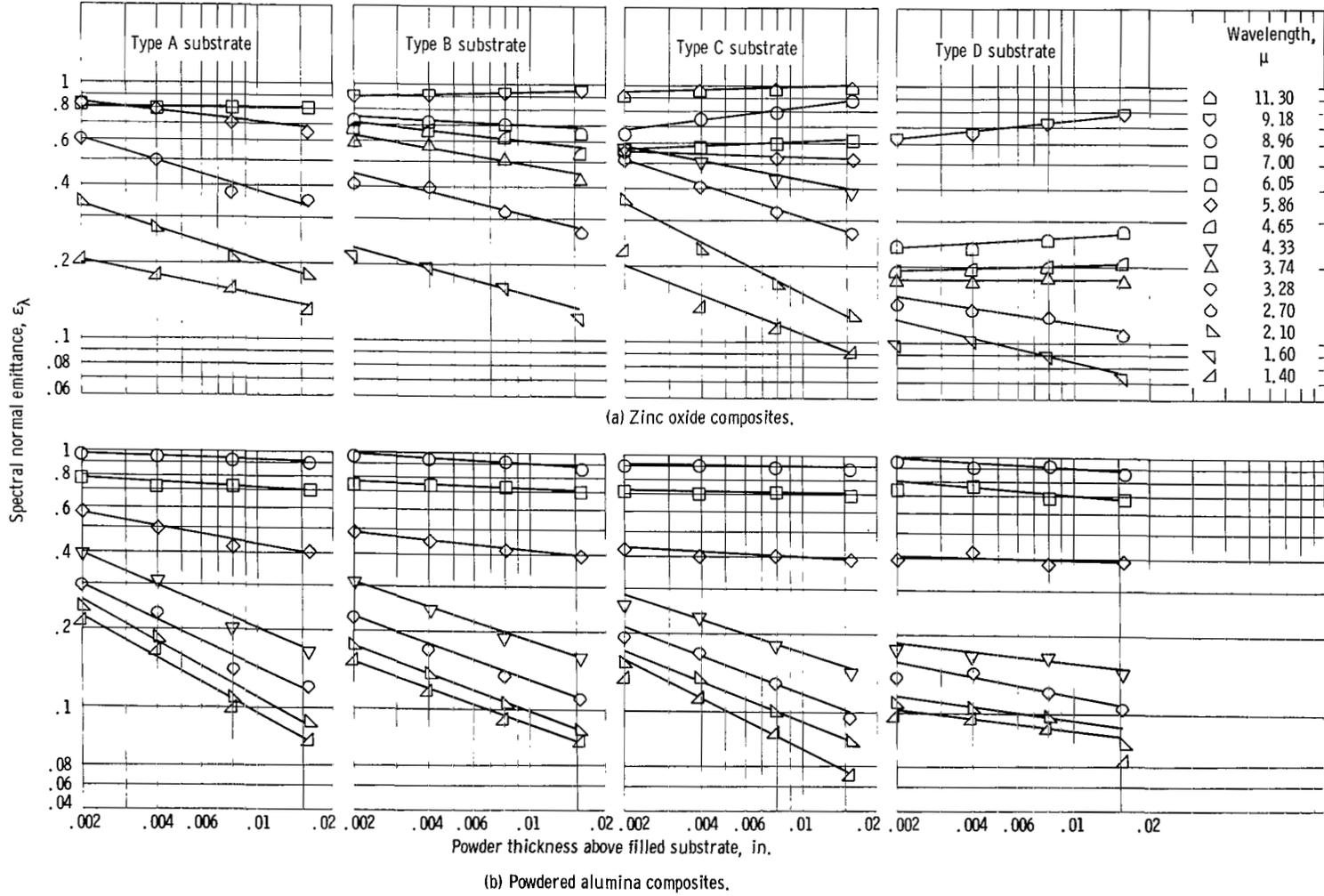


Figure 12. - Composite spectral emittance as function of thickness.

and results in the higher ZnO composite emittance.

## Solar Absorptance and Ratio of Solar Absorptance to Emittance

The solar absorptance  $\alpha_s$  and the ratio of absorptance to emittance  $\alpha_s/\epsilon_{t,h}$  were calculated for the composites of powdered  $Al_2O_3$  and included in table II. This calculation was not made for the ZnO composites because of the uncertainties of the effect of surface temperature on the spectral emittance at the lower wavelengths. The solar absorptance was calculated by using the normal composite emittance data in figure 10 and the following equation:

$$\alpha_s = \frac{5800b_1}{\sigma} \int_0^{\infty} \epsilon_{\lambda} \frac{W_{\lambda}}{W_{\lambda m}} d\lambda \quad (3)$$

where 5800 was taken to be the blackbody source (sun) temperature in degrees K. The lowest  $\alpha_s/\epsilon_{t,h}$  values occur at the lower surface temperature and thicker coating.

## Linear Variation of Composite Emittance with Thickness

Figure 12 presents the variation at  $T_s = 880^{\circ} \pm 8^{\circ}$  K of the composite emittance with coating thickness for the powdered ZnO and  $Al_2O_3$  composites. The data were taken from figures 3 and 9. The symbols indicate convenient wavelengths at which the data were reduced from the spectrophotometer traces. The parameter is the wavelength. Within experimental error, figure 12 shows a linear relation between the logarithm of the composite spectral emittance and the logarithm of the coating thickness above the filled substrate for all composites. Because of the linear relation shown in figure 12, two measurements of composite spectral emittance at coating thicknesses of 0.05 and 0.41 millimeter (0.002 and 0.016 in.) on a given substrate are sufficient to determine the composite emittance at any intermediate coating thickness.

## CONCLUDING REMARKS

Measurements of the composite normal spectral emittance at wavelengths of 1.2 to 14.1 microns and a specimen temperature of  $880^{\circ} \pm 8^{\circ}$  K were made for ZnO and

$\text{Al}_2\text{O}_3$  and flame-sprayed  $\text{Al}_2\text{O}_3$  applied to substrates with widely different emittance characteristics. It was found that the spectral normal emittance of ZnO and powdered  $\text{Al}_2\text{O}_3$  changed greatly with coating thickness at wavelengths of about 1.2 to 6 microns when the powders were spread on the substrate of highest emittance (approx. 0.9). Smaller variations in composite emittance with thickness were observed as the substrate emittance was decreased. Also, the change in composite emittance with coating thickness depended on wavelength; the largest variations occurred at the lower wavelengths. At 2 to 3 microns, increasing the ZnO or  $\text{Al}_2\text{O}_3$  powder thickness from about 0.05 to 0.41 millimeter (0.002 to 0.016 in.) above the filled substrate of highest emittance reduced the spectral normal emittance by as much as one-half. The variation of emittance with coating thickness of the composites of flame-sprayed  $\text{Al}_2\text{O}_3$  was found to be small.

It was also observed that the normal spectral emittance of the ZnO composites varied when the coatings were spread to equal thickness on the substrates of widely different emittance characteristics. The variations depended on wavelength. The largest variations occurred in the region from 2 to 9 microns. The variations were smaller on either side of this wavelength region. At 5 microns and within experimental error, changing the substrate emittance by a factor of about  $3\frac{1}{2}$  resulted in an equal change in composite emittance when ZnO coating thicknesses were 0.05 millimeter above the filled substrate. These variations in composite emittance, particularly at wavelengths of 2 to 9 microns, may be attributed in part to radiant energy transmission through the translucent ZnO powder from the substrates of varying emittance. This conclusion is logical because variations of coating emittance, reflectance, and transmittance at a given thickness are probably small. To confirm further that the ZnO powder was translucent, varying thicknesses of ZnO powder were spread on a sodium chloride window, and the transmittance was found to be large. A thickness of 0.05 millimeter of ZnO on the sodium chloride window transmitted from 50 to 80 percent of the incident light at wavelengths from about 4.5 to 15 microns. This composite transmittance of the multicrystalline ZnO was found to be surprisingly high at wavelengths of 8 to 13 microns as compared with the single crystal ZnO transmittance. The transmittance experiment also indicated that the ZnO powder becomes opaque at thicknesses of about 1.1 millimeter (0.044 in.).

The composite emittance data of the powdered  $\text{Al}_2\text{O}_3$  indicate that the coating is translucent from about 1.2 to 6.5 microns and at coating thicknesses less than about 0.2 millimeter (0.008 in.). In general, the powdered  $\text{Al}_2\text{O}_3$  is much less translucent than the ZnO.

Measurements at wavelengths of 0.37 to 2 microns of the spectral reflectance of composites of powdered  $\text{Al}_2\text{O}_3$  and ZnO on various substrates were obtained at room temperature. The results showed negligible variation of the emittance with coating thickness or substrate quality. A theoretical interpretation of these experimental results

has not been developed at this time. Thus, a complete explanation of the many phenomena observed in these experiments is not available. Data, however, indicate that there is a linear logarithmic relation between the ZnO and powdered Al<sub>2</sub>O<sub>3</sub> composite emittance and the coating thickness.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, August 5, 1965.

## REFERENCES

1. Liebert, Curt H. ; and Hibbard, Robert R. : Performance of Solar Reflectors When Applied to Storage of Cryogenic Propellants in Space. NASA TN D-2509, 1964.
2. Richmond, J. C. : Relation of Emittance to Other Optical Properties. J. Res. Natl. Bur. Std., sec. C - Engineering and Instrumentation, vol. 67C, no. 3, July-Sept. 1963, pp. 217-226.
3. Moore, Dwight G. ; Hayes, Warren D., Jr. ; and Crigler, Alfred W. : Velocity Measurements of Flame-Sprayed Aluminum Oxide Particles. Rept. No. WADC TR 59-658, pt. 2, Oct. 1959.
4. Streed E. R. ; McKellar, L. A. ; Rolling, R., Jr. ; and Smith, C. A. : Errors Associated with Hohlraum Radiation Characteristics Determinations. Measurement of Thermal Radiation Properties of Solids, NASA SP-31, 1963, pp. 237-252.
5. Haire, A. ; and Hays, L. : Energy Conversion Systems Reference Handbook. Vol. VII: Heat Exchangers. Rept. No. WADD TR 60-699, Sept. 1960.
6. Clark, Howard E. ; and Moore, Dwight, G. : Equipment for Measuring Thermal Emittance of Ceramic Oxides to 1800<sup>o</sup> K. Symposium of Thermal Radiation of Solids, ASD USAF, NBS, NASA, San Francisco (Calif.), Mar. 4-6, 1964, Univ. Calif. Press, 1964.
7. Heiland, G. ; Mollwo, E. ; and Stöckmann, F. : Electronic Processes in Zinc Oxide. Vol. 8 of Solid State Physics, F. Seitz and D. Turnbull, eds., Academic Press, Inc., 1959, pp. 191-323.
8. Harrison, Thomas Randolph: Radiation Pyrometry and Its Underlying Principles of Radiant Heat Transfer. John Wiley & Sons, Inc., 1960.

9. Dunkle, R. V. : Emissivity and Inter-Reflection Relationships for Infinite Parallel Specular Surfaces. Symposium on Thermal Radiation of Solids, ASD, USAF, NBS, NASA, San Francisco (Calif. ), Mar. 4-6, 1964, Univ. Calif. Press, 1964.

2.22/72  
19/

*"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

## NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

**TECHNICAL REPORTS:** Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

**TECHNICAL NOTES:** Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

**TECHNICAL MEMORANDUMS:** Information receiving limited distribution because of preliminary data, security classification, or other reasons.

**CONTRACTOR REPORTS:** Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

**TECHNICAL TRANSLATIONS:** Information published in a foreign language considered to merit NASA distribution in English.

**TECHNICAL REPRINTS:** Information derived from NASA activities and initially published in the form of journal articles.

**SPECIAL PUBLICATIONS:** Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

*Details on the availability of these publications may be obtained from:*

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546