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SUMMARY

An investigation was performed to determine the hemispherical total emittance and normal solar absorptance characteristics of nine thermal control coating systems. The coating systems tested were the following: (1) a two-component coating consisting of a spinel basecoat and a stannic oxide topcoat, (2) three zinc-oxide pigmented coatings with different binders, (3) two titanium-dioxide pigmented coatings, (4) two lithium aluminum silicate pigmented coatings, and (5) one zirconium dioxide pigmented coating. Both the emittance and absorptance measurements were made calorimetrically on the same test apparatus using the same specimen. All specimens were tested in vacuum, and emittance measurements were made at temperatures between 300° and 575° K. Absorptance measurements were made between 390° and 575° K.

The results presented consist of the emittance and absorptance data for each coating as a function of test temperature. Seven of the coatings had emittance values of 0.88 or greater, and eight coatings had absorptance values less than 0.30 over the entire test temperature range. Using measured values of coating mass per unit area (area density) obtained from the test specimens, the coatings tested added a significant fraction to the mass of two sample low temperature space radiator designs. The dependence of emittance and absorptance on coating thickness was established for one of the test coatings and the possible need for an optimum coating thickness with respect to radiator mass is discussed. The factors limiting the application of the test coatings to space radiators are also discussed, and recommendations are made for future testing of similar coating systems.

INTRODUCTION

In the foreseeable future, space electric powerplants capable of generating up to 35 kilowatts will be required to satisfy the auxiliary power requirements for a variety of missions. Rankine cycle systems such as SNAP-2 (Space Nuclear Auxiliary Power Systems) and SNAP-8 (ref. 1) or the Solar Brayton cycle (ref. 2) have been proposed to fill this requirement for electric power. The waste-heat radiators of these power systems typically cover a large surface area and comprise a large fraction of the total powerplant mass. For the power systems cited, the maximum radiator temperature encountered is on the order of 600° K. Similar low temperature radiators will also be required for secondary cooling circuits of other higher power systems (e.g., 300 W or more). For these applications, a coating will be required to enhance emittance ϵ and reduce the solar absorptance α_s of the surface (ref. 3).

Radiator surfaces operating in the region of 600° K or less, emittance levels of 0.90 or greater, and solar absorptance levels of 0.30 or less are desired (ref. 3). A reduction in emittance or an increase in solar absorptance will require the addition of radiator surface area that will increase the radiator mass. In addition to the effect of emittance and absorptance levels on radiator area and radiator mass, the coating itself contributes mass. Preliminary calculations have indicated that the mass of the coating could amount to 10 percent of the entire radiator mass for a radiator operating at about 410° K. Consequently, there is a need for data on coating density.

Several available coatings developed originally for use as passive thermal control surface coatings were selected for investigation as possible coatings for low-temperature space radiators. The investigation was conducted at the NASA Lewis Research Center using coatings furnished by various suppliers. All of the coatings were reported to have favorable characteristics as potential coatings for space radiators: they could withstand temperatures of 500° to 600° K in vacuum, could be applied to large surface areas, and could be cured by using conventional equipment. Several of the coatings tested had also demonstrated stable solar absorptance and emittance values in ultraviolet or nuclear radiation environments (refs. 4 to 7).

The published data (refs. 4 to 7) for the subject coatings consisted mainly of hemispherical and normal total emittance measurements as a function of temperature and values of room-temperature normal solar absorptance. The reported emittance measurements had been made directly by calorimetric methods or calculated from spectral reflectance (absorptance) measurements. The normal solar absorptance measurements were obtained entirely from spectral data. Typically, the spectral measurements for the normal total emittance and normal solar absorptance involved two separate specimens and measuring devices and were made in air at room temperature. These test conditions differ markedly from the anticipated space radiator operating conditions.

The principal purpose of this investigation was to provide concurrent measurements of hemispherical total emittance and normal solar absorptance in a vacuum at temperatures from 300° to 575° K. In addition, values of hemispherical total emittance and normal solar absorptance were measured for the pigments and binders of several of the coatings. The effect of coating thickness on the level of the emittance and solar absorptance was also investigated for one of the coatings. Calorimetric measurements of hemispherical total emittance and normal solar absorptance (hereinafter termed emittance and absorptance, respectively) using the same specimen were obtained. The results show the variation of the emittance and absorptance with temperature for each coating. No extensive attempts were made to compare the data of this investigation with published data. In addition, the significant features of each coating are discussed together with the factors pertaining to their application to space radiators.

SYMBOLS

A	area of test surface, sq cm
H	intensity of simulated solar irradiance, W/sq cm
P	power dissipated in heater plate without solar irradiance, W
P'	power dissipated in heater plate with solar irradiance, W
T	specimen substrate temperature, $^{\circ}K$
T_o	radiation receiver temperature, $^{\circ}K$
α_s	normal solar absorptance of specimen
ϵ	hemispherical total emittance of specimen
σ	Stefan-Boltzmann Constant, W/(sq cm)($^{\circ}K^4$)

EXPERIMENTAL APPARATUS

The measuring apparatus used in these tests has the following characteristics:

(1) Vacuum test environment (approx. 10^{-7} torr)

(2) Steady-state calorimetric method of measurement

(3) Measurements of emittance and absorptance are made on the same specimen.

The apparatus had been previously designed and constructed at the Lewis Research Center. A complete description of the apparatus including the derivation of working equations is given in reference 8.

Measuring Equipment

Figure 1 shows a cutaway drawing of the test specimen assembly and heat shield. The test specimen consists of an aluminum alloy substrate (2024-T4) 2.54 centimeters square with the coating applied to one side. The test specimen is attached to a heater plate with two mounting screws and is placed in a heat shield as shown in figure 1. The holes drilled in the test specimen for mounting purposes account for less than 1/2 percent of the total area of the test surface. The test specimen assembly (test specimen and heater plate) is held in the heat shield with insulated screws to minimize conductive heat transfer to the heat shield. The test specimen assembly and heat shield are both heated with separate resistive heating elements and are automatically controlled to the same temperature by thermocouples mounted on the heater plate and the heat shield.

Figure 2 shows a schematic diagram of the test apparatus. The entire heat shield assembly is placed in an evacuated liquid-nitrogen-cooled test chamber. The walls are blackened with carbon black and the effective absorptance of the radiation receiver is calculated to be greater than 0.99. A quartz window at one end of the test chamber admits simulated solar energy during the absorptance tests. The solar simulator utilizes a carbon arc energy source and associated optics similar to those described in reference 9.

Test Method

A steady-state calorimetric method of measurement is used in these tests. Since the test specimen assembly is isolated in a heat shield maintained at the specimen temperature, the only mode of heat transfer out of the test specimen is by thermal radiation from the test surface. The emittance is then determined by comparing the steady-state power dissipated in the heater plate with the rate of emission of a blackbody at the test temperature. Hence,

$$\epsilon = \frac{P}{\sigma A\left(T^4 - T_o^4\right)} \tag{1}$$

Test specimen thermal equilibrium is assured by maintaining the temperature constant within ±1/4° K for 15 minutes prior to power measurement.

The absorptance is determined by irradiating the specimen with simulated solar energy and remeasuring the power in the heater plate required to maintain the specimen at the test temperature. The difference in power is the rate at which solar energy is being absorbed. Hence,

$$\alpha_s = \frac{P - P'}{AH} \tag{2}$$

It should be noted that the specimen temperature used in the calculation of emittance and as the reference value in the absorptance measurement is the average temperature of the substrate beneath the coating and not the external surface temperature of the coating. Hence, the values of emittance and absorptance measured with this apparatus are "effective" values inherently adjusted for coating thickness, thermal conductivity, and thermal resistance in the bond between the coating and the substrate.

Test Accuracy

The accuracy of the test equipment and measurements are discussed in reference 8. The emittance reading at lower temperatures (300° to 400° K) is estimated to be accurate within ±5 percent and repeatable within ±1 percent for the range of emittance measurements in this report. At higher temperatures (500° to 600° K), the equipment is more accurate and emittance is estimated to be accurate within ±3 percent. Contributions to this error include errors in temperature measurement, heat losses due to incomplete isolation of the test specimen assembly, and nonequilibrium of specimen temperature during measurement.

The absorptance measurement error arises from two sources: instrument error and simulator error. Instrument error is similar to the measured emittance error discussed previously and is estimated to be ±5 percent and the repeatability ±4 percent over the entire temperature range. The error due to the simulator arises from the mismatch between the measured spectral distribution of the simulator and the spectral distribution of solar energy in a near-earth orbit (ref. 10). Figure 3 shows the most recent measurement of the spectral distribution of the simulator along with the solar spectrum as determined by F. S. Johnson (ref. 10) in units of percent of total energy per 0.05 micron bandwidth. An analysis using the two spectral distributions in figure 3 and a zinc oxide spectral absorptance curve from reference 4 (p. 30) indicated that the solar absorptance using the spectral distribution of the simulator would be 0.02 absorptance units lower than the solar absorptance calculated using the solar spectrum of reference 10. This value would vary for different coatings because of their individual spectral absorptance characteristics. The calculated variation is due to the deficiency in ultraviolet radiation in the simulator in the wavelength region where the absorptance of zinc oxide is high. However, no corrections were made to the absorptance data in this report because of the inaccuracies in the measured spectral distribution of the simulator, the inaccuracies in the measured spectral absorptance of the various coatings, and possible errors in the solar curve (ref. 10).

Test Samples

The description that follows outlines the composition and variables measured of each of the coating systems tested in this investigation. A summary of the coating systems and the variables tested is presented in table I. In general, three coated specimens were prepared and tested corresponding to each of the variables cited in the table. The substrates were made from 2024-T4 aluminum alloy 2.54 centimeters square by 1.52 millimeters thick coated on one side. The emittance and absorptance of the aluminum substrates were not measured.

One coating (coating 4) was applied in specified thicknesses to assess the effect of thickness on the emittance and absorptance levels. The remaining coatings were applied in thicknesses recommended by the supplier to attain optimum thermal radiation properties. The mass and thickness of the applied coating were determined before testing by measuring the specimens before and after coating. It was estimated that the thickness was accurate to 0.002 millimeter, and the mass accurate to 0.2 milligram. The detailed composition, application techniques, and supply source for each coating are given in appendix A.

Stannic oxide pigmented coating (coating 1). - This coating was originally developed as a space radiator coating for Space Nuclear Auxiliary Power Systems (e.g., SNAP-2, ref. 5). The coating was composed of two separate and distinct layers utilizing an aluminum metaphosphate ($AlPO_4$) binder. The first coating layer or basecoat consisted of nickel-chromium-cobalt ($NiO \cdot Cr_2O_3 \cdot Co_2O_3$) spinel pigment applied to the substrate and cured at either 500° or 580° K. The second, and final, layer was applied over the surface of the basecoat and consisted of a thin (approx. 0.0127 mm (0.0005 in.)) coating of stannic oxide (SnO_2). Final curing was carried out at either 500° or 580° K. This coating was capable of effective operation at temperatures up to 630° K and was suitable for application to aluminum and copper substrates.

Specimens were supplied to check the effect of (1) the individual emittance and absorptance characteristics of the progressive layers of binder, basecoat, and complete coating as temperature varied, and (2) the effect of the two curing temperatures on the emittance and absorptance values.

Zinc oxide pigmented coatings (coatings 2, 3, and 4). - This series of coatings was originally developed for use as passive thermal control surfaces (ref. 4). Three different binders were used with zinc oxide (ZnO) as the pigment. Coating 2 employed a commercial methyl silicone binder, while coating 3 used a methyl silicone binder synthesized by the investigators of reference 7. Coating 4 used a commercial potassium silicate binder. Coatings 2 and 3 were theoretically capable of extended operation up to 500° K in vacuum, while coating 4 could withstand 600° K temperatures. These coatings were developed to achieve low stable values of solar absorptance (e.g., approx. 0.20) under exposure to ultraviolet radiation. The thermal emittance characteristics of these three coatings were not optimized in the original investigation, but approximate values of $\epsilon = 0.90$ at 360° K were reported (ref. 4). These three coatings were cured at room temperature and did not require the elevated-temperature curing cycle specified for coating system 1.

The variables studied for coatings 2 and 3 were the individual variations of emittance and solar absorptance with temperature for (1) the binder alone, and (2) the complete coating. The measurements on coating 4 involved a variation of coating thickness and substrate preparation (e.g., as received or abraded with no. 60 aloxite metal cloth).

Titanium dioxide pigmented coatings (coatings 5 and 6). - These coatings were selected because of test data from several space satellite experiments (ref. 11). Both of the coatings had titanium dioxide as a pigment and used a polymethyl vinyl siloxane elastomer as a binder. However, coating 5 was applied as an air drying paint, while coating 6 was applied as an adhesive-backed tape (ref. 6). Both coatings are stable in vacuum at temperatures up to 550° K. Only the emittance and absorptance characteristics were analyzed for these coatings.

Lithium-aluminum-silicate pigmented coatings (coatings 7 and 8). - Both of these coatings used a lithium-aluminum-silicate pigment ($Li\text{-}Al\text{-}SiO_4$) and a potassium silicate binder. Coating 7 used a commerical grade pigment and binder, while coating 8 was synthesized by the supplier using high purity constituents to achieve increased stability of the solar absorptance. Both of the coatings had demonstrated stable operation in vacuum at temperatures up to 640° K. Only the emittance and absorptance characteristics were analyzed for these coatings.

Zirconium dioxide - silicon dioxide pigmented coating (coating 9). - This coating used a zirconium dioxide - silicon dioxide pigment ($ZrO_2 \cdot SiO_2$) synthesized by the supplier and a potassium silicate binder. The coating was capable of operation in vacuum at temperatures up to 640° K. Emittance and absorptance characteristics were analyzed for this coating.

RESULTS AND DISCUSSION

The individual data for each specimen obtained in the investigation appear in table II. The emittance and absorptance values for each test temperature are shown together with the values of coating thickness, mass, and area density. Emittance measurements were made over the temperature range of 300° to 575° K for both increasing and decreasing temperatures. Absorptance measurements were made between 390° and 575° K. In general, at least two test runs were made on each specimen.

The emittance and absorptance values appearing on the subsequent curves were obtained as follows: The data were taken at seven nominal temperature values (295°, 340°, 390°, 435°, 480°, 520°, and 565° K) established at convenient thermocouple voltage levels. Slight variations in the reference temperature produced variations in the actual test specimen temperatures. To make the curves clear, an average of all data within approximately 6° to 7° K of a nominal temperature was taken to produce a single point for each specimen. The data for each of the specimens were then averaged to obtain a single point at each nominal temperature.

Several of the coatings exhibited significant changes in emittance and/or absorptance after the specimen temperature was raised to high values and returned to room temperature. For these specimens new data points for the curves were computed using the same techniques described above. The data points used in these computations are indicated in table II.

Each specimen was contained in the vacuum chamber for approximately 48 hours. Of this total time, approximately 16 hours were in the test temperature range; the balance of the time was at ambient temperature. The exposure to simulated solar energy was approximately 3 to 4 hours per specimen; hence the emittance and absorptance values reported may be considered initial values free from any long term degradation effects of vacuum, temperature, and ultraviolet radiation.

Absorptance measurements were generally not made below 390° K because the absorptance measuring method is inherently less accurate at these lower temperatures. Also, comparatively few absorptance measurements were made because of the increased time required to achieve thermal equilibrium.

Coating Systems

Stannic oxide pigmented coating (coating 1). - Figure 4 shows the variation of emittance and absorptance with temperature, respectively, for the components of coating 1 (1a and 1b) and the complete coating at two curing temperatures. Both of the complete coatings had essentially the same area density and thickness (approx. 14.4 to 15.0 mg/sq cm and 0.067 to 0.084 mm). These coatings exhibited good adherence to the aluminum substrate during the experiments.

The emittance values for the aluminum metaphosphate binder and nickel-chromium-cobalt spinel basecoat are shown in figure 4(a). It is interesting to note that the emittance levels of the coating components progressively increase, from binder to basecoat to complete coating. However, the final level of emittance for the completed coating is higher than that for any of the individual components. The trend of emittance for the complete coating increased from 0.91 to 0.96 over the test temperature range. Published data for the emittance of stannic oxide without the spinel basecoat (ref. 7) are 3 to 5 percent lower than the emittance for the complete coating measured in this investigation. The emittance values shown for the complete coating in figure 4(a) were essentially the same for both curing temperatures.

The absorptance values for the coating components and complete coatings were relatively insensitive to temperature and remained essentially constant between 390° and 575° K. The average absorptance level for the aluminum metaphosphate binder was 0.68, and the absorptance level for the spinel basecoat and binder was 0.96. Although published solar absorptance values for stannic oxide are about 0.26 (ref. 4, p. 38), the level of absorptance for the complete coating was about 0.45. The reason for this large discrepancy was not determined.

The absorptance values (fig. 4(b) indicated that very little initial difference existed between the coatings cured at 500° K (1d) and the coating cured at 580° K (1c). Prior to testing, both classes of specimens were the same white color. The specimens for coating 1d were visibly darkened by the testing procedure and appeared off-white in color and exhibited an absorptance increase of about 0.05 unit. The specimens for coating 1c exhibited stable and repeatable absorptance values over the entire test temperature range.

Zinc oxide pigmented coatings (coatings 2, 3, and 4). - Figure 5 gives the emittance and absorptance values for both coating and binder alone for coating 2. The coating mass per unit area was about 72.1 milligrams per square centimeter and the thickness averaged 0.29 millimeter. The emittance values of the coating were uniformly high (0.92 to 0.96) and were unaffected by the test temperature cycle. The absorptance level of the coating was constant, approximately 0.22 over the temperature range tested.

The test at a maximum temperature of 571° K produced surface cracks in the coating for the first coated specimen. The maximum temperature of the remaining two specimens was limited to 543° K; however, the appearance of the surface cracks persisted. The random pattern of fine cracks that developed over the coated surface is shown in figure 6. The binder alone did not exhibit any observed changes in appearance. The presence of the cracks is presumed to be due to a combination of the increased coating thickness and the combined effects of temperature and vacuum. The cracking had no apparent effect on the emmittance and absorptance values, and the coatings adhered to the substrate after testing.

Figure 7 shows emittance and absorptance for the binder alone and for the complete coating for coating 3. The thickness for the complete coating ranged from 0.80 to 0.11 millimeter, and the mass per unit area averaged 27.2 milligrams per square centimeter. The trend of emittance for the complete coating (3b) increased from 0.85 to 0.90 over the temperature range tested, while the absorptance decreased from 0.27 to 0.22 over nearly the same temperature range. The emittance and absorptance values for the binder alone (3a) were not very different from those for the completed coating, but exhibited opposite trends with temperature. The complete coating also displayed an effect of the test temperature cycle on the emittance values. After the initial test run, the emittance levels were reduced by 0.03 to 0.07 unit as shown on the figure by the tailed symbols. The emittance values of the binder alone also displayed essentially the same characteristic after the initial test run. The absorptance values were not observably affected by the test temperature cycle.

Coating 3 had the same tendency as coating 2 to develop surface cracks at temperatures of approximately 550° K. However, cycling one specimen to a temperature of only 527° K markedly reduced the cracking of the coating, and one specimen heated only to 483° K showed no observable cracking. The synthetic methyl silicone resin binder displayed cracking in both specimens, one tested to 484° K and the other to 572° K. A typical resin-coated specimen is shown after testing in figure 8.

Coating 4 consisted of zinc oxide pigment in a potassium silicate binder and was first applied to smooth aluminum substrates. The coating was initially applied in thickness ranging from 0.15 to 0.22 millimeter (6 to 9 mils); however, these specimens lost excessive amounts of coating during the testing procedure. Excessive scatter, was obtained with these coatings; consequently, the emittance data were not plotted. However, these data are included in table II. A second series of specimens was prepared using roughened aluminum substrates (see appendix A). The coatings were applied at two different thicknesses of 0.11 and 0.22 millimeter (4.5 and 9 mils). The emittance data are plotted against test temperature for the two thicknesses in figure 9. Generally, the level of emittance for the 0.11 millimeter coating thickness ranged from 0.95 to 0.98 up to 400° K. At 570° K the emittance dropped to 0.90. The thicker 0.22-millimeter coating exhibited emittance of 0.95 up to 400° K and dropped to around 0.80 at 570° K. It is possible that the reduced emittance for the 0.22-millimeter-thick coating may be attributed to a loss of adherence encountered in thicker coatings of this type (ref. 4), which causes an increase in the thermal resistance across the coating and further lowers the measured emittance values.

Both coating thicknesses tested showed a slightly reduced level of emittance after one cycle through the test temperature range, as shown in figure 10 by the tailed symbols. However, the reduced level of emittance observed after thermal cycling for both coating thicknesses tested cannot be attributed to the lack of adherence since the magnitude of the reduction in emittance for both coating thicknesses is approximately the same (2 to 3 percent). This behavior of the coatings is more suggestive of a chemical change induced in the specimens by heating to 570° K.

Figure 10 shows the absorptance for three different coating thicknesses of coating 4 (0.11, 0.16, and 0.22 mm or 4.5, 6.4, and 9.0 mils, respectively). The 0.16-millimeter-thick coating was applied to a smooth aluminum substrate while the 0.11 and 0.22-millimeter-thick coatings were applied to roughened substrates. The trend toward lower absorptance values with increased coating thickness is apparent in figure 10. The 0.11-millimeter-thick coating had an absorptance value of 0.20 to 0.22. The 0.16-millimeter-thick coating had a constant absorptance value of approximately 0.18, while the 0.22-millimeter-thick coating had a constant value of absorptance of 0.16 throughout the same range of temperature.

Each of the three coating thicknesses showed a tendency toward an increased absorptance value after one cycle through the test temperature range, as shown by the tailed points. It is surmised that this observed change in absorptance is attributed to the chemical change and darkening of the specimens mentioned previously in connection with figure 8(a), and (b). In general, the observed changes in absorptance and emittance level were not apparent until the specimens were cycled above 450° to 480° K. In all cases, the drop in emittance and increase in absorptance were greater after testing to the higher temperatures (570° K).

Figure 11 shows the 0.11- and 0.22-millimeter-thick coated specimens after testing. The 0.11-millimeter-thick coating appears more integral and sound while the 0.22-millimeter-thick coating developed a pattern of cracks over the surface that was more intense at the edge of the specimen. The appearance of the cracks attests to the reduction in adherence encountered with the thicker coatings (ref. 4). The specimens for both coating thicknesses were also observed to be slightly darkened by the testing.

Specimens prepared with the binder alone for coating 4 were not sufficiently adherent to permit testing and were not included in the investigation.

Titanium dioxide pigmented coatings (coatings 5 and 6). - Figure 12 shows emittance and absorptance against temperature for the two coatings. Both the paint (coating 5) and the adhesive-backed tape (coating 6) had an area density of approximately 32 milligrams per square centimeter and were approximately 0.20 millimeter thick.

There was no measurable difference in the level of the emittance for the two coatings (fig. 12). The emittance level was approximately 0.92 at 300° K, rose to 0.94 at 400° K, and dropped gradually to 0.89 at 570° K. There were no effects of the temperature cycle on emittance observed for these two titanium dioxide pigmented coatings, and all emittance values at the lower test temperatures were reproduced after cycling to 570° K. Blisters developed beneath the surface of the tape after exposure to heating in the vacuum were presumed to be caused by entrapped gasses in the adhesive. As viewed through the quartz window of the test chamber (fig. 2), the blisters were first visible at about 450° K and gradually increased in size as the temperature increased. These blisters, however, did not affect the measured emittance level. Both coatings remained firmly attached to the substrate.

The absorptance level for the paint coating 5 had an initial value of about 0.21 between 400° and 500° K. Upon heating to 560° K the three painted specimens each had widely different absorptance values. One specimen had an absorptance value of 0.19 at 560° K, while the remaining two specimens had values of 0.28. These points are shown in figure 12(a) by the dashed lines.

The absorptance values for coating 6 (tape) were approximately 0.24 at 390° K and gradually decreased to 0.22 at 565° K (fig. 12(b)). The absorptance values of coating 5 (paint) were affected by the test temperature cycle to 560° K, as shown by the tailed symbols. There were no observed changes of absorptance due to thermal cycling for coating 6.

Lithium-aluminum-silicate pigmented coatings (coatings 7 and 8). - The area coating densities averaged 21.8 milligrams per square centimeter and had an average thickness of 0.17 millimeter. Figure 13(a) shows emittance and absorptance against temperature for the commercial lithium-aluminum-silicate pigmented coating. The level of emittance was 0.96 at 300° K, approached 0.99 at 390° K, and dropped to 0.87 at 570° K. The emittance levels were affected by the test temperature cycle, and the emittance values after exposure to one and two thermal cycles to 570° K are shown by the tailed symbols. The value after two cycles (0.90) at 435° K compared with an initial value of 0.97 measured at the same temperature and the values for the first temperature cycle appear to indicate a strong cumulative damage effect.

The values of absorptance for coating 7 had considerable scatter with an average level of about 0.26 to 0.27 up to 570° K. The average and extreme values are shown in figure 13(a). The scatter was too great to enable any effects of thermal cycling to be noted; however, all of the specimens for coating 7 were visibly darkened by the test cycle.

Figure 13(b) shows emittance and absorptance values against temperature for coating 8, the synthetic lithium-aluminum-silicate coating. The initial emittance level for coating 8 is quite similar to the commercial pigmented coating (coating 7), as shown in figure 13(a). Both coatings showed approximately the same drop in emittance level after one temperature cycle. The absorptance level for coating 8 was stable, consistent, and at a lower level (α_s = 0.17 to 0.18) than the level for coating 7. The absorptance level for coating 8 showed no effects of thermal cycling and was not visibly darkened after testing. Both of these effects are undoubtedly caused by the higher purity ingredients.

Synthetic zirconium dioxide - silicon dioxide pigmented coating (coating 9). - The coating had an average area density of 14.5 milligrams per square centimeter and an average thickness of 0.068 millimeter. Figure 14 shows the emittance and absorptance values against temperature for coating 9. The level of emittance was 0.94 at 300° K, increased to 0.96 at 345° K, and gradually decreased to 0.78 at 570° K. The emittance levels were reduced 2 to 3 percent after exposure to the peak test temperature cycle. The absorptance level for coating 9 rose gradually from 0.20 to 0.23 between 390° and 565° K. There was no evidence of thermal cycling on the absorptance values; however, all specimens had acquired a few small discolored spots after testing.

Comparisons

Table III contains a summary of the emittance and absorptance data for all of the complete coatings tested. Also included in the table are thickness and mass data together with pertinent comments on the performance of each coating. Values of emittance and absorptance were taken from the data curves at 390° and 550° K, and the ratio of absorptance to emittance α_s/ϵ was calculated from these values. Several observations can be made concerning the possible use of the various coatings on space radiators operating at the two temperatures listed in the table.

General characteristics. - Of all the coatings tested, coatings 1c and 1d had the lowest values of area density, the highest emittance level at 550° K, and unfortunately absorptance levels approximately twice as high as the other coatings. Consequently, coatings 1c and 1d would be applicable to radiators operating at temperatures of 550° K or greater or in applications that do not require low values of solar absorptance.

The coatings made of zinc oxide pigment, 2b, 3b, 4b, and 4c exhibited widely differing properties. Coating 2b had high values of emittance and low values of absorptance compared with the other coatings tested; however, this coating had the greatest area density. The cracks that developed on the surface of coating 2b at 480° K and above restrict this coating to radiators operating at the lower temperatures (e.g., 390° K). Coating 3b was 60 percent lighter than coating 2b; however, the emittance level was below 0.90 throughout the entire test temperature range. This coating also had a higher level of absorptance at 390° K and a tendency to develop surface cracks at 480° K and above. Consequently, this coating is considered marginal for space radiator applications. The thicker specimens of coating 4 (4c) developed surface cracks during testing. Coating 4c also exhibited lower values of both emittance and absorptance than those for the thinner coating 4b. Consequently, increasing the thickness of coating 4 will achieve low values of solar absorptance. However, area density is increased, emittance is decreased, and the mechanical properties of the coating are degraded. Hence, coating 4b could be used on both 390° and 550° K radiators, and coating 4c would be more suited to the lower temperature range.

Coatings 5 and 6 were both made from the same titanium dioxide pigment and polymethyl vinyl siloxane binder; however, they were formulated into a paint and an adhesive-backed tape, respectively. Their levels of emittance, absorptance, and area density were almost identical. The only observed variation between them was the tendency for blisters to develop beneath the surface of the tape (coating 6). Their emittance levels dropped below 0.90 at 550° K. Consequently these coatings would be considered marginal for use on radiators operating at this temperature.

Coatings 7 and 8 were both made from the lithium-aluminum-silicate pigment and potassium silicate binder; however, coating 8 was synthesized using high purity ingredients. The area density and emittance level of these two coating systems were almost identical. The absorptance level, however, for the synthetic coating (coating 8) was approximately 30 percent lower than the absorptance level of the coating with the commercial purity ingredients (coating 7). Also, coating 8 did not discolor during the test, while coating 7 darkened after testing to temperatures above 480° K. The high level of emittance at 390° K would make both coatings 7 and 8 candidates for use on lower temperature radiators. Coating 8 would be more favorably considered over coating 7 because of the 30 percent lower absorptance value.

Coating 7, formulated from commercial lithium-aluminum-silicate had excessive scatter in the measured absorptance values compared with the values of coating 8 formulated from higher purity ingredients. No definite change in absorptance was determined for this observed variation because of the inconsistencies in the measured values between coatings 7 and 8.

Coating 9 had one of the lowest values of area density of all the coatings tested; however, the emittance level was reduced to 0.81, and the absorptance rose to 0.23 at 550° K. Consequently, this coating would not be considered for radiators operating in the 550° K range. Coating 9, however, would be favorably considered for radiators operating at 390° K since the emittance and absorptance levels were 0.95 and 0.20, respectively.

Temperature dependence. - Since both the emittance and absorptance measurements were made at temperature, any trends of these properties with temperature can be noted. Some of the coatings had emittance curves that were unaffected by temperature, such as coatings 2b and 3b; however, the emittance values of coatings 4c and 9 both dropped from 0.95 to 0.81 in the temperature range 390° to 500° K. This is a considerable change in emittance and points out the necessity of making measurements of emittance over the anticipated range of radiator operating temperatures.

In general, the variations of absorptance with temperature are not as large as these of emittance; however, in one coating, 3b, the absorptance dropped from 0.27 to 0.22 in the 390° to 550° K temperature range. Two other coatings (4b and 9) had changes of +0.03 absorptance unit over the same temperature range. Several of the coatings (1c, 1d, 7, and 9) had the tendency to discolor during testing. Also coatings 2b, 3b, and 4c all developed surface cracks at temperature during testing. This further attests to the necessity of making absorptance measurements at radiator operating temperatures.

Temperature cycling. - Some of the coatings tested displayed changes in initial emittance and/or absorptance level after one cycle through the test temperature range. Coatings 3b, 4b, 4c, 7, 8, and 9 showed decreases in emittance ranging from 0.02 to 0.05 unit after one cycle through the test temperature range. The remaining coatings were unaffected and retained their initial emittance values after the temperature cycle. It is interesting to note that all the coatings having potassium silicate as a binder exhibited such decreases in initial emittance values. Coating 3b, however, which had the synthetic methyl silicone binder is also included in this group.

Only coatings 1d, 4b, 4c, and 5 showed increases of 0.03 to 0.05 unit in absorptance after one cycle through the test temperature range. There appears to be no common factor or formulation ingredient among the coatings displaying the changed values. Coating 1c, however, had the same formulation and application procedure as coating 1d; coating 1c was cured at 580° K, and coating 1d at 500° K. The coating cured at the lower temperature had the least stable absorptance values. Coatings 5 and 6 were composed of identical pigment and binder combinations; however, coating 5 was formulated as a paint while coating 6 was formulated as a tape. The paint formulation had the least stable absorptance values. Coatings 4b and 4c both showed increases in absorptance after cycling, but these coatings were actually the same pigment-binder combinations applied in different thicknesses.

The indicated increase in reduction of emittance after a second temperature cycle observed for coating 7 (fig. 13(a)) points to the importance of conducting adequate temperature cycling tests in the evaluation of suitable coatings for space radiator applications.

Coating mass. - In table IV are given the percent of additional radiator mass added to two illustrative planar space radiator designs by the coatings. Details of the two radiator geometries, referred to as the secondary-cooling radiator and the Brayton cycle radiator were obtained from reference 12. The secondary-cooling radiator used ether as the coolant and had an inlet temperature of 340° K and an outlet temperature of 325° K. The Brayton cycle radiator used argon as the coolant and had an inlet temperature of 422° K and an outlet temperature of 283° K. The percent of additional mass added by the various coatings to the secondary-cooling radiator ranged from low values of 12.7 and 12.8 percent for coatings 1c and 9, respectively, to a high value of 63.9 percent for coating 2b. The percent additional mass added to the Brayton cycle radiator ranged from 4.5 to 22.9 percent for coatings 1c and 2b, respectively. Thus, the radiator coating can comprise a sizable portion of the total radiator mass.

Thickness variations. - Figure 15 shows values of emittance and absorptance plotted against thickness for coating 4 (zinc oxide pigment - potassium silicate binder). The values for thicknesses of 0.11 and 0.12 millimeter were obtained from specimens having roughened substrates, while the absorptance values for 0.16-millimeter-thick coatings were obtained from specimens having nonroughened substrates. Absorptance and emittance values for both 390° and 550° K are shown in the figure. The data of figure 15 show that increasing the thickness from 0.11 to 0.22 millimeter reduces the absorptance from 0.19 to 0.16 at 390° K. However, the percent of additional radiator mass due to the coating increases from 21.3 to 41.2 percent for the secondary cooling radiator, as indicated in table IV. At the higher operating temperature, the same change in thickness reduces the absorptance from 0.22 to 0.16 and increases the percent of additional radiator mass from 7.6 to 14.8 percent for the Brayton cycle radiator. In addition, the emittance values for coating 4 decrease with increasing thickness (e.g., from 0.99 to 0.95 at 390° K and from 0.92 to 0.81 at 550° K). The reduction in emittance level resulting from the increases in thickness will cause a further radiator mass penalty because of the required increase in radiating area. It is apparent therefore that data for the variation of coating performance with thickness are desirable and that radiator design optimization procedures based on the characteristics of the individual coating should be conducted.

CONCLUDING REMARKS

Many of the coating systems tested were potentially capable of providing the required emittance and absorptance values for space radiator application. With the exception of coatings 2b and 3b (zinc oxide pigment - methyl silicone binder), the coatings also had the potential of operating in both temperature ranges of 390° and 550° K. The absorptance values of the coatings were under 0.30, except for coatings 1c and 1d (stannic oxide - nickel-chromium-cobalt spinel pigment - aluminum phosphate binder), which had measured absorptance values of 0.45 to 0.48. The emittance values of the coatings were 0.88 or greater over the entire test temperature range, except for coatings 4c (zinc oxide pigment - potassium silicate binder) and 9 (zirconium dioxide - silicon dioxide pigment - potassium silicate binder).

The performance of the coatings can be sensitive to temperature cycle and total thickness. Furthermore, the mass of the coating could constitute a significant addition to the total radiator mass for typical applications. Therefore, the final coating selection for a particular application will depend on a large number of factors. In particular, further testing will be required to establish more completely the characteristics of low-temperature coatings. Such tests should include the following:

(1) Additional tests to determine the effect of coating thickness on the emittance and absorptance levels for eventual use in optimizing the mass of the coated radiator

(2) Tests under conditions of varying temperature to assess the magnitude of the changes on initial emittance and absorptance levels with temperature cycling

(3) Long term tests at temperature in vacuum to establish the variation of the emittance and absorptance levels

(4) Long term tests at temperature to establish the degree of adhesion of the coating to the substrate

(5) Redetermination of the application techniques, area density, and thickness values for the coatings as applied to large (full scale) panels

(6) Tests of candidate coatings under simultaneous action of additional environmental factors such as ultraviolet radiation, energetic particles, nuclear radiation, meteoroid impingement, and launch vibrations

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 1, 1965.

APPENDIX A

COATING FORMULATION AND APPLICATION PROCEDURES

I. Coating 1: AI-93 (Atomics International; data from J. R. Crosby - Atomics International Division: North American Aviation Corp.)

(1) Pigment: topcoat, stannic oxide (SnO_2); basecoat, chromium-nickel-cobalt ($1.0\ NiO \cdot 0.75\ Cr_2O_3 \cdot 0.75\ Co_2O_3$)

(2) Binder: Aluminum metaphosphate ($AlPO_4$)

(3) Ingredients, parts by weight:

(a) Topcoat:	120 SnO_2 87 $AlPO_4$ 50 H_2O
(b) Basecoat:	65 $NiO \cdot Cr_2O_3 \cdot Co_2O_3$ 40 SiO_2 87 $AlPO_4$ 20 H_2O

(4) Application procedure (for aluminum substrate):

(a) Grit blast specimen surface.

(b) Oxidize specimen in air at final curing temperature for 30 minutes (e.g., 500° or 580° K). This operation is necessary to preclude attack of the aluminum substrate by the $AlPO_4$ binder.

(c) Apply basecoat and binder.

(d) Cure at either 500° or 580° K for 30 minutes.

(e) Cool and apply topcoat and binder.

(f) Cure at either 500° or 580° K for 30 minutes.

II. Coating 2: Illinois Institute of Technology Research Institute IITRI S-13 (ref. 4, p. 177)

(1) Pigment: Zinc oxide (ZnO) (New Jersey Zinc Sp-500)

(2) Binder: Methyl silicone, General Electric (G.E. LTV-602)

(3) Ingredients, parts by weight (refer to ref. 4 for additional formulation details):

240 ZnO
100 (G.E. LTV-602)
1 (G.E. SRC-05(catalyst))
183 Toluene
Pigment concentration, 30 volume percent
Solids content, 40 volume percent

(4) Application procedure (applicable to any surface to which primer will adhere):

(a) Prime surface (use General Electric SS-4004 or General Electric SS-4044; spray application).

(b) Air dry 1 hour.

(c) Add SRC-05 catalyst to paint immediately before application; apply paint to primed surface (spray application).

(d) Air dry 16 hours. (Curing can be slightly accelerated by heating to 340° or 360° K for 1 hr.)

III. Coating 3: IITRI S-33 (Ref. 4, p. 179).

(1) Pigment: Zinc oxide (New Jersey Zinc Sp-500)

(2) Binder: Methyl silicone (experimental resin, IITRI R-9)

(3) Curing Agent: Tetrabutoxy titanium (DuPont TBT)

(4) Ingredients, parts by weight (refer to Ref. 4 for formulation details):

316 ZnO
100 (IITRI R-9)
1 TBT
225 Toluene
Pigment concentration, 40 volume percent
Solids content, 40 volume percent

(5) Application procedure:

(a) Abrade surface with no. 60 aloxite metal cloth (light sandblast also acceptable).

(b) Spray paint surface using clean prepurified gas (nitrogen recommended).

(c) Air dry until solvent evaporates (1 to 2 hr).

(d) Cure at 416° K for 1 to 2 hours.

IV. Coating 4: IITRI Z-93 (ref. 4, p. 175)

(1) Pigment: Zinc oxide (New Jersey Zinc SP-500) calcined at 975° K for 16 hours.

(2) Binder: Potassium silicate (Sylvania Electric Products PS7)

(3) Ingredients: Refer to reference 4 for milling sequence

Pigment-to-binder weight ratio, 4.30

Solids content, 56.9 volume percent

Typical batch: ZnO, 100 g
PS7, 50 cc (35 percent solution)
Distilled water, 50 cc

Note: Paint must be mixed just prior to application; shelf life must not exceed 24 hours.

(4) Application Procedure:

(a) Abrade surface with no. 60 aloxite metal cloth. (step (1) omitted on coating 4a, table I)

(b) Wash thoroughly with detergent and water

(c) Apply paint to surface (spray application using clean, prepurified gas; nitrogen recommended).

Note: Approximately 0.025 mm (0.001 in.) coating thickness results per spray application cycle. Repeat applications as required allowing coatings to air dry between applications.

(d) Cure in air. Improved physical properties result after heat curing at 415° K.

V. Coating 5: Thermatrol (Lockheed Missiles and Space Co.; data from L. A. McKellar; Lockheed Missiles and Space Company, Research Laboratory.)

(1) Pigment: Titanium dioxide

(2) Binder: Polymethyl vinyl siloxane elastomer
Pigment-to-binder weight ratio, 1
Solids content not given

(3) Application Procedure:

(a) Wash surface with detergent, rinse with distilled water, and air dry.

(b) Spray prime surface with one coat of Dow-Corning primer DC-A4094.

(c) Air dry 15 minutes.

(d) Spray coat to required thickness

(e) Air dry: 2 hours, "tack free"
24 hours, hard
7 days, fully cured, maximum stability and strength

VI. Coating 6: Thermatrol tape (Lockheed Missiles and Space Co; data from L. A. McKellar, Lockheed Missiles and Space Company, Research Laboratory.)

(1) Pigment: Titanium dioxide

(2) Binder: Polymethyl vinyl siloxane elastomer
Pigment-to-binder weight ratio, 1
Solids content not given
Paint applied to adhesive-backed film (composition not available)

(3) Application procedure:

(a) Clean surface by washing with detergent and water or vapor degrease.

(b) Remove first protective covering from adhesive side of tape and apply tape to substrate taking care to avoid bubbles of trapped air.

(c) Remove second protective cover from coating surface prior to use.

VII. Coating 7: Lithafrax (Lockheed Missiles and Space Co.; data from L. A. McKellar, Lockheed Missiles and Space Company, Research Laboratory.)

(1) Pigment: Commercial lithium-aluminum-silicate, supplier not given

(2) Binder: Potassium silicate
Pigment concentration, 4 volume percent
Solids content and pigment binder weight ratio not given

(3) Application procedure:

(a) Clean surface by washing with detergent and distilled water or vapor degrease.

(b) Spray coat to desired thickness (primer not required).

(c) Air dry 6 hours.

VIII. Coating 8: (Lockheed Missiles and Space Co. (LMSC); Synthetic lithium-aluminum-silicate data from L. A. McKellar, Lockheed Missiles and Space Company, Research Laboratory.)

(1) Pigment: Lithium-aluminum-silicate (synthesized by LMSC)

(2) Binder: Potassium silicate
Pigment volume concentration not given
Pigment-to-binder weight ratio not given
Solids content not given

(3) Application procedure: Same as coating 7

IX. Coating 9: (Lockheed Missiles and Space Co., synthetic zirconium silicate data from L. A. McKellar, Lockheed Missiles and Space Company, Research Laboratory.)

(1) Pigment: Zirconium dioxide - silicon dioxide (synthesized by LMSC)

(2) Binder: Potassium silicate
Pigment volume concentration not given
Pigment-to-binder weight ratio not given
Solids content not given

(3) Application procedure: Same as coating 7

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TABLE I. - TEST COATINGS AND VARIABLES

Coating	Experimental variable	Supplier	Supplier's coating designation	Pigment	Binder
1a 1b 1c 1d	Binder only cured at 580° K Binder with basecoat cured at 580° K Complete coating cured at 580° K Complete coating cured at 500° K	Atomics International	AI-93	Stannic oxide topcoat with nickel-chromium-cobalt ($NiO \cdot Cr_2O_3 \cdot Co_2O_3$) basecoat	Aluminum metaphosphate
2a 2b	Binder only Complete coating	Illinois Institute of Technology Research Institute (IITRI) IITRI	S-13	Zinc oxide	Commercial methyl silicone
3a 3b	Binder only Complete coating	IITRI IITRI	S-33	Zinc oxide	Synthetic methyl silicone
4a 4b 4c	0.16-mm-thick smooth substrate 0.11-mm-thick abraded substrate 0.22-mm-thick abraded substrate	IITRI IITRI IITRI	Z-93	Zinc oxide	Potassium silicate
5	Paint formulation	Lockheed Missiles and Space Co. (LMSC)	Thermatrol paint	Titanium dioxide	Polymethyl vinyl siloxane elastomer
6	Adhesive-backed tape formulation	LMSC	Thermatrol tape	Titanium dioxide	Polymethyl vinyl siloxane elastomer
7	Commercial ingredients	LMSC	Lithafrax	Lithium-aluminum-silicate	Potassium silicate
8	Synthetic high-purity ingredients	LMSC	Lithafrax	Lithium-aluminum-silicate	Potassium silicate
9	Synthetic high-purity ingredients	LMSC	---------	Zirconium dioxide - silicon dioxide	Potassium silicate

TABLE II. - EXPERIMENTAL DATA

(a) Coating 1a: Aluminum metaphosphate binder

Specimen	Mass, mg	Thickness, mm	Area density, mg/sq cm	Test	Temperature, $^{\circ}$K	Emittance, ϵ	Absorptance, α_s
1	6.7	0.005	1.04	1	275	0.75	
				2	297	0.76	
					298	.77	
					343	.79	
					394	.80	0.66
					435	.79	.68
					482	.79	.67
					525	.79	.67
					571	.79	.69
2	7.4	0.015	1.15	1	274	0.73	
					300	.75	
					345	.77	
					372	.77	
				2	298	0.75	
					344	.77	
					395	.78	0.69
					439	.78	.69
					482	.78	.70
					526	.78	.72
					572	.78	.72
				3	435	0.78	0.69
					480	.78	.70
					524	.77	.69
					571	.77	.70
3	4.5	0.025	0.70	1	270	0.71	
					299	.74	
					394	.76	
				2	294	0.76	
					393	.77	0.69
					480	.77	.70
					438	.76	.68
					344	.78	

(b) Coating 1b: Nickel-chromium-cobalt spinel basecoat with aluminum metaphosphate binder

Specimen	Mass, mg	Thickness, mm	Area density, mg/sq cm	Test	Temperature, $^{\circ}$K	Emittance, ϵ	Absorptance, α_s
1	21.5	0.024	3.34	1	297	0.83	
					394	.87	0.99
					480	.89	1.00
					522	.90	.98
				2	295	0.83	
					341	.86	
					435	.87	1.00
					436	.87	1.00
					522	.90	.84
					568	.90	.98
[a]1	21.5	0.024	3.34	3	300	.85	
					396	.88	.99
				4	396	.88	.96
					481	.90	.95
					568	.91	1.00
				5	289	0.86	
					334	.86	
					386	.87	0.94
					476	.89	.97
					567	.90	.94
2	25.3	0.020	3.92	1	295	0.84	
					389	.88	0.90
					473	.89	.90
					516	.90	.92
3	18.4	0.028	2.85	1	299	0.82	
					344	.85	
					394	.87	
				2	298	0.83	
					436	.87	0.97
					478	.88	.98
					520	.89	.95
					564	.90	
				3	473	0.88	0.94
					562	.90	.96

[a] Reinstrumented and measured 30 days after first measurement.

TABLE II. - Continued. EXPERIMENTAL DATA

(c) Coating 1c: Stannic oxide with nickel-chromium-cobalt ($NiO\cdot Cr_2O_3\cdot Co_2O_3$) spinel pigment basecoat and aluminum metaphosphate binder cured at 580° K for 30 minutes

Specimen	Mass, mg	Thickness, mm	Area density, mg/sq cm	Test	Temperature, °K	Emittance, ϵ	Absorptance, α_s
1	92.5	(b)	14.3	1	297	0.91	
					394	.94	0.45
					479	.96	.48
				2	296	0.90	
					394	.94	0.43
					480	.95	.45
					557	.96	.45
2	92.8	(b)	14.4	1	390		0.45
					554	0.97	.50
					523	.97	.51
				2	263	0.88	
					295	.91	
					391	.95	0.47
					478	.97	.46
3	94.1	(b)	14.6	1	299	0.91	
					345	.93	
					397	.94	0.45
				2	296	0.91	
					393	.95	0.43
					480	.96	.45
					566	.96	.48
					524	.96	.44
					434	.95	.46

(d) Coating 1d: Stannic oxide with nickel-chromium-cobalt ($NiO\cdot Cr_2O_3\cdot Co_2O_3$) spinel pigment basecoat and aluminum metaphosphate binder cured at 500° K for 30 minutes

Specimen	Mass, mg	Thickness, mm	Area density, mg/sq cm	Test	Temperature, °K	Emittance, ϵ	Absorptance, α_s
1	94.9	(b)	14.7	1	297	0.91	
					395	.94	0.45
					479	.95	
				2	296	0.92	
					393	.95	0.44
					478	.95	.45
					546	.96	.48
					434	.95	^{c}.49
				3	296	0.92	
					394	.95	0.44
					478	.97	^{c}.50
					549	.97	^{c}.55
				4	295	0.92	
					342	.94	^{c}0.51
					393	.96	^{c}.51
2	97.7	(b)	15.1	1	295	0.92	
					395	.95	0.47
					481	.97	.51
					550	.97	.53
				2	297	0.91	
					342	.94	^{c}0.53
					394	.98	^{c}.52
					482	.97	^{c}.53
					551	.97	
					516	.97	^{c}.51
3	96.7	(b)	15.0	1	297	0.90	
					307	.91	
					316	.92	
					325	.93	
					335	.93	
					344	.93	
					353	.93	
					363	.94	
					372	.94	
				2	297	0.90	
					370	.94	
					379	.94	
					394	.95	
					404	.95	
					421	.95	
					430	.95	
					438	.95	
					447	.96	
					456	.95	
					465	.96	
					473	.96	
				3	295	0.91	
					392	.95	0.47
				4	299	0.90	
					396	.95	
					481	.96	0.50
				5	293	0.90	
					389	.94	^{c}0.51
					476	.96	^{c}.52
					546	.96	^{c}.52

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[b] Average thickness, 0.067 to 0.084 mm.

[c] Data appear as tailed symbols in figures and denote effect of test temperature cycle.

TABLE II. - Continued. EXPERIMENTAL DATA

(e) Coating 2a: Commercial methyl silicone binder (General Electric LTV-602)

Specimen	Mass, mg	Thickness, mm	Area density, mg/sq cm	Test	Temperature, °K	Emittance, ϵ	Absorptance, α_s
1	100.1	0.16	15.5	1	298	0.88	
					393	.87	0.34
					482	.83	.33
					566	.73	
					423	.85	.33
2	88.5	0.12	13.7	1	300	0.87	
					345	.87	0.37
					397	.87	.33
					346	.87	
				2	300	0.87	
					396	.87	0.36
					482	.83	.35
3	94.4	0.15	14.6	1	300	0.86	
					484	.82	0.37
					410	.85	
				2	296	0.85	
					394	.85	0.35
					421	.83	.37
					562	.79	.37
					427	.85	.35

(f) Coating 2b: Zinc oxide pigment with commercial methyl silicone binder (IITRI S-13)

1	464.8	0.29	72.1	1	301	0.93	
					323	.93	
					345	.94	
				2	297	0.93	
					394	.94	0.22
					395	.95	.23
					482	.94	.21
					571	.95	.24
				3	290	0.92	
					433	.97	0.30
					568	.96	.28
2	511.5	0.32	79.4	1	298	0.93	
					395	.95	0.22
					481	.94	.17
				2	296	0.94	
					394	.97	0.26
					481	.98	.22
				3	297	0.93	
					395	.96	0.21
					482	.97	.22
					551	.96	.21
3	425.9	0.27	65.9	1	296	0.91	
					395	.94	0.21
					482	.94	.14
					543	.96	.13
				2	293	0.92	
				3	294	0.93	
					340	.95	
					393	.97	0.25
					438	.98	.23
					483	.98	.24
					543	.98	.21

(g) Coating 3a: Synthetic methyl silicone binder (IITRI R-9)

Specimen	Mass, mg	Thickness, mm	Area density, mg/sq cm	Test	Temperature, °K	Emittance, ϵ	Absorptance, α_s
[d]1	72.7	0.091	11.3	1	298	0.87	
					395	.84	
				2	395	0.80	
					438	.75	
					482	.67	
					526	.61	
					572	.58	
					482	.58	
					394	.53	
				3	394	0.51	0.29
					438	.44	.28
					483	.40	.26
					344	.49	.27
					345	.47	.25
2	71.4	0.093	11.1	1	300	0.86	
					345	.88	
					397	.85	0.30
					448	.81	.30
				2	300	[c]0.83	
					345	[c].83	
					396	[c].81	0.31
					440	[c].77	.29
					484	[c].74	.32

(h) Coating 3b: Zinc oxide pigment with synthetic methyl silicone binder (IITRI S-33)

1	192.3	0.11	29.8	1	300	0.86	
					396	.88	
					483	.87	0.19
					557	.91	.21
				2	295	[c]0.85	
					392	[c].85	0.27
					482	[c].83	.27
					557	[c].82	.24
2	176.5	0.086	27.4	1	299	0.84	
					344	.86	
				2	298	0.85	
					393	.88	0.27
					396	.89	.28
					440	.89	.26
					483	.89	.25
3	157.6	0.086	24.4	1	299	0.83	
					396	.86	
				2	295	0.84	
					344	.86	
					395	.86	0.27
					439	.87	
					482	.86	.21
					526	.89	.22

[c] Data appear as tailed symbols in figures and denote effect of test temperature cycle.

[d] Data not plotted for this specimen.

TABLE II. - Continued. EXPERIMENTAL DATA

(i) Coating 4a: Zinc oxide pigment with potassium silicate binder (IITRI Z-93); nonroughened substrate; emittance data not plotted

Specimen	Mass, mg	Thickness, mm	Area density, mg/sq cm	Test	Temperature, °K	Emittance, ϵ	Absorptance, α_s
1	247.0	0.27	38.3	1	279	0.92	
				2	298	0.93	
					394	.95	0.17
					481	.90	.18
					569	.82	.19
				3	391	0.92	0.19
					480	.88	.20
				4	293	0.93	
					391	.93	0.20
					481	.88	.21
					525	.85	
					569	.83	.24
2	277.6	0.16	42.9	1	299	0.90	
					441	.86	0.20
					397	.87	
				2	298	0.89	
					395	.88	0.19
					483	.81	.23
					569	.72	.26
					526	.75	.26
					434	.81	.27
3	268.0	0.19	41.6	1	298	0.90	
					344	.89	0.17
					300	.88	
				2	299	0.89	
					345	.89	0.20
					397	.86	.17
					346	.87	.17
				3	297	0.87	
					352	.87	0.17
					430	.84	.17
					483	.78	.18
					395	.83	.18
				4	292	0.86	
					391	.84	0.17
					480	.78	.18
					568	.69	.17
					419	.79	.19
					336	.81	

(j) Coating 4b: Zinc oxide pigment with potassium silicate binder (IITRI Z-93); roughened substrates

1	155.1	0.11	24.1	1	299	0.95	
					344	.97	
					395	.98	0.19
				2	297	0.95	
					394	.98	0.19
					481	.95	.20
					570	.89	.22
				3	388	^{c}0.95	^{c}0.20
2	155.1	0.11	24.1	1	299	0.96	
					345	.98	
				2	298	0.96	
					396	.98	0.20
					482	.95	.20
					571	.90	.22
					431	^{c}.96	^{c}.23

(k) Coating 4c: Zinc oxide pigment with potassium silicate binder (IITRI Z-93); roughened substrates

Specimen	Mass, mg	Thickness, mm	Area density, mg/sq cm	Test	Temperature, °K	Emittance, ϵ	Absorptance, α_s
1	307.5	0.22	49.1	1	299	0.96	
					396	.95	0.15
					483	.89	.17
					572	.81	.17
				2	285	^{c}0.92	
					334	^{c}.93	
					429	^{c}.90	^{c}0.18
					522	^{c}.95	^{c}.16
2	291.9	0.23	45.2	1	297	0.96	
					395	.96	0.16
					482	.89	.16
					570	.78	.17
					426	.88	.19
3	302.9	0.22	47.0	1	298	0.96	
					343	.98	
					395	.97	0.16
					481	.91	.18
				2	297	0.94	
					342	.96	
					394	.96	0.16
					431	.93	
					481	.90	.16
					567	.81	.14
				3	293	^{c}0.93	
					338	^{c}.93	
					390	^{c}.92	^{c}0.17

(l) Coating 5: Titanium dioxide pigment (paint)

1	211.2	0.19	32.7	1	299	0.91	
					344	.93	
					396	.93	0.20
				2	297	0.91	
					342	.93	
					394	.93	0.23
					438	.93	.22
					482	.91	.24
					569	.88	.28
				3	294	0.91	
					437	.92	^{c}0.27
2	207.6	0.18	32.1	1	341	0.93	
					394	.94	0.22
				2	298	0.91	
					396	.93	0.22
					481	.92	.20
					566	.88	.19
				3	293	0.90	
					337	.93	
					388	.93	^{c}0.25
					431	.93	^{c}.27
					476	.93	^{c}.24
3	188.1	0.17	29.2	1	298	0.92	
					394	.94	0.19
					480	.93	.21
					565	.90	.28
				2	422	0.92	
					479	.93	

[c] Data appear as tailed symbols in figures and denote effect of test temperature cycle.

TABLE II. - Concluded. EXPERIMENTAL DATA

(m) Coating 6: Titanium dioxide pigment (tape)

Specimen	Mass, mg	Thick-ness, mm	Area density, mg/sq cm	Test	Temper-ature, ^{o}K	Emit-tance, ϵ	Absorp-tance, α_s
1	209.2	0.20	32.4	1	298	0.90	
					343	.91	
					395	.90	0.23
				2	298	0.90	
					395	.91	0.22
					481	.86	.21
					439	.88	.25
					358	.91	
2	207.3	0.21	32.1	1	299	0.92	
					344	.93	
					395	.94	
				2	299	0.92	
					395	.94	0.24
					482	.91	.23
					439	.92	
					363	.95	
3	206.3	0.19	32.0	1	296	0.92	
					564	.90	0.23
				2	293	0.93	
					391	.94	0.25
					478	.92	.25
					570	.89	.22

(n) Coating 7: Commercial lithium-aluminum-silicate pigment with potassium silicate binder

1	153.9	0.18	23.8	1	296	0.98	
					343	1.00	
					394	.99	0.20
				2	296	0.98	
					393	.99	0.20
					480	.95	.21
					572	.86	.24
				3	295	0.96	
					392	.96	0.23
					480	.92	.24
					573	.86	.24
					523	.89	
					434	[c].90	
2	156.2	0.20	24.2	1	299	0.98	
					395	1.00	0.22
					482	.97	.27
					573	.88	.30
				2	288	[c]0.97	
					336	[c].98	
					387	[c].97	0.30
					478	[c].93	.30
					574	[c].87	.31
3	110.3	0.13	17.1	1	299	0.98	
					345	.99	
					396	.99	0.26
					440	.97	.27
				2	298	0.97	
					345	.98	
					395	.98	0.27
					438	.98	
					483	[c].94	.29
					439	[c].96	

(o) Coating 8: Synthetic lithium-aluminum-silicate pigment with potassium silicate binder

Specimen	Mass, mg	Thick-ness, mm	Area density, mg/sq cm	Test	Temper-ature, ^{o}K	Emit-tance, ϵ	Absorp-tance, α_s
1	159.1	0.21	24.7	1	299	1.00	
					396	.99	0.16
					483	.95	.17
					574	.86	.20
				2	290	1.00	
					336	.98	
					433	.95	0.19
					526	.89	.18
					386	[c].96	
2	126.2	0.15	19.5	1	293	0.98	
					394	.98	0.15
					481	.93	.16
					438	.95	
				2	274	[c]0.96	
					286	[c].97	
					296	[c].97	
					342	[c].97	
					393	[c].96	0.15
					479	[c].93	.15
					569	[c].84	.16
3	135.5	0.16	21.0	1	282	0.96	
					290	.99	
					298	.99	
				2	297	0.98	
					480	.95	0.19
					572	.87	.19
					525	[c].90	
					429	[c].95	

(p) Coating 9: Synthetic zirconium dioxide - silicon dioxide pigment with potassium silicate binder

1	89.7	0.071	13.9	1	297	0.94	
					342	.95	
					394	.96	
				2	294	0.95	
					391	.96	0.22
					478	.90	.22
					570	.80	.25
					422	[c].90	
2	85.9	0.056	13.3	1	296	0.94	
					343	.96	
					393	.95	0.19
				2	294	0.94	
					391	.95	
					479	.89	0.21
					571	.79	.22
				3	386	[c]0.91	0.21
					477	[c].86	.21
					478	[c].86	
3	105.3	0.081	16.3	1	295	0.94	
					392	.96	0.19
					479	.90	.21
					571	.76	
				2	288	[c]0.93	
					333	[c].94	
					382	[c].93	0.20
					427	[c].91	
					474	[c].87	.21
					522	[c].83	

[c] Data appear as tailed symbols in figures and denote effect of test temperature cycle.

TABLE III. - EXPERIMENTAL RESULTS FOR COMPLETE COATINGS

Coating	Calculated area density, mg/sq cm	Coating thickness, mm	Emittance, ϵ			Absorptance, α_s			Ratio of absorptance to emittance, α_s/ϵ		Remarks
			Temperature, °K		Effect of test temperature cycle	Temperature, °K		Effect of test temperature cycle			
			390	550		390	550		390° K	550° K	
1c	14.4	0.067	0.94	0.96	----------	0.45	0.46	---------	0.48	0.48	Darkened slightly after test
1d	15.0	.084	.94	.96	----------	.46	.48	0.05 unit	.49	.50	Darkened slightly after test
2b	72.1	.29	.96	.96	----------	.22	.22	---------	.23	.23	Coating cracked above 480° K
3b	27.2	.092	.88	.89	-0.05 unit	.27	.22	---------	.31	.25	Coating cracked above 480° K and adhesion deteriorated above 525° K
4b	24.0	.11	.99	.92	-.03 unit	.19	.22	.03 unit	.19	.24	----------------------------
4c	46.6	.22	.95	.81	-.03 unit	.16	.16	.03 unit	.17	.20	Surface cracks noted after test
5	31.4	.18	.94	.89	----------	.21	.20	.04 unit	.22	.23	----------------------------
6	32.1	.20	.94	.89	----------	.22	.21	---------	.23	.24	Blisters developed beneath film
7	21.7	.17	.99	.89	-.03 unit	.26	.28	Scatter	.26	.32	Considerable darkening above 480° K
8	21.8	.17	.98	.88	-.02 unit	.17	.19	---------	.21	.22	----------------------------
9	14.5	.068	.95	.81	-.03 unit	.20	.23	---------	.21	.28	Darkened slightly during test

TABLE IV. - ADDITIONAL RADIATOR MASS ADDED

BY COATING

Coating	Area density, mg/sq cm	Mass added, percent	
		To secondary-cooling radiator (a)	To Brayton cycle radiator (b)
1c	14.4	12.7	4.5
1d	15.0	13.3	4.8
2b	72.1	63.9	22.9
3b	27.2	24.0	8.6
4b	24.0	21.3	7.6
4c	46.6	41.2	14.8
5	31.4	27.8	10.0
6	32.1	28.4	10.2
7	21.7	19.2	6.9
8	21.8	19.3	6.8
9	14.5	12.8	4.6

[a] Ref 12; radiator mass, 66.7 Kg; radiator area, 58.9 sq m (excludes header mass and area).

[b] Ref 12; radiator mass, 233.0 Kg; radiator area, 73.0 sq m (excludes header mass and area).

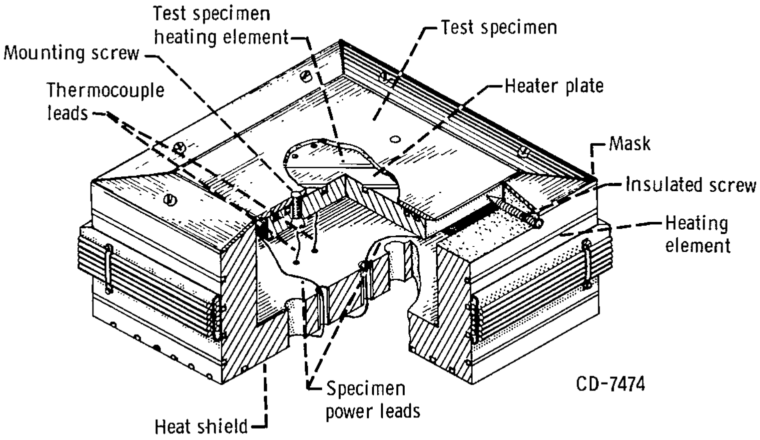


Figure 1. - Test specimen assembly and heat shield.

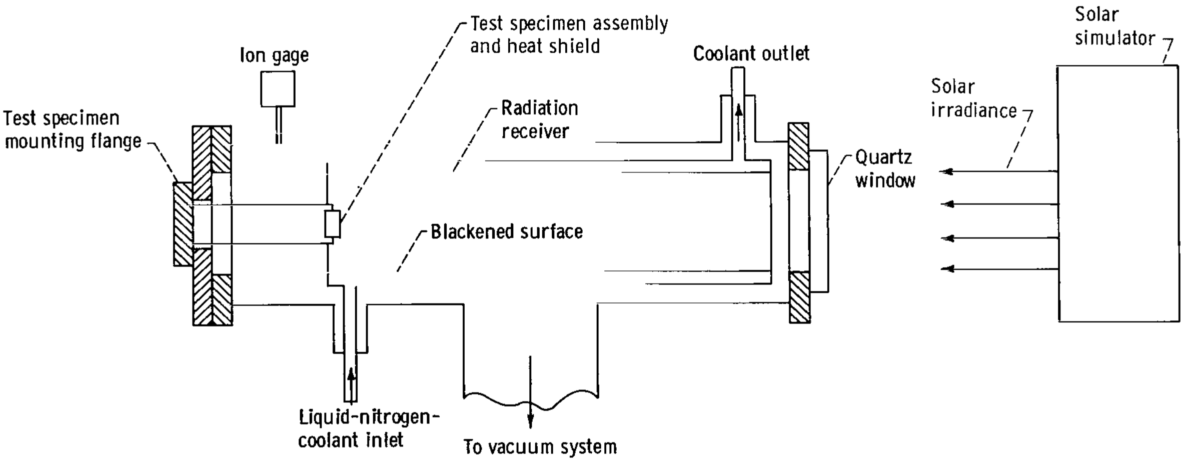


Figure 2. - Schematic of test apparatus.

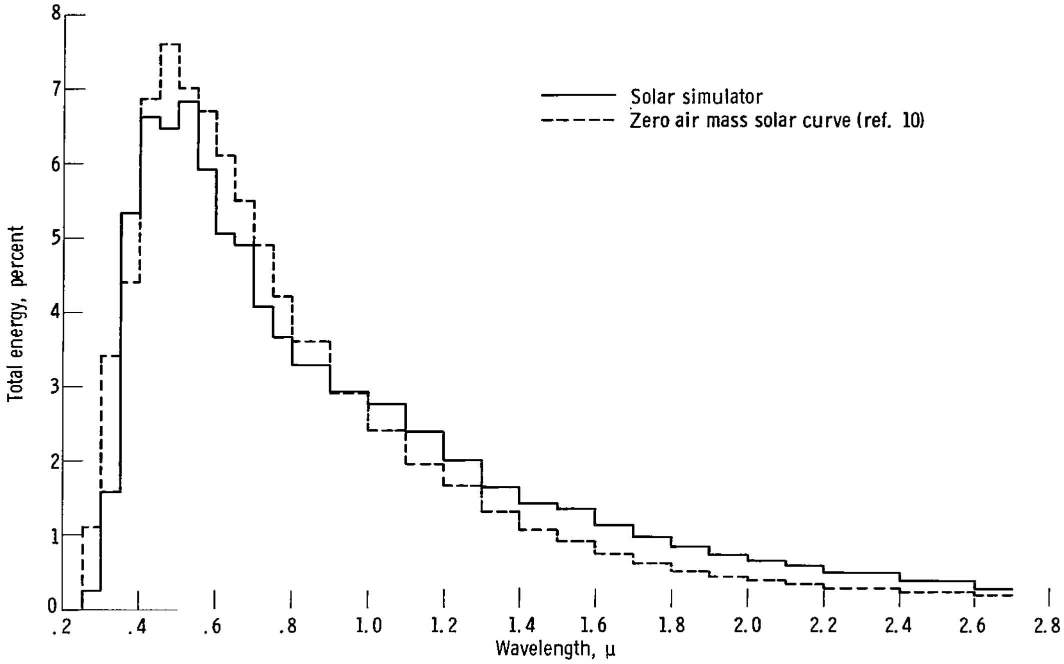
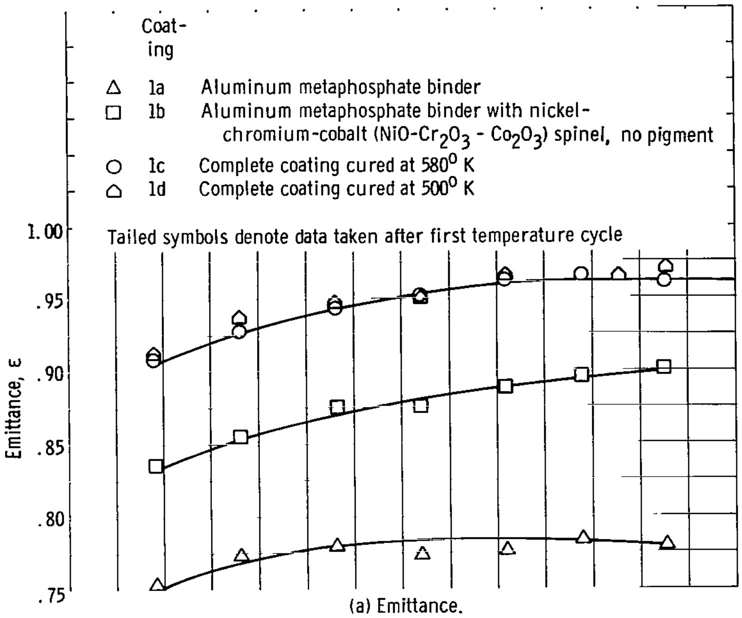
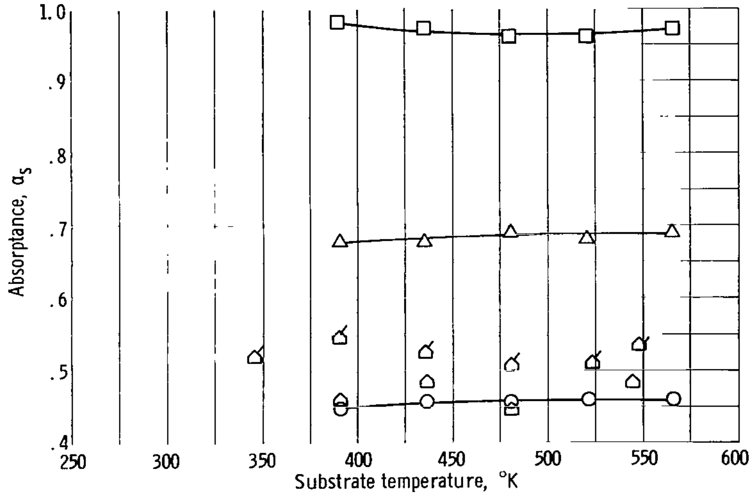


Figure 3. - Percent of total energy in 0.05-micron band increments against wavelength.



(a) Emittance.



(b) Absorptance.

Figure 4. - Emittance and absorptance for coating 1.

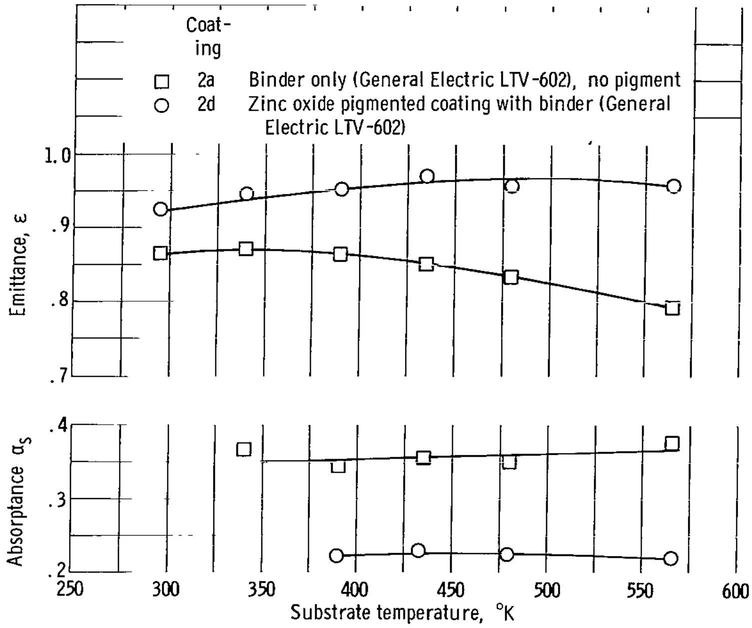


Figure 5. - Emittance and absorptance for coating 2.

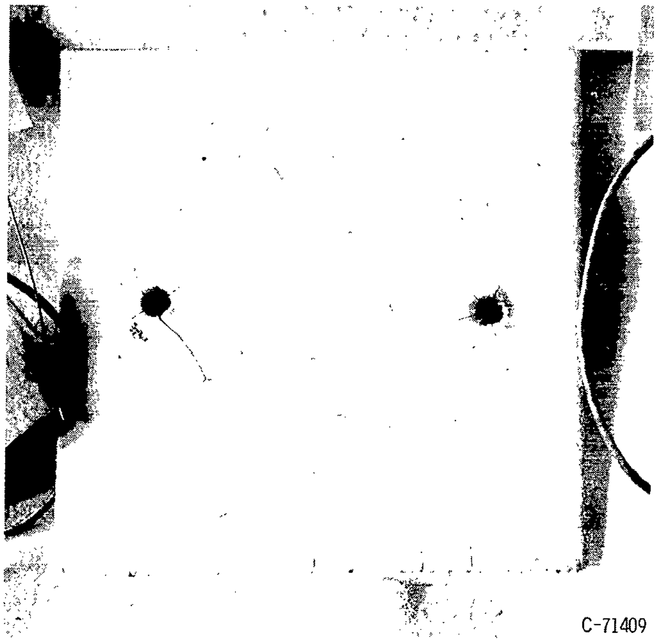

C-71409

Figure 6. - Surface cracks in zinc oxide pigmented methyl silicone coating (coating 2b) after testing to 540° K. Specimen size, 2.54 by 2.54 centimeters.

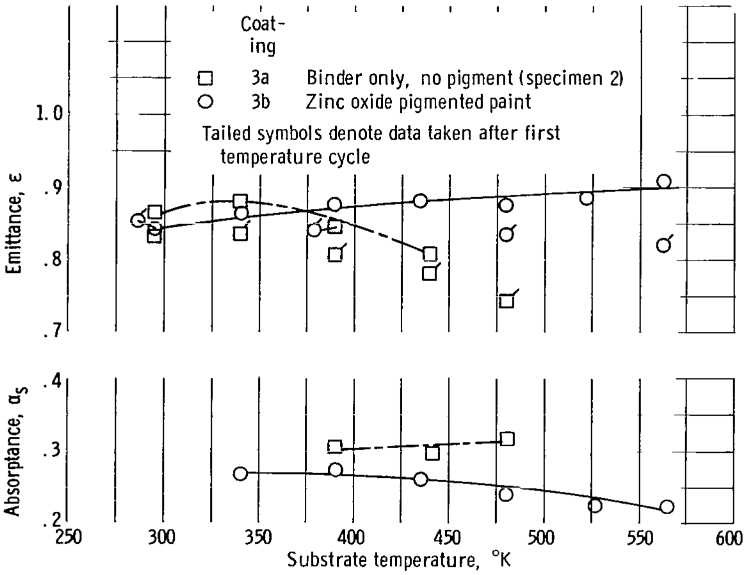
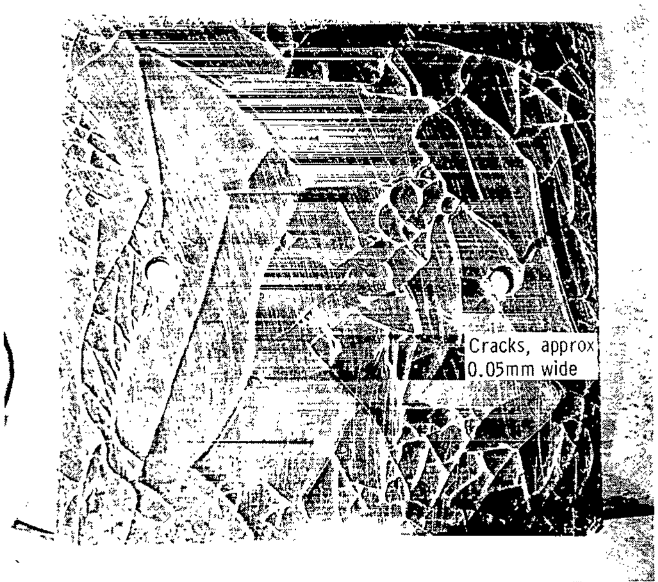


Figure 7. - Emittance and absorptance for coating 3.



C-71411

Figure 8. - Synthetic methyl silicone resin after testing to 572° K (coating 3a).

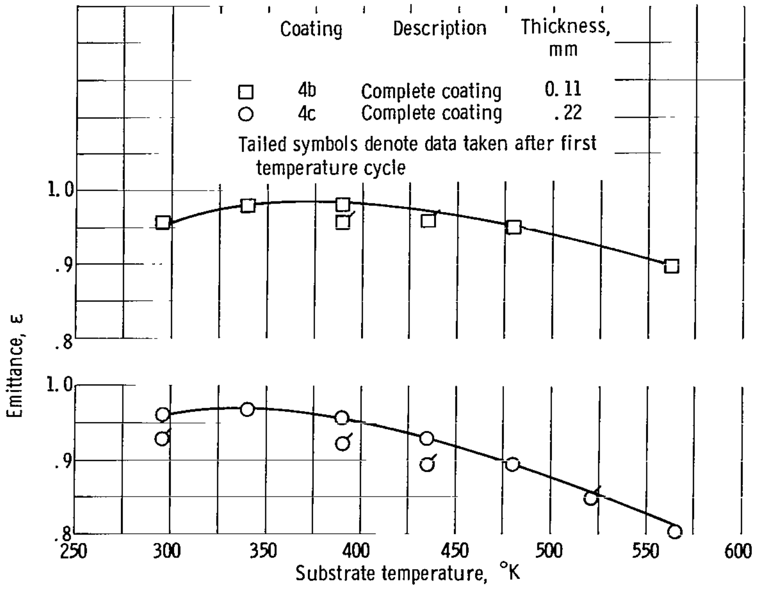


Figure 9. - Emittance for coating 4, for two thicknesses.

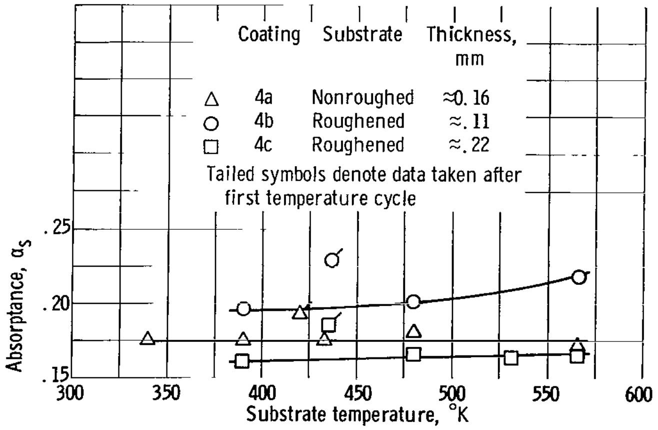
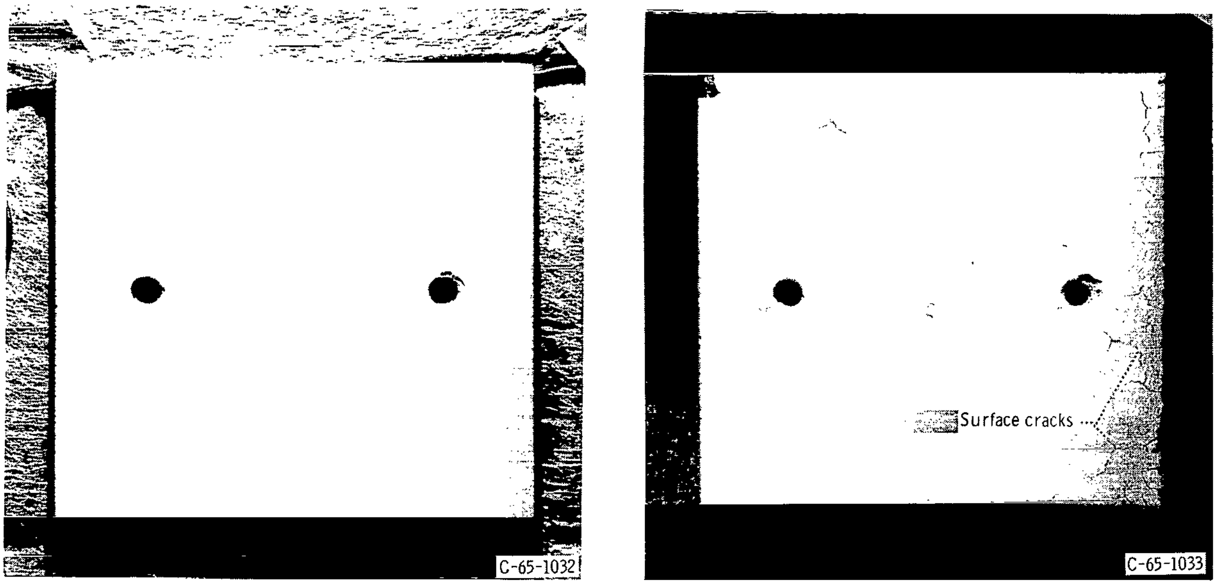
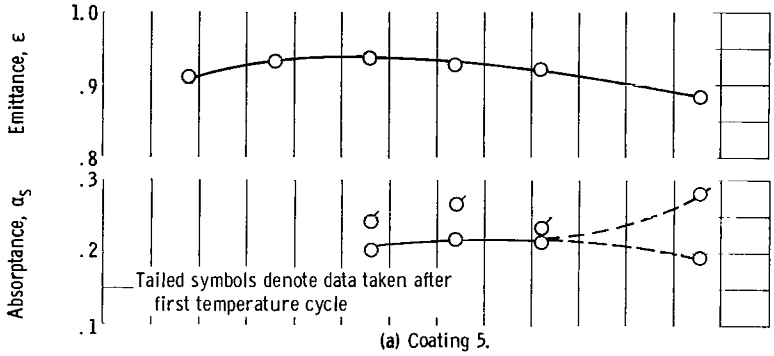


Figure 10. - Absorptance for coating 4 with varying thickness.

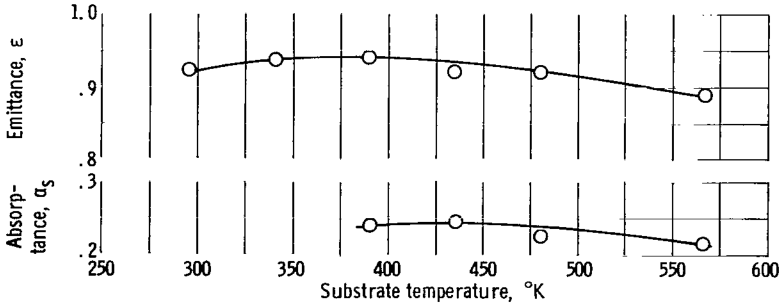


Thickness, mm: 0.11 0.22

Figure 11. - Appearance of zinc oxide pigmented potassium silicate coating (coating 4) after testing to 570° K.

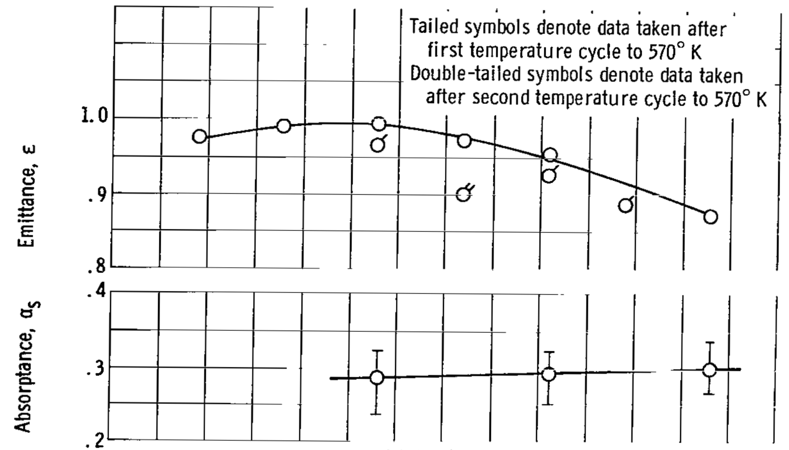


(a) Coating 5.

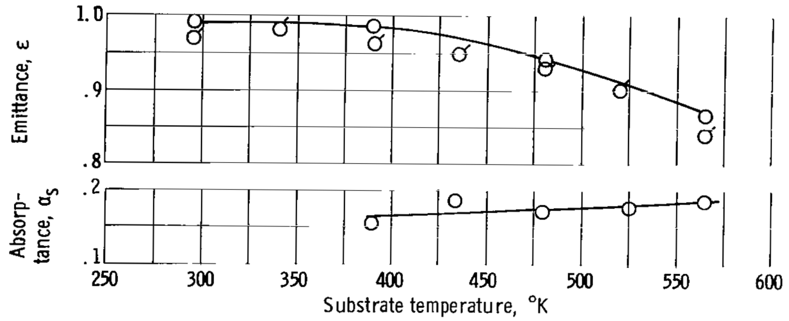


(b) Coating 6.

Figure 12. - Emittance and absorptance for coatings 5 and 6.

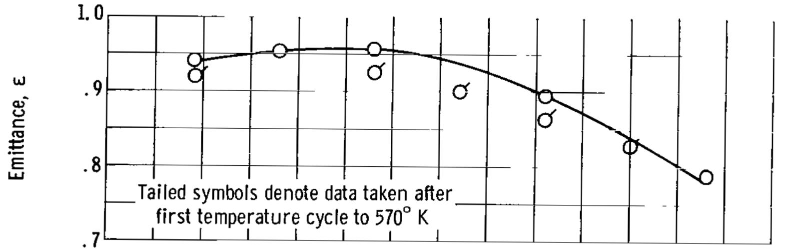


(a) Coating 7.

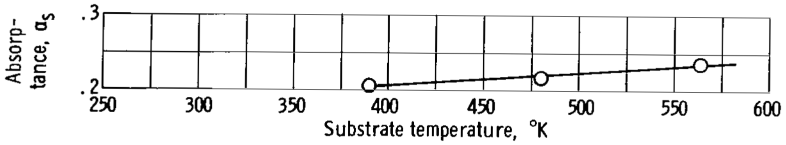


(b) Coating 8.

Figure 13. - Emittance and absorptance for coatings 7 and 8.



(a) Emittance



(b) Absorptance

Figure 14. - Emittance and absorptance for coating 9.

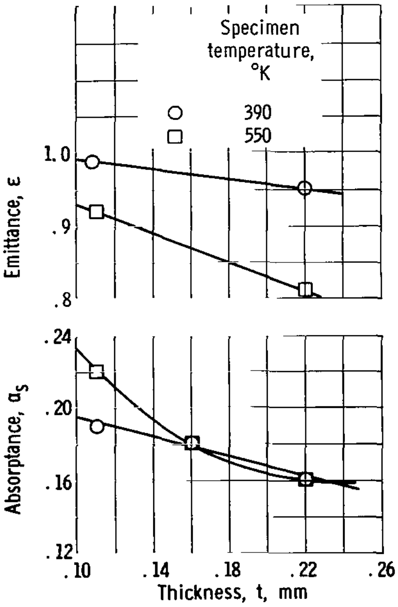


Figure 15. - Emittance and absorptance against coating thickness for coating 4 at two specimen temperatures.

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> —NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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