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by Charles V. Woerner

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SUMMARY

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Two white paints prepared for application to inflatable space structures have been studied: a zinc-oxide-pigmented methyl silicone elastomer and a titanium-dioxide-pigmented epoxy. The data show that either coating can be used on an inflatable structure. The mechanical properties of the silicone paint and the white epoxy paint are excellent, even after cycling through a temperature range of 90° C to -196° C. The white epoxy paint is found not to be a stable paint for long duration exposure to ultraviolet radiation. The zinc-oxide-pigmented methyl silicone elastomer is reasonably stable under the influence of ultraviolet radiation with an increase of 6 to 15 percent of the initial value of solar absorptance when exposed to 1000 equivalent sun hours of simulated solar ultraviolet radiation. The solar absorptance of both paints is affected much less by electron radiation than by ultraviolet radiation for equivalent exposure times in space for an orbit comparable to that of the 12-foot-diameter sphere, Explorer XIX (1963 53A).

Author

INTRODUCTION

Passive temperature control was used to maintain the Explorer IX (1961 Delta I) satellite temperatures within a safe operating range (ref. 1). The same method was used for the Explorer XIX (1963 53A) and Explorer XXIV (1964 76A) satellites. The satellites were lightweight inflatable spheres having a 12-foot diameter and were designed and constructed by the Langley Research Center (ref. 2). The 12-foot-diameter sphere is constructed of a four-ply laminate consisting of alternate layers of 0.5-mil-thick aluminum foil and 0.5-mil-thick plastic film. One layer of the aluminum foil forms the outside surface of the satellite and one layer of the plastic film forms the inside surface. The Explorer IX satellite was placed into orbit on February 16, 1961; the Explorer XIX satellite, on December 19, 1963. (See ref. 3.) The Explorer XXIV satellite was placed into orbit on November 21, 1964. The material utilized as the passive thermal-control coating for the Explorer IX satellite was an epoxy (epichlorohydrin bisphenol-A) paint pigmented with titanium dioxide; this paint was obtained commercially. The material utilized as the passive thermal-control coating for the Explorer XIX and Explorer XXIV satellites was a methyl silicone elastomer pigmented with zinc oxide.

The original formula for the zinc-oxide-pigmented methyl silicone elastomer was developed by The Illinois Institute of Technology Research Institute (IITRI) under NASA contract. (See ref. 4.)

The purpose of the present paper is to present the optical, thermal, and mechanical properties of the white epoxy paint and the zinc-oxide-pigmented methyl silicone elastomer and to show the effects of simulated solar ultraviolet radiation and high-energy electron radiation on these two passive temperature-control coatings. At the time the present investigation was begun some research had already been carried out by IITRI with regard to the stability of the optical properties of the zinc-oxide-pigmented methyl silicone elastomer and these investigations indicated that it was possibly a reasonably stable coating. However, the IITRI coating, prepared under laboratory controlled conditions of mixing and spraying, was not necessarily the same as that prepared by the larger scale mixing, spraying, and handling techniques required for application to a large satellite such as Explorer XIX.

PHYSICAL REQUIREMENTS OF THE COATINGS

The coatings that were utilized as thermal-control surfaces for the 12-foot-diameter inflatable spheres were applied in the form of dots, distributed evenly over the satellite skin surface to give proper temperature control regardless of satellite orientation in sunlight. These coatings had to meet the following physical requirements:

1. The coating should adhere to aluminum foil.

2. The coating should be easy to apply to the surface.

3. The coating should have a ratio of solar absorptance to thermal emittance α/ϵ of approximately 0.40 or less. The lower the value of the ratio α/ϵ, the less painted area is required to control the temperature of the 12-foot-diameter inflatable sphere.

4. The desired value of the ratio α/ϵ should be obtained with a thin coating to minimize the weight required.

5. The ratio α/ϵ of the coating should not increase by more than 30 percent when the coating is exposed to solar ultraviolet radiation and high-energy electron radiation.

6. The coating should withstand temperature cycling between 90° C and -160° C without peeling from the aluminum surface.

7. The coating should withstand the creasing, twisting, and flexing required to fold and package the 12-foot-diameter sphere for flight.

ZINC-OXIDE-PIGMENTED METHYL SILICONE ELASTOMER

The original formula for the zinc-oxide-pigmented methyl silicone elastomer (known as S-13) as obtained from IITRI is given in table I. It consists basically of four constituents: a binder, methyl silicone elastomer; a pigment, zinc oxide (purity of 99.80 percent and mean particle size of 0.25μ to 0.35μ); a thinner, toluene (purity of 99.91 percent toluene); and a catalyst for the elastomer. The constituents of the zinc-oxide-pigmented methyl silicone elastomer (hereinafter called silicone paint) were obtained commercially and then mixed in porcelain jar mills. The grinding stones were made of hard porcelain and were cylinders of 1/2 inch diameter and 1/2 inch length. For the main part of the grinding operation, the pigment was mixed with only one-half the total toluene used in the formula; the volume of this mix was just sufficient to cover the grinding stones when the jar mill was one-half full of grinding stones. The other half of the toluene was added 1/2 hour prior to completion of the 16 hours grinding time. The catalyst was added when the silicone paint was ready to spray. Once the catalyst was added, a working time of only 1 hour was available but this presented no problems. The silicone paint was sprayed with commercial spray guns with compressed air or nitrogen. Prior to spraying the silicone paint the surface had to be primed with a primer compatible with the silicone elastomer. The primer coat, General Electric SS-4044, was approximately 1/10 mil thick. Unless the surface was primed before painting, the silicone paint could be stripped off in one large sheet.

TABLE I

ORIGINAL FORMULA OF ZINC-OXIDE-PIGMENTED METHYL SILICONE ELASTOMER PAINT (S-13)

[Formula obtained from IITRI]

	Parts by weight
Zinc oxide	2.4
Silicone elastomer	1.0
Toluene	1.838
Catalyst	0.005

The original formula resulted in a silicone paint mixture that has two disadvantages. First, the paint covering was slightly tacky which was undesirable for application to an inflatable structure because of the necessity for folding and packaging the sphere and, second, as sprayed the silicone paint mixture was too fluid. The concentration of zinc oxide was increased in the formula to reduce the tackiness. In order to increase the viscosity, the amount of toluene was reduced to only three-fourths that in the original formula. This change was accomplished by grinding with the same amount of toluene as before but reducing the amount of toluene added just prior to completion of the grinding. The modified formula is given in table II. Another proposed formula, in which only one-half the original toluene was used, resulted in a paint that was too viscous. During the time the mixing and spraying techniques were being developed, the silicone paint

TABLE II

MODIFIED FORMULA OF ZINC-OXIDE-PIGMENTED METHYL SILICONE ELASTOMER PAINT USED ON 12-FOOT-DIAMETER INFLATABLE SPHERES

	Parts by weight
Zinc oxide	2.88
Silicone elastomer	1.0
Toluene	1.378
Catalyst	1 drop per 12 g of mixed paint

was ground in $\frac{1}{2}$-pint quantities. The final mixtures were ground in a $1\frac{1}{3}$-gallon-capacity jar mill with a paint yield of approximately $1\frac{2}{3}$ quarts.

Several of the paint batches produced by the preceding method had an off-shade of yellow. This off-shade of yellow has been attributed to a spectral shift caused by lattice distortion induced by grinding. In order to reduce this yellowing, the quantity of grinding stones was reduced so that they filled the jar mill only one-third full. The paint for the Explorer XIX satellite was made with this reduced quantity of grinding stones. Subsequent paints have been made with the quantity of grinding stones further reduced so that they filled the jar mill only one-fourth full. The paint used on the Explorer XXIV satellite, for example, was made with this further reduced quantity of stones.

MECHANICAL, THERMAL, AND OPTICAL PROPERTIES

Flexibility and Resistance to Temperature Changes

The flexibility and resistance to damage from large and rapid temperature changes had to be exceptional for the paints applied to the 12-foot-diameter inflatable spheres. These physical properties had to far exceed those usually accepted for paints. The bending, twisting, and flexing necessary to fold and package the sphere for transport into orbit can be seen in figure 1. The vibration environments for type approval and flight acceptance testing of the Explorer IX and Explorer XIX, payloads for the Scout vehicle, are given in tables IV and VI of reference 3. The 12-foot-diameter prototype spheres were successfully folded, packaged, and vibration tested with only minor chipping around the edges of the white epoxy paint dots and no apparent damage to the silicone paint dots. The vibrations were no doubt damped out by the folded sphere.

The temperature cycle in orbit for the paints is similar to that of figure 6 of reference 1 which represents the variation of the average temperature of the sphere skin for an orbit; however, portions of the sphere skin will become hotter or colder than the extremes indicated in this figure.

Twelve specimens of the silicone paint were cycled 24 times through a temperature range of 90° C to -196° C. This range was more than required but a temperature of -196° C corresponds to that of liquid nitrogen which was a convenient temperature to obtain for testing purposes. The cycle period was 2 minutes for convenience, which was possibly too rapid to be realistic in

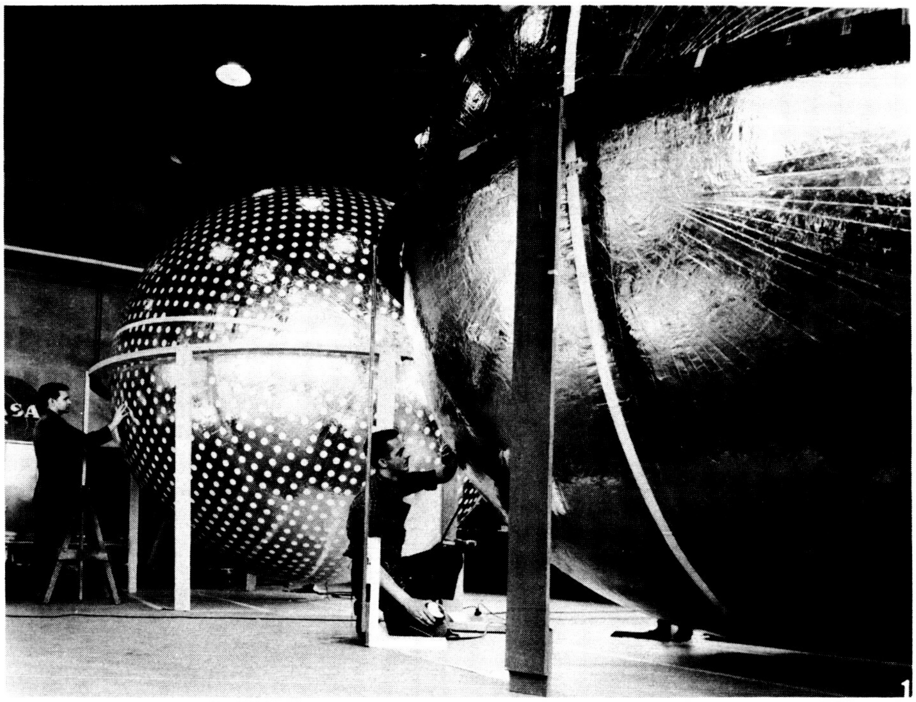
TABLE III

TEMPERATURE CYCLE TESTS

Specimen	Paint thickness, mils	Results[a]
Silicone elastomer paint sprayed on aluminum-foil—plastic-film laminate		
1	1.4	No change in specimen
2	.9	No change in specimen
3	1.6	No change in specimen
4	2.7	No change in specimen
5	2.3	No change in specimen
6	2.0	No change in specimen
7	3.35	No change in specimen
8	4.2	No change in specimen
9	3.3	No change in specimen
10	7.5	One crack which appeared to be result of an accidental bend while specimen was frozen and brittle, adhesion was still excellent
11	6.6	No change in specimen
12	6.63	No change in specimen
White epoxy paint sprayed on aluminum-foil—plastic-film laminate		
13	1.0	No change in specimen
14	.5	No change in specimen
15	1.0	No change in specimen
16	1.0	No change in specimen
17	1.0	No change in specimen
18	.5	No change in specimen

[a] Test consisted of 24 cycles through a temperature range of 90° C to -196° C.

representing the actual behavior in orbit. Six specimens of the white epoxy paint were also cycled 24 times through this temperature range. The results of these tests for the silicone paint and the white epoxy paint are given in table III. All the paint specimens were sprayed as 2.4-inch-diameter dots on the aluminum-foil surface of 6-inch-square specimens of the four-ply laminate. The four-ply laminate consisted of alternate layers of 0.5-mil-thick aluminum foil and 0.5-mil-thick plastic film. All the silicone paint specimens withstood the 24 cycles. One specimen had a crack in it which appeared to be the result of an accidental bend while the specimen was frozen and brittle. After completion of the temperature cycles, the silicone paint specimens were as flexible as before and still showed excellent adhesion to the aluminum foil. All the white epoxy paint specimens withstood the 24 cycles with no apparent deterioration in mechanical properties.



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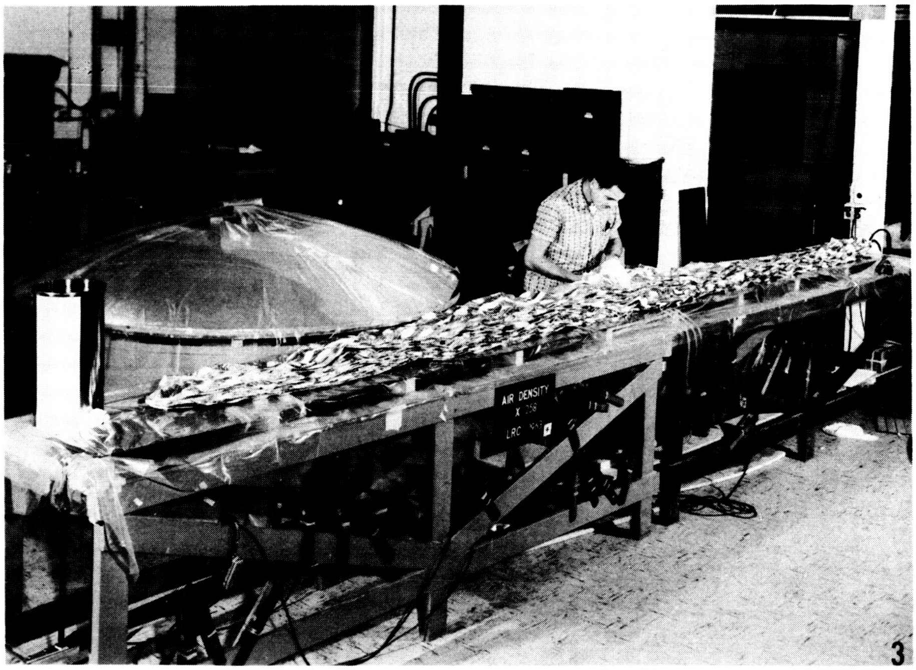

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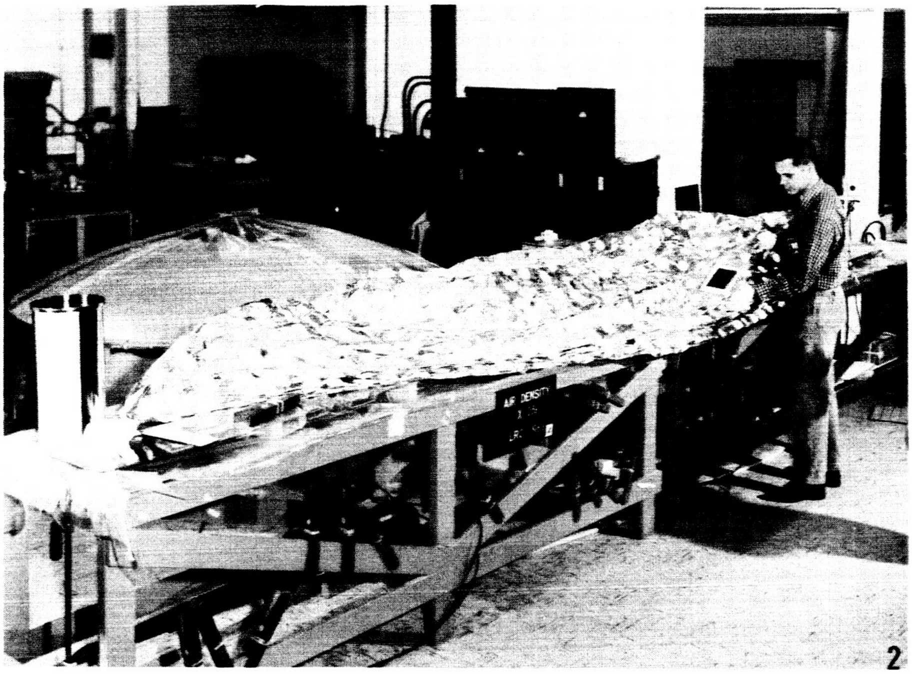
Figure 1.- The folding and packaging of 12-foot-



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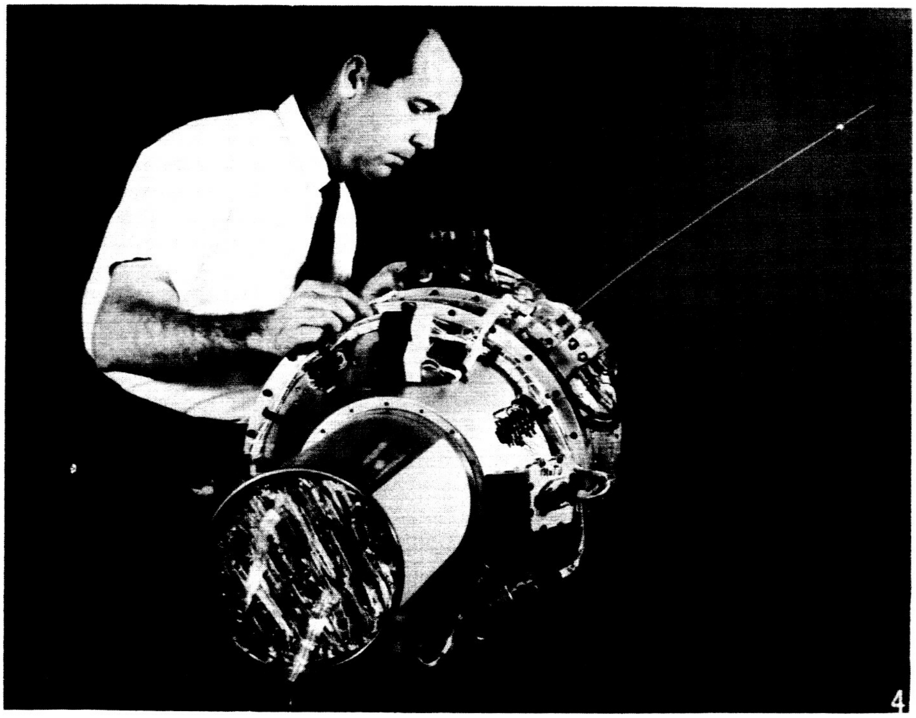

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diameter inflatable sphere for transport into orbit. L-65-41

Thermal Emittance

Apparatus.- The emittance was obtained on an equilibrium temperature apparatus developed at the Langley Research Center. This apparatus consists essentially of two coaxial cylinders as shown in figure 2. The outer cylinder is cooled to liquid nitrogen temperature. The inner cylinder which has an outside diameter of 5/8 inch is heated by passing an electric current through it. Figure 3 shows the inner or heated cylinder removed from the outer or cooled cylinder and a test specimen partially installed. The specimen consists of a sample of the four-ply laminate that is sprayed with white epoxy paint or is primed and then sprayed with silicone paint.

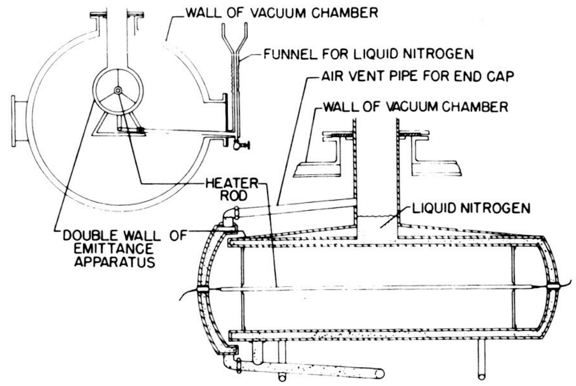

Figure 2.- Cross sections of vacuum chamber and emittance apparatus.

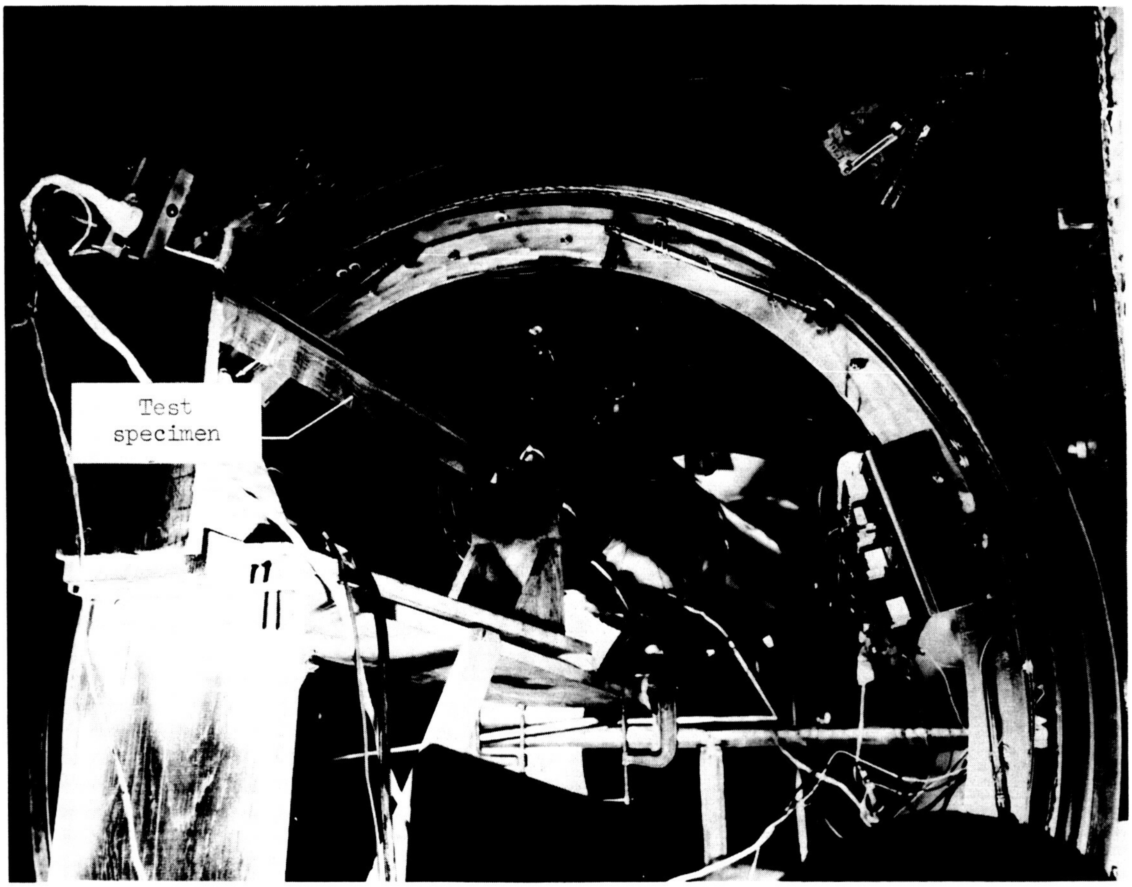

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Figure 3.- Emittance apparatus with specimen tube withdrawn and test specimen of painted four-ply laminate partially mounted.

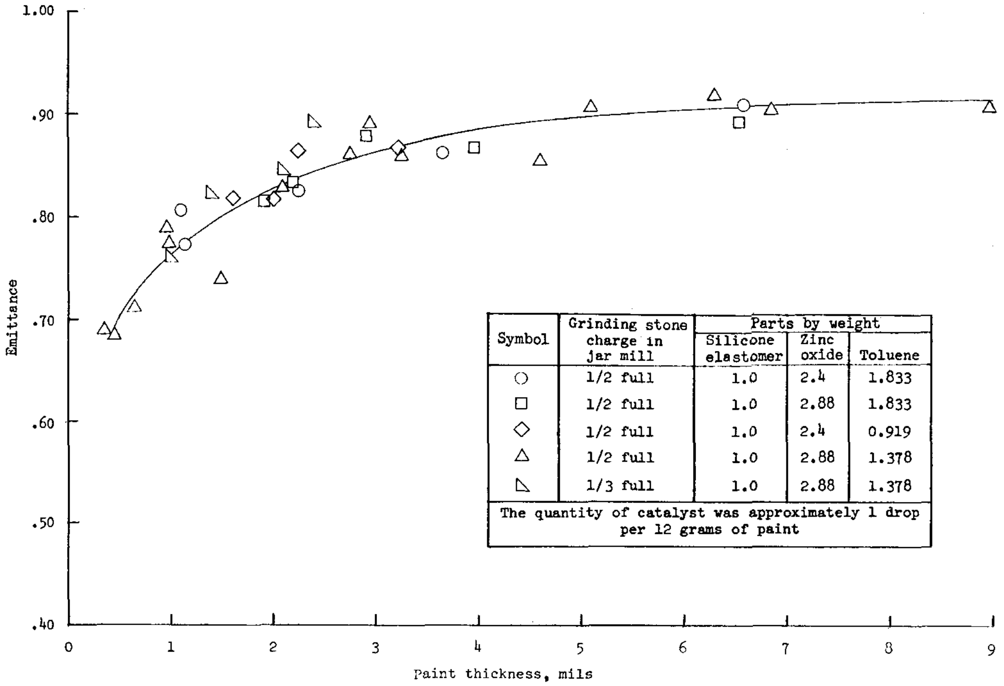
The laminate is adhesively bonded to the outside surface of the heated cylinder with a very thin layer of thermosetting resin so that no appreciable temperature difference can exist between the radiating surface of the painted laminate and the heated cylinder. The emittance is determined by heating the test specimen on the inner cylinder to some predetermined temperature and recording the electrical power required to maintain the test specimen at this temperature in thermal equilibrium. The temperature of the inner cylinder is monitored by thermocouples embedded in the cylinder wall. Only the center 22 inches of the heated cylinder shown in figure 2 is used for a test-section area. A small lead is passed through each end of the heated cylinder and embedded in the wall at each end of the test section to measure the voltage drop across the test section while passing a current through it. The test-specimen size used to determine emittance is therefore $\frac{5}{8}\pi$ inches by 22 inches or approximately 44 square inches. For a more detailed description of the apparatus and the method of testing, see reference 5. With this emittance apparatus, the rate of radiative heat loss is equal to the electrical power absorbed by the heated cylinder. The total hemispherical emittance ϵ is calculated by the following equation:

$$\epsilon = \frac{EI}{\sigma A T^4}$$

where

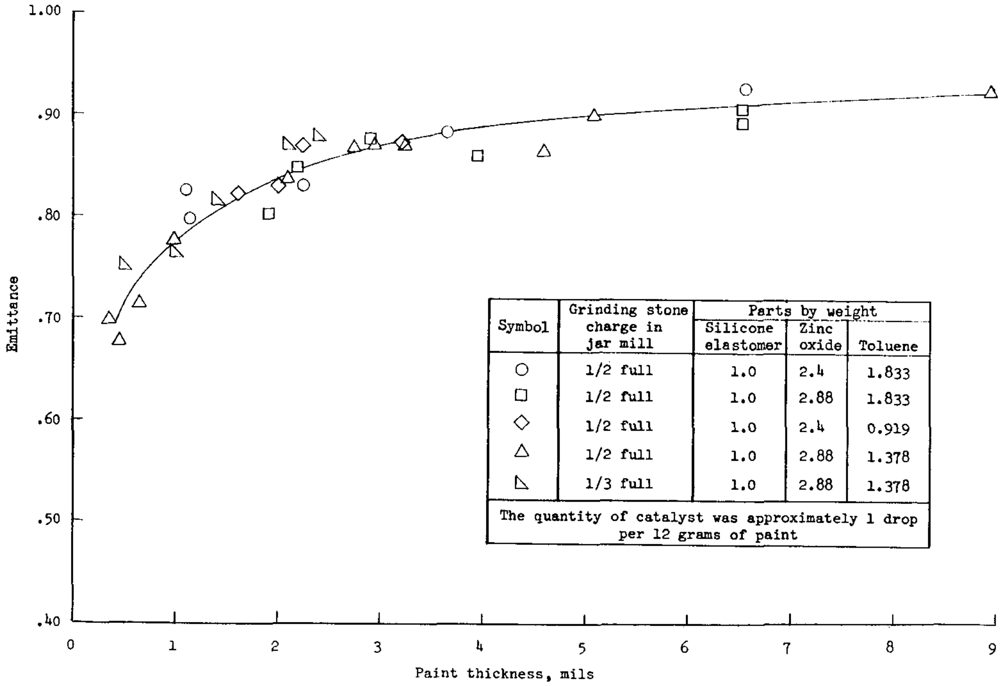
A	radiating area of test section
E	voltage drop across test section
I	current flow through heated cylinder
T	temperature of test section
σ	Stefan-Boltzmann constant

Thermal emittance was also measured by a spectrophotometer. The spectrophotometer data were obtained by measurements of spectral reflectances of the test surfaces over the wavelength range from 4μ to 14.5μ. This wavelength region contains only 55 percent of the spectral-energy distribution for a 295° K blackbody. Emittance was calculated by an energy-weighted method using the spectral distribution curve of monochromatic emissive power for an ideal radiator at a temperature of 295° K. The test specimens for the spectrophotometer were prepared by priming the aluminum-foil surface of the four-ply laminate and spray painting the primed surface with the silicone paint. Next, the painted laminate was bonded with a thermosetting resin to a $\frac{59}{64}$-inch-diameter flat aluminum disk and trimmed to that size. Finally, the disk was mounted in the specimen holder of the spectrophotometer. The white epoxy paint specimens for the spectrophotometer were spray painted directly onto the polished aluminum disks.



Symbol	Grinding stone charge in jar mill	Parts by weight		
		Silicone elastomer	Zinc oxide	Toluene
○	1/2 full	1.0	2.4	1.833
□	1/2 full	1.0	2.88	1.833
◇	1/2 full	1.0	2.4	0.919
△	1/2 full	1.0	2.88	1.378
◺	1/3 full	1.0	2.88	1.378
The quantity of catalyst was approximately 1 drop per 12 grams of paint				

(a) Thermal emittance at -25° C.



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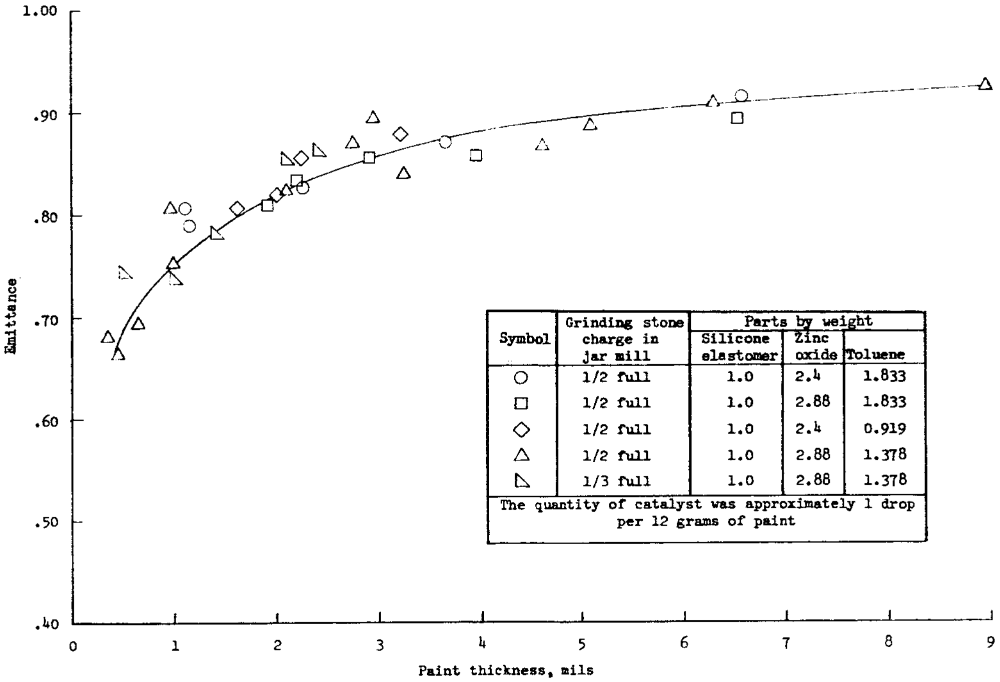
△	1/2 full	1.0	2.88	1.378
◺	1/3 full	1.0	2.88	1.378
The quantity of catalyst was approximately 1 drop per 12 grams of paint				

(b) Thermal emittance at 25° C.

Figure 4.- Variation of thermal emittance of zinc-oxide-pigmented methyl silicone elastomer paint with paint thickness on aluminum foil.



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△	1/2 full	1.0	2.88	1.378
◺	1/3 full	1.0	2.88	1.378

The quantity of catalyst was approximately 1 drop per 12 grams of paint

(c) Thermal emittance at 75° C.

Figure 4.- Concluded.

Results and discussion.- The thermal emittance (total hemispherical) of the silicone paint on the aluminum-foil surface of the four-ply laminate is shown in figure 4(a) plotted against thickness at a temperature of -25° C. Similar data are shown in figures 4(b) and 4(c) at temperatures of 25° C and 75° C. The data indicate that the emittance is about 0.75 to 0.80 for a 1-mil-thick coating and about 0.90 for a coating that is several mils thick. Figure 5, a crossplot of figure 4, shows that the thermal emittance is approximately independent of temperature in the range from -25° C to 75° C and varies only with thickness. The data were measured on the equilibrium temperature apparatus.

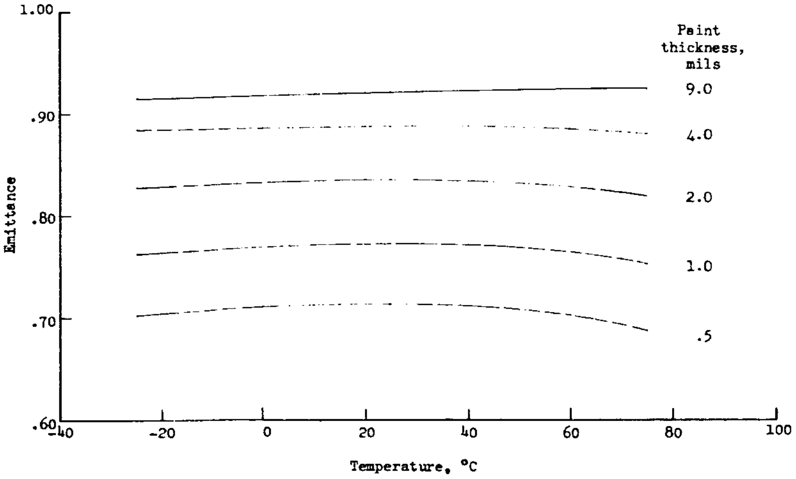
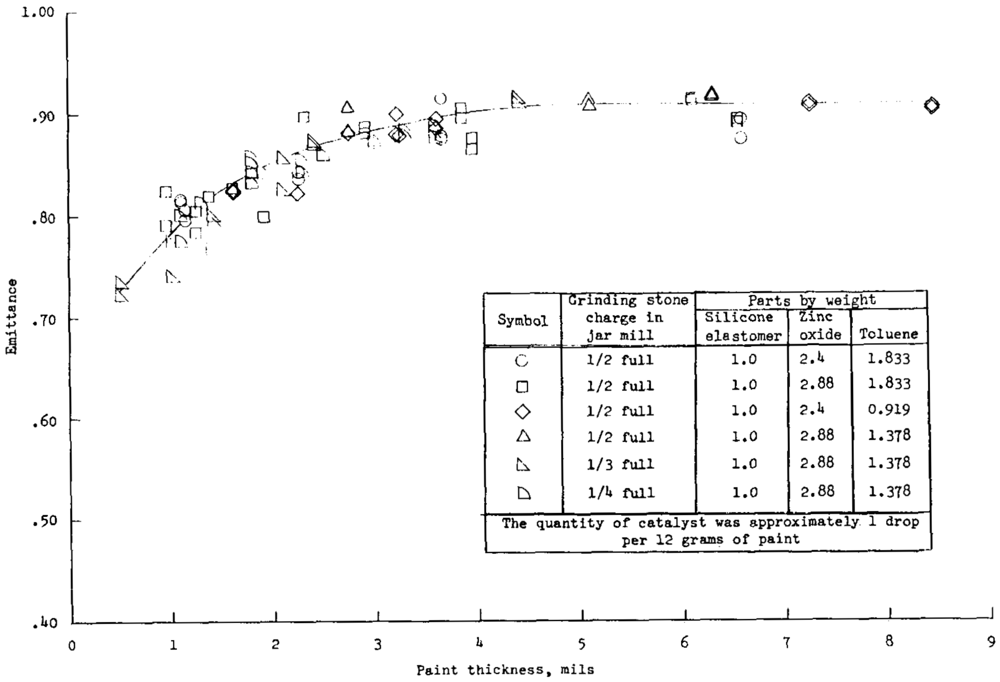


Figure 5.- Variation of thermal emittance of zinc-oxide-pigmented methyl silicone elastomer paint with temperature for several paint thicknesses on aluminum foil.



Symbol	Grinding stone charge in jar mill	Parts by weight		
		Silicone elastomer	Zinc oxide	Toluene
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◇	1/2 full	1.0	2.4	0.919
△	1/2 full	1.0	2.88	1.378
◺	1/3 full	1.0	2.88	1.378
◸	1/4 full	1.0	2.88	1.378

The quantity of catalyst was approximately 1 drop per 12 grams of paint

Figure 6.- Variation of thermal emittance of zinc-oxide-pigmented methyl silicone elastomer paint with paint thickness on aluminum foil. (Data measured on spectrophotometer and summed for a 295° K blackbody distribution for the spectral range of 4μ to 14.5μ.)

Figure 6 shows the emittance measured by the spectrophotometer plotted against thickness of the silicone paint. The emittance is calculated based on the average for only 55 percent of the blackbody distribution and the spectrophotometer data give very nearly normal emittance; nevertheless, the emittance values thus obtained for a 295° K silicone paint surface are in good agreement with the data of figure 4(b) which are the total hemispherical emittance for a 298° K silicone paint surface as measured on the equilibrium temperature apparatus.

The white epoxy paint sprayed on the Explorer IX satellite was 1 mil thick. Thermal emittance for this thickness of white epoxy paint sprayed on the aluminum-foil side of the four-ply laminate is 0.85 at 298° K as measured on the equilibrium temperature apparatus. The emittance of the white epoxy paint as measured on the spectrophotometer is 0.91 at 295° K.

Solar Absorptance

Figure 7 shows the solar absorptance for the silicone paint on the aluminum-foil surface of the four-ply laminate plotted against paint thickness

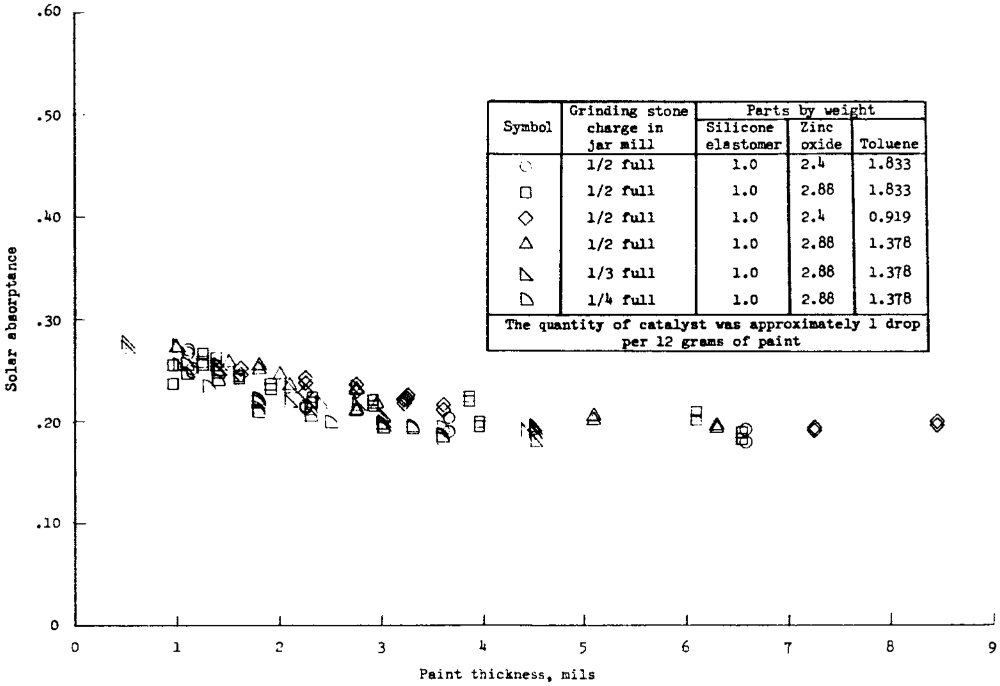

Figure 7.- Variation of solar absorptance of zinc-oxide-pigmented methyl silicone elastomer paint with paint thickness on aluminum foil.

for the grinding mixes with the jar mills one-half, one-third, and one-fourth full of grinding stones. All silicone paint thicknesses include the primer thickness, which is approximately 1/10 mil. The solar absorptance was determined from measurements of spectral reflectances for the test specimens of the silicone paint over the wavelength range, 0.2μ to 2.1μ, which includes 95 percent of the total solar spectral energy. A spectrophotometer equipped with a barium sulfate coated integrating sphere attachment was used to obtain these measurements. Solar absorptance was calculated by an energy-weighted method using the spectral distribution reported in reference 6 for the sun and the data obtained from the spectrophotometer. The data of figure 7 show that solar absorptance decreases with increasing paint thickness but is sufficiently constant that thickness is not too critical. The data points for the mixes ground with the jar mills one-half full of grinding stones tend to lie above the data points for the mixes ground with the jar mills one-fourth full of grinding stones. The difference is associated with the previously mentioned yellowing that occurs when the larger quantity of grinding stones is used. The test specimens of silicone paint prepared for the solar absorptance measurements were identical with those prepared for the spectrophotometer that was used to obtain thermal emittance.

The white epoxy paint of 1 mil thickness on the Explorer IX satellite had a solar absorptance of 0.30. This value was measured on this spectrophotometer, and the white epoxy paint specimens were the same as those prepared for the spectrophotometer that was used to obtain thermal emittance.

The 1-mil thickness of white epoxy paint on the Explorer IX satellite has a ratio of solar absorptance to thermal emittance of approximately 0.35. A comparison of figures 4 and 7 shows that the silicone paint has a ratio of solar absorptance to thermal emittance of between 0.20 and 0.33, depending on the thickness of the coating.

STABILITY OF THERMAL AND OPTICAL PROPERTIES

Stability Under Vacuum

Five specimens of the silicone paint were stored in a vacuum of 2×10^{-6} torr for 3600 hours or 5 months. The specimens were the type mounted on the $\frac{59}{64}$-inch-diameter polished aluminum disks. The four-ply laminate was primed and spray painted prior to bonding it to the aluminum disks. The thermal emittance and solar absorptance were determined before and after the vacuum storage. The data were measured on the spectrophotometers. For all five specimens the solar absorptance decreased and the thermal emittance increased; therefore, the ratio α/ϵ decreased. (See table IV.)

TABLE IV

LONG-TERM VACUUM STORAGE EFFECTS ON ZINC-OXIDE-PIGMENTED METHYL SILICONE ELASTOMER PAINT

Formula, weight in grams	Paint thickness, mils	Initial solar absorptance, α_i	Initial emittance, ϵ_i	α_i/ϵ_i	Hours in vacuum (a)	Final solar absorptance, α_f	Final emittance, ϵ_f	α_f/ϵ_f	Percent change in α_i/ϵ_i
Zinc oxide 576 Silicone elastomer 200 Catalyst 1.9 Toluene 366.6	1.25	0.255	0.805	0.317	3600	0.252	0.824	0.306	-3.5
Zinc oxide 960 Silicone elastomer 400 Catalyst 3.5 Toluene 735.2	1.11	0.267	0.816	0.327	3600	0.258	0.835	0.309	-5.5
Zinc oxide 576 Silicone elastomer 200 Catalyst 1.8 Toluene 366.6	1.38	0.262	0.801	0.327	3600	0.250	0.834	0.300	-8.3
Zinc oxide 1440 Silicone elastomer 600 Catalyst 4.2 Toluene 551.4	3.61	0.211	0.893	0.236	3600	0.202	0.916	0.221	-6.4
Zinc oxide 1440 Silicone elastomer 600 Catalyst 4.2 Toluene 551.4	2.75	0.229	0.880	0.260	3600	0.220	0.906	0.243	-6.5

[a] Vacuum was 2×10^{-6} torr.

Stability Under Ultraviolet Radiation

The stability of the properties affecting the heat balance of a satellite were investigated by exposing samples of each paint in vacuum to radiation from a mercury arc lamp. The silicone paint specimens were the type sprayed on the aluminum-foil surface of the four-ply laminate prior to bonding the laminate to the polished aluminum disks, and the white epoxy paint was sprayed directly on the polished aluminum disks. The apparatus used for these tests is shown in figure 8. The test apparatus had a cooled mounting surface for the test specimens. The circulated coolant was maintained at a temperature of 0° C with a refrigerated recirculating bath. The radiation from the mercury arc lamp was projected through a quartz window onto the test specimens. The effects of the lamp radiation are assumed to give a general indication of the effects of solar ultraviolet radiation on the white paints during irradiation in the space environment although the spectrum was not completely similar to the solar spectrum. Figure 9 shows the ratio of the irradiance at a distance of 25 centimeters from the lamp to that of solar irradiance for different wavelength increments in the spectral region from 0.22μ to 0.40μ. The ratio of the total irradiance from the lamp to that from the sun in this region is about 2.7. Figure 9 is based on the manufacturer's data for the GE B-H6 mercury arc lamp (ref. 7) and a distance of 25 centimeters between the specimens and the lamp. The intensity was monitored and the lamps were changed whenever the intensity decreased to 85 percent of the initial intensity. The ultraviolet degradation tests were performed in two vacuum systems. One chamber was maintained in the pressure range of 1×10^{-6} to 6×10^{-7} torr by an ion pump. The other chamber was similar to the first except that a diffusion pump was used to maintain a pressure of 2×10^{-6} torr.

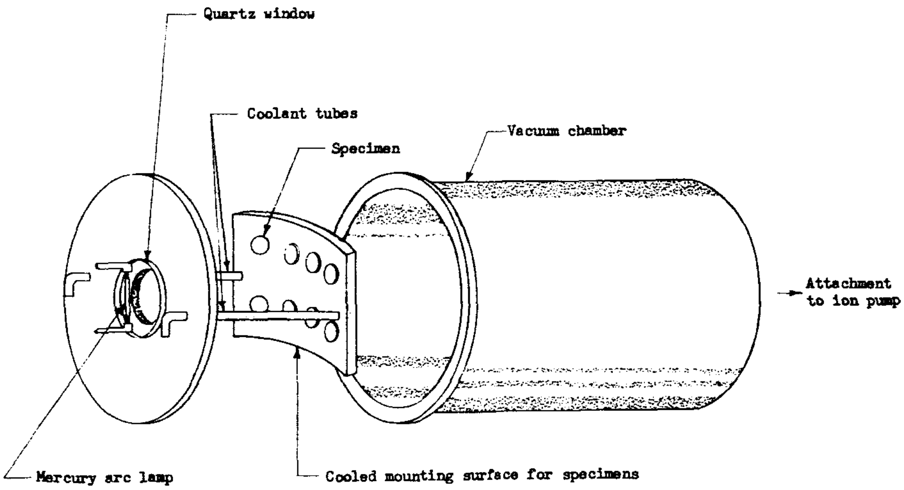

Figure 8.- Apparatus for study of ultraviolet radiation effects on materials.

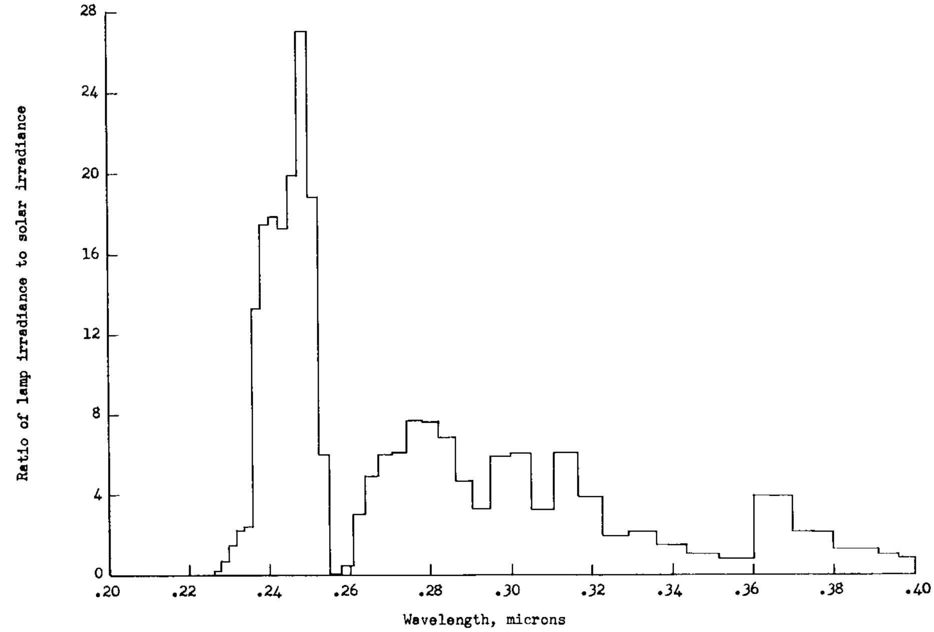

Figure 9.- Ratio of mercury arc lamp irradiance to solar irradiance for various wavelength bands and a distance of 25 cm between lamp and specimen.

The results of the stability tests of the paints under ultraviolet radiation indicated that the thermal emittance was not affected by exposure to ultraviolet radiation. (See table V.) Solar absorptance was therefore the property of most importance in the study of paint stability. Figure 10 shows the ratio of the final value to the initial value of solar absorptance for the silicone paint plotted against the number of hours of exposure to the ultraviolet radiation for several tests in the vacuum chamber with the diffusion-pump system. The data appear to be highly scattered. Figure 11 shows a similar plot for several tests in the ion-pump system. The faired curve is for the specimens used in the third test. The data for the third test were obtained for silicone paint specimens that were sprayed from mixes that were made after the jar mill grinding technique was perfected and the highest purity toluene available was utilized. The data show that the later jar mill mixes yielded a silicone paint that increased its solar absorptance by 6 percent after exposure to 1000 equivalent hours of simulated solar ultraviolet radiation. The data for the first test and second test are shown for comparison with the faired data. The solar absorptance of the

TABLE V

EFFECT OF ULTRAVIOLET RADIATION ON ZINC-OXIDE-PIGMENTED METHYL SILICONE ELASTOMER PAINT

Specimen	Initial emittance	Ultraviolet exposure time, equivalent sun hours	Final emittance
1	0.890	935.5	0.889
2	.842	935.5	.840
3	.873	935.5	.877
4	.873	935.5	.879
5	.825	984.5	.825
6	.881	890.8	.883
7	.911	890.8	.910
8	.921	890.8	.921
9	.918	890.8	.921
10	.870	933.5	.867
11	.912	933.5	.907
12	.734	933.5	.738

earlier mixes of silicone paint increased 10 to 20 percent in approximately 900 equivalent hours of simulated solar ultraviolet radiation. A comparison of figures 10 and 11 indicates that different results exist for the effect on solar absorptance for identical tests made in a diffusion-pump system versus an ion-pump system. The IITRI data for similar specimens indicate agreement with figure 11. (See ref. 4.) The data of figure 10 are questionable and cannot be explained at this time. The higher and erratic degradation of the solar absorptance of the specimens tested in the diffusion-pump system may be a result of the oil vapors that could exist within the system.

Figure 12 shows the ratio of the final value to the initial value of solar absorptance for the white epoxy paint plotted against the number of hours of exposure to the ultraviolet radiation for several tests in both the diffusion-pump system and the ion-pump system. The test data indicate that the solar absorptance of this paint is not affected by the type of vacuum pumping system. The data also show that the solar absorptance increased by 70 percent after exposure to 1000 equivalent hours of ultraviolet radiation.

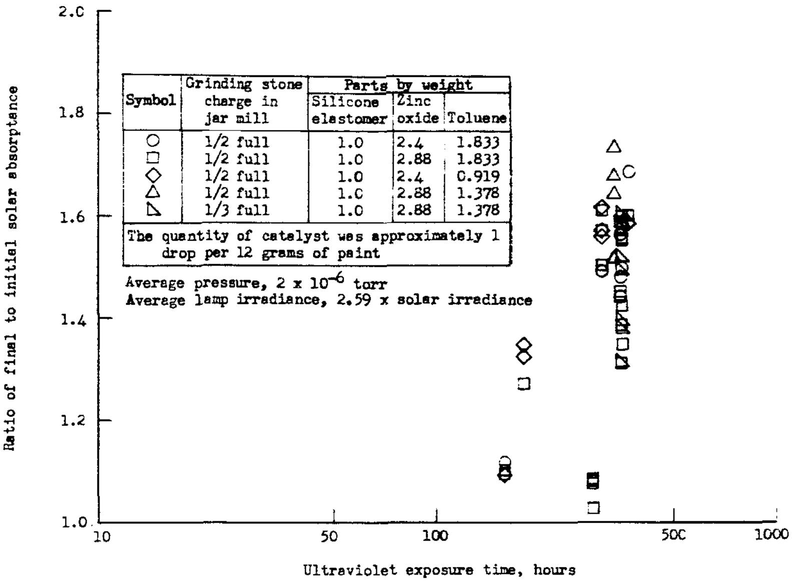

Figure 10.- Variation of ratio of final to initial solar absorptance with ultraviolet exposure time to mercury arc lamp for zinc-oxide-pigmented methyl silicone elastomer paint tested in diffusion-pump vacuum system.

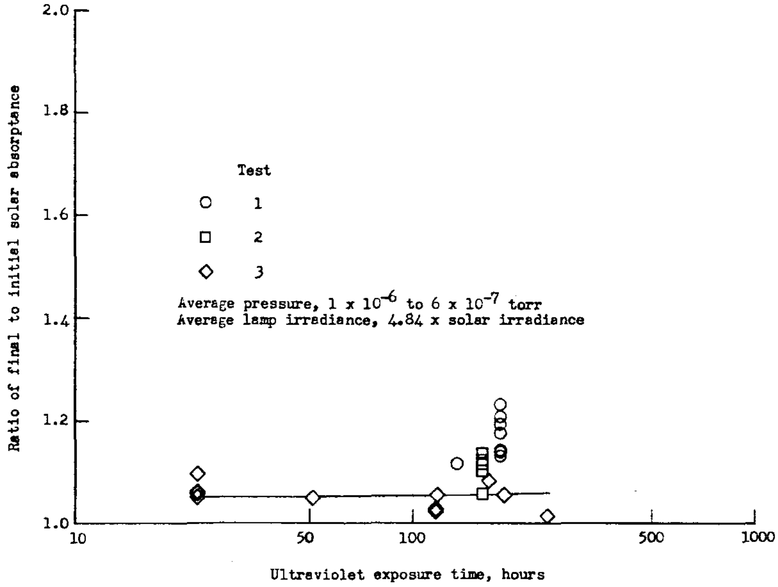

Figure 11.- Variation of ratio of final to initial solar absorptance with ultraviolet exposure time to mercury arc lamp for zinc-oxide-pigmented methyl silicone elastomer paint tested in ion-pump vacuum system.

Shown in figure 13 are the faired curves for the data of the final mixes (third test) of the silicone paint and the white epoxy paint as affected by ultraviolet radiation exposure time in an ion-pump system. The white epoxy paint degrades much more under the influence of ultraviolet radiation than does the silicone paint. In reference 8, the vectorial reflectance of the Explorer IX satellite material, aluminum foil and white epoxy paint, is given. Equations are developed for the theory of radiation force, but no attention is given to the fact that the reflectance of the paint surface will change because of degradation under solar ultraviolet radiation.

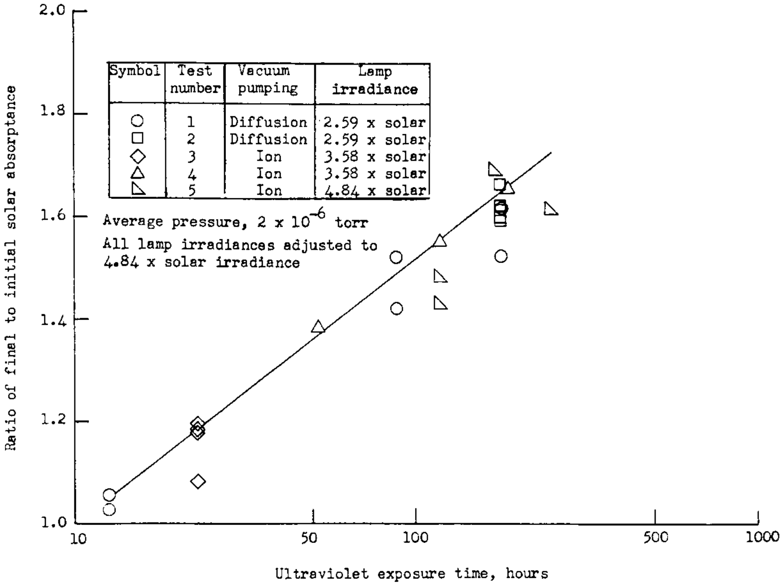

Figure 12.- Variation of ratio of final to initial solar absorptance with ultraviolet exposure time to mercury arc lamp for white epoxy paint tested in two types of vacuum systems.

Stability Under Electron Radiation

Twenty-one specimens of the silicone paint and four specimens of the white epoxy paint were subjected to electron radiation. The specimens were disk type so that the thermal emittance and solar absorptance could be measured on spectrophotometers both before and after exposure to electron radiation. For these tests the specimens were mounted on a $\frac{1}{4}$-inch-thick stainless-steel bar that was placed in the electron beam. The specimens were irradiated

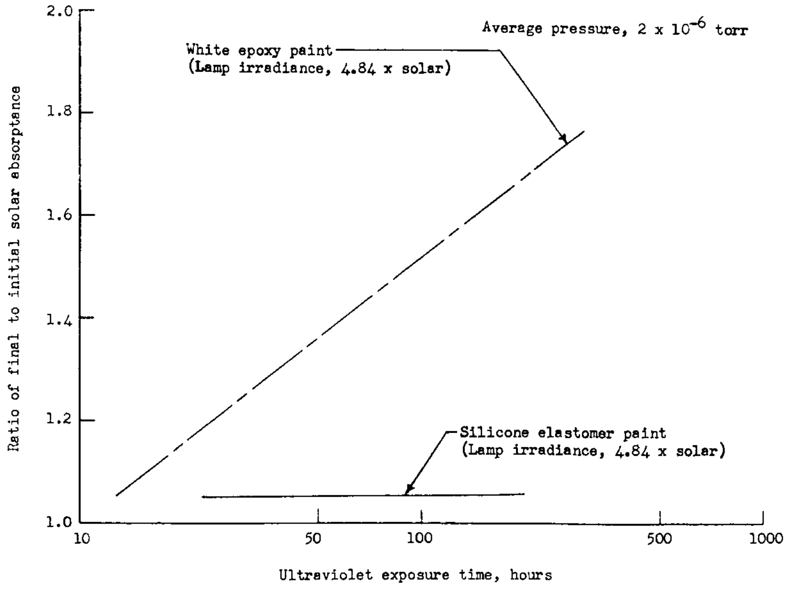

Figure 13.- Variation of ratio of final to initial solar absorptance with ultraviolet exposure time to mercury arc lamp for both paint coatings tested in ion-pump vacuum system.

with a beam of 1.2 MeV electrons. The total dose was 1×10^{15} electrons/cm^2. Twelve specimens of the silicone paint were irradiated at atmospheric pressure. The other nine silicone paint specimens and the four white epoxy paint specimens were irradiated while at a pressure of 3×10^{-6} torr. The results of these tests are given in table VI. The dose of 1×10^{15} electrons/cm^2 represents a approximately 800 hours of exposure in space for an orbit comparable with the orbit of the 12-foot-diameter sphere, Explorer XIX. The percentage degradation of the optical and thermal properties of the paints in the presence of electron radiation is much smaller than that from simulated solar ultraviolet radiation for equivalent exposure times (one-sixth to one-fifteenth as much for silicone paint and negligible for white epoxy paint).

TABLE VI

EFFECTS OF HIGH ENERGY ELECTRON RADIATION ON PAINTS

[Tests were made at an electron beam energy of 1.2 MeV for a total dose of 1×10^{15} electrons/cm^2]

Specimen	Paint thickness, mils	Initial solar absorptance, α_i	Initial emittance, ϵ_i	α_i/ϵ_i	Pressure, torr	Final solar absorptance, α_f	Final emittance, ϵ_f	α_f/ϵ_f	Percent change in α_i/ϵ_i
Zinc-oxide-pigmented methyl silicone elastomer paint									
A-20-1	1.4	0.249	0.767	0.323	atm.	0.251	0.772	0.325	0.6
A-20-2	1.4	.240	.797	.301	3×10^{-6}	.240	.794	.302	.3
B-20-1	2.3	.211	.842	.250	atm.	.212	.851	.249	-.4
B-20-2	2.3	.205	.854	.240	3×10^{-6}	.206	.847	.243	1.2
C-20-1	3.0	.198	.870	.228	atm.	.198	.871	.227	-.4
C-20-2	3.0	.194	.872	.222	3×10^{-6}	.188	-----	-----	---
D-20-1	3.6	.194	.873	.222	atm.	.197	.879	.224	.9
D-20-2	3.6	.183	.887	.206	3×10^{-6}	.182	.872	.209	1.5
E-20-1	3.6	.185	.880	.210	atm.	.187	.883	.212	.9
E-20-2	3.6	.186	.888	.209	3×10^{-6}	.182	.874	.208	-.5
F-20-1	1.1	.256	.775	.330	atm.	.258	.778	.331	.3
F-20-2	1.1	.247	.800	.309	3×10^{-6}	.247	.790	.312	1.0
G-20-1	1.3	.234	.813	.288	atm.	.237	.816	.290	.7
H-20-1	1.8	.213	.851	.250	atm.	.215	.854	.252	.8
H-20-2	1.8	.210	.856	.245	3×10^{-6}	.209	.847	.247	.8
I-20-1	1.9	.219	.841	.260	atm.	.222	.847	.262	.8
J-20-1	1.8	.222	.833	.266	atm.	.225	.837	.269	1.1
J-20-2	1.8	.221	.843	.262	3×10^{-6}	.222	.828	.268	2.3
K-20-1	2.5	.199	.859	.232	atm.	.203	.861	.236	1.7
L-20-1	3.3	.195	.878	.222	atm.	.197	.880	.224	.9
L-20-2	3.3	.194	.883	.220	3×10^{-6}	.192	.875	.219	-.5
White epoxy paint									
WE-3-7	1.1	0.302	0.912	0.331	3×10^{-6}	0.305	0.912	0.334	0.9
WE-3-8	1.2	.300	.915	.328	3	.299	.915	.327	-.3
WE-3-9	1.0	.310	.911	.340	3	.310	.907	.342	.6
WE-3-10	1.0	.301	.918	.328	3	.300	.911	.329	.3

CONCLUSIONS

The optical, thermal, and mechanical properties of the passive temperature-control coatings for the Explorer IX, Explorer XIX, and Explorer XXIV satellites have been studied in ground tests. The coating for Explorer IX was a white epoxy paint. The coating for Explorers XIX and XXIV was a zinc-oxide-pigmented methyl silicone elastomer paint (hereinafter called silicone paint). From an evaluation of these studies it can be concluded that:

1. The silicone paint can be prepared with a minimum of effort and can be catalyzed and sprayed without severe problems.

2. Both paints exhibit good mechanical properties. The silicone paint, if applied to a previously primed surface, is excellent in adhesion, bending, and folding.

3. Both paints can be used on a flimsy structure such as the material used for the 12-foot-diameter inflatable spheres. This material is a four-ply laminate consisting of alternate layers of aluminum foil and plastic film with a total thickness of approximately 2 mils. The paints withstood the folding and packaging necessary to prepare the foldable spheres into their package configuration for orbital launch and withstood the vibration testing that simulated a vehicle launching.

4. A ratio of solar absorptance to thermal emittance of approximately 0.35 can be obtained with a 1 mil thickness of white epoxy paint. A ratio of solar absorptance to thermal emittance of between 0.20 and 0.33 can be obtained for the silicone paint, depending on the thickness of the coating.

5. Solar absorptance of the silicone paint was decreased by reducing the number of grinding stones in the jar mills used for preparing the paint.

6. The white epoxy paint and the silicone paint after cycling through a temperature range of 90° C to -196° C retained their excellent adhesive quality.

7. The white epoxy paint is not a stable paint for long duration use inasmuch as the solar absorptance increased 70 percent when exposed to 1000 equivalent hours of simulated solar ultraviolet radiation.

8. The silicone paint is a reasonably stable paint with an increase of 6 to 15 percent of the initial value of solar absorptance when exposed to approximately 1000 equivalent hours of simulated solar ultraviolet radiation.

9. The silicone paint may be sensitive to the type of vacuum system used for studying the effect of ultraviolet radiation on its solar absorptance. The specimens that were tested in a vacuum chamber that was evacuated by a diffusion pump had a larger and more highly scattered increase in solar absorptance than the specimens tested in a vacuum chamber that was evacuated by an ion pump. This difference did not exist for the ultraviolet radiation tests for the white epoxy paint.

10. The solar absorptance of both paints is affected much less by electron radiation than by ultraviolet radiation for equivalent exposure times in space for an orbit comparable with the orbit of the 12-foot-diameter sphere, Explorer XIX.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 11, 1965.

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