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MEASUREMENT OF HEMISPHERICAL TOTAL EMITTANCE AND NORMAL SOLAR ABSORPTANCE OF SELECTED MATERIALS IN THE TEMPERATURE RANGE 280° TO 600° K

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SUMMARY

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A steady-state heat-balance method is used in making measurements of thermal-radiation parameters. The hemispherical total emittance and normal solar absorptance are measured in the temperature range 280° to 600° K. Results are given for the following surfaces which are applied to an aluminum substrate: four plasma-sprayed ceramics, zirconium silicate, strontium titanate, calcium titanate, and barium titanate; two ceramics applied by the Rokide Process, Rodide MA and Rokide ZS; anodized aluminum, plain and electrophoretically blackened; two multiple layer coatings; and Tile Coat paint.

author

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INTRODUCTION

The temperature control of space systems is primarily dependent on the thermal-radiation parameters of the materials used on the vehicle surface viewing the space environment. The important radiation parameters are hemispherical total emittance and normal solar absorptance, (hereinafter referred to as emittance and absorptance). The relative importance of these parameters depends on the temperature level and the environment of the space system. For example, the size of a radiator with a required heat-rejection rate and given temperature level is primarily dependent on the emittance. The absorptance is of importance

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[redacted]

to any space system of moderate temperature (under 600° K) with a view of the sun. The choice of materials for a space system is also governed by the overall space environment, the desired temperature range, and the expected useful life of the space system.

This paper describes measurements of emittance, absorptance, and their ratio for a variety of applicable materials. The temperature range covered by the measurements is 280° to 600° K. The radiation parameters of such materials as plasma-sprayed ceramics, painted coatings and composite coatings consisting of thin layers of vapor deposited compounds were measured. The ultimate uses of such materials include low temperature radiators (under 600° K) and temperature control surfaces of spacecraft.

Measurements were made on an apparatus designed and built at the Lewis Research Center. This paper gives a brief description of the apparatus and methods used in making these measurements. A more complete description is given in reference 1. Results are given for several different materials together with descriptions of the materials.

MEASURING TECHNIQUE

A steady-state heat-balance method is used in measuring the radiation parameters. A test specimen is placed in a controlled environment and isolated in such a manner that the only form of heat transfer out of the specimen is accomplished by radiation, that is, the test surface radiates to a cold sink of known temperature. With a test specimen of known area, the specimen temperature and power required to maintain that temperature constant are measured. With this data, the emittance can be calculated by means of the Stefan-Boltzmann Law.

The absorptance is determined in a two-stage measurement. The power required to maintain the specimen at the same temperature is measured under two conditions; first, with and, then, without simulated solar energy incident normally on the specimen. The difference in the two power measurements is the rate at which solar energy is being absorbed. By knowing the incident solar flux the absorptance is calculated.

DESCRIPTION OF APPARATUS

A cutaway view of the test specimen assembly and heat shield is shown in figure 1. The test specimen consists of a 1-inch square substrate of aluminum with the test surface applied or bonded to one side. A heater plate with resistive heating is attached to the other side of the substrate. The test specimen assembly is placed in a heat shield, which covers the back and edges of the heater plate and the specimen. The heat shield and the heater plate are controlled to the same temperature with two similar automatic temperature controllers. This assures that there is no heat loss by radiation from the back and edges of the test specimen assembly. The power and thermocouple leads from the test specimen assembly are routed such that only a negligible amount of power is lost. A thermocouple is placed directly on the specimen substrate for temperature measurement of the test specimen. It has been found that if a thin layer of vacuum grease is spread between the header plate and the specimen substrate, the thermal conduction across the interface is greatly increased. No adverse effects on radiation parameters due to contamination by the grease have been observed.

The specimen assembly and the heat shield are placed in a test chamber evacuated to approximately 10^{-7} torr. A schematic of the test chamber is given in figure 2. The chamber is a hollow cylinder with the test specimen assembly and the heat shield mounted from one end flange. A quartz window is placed on the opposite end of the chamber to admit simulated solar radiation when needed. A hollow sleeve with blackened walls is built into the chamber, and liquid nitrogen is circulated through it to obtain a known low temperature sink. About 99 percent of the total solid angle viewed by the test surface is occupied by the cold sink.

The solar simulator for the absorptance tests utilizes a carbon arc lamp as an energy source. The output of the simulator is a collimated beam with a flux density equal to that of solar radiation outside the atmosphere of the earth ($0.14\ w/cm^2 \pm 2\%$). The irradiance in the test plane is maintained within the indicated limits by an automatic controller, which continuously positions a pair of condensing lenses in the simulator. The normalized spectral distribution of the irradiance of the simulator has been measured, and the best known value is plotted in figure 3. Due to difficulties in measuring such spectral distributions, some error could be present in this curve. For comparison, the Johnson curve is also plotted infigure 3. The Johnson curve is the spectral distribution of solar energy outside the atmosphere of the earth.[2] The area under each curve is equivalent to one solar constant ($0.14\ w/cm^2$). A complete discussion of a similar solar simulator is given in reference 3.

The total output of the simulator is calibrated to one solar constant by two different methods. One method uses a narrow angle pyrheliometer, and the second uses a blackbody absorptance reference. The absorptance reference is a surface of notches formed by stacking razor blades side by side in a manner similar to that described in reference 4. The absorptance of the reference has been computed to be greater than 0.99 with the assumption of specular reflection. Tests have shown that the absorptance is independent of the inclination from the normal of the reference surface up to an angle of 30°. The inclination angle is generated by rotating the reference about an axis parallel to the razor blade edges. The two methods of calibration agree to within 2 percent.

An accuracy of ±5 percent[1] for the emittance is estimated with temperature measurement and power losses as the main sources of error. The inaccuracy in absorptance can be attributed to two basic sources of error. The first is associated with temperature control and power measurement, and is estimated to be ±5 percent. The second source of error is due to the solar simulator. This is caused by day-to-day shifts in the calibration and the spectral mismatch between the Johnson curve and the spectral distribution of the simulator. An example of the latter form of error would occur when the spectral absorptance of a specimen was high in a wavelength band where the simulator had an excess of output energy. In this case, more energy would be absorbed in the test than under a true solar source. This leads to an error in the measured absorptance. This type of error occurs in the absorptance measurement of Tile Coat paint reported in this paper.

RESULTS

Ceramic Coatings

Measurements of emittance and absorptance have been made on several ceramic coatings applied to aluminum substrates. These coatings are being investigated for possible use on radiators in both low and high temperature ranges. Measurements were made on various thicknesses of six different materials. Figures 4 to 9 show emittance as a function of temperature for the six different ceramics. Table I gives the emittance at 500° K for each specimen. The ceramic coatings that were measured are barium titanate, calcium titanate, Rokide MA, Rokide ZS, strontium titanate, and zirconium silicate. On each graph, the coating mass per unit area and the approximate thickness are given for each specimen. The coating mass was determined by weighing the specimen before and after application of the coating. The approximate thickness is presented only to give an indication of the coating thickness. The error in these measurements is estimated at ±0.02 millimeter. It is seen that there is little temperature dependence of emittance in the temperature region studied; however, there is an increase in emittance as coating mass increases. This can be seen in figure 10, in which emittance at 500° K is plotted against coating mass. For any of these specific coatings, increasing the coating mass up to approximately 15 milligrams per centimeter squared increases the emittance of the coating. Beyond 15 milligrams per centimeter squared, there is little further change in emittance. Comparison of the emittance values with those published in reference 5 show a general agreement in the overlapping temperature region.

The absorptance data of each specimen is given in Table I. In general the absorptance is constant with temperature over the measured range 400° to 600° K. Some of the coatings, however, showed a marked drop in absorptance during the first heating to 600° K. After the initial heating, these specimens exhibited no further change in absorptance. This change is always a drop in absorptance, never an increase. The decrease is approximately 0.10 and is noticed in the barium and calcium titanates. It is suspected that impurities in the coatings, such as water vapor, are the reason for the high initial absorptances. During the first heating cycle, these impurities are released, and the absorptance values drop. The final stabilized absorptance values are those given in Table I. All the ceramic coatings had a matted texture finish and were grey in color. The calcium titanate had a red tint which disappeared during testing. A few specimens acquired dark specks during testing.

Anodized Aluminum

Measurements of emittance and absorptance were made on four anodized aluminum specimens. Two of the specimens had a layer of carbon electrophoretically deposited into the pores of the anodized aluminum. Two other anodized specimens were left plain. The purpose of the carbon black coating is to obtain a lightweight, high emittance coating. It was desired to determine the increase in emittance caused by adding the carbon layer to the anodized aluminum specimens.

The aluminum specimens were anodized in a sulfuric acid electrolyte to a thickness of 1 mil. To apply the black coating, the anodized specimens were placed in an anionic colloidal dispersion of carbon black in water. The carbon was then electrophoretically deposited into the pores of the anodized aluminum. The deposition conditions were 30 volts dc for 1 to 2 minutes. The carbon black was then sealed in boiling water. Further details on the coating processes may be found in reference 6.

The emittance measurements were made in the temperature range 300° to 600° K. Emittance against temperature plots for the two plain anodized specimens are given in figure 11. Specimen 1 in figure 11 was duller in appearance than specimen 2. This could account for the difference in emittance between the two. The emittance data for the two blackened specimens is given in figure 12. These two specimens were similar in appearance and were black in color.

The addition of the carbon layer has a definite effect on emittance. The two plain specimens both exhibit decreasing emittance with increasing temperature, while the black specimens have increasing emittance with increasing temperature. The difference in emittance between plain and blackened specimens at 600° K is on the order of 25 percent with the black specimens around emittance of 0.95. A summary of data for the anodized specimens is presented in Table II. The absorptance values were constant over the measured temperature range. A large increase in absorptance occurs because of the addition of the carbon layer.

Tile Coat Paint

Measurements of emittance and absorptance have been made on aluminum substrates coated with Tile Coat, a white epoxy-based paint. Measurements were made on two specimens around 320° K. The paint was applied to the substrates in two different methods. The first substrate was dipped into the paint. Any excess paint on the substrate was then drained off by tilting the substrate. This method resulted in a smooth even coating. The paint was sprayed on the other substrate resulting in a whiter coating. The thickness of the paint coatings were both about 0.2 millimeter. The data for the two specimens is given in Table II.

The emittance is consistent and agrees with previous results published in reference 7. From Table II it is seen that the method of application affects the absorptance values. The sprayed coating had an absorptance that was 11 percent lower than the dipped coating. The absorptance data reported herein is much higher than that in reference 7 (absorptance $\alpha = 0.20$). Part of this difference can be attributed to spectral mismatch between the solar simulator used in the measurements reported herein and the Johnson Curve.

An attempt was made to estimate the error in absorptance readings due to this spectral mismatch. An analysis using the spectral absorptance of Tile Coat paint given in reference 7 and the spectral distribution of the solar simulator given in figure 3 indicates that the absorptance readings reported herein are 15 percent high. This error would apply only to a coating with the spectral absorptance of reference 7. This type of spectral absorptance (highly absorbing in the ultraviolet, a sharp edge at about 0.4 microns, and a low absorptance through the visible and near infrared) is typical of white paint pigments.

Multiple Layer Coatings

A series of measurements of absorptance and emittance in the temperature range 300° to 415° K was made on a proposed coating for a micrometeoroid satellite. The purpose of these measurements was to select a coating with a desired absorptance to emittance ratio. The coating consisted of four layers of material. Figure 13 shows a cross section of the coating. The base was 0.25-millimeter stainless steel with 12 microns of Mylar cemented to it. Vapor-deposited coatings of aluminum and silicon monoxide of various thicknesses were applied over the Mylar for thermal control purposes. The silicon monoxide layer was the outer surface of the coating. Table III shows emittance, absorptance, and the absorptance to emittance ratio for specimens with various thicknesses of aluminum and silicon monoxide. The silicon monoxide coating is the most important in determining the radiation parameters of the surface. Increasing thicknesses of silicon monoxide cause increasing emittance and decreasing absorptance to emittance ratios. The absorptance does not change much or show any trend with aluminum or silicon monoxide thicknesses. All data were consistent over the narrow temperature range, and no temperature dependence could be noted. Further work on the dependence of emittance on silicon monoxide thickness may be found in reference 8.

CONCLUDING REMARKS

The apparatus is capable of making measurements of the radiation parameter of a wide variety of materials. For a given specimen, the emittance measurements are repeatable to within $\pm 1\frac{1}{2}$ percent, while the absorptance values repeat to within ±5 percent. In general, where comparisons are available, the measured emittance data agree with published results. There is a large difference, however between measured and published absorptance data for Tile Coat paint, which is the only absorptance data comparison made. This seems to indicate that if any error is inherent in the measurements reported herein it is with the irradiance of the solar simulator or with application and handling techniques. It can be concluded that there is a thickness of ceramic coating beyond which additional application of ceramic has little effect on emittance. Similarly, emittance values over a large range can be achieved with proper selection of thicknesses of the vapor-deposited layers for the multiple layer coating.

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TABLE I. - EMITTANCE AND ABSORPTANCE FOR CERAMIC COATINGS

Substance	Mass/unit area, (mg/cm^2)	Emittance,[a] (ϵ)	Absorptance,[b] (α)
Barium titanate	5.9	0.75	0.65
	17	.82	.61
	49	.87	.74
Calcium titanate	6.2	0.75	0.72
	11.3	.82	.70
	23	.88	.70
Rokide MA	2.3	0.55	0.55
	6.0	.71	.58
	31	.82	.41
Rokide ZS	6.5	0.79	0.54
	32	.89	.45
Strontium titanate	12	0.81	0.73
	28	.82	.76
	40	.83	.64
Zirconium silicate	8.3	0.83	0.46
	9.5	.83	.38
	29	.86	.37

[a] At 500° K.

[b] Measurement at 400° to 600° K.

TABLE II. - EMITTANCE AND ABSORPTANCE FOR ANODIZED ALUMINUM AND TILE COAT PAINT

Coating	Emittance, (ϵ)		Absorptance, (ϵ)	
	Value	Measured temperature	Value	Temperature range
Anodized plain 1	0.83	500° K	0.57	400° to 600° K
Anodized plain 2	0.71	500° K	0.48	400° to 600° K
Anodized blackened 1	0.94	500° K	0.97	400° to 600° K
Anodized blackened 2	0.97	500° K	0.97	400° to 600° K
Dipped Tile Coat	0.89	320° K	0.38	320° K
Sprayed Tile Coat	0.89	320° K	0.34	320° K

TABLE III. - CHARACTERISTICS OF MULTIPLE LAYER COATINGS

Thickness of coating, micron		Emittance, (ϵ)	Absorptance, (α)	Absorptance to emittance ratio, (α/ϵ)
Aluminum	Silicon monoxide			
1.0	0.6	0.16	0.19	1.2
1.0	1.2	.46	.15	.33
1.0	0	.06		
[a]1.0	.6	.15	.18	1.2
[b] .1	1.1	.26	.13	.50
[b] .1	.7	.15	.13	.86

[a] 1 micron of silicon monoxide replaces 12 microns of Mylar.

[b] 6 microns of Mylar replaces 12 microns of Mylar.

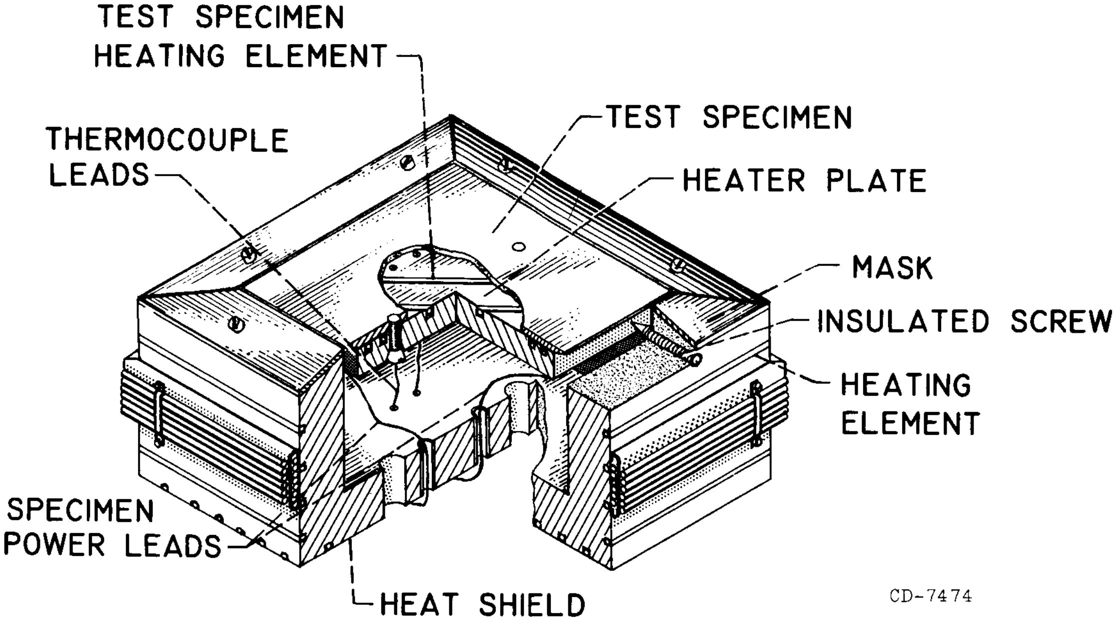

Figure 1. - Test specimen assembly and heat shield.

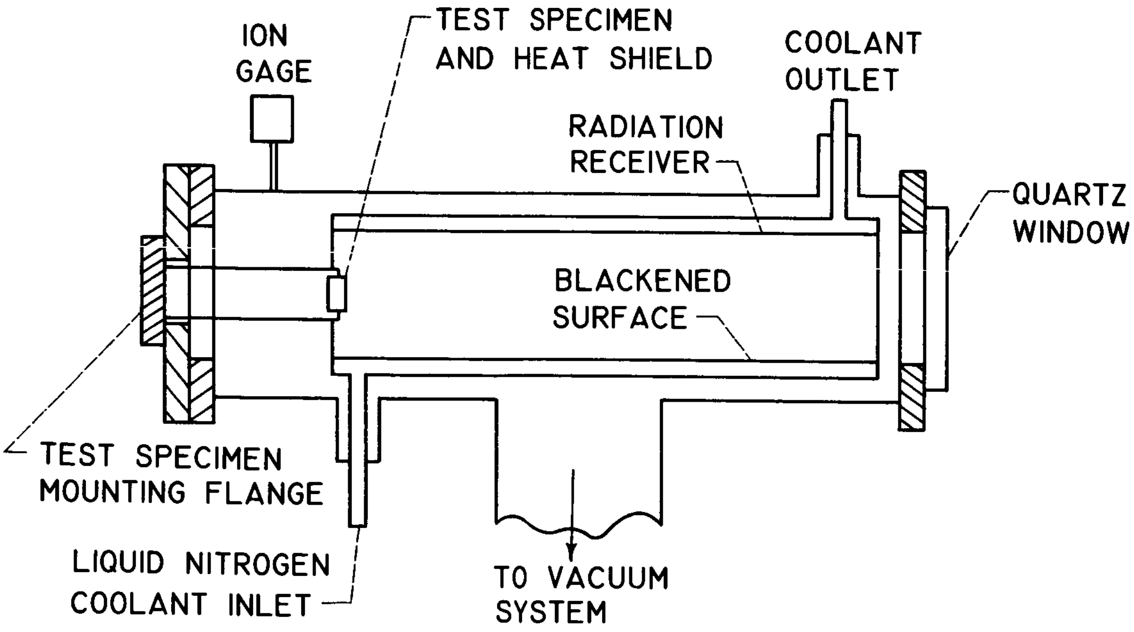

Figure 2. - Schematic of test chamber.

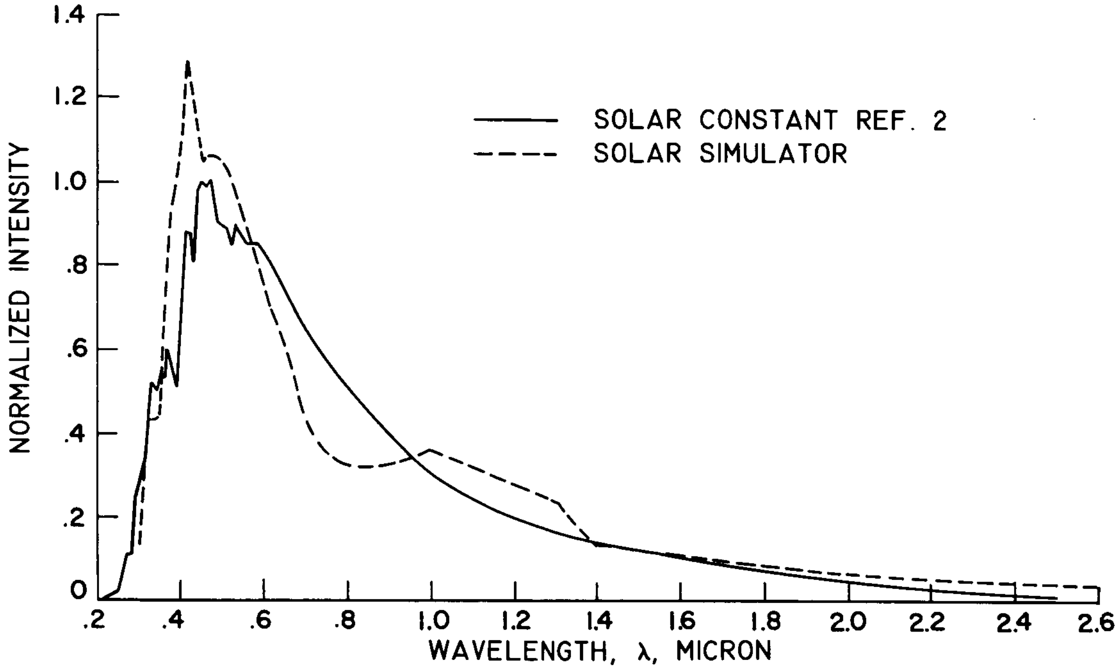

Figure 3. - Normalized spectral distribution of solar simulator irradiance.

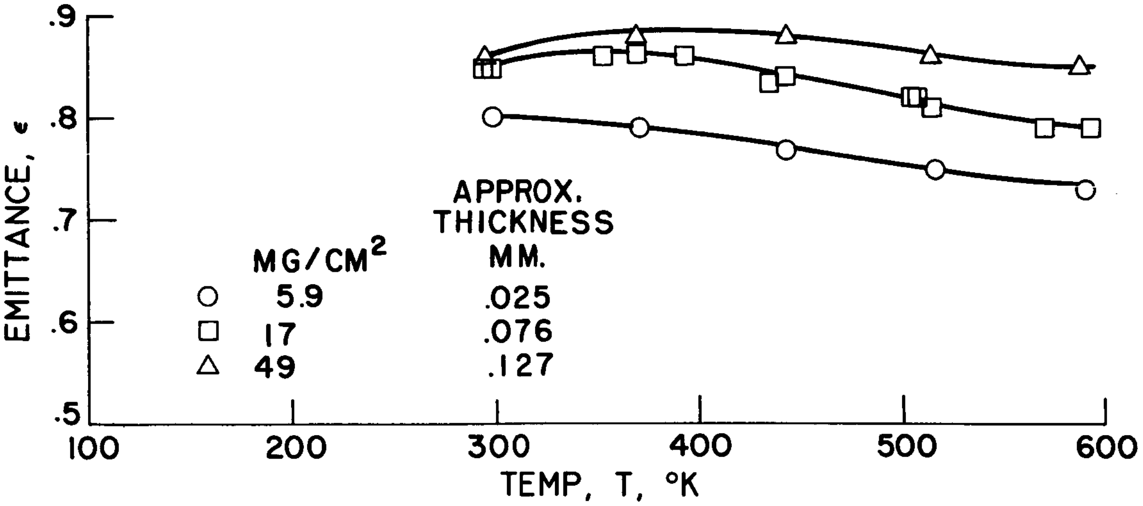

Figure 4. - Emittance as a function of temperature (barium titanate).

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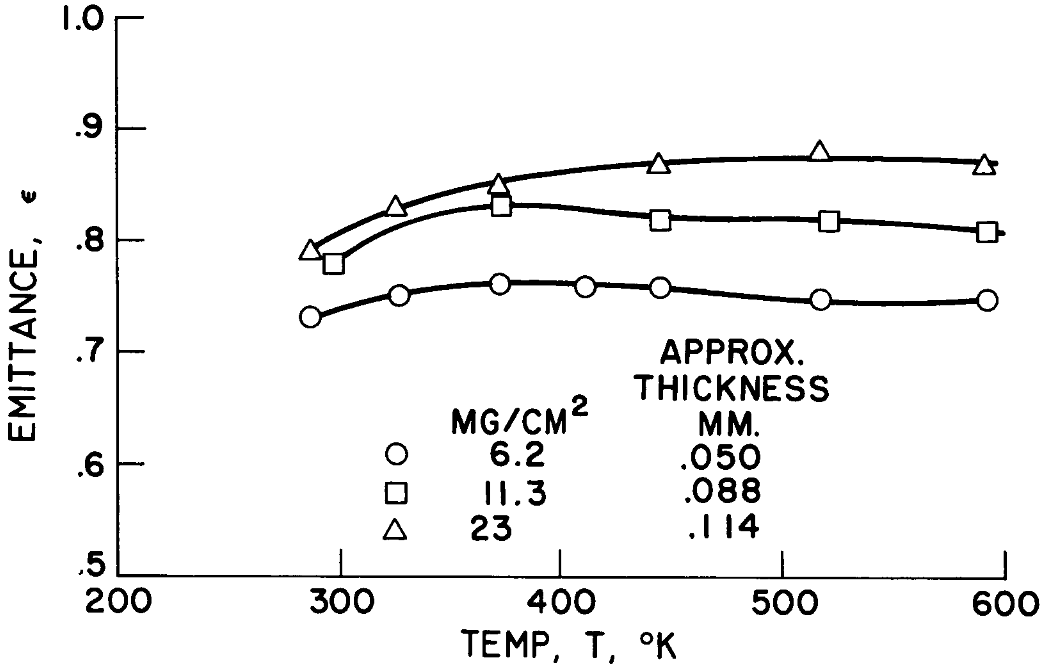

Figure 5. - Emittance as a function of temperature (calcium titanate).

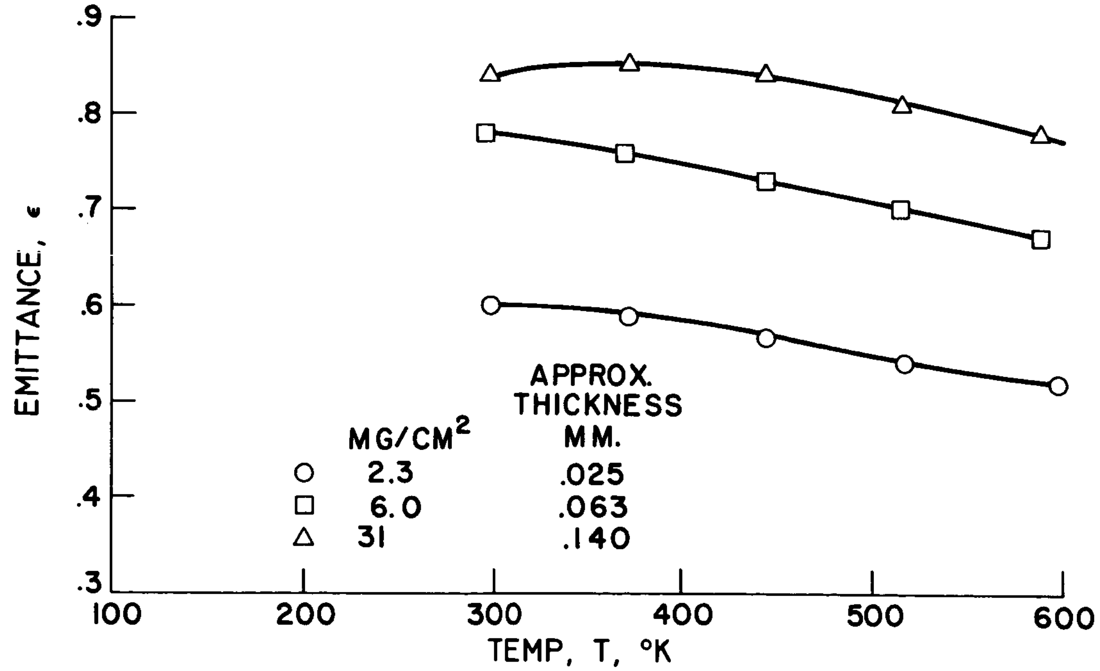

Figure 6. - Emittance as a function of temperature (Rokide MA).

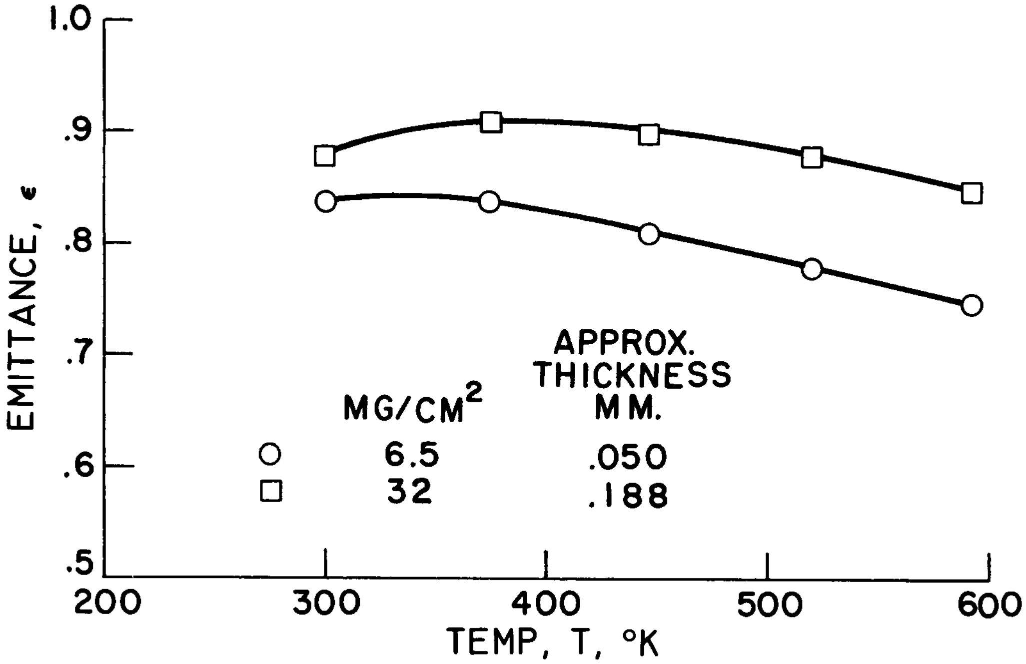

Figure 7. - Emittance as a function of temperature (Rokide ZS).

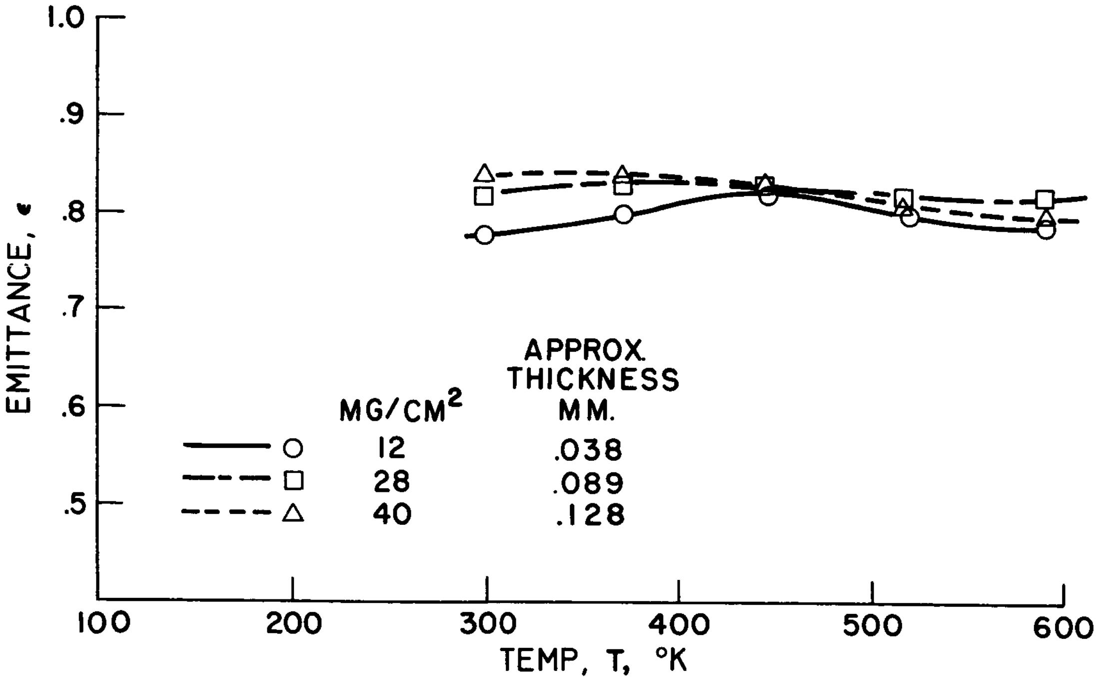

Figure 8. - Emittance as a function of temperature (strontium titanate).

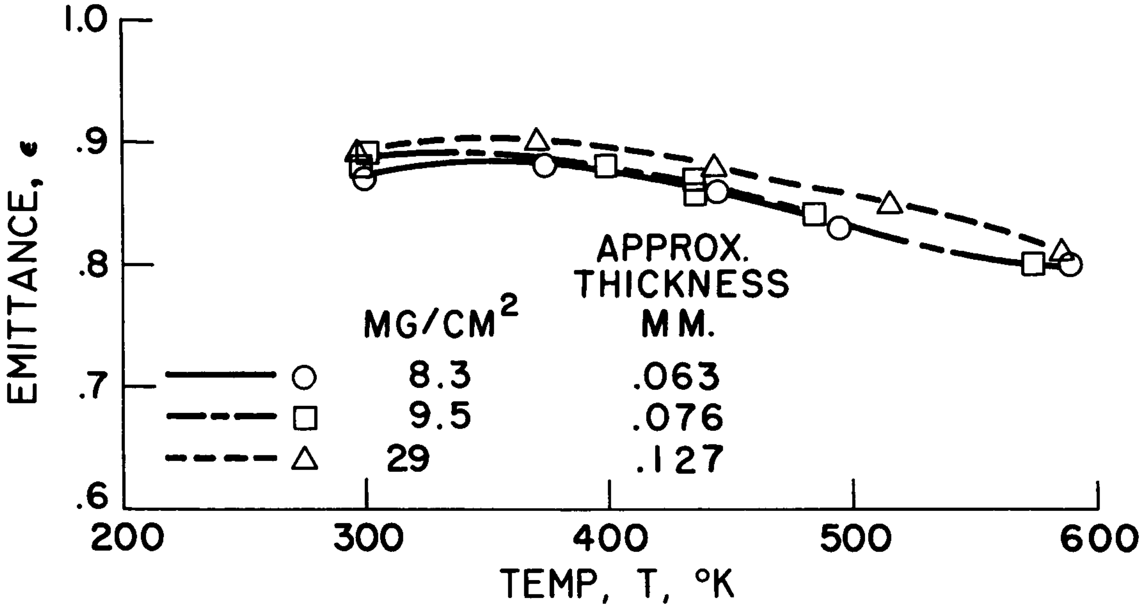

Figure 9. - Emittance as a function of temperature (zirconium silicate).

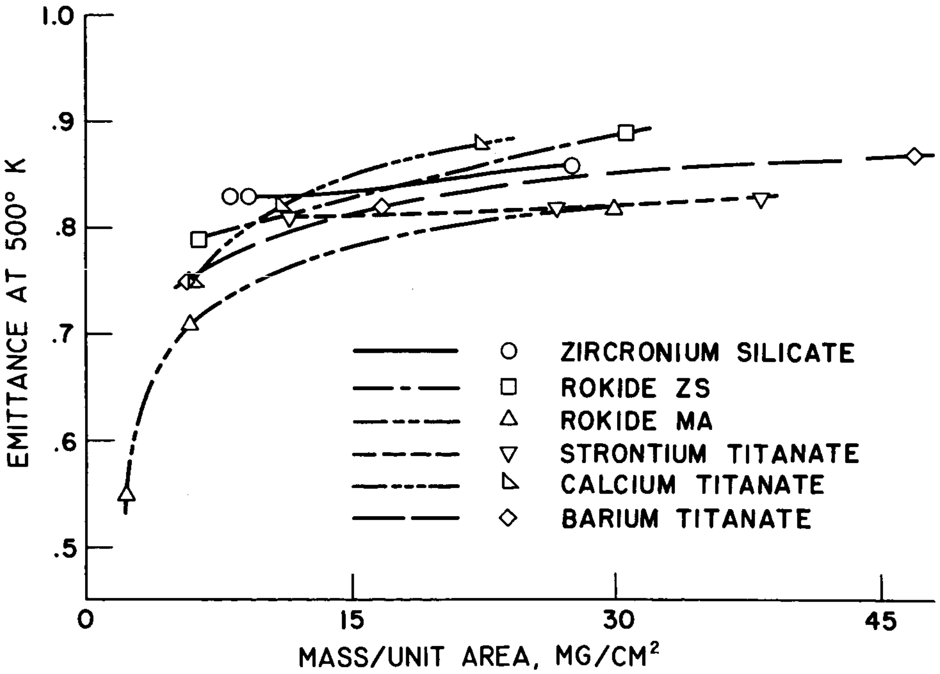

Figure 10. - Emittance of ceramics at 500° K as a function of coating mass per unit area.

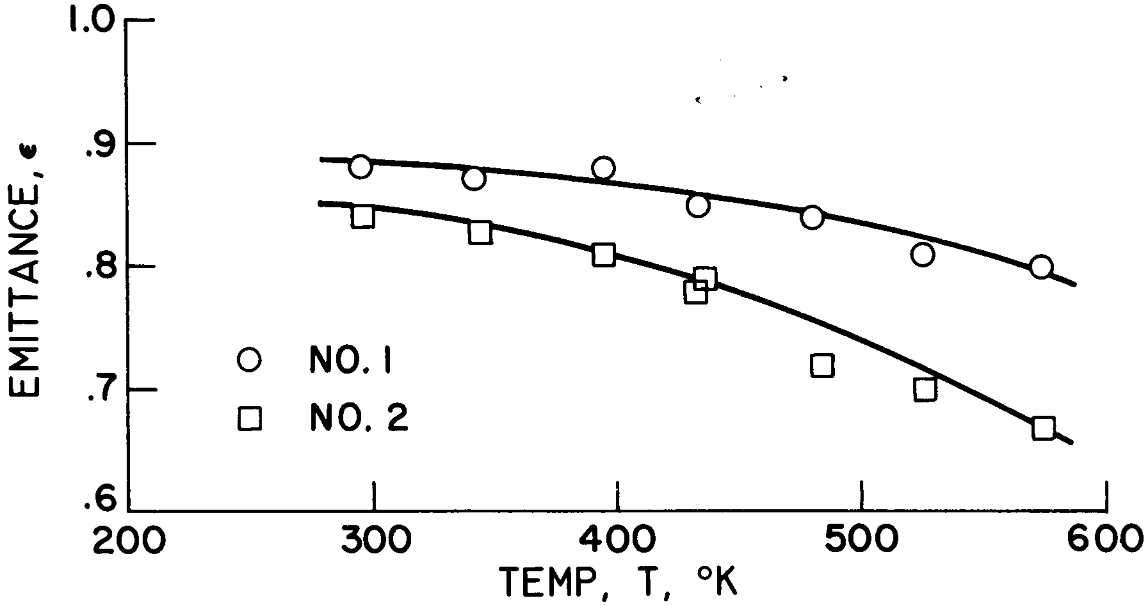

Figure 11. - Emittance as a function of temperature (plain anodized aluminum).

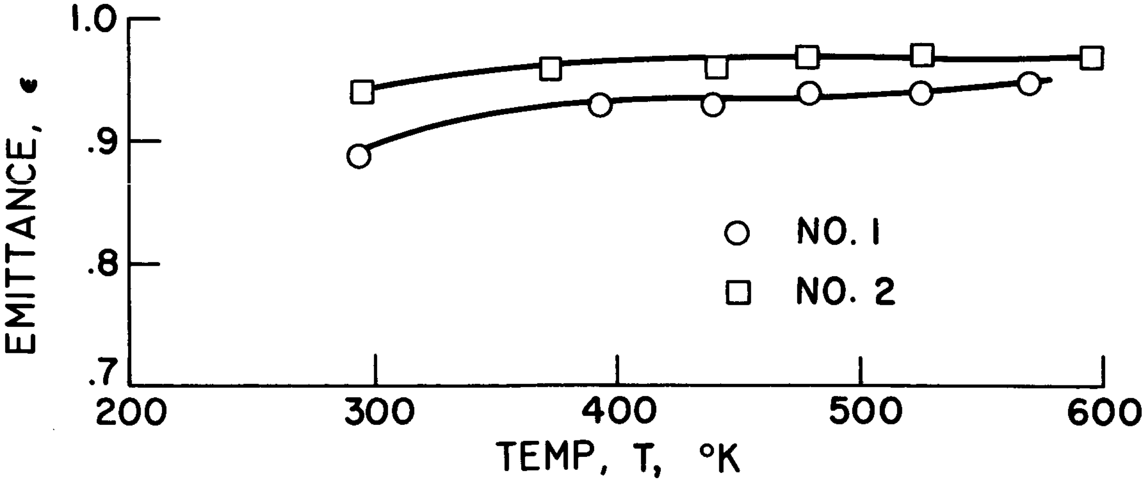

Figure 12. - Emittance as a function of temperature (blackened anodized aluminum).

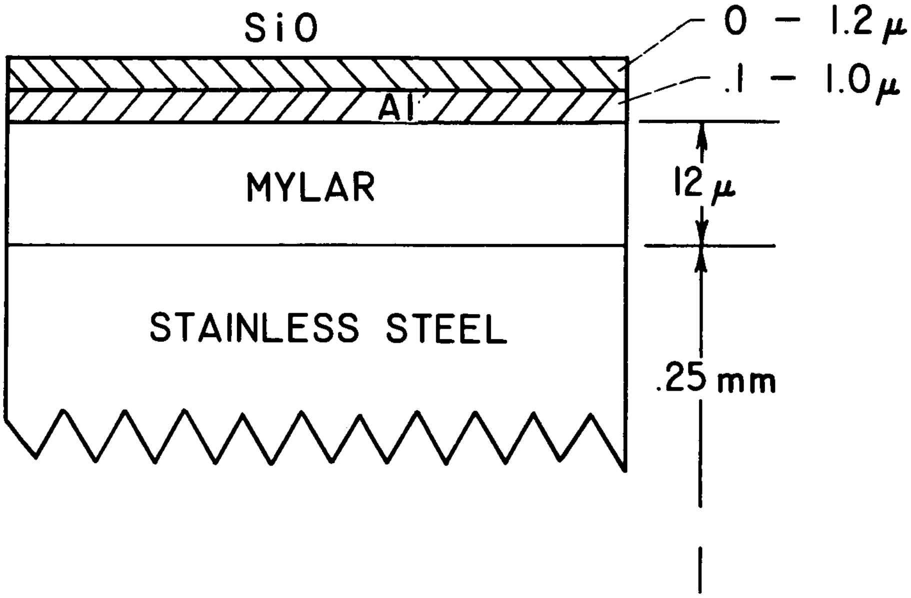

Figure 13. - Cross section of multiple layer coating with vapor-deposited aluminum and silicon monoxide.