EMISSIVITY COATINGS
FOR LOW-TEMPERATURE
SPACE RADIATORS

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FOREWORD

The results of the research activities carried out during the first quarterly period (1 July through 30 September 1965) of Contract NAS 3-7630, entitled Emissivity Coatings for Low-Temperature Space Radiators, are reported in this document. This work is being done by Lockheed Missiles & Space Company for the Lewis Research Center of the National Aeronautics and Space Administration.
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Section 1
INTRODUCTION AND SUMMARY

The major objective of this program is the evaluation of candidate coatings for low-
temperature spacecraft radiators. The use of nuclear reactors for power sources on
spacecraft having long operational lifetimes presents several complex problems with
regard to the choice of radiator coatings. The surfaces must show a high total hemi-
spherical emittance at operating temperature with a low absorptance to energy in the
solar spectrum. The latter is of importance because of the low operating temperature
level of the radiator, 530°K or less. The stability of the radiative properties of the
coating in the space environment is a critical factor as changes in either absorptance
or emittance during the mission would result in severe problems with the operating
power system. Changes in the radiative properties, particularly in solar absorptance,
may occur because of exposure to temperature, vacuum, temperature cycling, and
the complex radiation fields attributed to the space environment and the reactor.

As little is presently known about the long-term behavior of coatings considered for
use on the low-temperature radiators for space vehicles with nuclear reactors, a
program was established to evaluate both organic and inorganic coatings for such
applications. This initial program has as its objective the evaluation of the proper-
ties and stability of candidate coatings under conditions of exposure to ultraviolet
radiation, vacuum, elevated temperatures, and temperature cycling. During the
first phase of the program, candidate materials will be exposed simultaneously to
ultraviolet radiation at a 1-sun level, maximum operating temperature, and vacuum
for 500-hr periods. The effects of temperature cycling will also be investigated.

The second phase of the program will be the exposure of two materials selected on
the basis of the results of the initial phase for 5,000 hr.
The tasks to be undertaken during this first quarterly period, as outlined in the program plan (Ref. 1), and the accomplishments under each task were:

- The literature survey was completed and recommendation forwarded to NASA regarding the eight materials to be selected for the test program. Five candidate coatings were selected on the basis of these results. The final three coatings are to be chosen during the next quarterly period. The coating selected, with the approval of the NASA project manager, are:
  
  Zinc oxide-methyl silicone
  Titanium dioxide-silicone
  Zinc oxide-potassium silicate
  Aluminum silicate-potassium silicate
  Zirconium silicate-potassium silicate

- Substrates for the candidate materials were prepared and procurement of two sets of test specimens was initiated. These are the titanium dioxide-silicone and zirconium silicate-potassium silicate systems. Preliminary arrangements were made to process the remaining three systems which are to be delivered during the next quarterly period.

- A detailed Test Plan was prepared and is submitted as a portion of this report.

- The ultraviolet exposure facility was designed, test chambers were fabricated and checked out, and assembly of instrumentation and sources was started.

Detailed discussion of activities for this quarter are presented in the following sections which cover the specific tasks.
2.1 INTRODUCTION

Successful operation of space vehicles demands that components be maintained within their design temperature limits. Control of temperatures on an operating spacecraft is based on the exchange of radiant energy with the vehicle's environment, and consequently on the optical properties of the external surfaces. The optical properties of greatest importance are the infrared emittance, $\epsilon$, and the solar absorptance, $\alpha_s$. A primary means of component temperature control is therefore through selection of external surfaces with the proper optical properties. It is imperative that the surfaces used are well specified in terms of optical and physical properties, and that the stability of these properties is established in the operational environment. The need for such materials has resulted in a vast research effort throughout the aerospace industry.

The use of nuclear reactors and radiation sources on spacecraft with relatively long operational lifetimes presents several unique problems in the choice of thermal-control surfaces. When the vehicle is generating significant amounts of energy internally, as in the case of a nuclear reactor, it is necessary to maintain a low ratio of solar absorptance to infrared emittance ($\alpha_s/\epsilon$) on the reactor radiator surfaces (Ref. 2). However, the environment encountered by such surfaces tends to increase this ratio or to impair the physical properties of the surfaces. Degradation of low-temperature reactor radiator surfaces may be caused by effects of vacuum, ultraviolet irradiation, elevated temperatures, temperature cycling, meteoroids, nuclear radiation, geomagnetically trapped electrons and protons, galactic cosmic radiation, solar cosmic radiation, solar x-rays, and solar extreme ultraviolet radiation.
At present very little is known about the behavior of thermal-control coatings to be encountered by radiators used on space vehicles with nuclear reactors on board. Consequently, a broad spectrum of candidate materials must be considered for such applications. Inorganic coatings, organic coatings, and the Optical Solar Reflector have been screened on the basis of a literature and technology survey (Refs. 2 through 87).

The stability of the surfaces is evaluated primarily in terms of alteration of optical properties. Adhesion and compatibility with the substrate material are also important. Samples are to be exposed to several environmental aspects considered to be potential sources of significant damage; i.e., ultraviolet irradiation, vacuum, elevated temperatures, and temperature cycling. In the choice of candidate materials, special attention must be given to the remaining environmental aspects expected or demonstrated to be sources of significant damage to thermal-control coatings; i.e., reactor radiation and particulate space radiation (Refs. 42 through 48).

The need for suitable low-temperature space radiator coatings presents several unique problems. These thermal-control coatings must be optically and physically stable at temperatures to $530^\circ K$ for extended periods of time in the combined space and nuclear environments.

Requirements of the space program have resulted in the development of surface materials which have desirable thermal-control properties and which have some degree of resistance to degradation in the space environment (Refs. 2 through 12). These materials studies have for the most part been conducted at room temperature, with fewer studies at elevated and cryogenic temperatures. It has been a general observation that exposure to ultraviolet and nuclear radiation will degrade the properties of low $\alpha_S/\epsilon$ surface materials by causing increases in solar absorptance, either by shifting the absorption band edge or by increasing the total absorption of the material in the solar wavelength region. Such changes in optical properties may be accounted for in satellite design when the extent of degradation for a specified exposure time is known.
Progress in the prediction of degradation rates and the development of stable materials has been hampered to some degree by the lack of precise knowledge concerning the mechanism of optical damage. Mechanisms have been postulated by various investigators in an attempt to rationalize specific results on a specific material. However, the processes of degradation are complex and for any given material several mechanisms appear to interact in producing the observed changes in spectral absorptance. While the postulated mechanisms have proved useful in guiding material development work, no complete picture is available which allows correlation from one exposure condition to another without experimental observations.

2.2 BACKGROUND

2.2.1 Effects of the Spacecraft Environment

The radiation encountered by space vehicles is generally the most important source of damage to passive thermal-control surfaces, particularly low $\alpha_s/\epsilon$ surfaces (solar reflectors). (See Ref. 2.) Candidate coatings are to be tested in the combined environments of ultraviolet radiation, vacuum, temperature, and temperature cycling. The present state of knowledge of optical processes in solid materials should guide the experimental work and the evaluation of results. Based on the knowledge gained and the available information on the interaction of penetrating radiation with solids, possible effects on the coatings of the penetrating radiation environment of space will be inferred. A brief resume of space environmental effects on optical properties follows.

Ascent environment. The operational environment of a spacecraft begins with the ascent of the vehicle from the launch pad. The primary sources of damage during ascent are elevated temperatures (Ref. 13). However, it is very likely that the critical low $\alpha_s/\epsilon$ surfaces of low-temperature space radiators will be protected by a shroud or fairing during ascent, and consequently will not experience temperatures above 365°K.
Vacuum. The extremely rarefied environment of vacuum makes volatilization of thermal-control coatings a possible problem. However, several coatings such as acrylics, silicones, and inorganic silicates that are used for thermal-control applications at LMSC have been extensively studied in various environmental tests with no noted indications of instability due to vacuum alone.

Extraterrestrial solar radiation. In general, the solar absorptance of low $\alpha_s/\varepsilon$ materials exposed to ultraviolet energy in a vacuum at room and elevated temperatures increases at a decreasing rate to some apparent saturation value (Refs. 14 through 24). Figure 2-1 shows the solar absorptance of six coatings as a function of exposure to ultraviolet radiation in sun-hours at room temperature (Ref. 24). The effect of ultraviolet radiation on the solar absorptance of thermal-control materials at 530° K is shown in Fig. 2-2 (Ref. 69) and Fig. 2-3 (Ref. 20).

For both the organic and inorganic systems the degradation is greater at increased temperatures from room temperature to 530° K. The degradation for some coatings has been studied over this temperature range (Ref. 24). The effect of exposure temperature on the increase in solar absorptance is shown for five coatings in Fig. 2-4.

The increase in solar absorptance ($\Delta\alpha_s$) has been correlated graphically to within ±10% as a function of temperature according to the relationship (Ref. 24):

$$\Delta\alpha_s = A'e^{-\frac{W'}{KT}}$$

For the case in which $\alpha_s$ is nearly linear with exposure, it can be shown that $W'$ can be considered an approximation of the energy of activation for the increase in solar absorptance due to temperature effects during a specific exposure. It should be noted that little physical significance can be attached to the value for $A'$. The values of $A'$ and $W'$ are shown in Table 2-1.
Fig. 2-1 Solar Absorptance Versus Exposure at Room Temperature
Fig. 2-2 Effect of Ultraviolet Radiation on Thermal Control Surfaces at 530°K and 10 Suns, Long-Term Exposure
Fig. 2-3 Effect of Ultraviolet Radiation on Thermal-Control Surfaces at 530° K and 10 Suns, Short-Term Exposure
Fig. 2-4 Effect of Exposure Temperature on Increase in Solar Absorptance
Table 2-1

PARAMETERS CORRELATING RESULTS OF TEMPERATURE-DEPENDENCY STUDIES

<table>
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<tr>
<th>Pigment/Binder</th>
<th>A'</th>
<th>W'(eV)</th>
</tr>
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<tr>
<td>Syn. Li-Al-SiO₂/KSiO₃</td>
<td>0.78</td>
<td>0.053</td>
</tr>
<tr>
<td>Li-Al-SiO₂/K₂SiO₃</td>
<td>0.50</td>
<td>0.049</td>
</tr>
<tr>
<td>ZrO₂·SiO₂/K₂SiO₃</td>
<td>0.33</td>
<td>0.032</td>
</tr>
<tr>
<td>TiO₂/epoxy</td>
<td>1.00</td>
<td>0.031</td>
</tr>
<tr>
<td>TiO₂/silicone</td>
<td>0.93</td>
<td>0.053</td>
</tr>
</tbody>
</table>

The spectral absorptance curves for the TiO₂/epoxy surface coating are shown in Fig. 2-5. An initial large change in absorptance due to exposure to ultraviolet radiation at 305° K is observed. At increasing temperatures the same exposure causes a general increase in absorptance with a fairly regular pattern. A slight decrease in absorptance in the infrared region is noted. The shape of the curve at 530° K appears to deviate from the pattern which may indicate that a different process or a different rate of degradation has begun, so extrapolation of the data beyond 530° K would be unwise.

The spectral absorptance curves for the ZrO₂·SiO₂/K₂SiO₄ surface coating in Fig. 2-6 show a large initial change in absorptance due to exposure to ultraviolet radiation at 305° K. As the exposure temperature increases, the absorptance increases in the visible and infrared regions of the spectrum, but decreases in the ultraviolet region. The net result is an increase in the solar absorptance with increasing temperature.

The ultraviolet absorption of pigmented coatings and the shift of the absorption edge may be related to the photolytic decomposition of the pigment material (Ref. 25). Studies are presently being made at LMSC on ZnO pigments (Ref. 66). For many pigments the band edge is at long enough wavelengths to protect an organic binder (Refs. 26 and 27). For such materials, much of the damage may occur within the
Fig. 2-5 Spectral Absorbance – TiO₂/Epoxy
Fig. 2-6 Spectral Absorptance – ZrO$_2$–SiO$_2$/K$_2$SiO$_3$
pigment or near pigment–binder interfaces. The liberation of oxygen at the pigment–
binder interface has been observed during irradiation where pigments such as ZnO
are used (Refs. 28 through 31). At elevated temperatures, the oxygen may be free
to diffuse into the binder and cause degradation.

The usual working assumption is that a reciprocal relationship exists between the
effects of time and ultraviolet irradiance, with regard to the damage produced; i.e.,
exposure to 1 sun for 10 hr will produce the same effect as exposure to 10 suns for
1 hr. This assumption serves as a useful first approximation; however, it has not
been completely proven for all of the materials under discussion. No long-term
exposures of thermal-control coatings at a 1-sun level and at elevated temperatures
have been attempted to verify or disprove this assumption. At least part of the
difficulty in attempting to prove or disprove reciprocal behavior of a given material
lies in lamp-to-lamp spectral output variations and temporal spectral shifts of a
given lamp output.

Meteoroids. Analysis of the estimates and experimental results of the impact flux,
mass flux, and particle concentration for meteoroids reveals that 30 to 300 impacts/cm²
occur during a 1-yr period in space, and that the area affected by each micrometeorite
particle is on the order of $10^{-16}$ cm². The general conclusion is that the optical
properties of thermal control surfaces of space vehicles with life-times of 2 yr or
less will not be significantly affected by meteoroid impact.

Penetrating radiation. For prolonged mission exposure and/or high-altitude (> 500 nm)
trajectories, constituents of the space environment other than ultraviolet irradiation
can induce first-order damage to optical surface materials; i.e., the intense high-
energy electron and the low-energy proton portions of the geomagnetically trapped
particle environment. In addition, for missions beyond the earth's geomagnetic field,
the low-energy proton portion of the quiescent solar plasma (solar wind), galactic
cosmic radiation, solar cosmic radiation from solar cosmic events, solar x-rays,
and solar extreme ultraviolet radiation must be considered. Of these, the solar flare

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and quiescent solar plasma could possibly enhance the degradation of thermal-control surfaces on vehicles with missions to the inferior planets or on solar probes.

The precise nature of the mechanisms of damage incurred in the optical properties of materials due to penetrating radiation is not presently known. Present knowledge on the behavior of solids in penetrating radiation fields will be used in this study (Refs. 32 through 48, 67, and 68). It can be generally postulated that the optical properties are changed because of a redistribution of electrons, and, in the case of organic materials, chemical changes as well.

The effect of geomagnetically trapped particles on the optical properties of surfaces has recently received attention at LMSC. Initial exploratory tests on the effects of the electron-only and electron-plus-ultraviolet environment in vacuum with samples maintained at known temperatures indicated that this environment can inflict serious damage to thermal-control coatings (Refs. 42 and 43). Optical damage caused by low-energy electrons \( (E < 1 \text{ MeV}) \) was generally lower at elevated temperatures \( (420^\circ \text{ K}) \) than at ambient temperatures.

At high altitudes the intensities of high-energy electrons decreases significantly, but the intensities of low-energy protons become higher. Because of the high reported intensities of low-energy protons, a series of exploratory tests were performed at LMSC to evaluate the degree of damage caused by this environment.

Selected coatings were exposed to various fluxes of 130 keV protons, in vacuum, with the coatings maintained at controlled temperatures (Refs. 44 and 45). Conventional white thermal control surfaces degraded severely after exposure to fluxes greater than approximately \( 10^{15} \rho/\text{cm}^2 \).

An analysis of the intensities of protons in the radiation belts indicates, for example, that it would take 50 to 100 days for a thermal-control surface to be bombarded by \( 10^{15} \text{ protons/cm}^2 \) \( (E > 100 \text{ keV}) \) in a circular equatorial orbit of approximately 10,000-nm altitude. Clearly, preliminary analysis of this environment and the
exploratory proton tests indicate that damage of engineering importance can occur as a result of the trapped low-energy proton environment.

An experimental investigation of nuclear radiation damage to thermal-control coatings was initiated at LMSC in November 1961. A total of six irradiation experiments were performed (Refs. 46 and 48). In general, it was observed that optical degradation due to a nuclear radiation environment is similar to that caused by incident ultraviolet radiation. In the LMSC work, the spectral absorptance of thermal-control surface materials shifts in the same manner as the shift observed in ultraviolet damage experiments. In the majority of the tests, the thermal-control surfaces were exposed at ambient temperature in a vacuum. However, other exposures were performed at elevated and cryogenic temperatures and in a simultaneous ultraviolet environment.

The theory of radiation damage effects predicts a temperature dependence for damage to materials during irradiation. Samples irradiated at temperatures above room temperature (> 300° K) become increasingly susceptible to ionizing gamma radiation. Since both inorganic and organic systems are damaged primarily by gamma radiation, the elevated temperature effects should be most readily observed in these types of thermal-control material systems. The effect of temperature on an inorganic silicate system is illustrated in Fig. 2-7.

Measurements of the absorptance properties of the samples tested during simultaneous ultraviolet and nuclear irradiation indicated synergistic effects. With the TiO₂/silicone surfaces, the solar absorptance would degrade 0.04 due to ultraviolet (alone) exposure for 1000 sun hr. Nuclear damage effects are displayed by solar absorptance changes of the white coatings of less than 0.02 typically. In a test environment combining the total dose of ultraviolet and nuclear irradiations, the degradation of the white coatings averaged 0.08. Effects of simultaneous nuclear and ultraviolet exposure are illustrated in Fig. 2-8.

In actual service, all reactor radiator surfaces will be exposed to ultraviolet radiation, vacuum, temperature, temperature cycling, and reactor radiation. In the tests in
Fig. 2-7  Nuclear Damage at Elevated Temperature With $10^{10}$ ergs/gm(C) and $3 \times 10^{14}$ Fast Neutrons/cm$^2$
Fig. 2-8 Effects of Simultaneous Nuclear and Ultraviolet Exposure on Spectral Absorptance of Thermatrol Paint 2A-100
this program the candidate coatings will be exposed to the first four. Potential damage from reactor radiation will help guide the selection of these coatings.

2.2.2 Thermal-Control Surfaces

Because of the severity of the environments to be encountered, a wide range of coating systems should be considered for use on low-temperature space radiators. Types of coatings potentially applicable for such uses include inorganic paints, organic paints, and new generation coatings such as the Optical Solar Reflector. Because of their relatively high $\alpha_s/\varepsilon$ ratios and poor stability in ultraviolet radiation, electrolytic coatings will not be considered for this program (Ref. 75).

Inorganic systems. Inorganic thermal-control paints have been studied and used successfully for many spacecraft applications (Refs. 8 through 12, 23 and 24, 49 through 54). Inorganic thermal-control paints have been under continuous development at LMSC for the past 5 years (Refs. 8 through 12, 49 through 52). These systems contain refractory silicaceous pigments in combination with aqueous alkali metal silicates. The vehicles are sodium and potassium silicates. The pigments most fully developed are lithium–aluminum silicate and zirconium silicate, plus other refractory silicates and oxides. Formulation is carried out by standard ball mill and other paint mill techniques, such that an easily workable product is obtained. Two classes of the paints have been developed: the first requires thermal curing at 420°C; the second cures at room temperature in a few hours. Practical formulations are available which have good suspension properties (do not settle into hard layers), are easily applied, can be shipped with no difficulty, and can be stored for over a year.

These systems show a high degree of thermal stability, excellent adhesion to most substrates, and good optical stability.

Inorganic materials generally degrade by changes in crystal or structural characters. These changes may take the form of color-center formation, phase changes, and
formation of defect structures. In some cases, oxidation-reduction reactions of impurities or major constituents may be involved. Assuming satisfactory initial adhesion and cohesion, mechanical damage to the coating is rarely observed.

An LMSC zirconium silicate/potassium silicate paint has displayed very stable physical and optical properties in the ultraviolet, nuclear, and combined ultraviolet nuclear environments (Ref. 48).

**Organic systems.** Organic paints are another group of thermal-control surfaces which have received considerable attention in the space industry (Refs. 8 through 12, 23 and 24, 53 through 61).

Commercial organic thermal-control paints have been in use on the LMSC Agena spacecraft for the past 6 years. These paints include room-temperature-curing and high-temperature-curing epoxies, acrylics, and silicone alkyds. Within the last three years LMSC personnel have developed, with the cooperation of Dow Corning Corporation, a stable room-temperature-curing TiO$_2$-pigmented silicone-base paint (Thermatrol white paint). (See Refs. 60 and 61). In addition to having a low $\alpha_s/\epsilon$ (0.19), this coating has demonstrated stability in the hostile space environments, including ultraviolet irradiation, temperature, vacuum, and electrons (Refs. 42, 43, 60, and 61). Additionally, on the basis of nuclear irradiation tests (Ref. 48), this paint was chosen for use on the Snap 10A Agena vehicle.

In general, organic materials in the ultraviolet environment degrade primarily by bond scission, ring cleavage, and similar phenomena. These changes result in loss of coating strength and integrity together with discoloration due to formation of new chemical species. Free radicals may be formed which can diffuse through the material and form bonds resulting in optical absorption. In the more drastic cases, gas evolution may occur along with cracking, blistering, exfoliation, or complete destruction of the coating as such. It is likely that the degradation of organic binder materials results from optically generated free radicals. Another source of optical degradation is the formation of electron-hole pairs, and subsequent trapping of freed electrons at
imperfection sites (Ref. 40). Because of thermal limitations, organic paint systems probably could not be used on radiators operating at temperatures much above 390°K.

2.3 SELECTION OF MATERIALS

Materials have been selected for evaluation largely in terms of evidence which indicates stability in the space and nuclear environment and relatively low \( \alpha_s/\epsilon \) ratios. In making the selection of recommended materials for study, the following criteria have been considered:

- Thermal stability
- Stability in radiation fields, especially ultraviolet and nuclear
- \( \alpha_s, \epsilon_{th}, \alpha_s/\epsilon \) ratio
- Adhesion characteristics
- Compatibility with substrates
- Reliability and reproducibility

Types of coatings potentially applicable for reactor radiators include inorganic coatings, organic coatings, and new generation coatings such as the Optical Solar Reflector.

On the basis of a literature and technology survey (Refs. 2 through 87) ten candidate coating materials were selected for detailed evaluation of optical properties and stability in ultraviolet radiation, especially at elevated temperatures. These candidate coatings are tabulated in Table 2-2, and the effects of ultraviolet radiation are shown in Table 2-3, with additional evaluations based on the previously listed criteria in Table 2-4. Of the candidate coating materials listed in the proposal (Ref. 1), the duPont polyimide has been eliminated and the four stannic oxide pigment and/or aluminum phosphate binder coatings have been reduced to one candidate coating.

A clear polyimide binder to use with a white pigment is not available. This type of coating has also been eliminated from further consideration at LMSC under the Air Force Contract AF 33(615)-1634 (study of cryogenic temperature-control coatings).
Table 2-2
CANDIDATE COATING MATERIALS

<table>
<thead>
<tr>
<th>Class</th>
<th>Material</th>
<th>Pigment</th>
<th>Pigment/Binder</th>
<th>Source</th>
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<td>Inorganic</td>
<td>Potassium Silicate</td>
<td>Zirconium Silicate</td>
<td>ZrSiO$_4$/K$_2$SiO$_4$</td>
<td>LMSC</td>
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<tr>
<td>Inorganic</td>
<td>Sodium Silicate</td>
<td>Lithium-Aluminum Silicate</td>
<td>Li-Al-SiO$_4$/Na$_2$SiO$_4$</td>
<td>LMSC</td>
</tr>
<tr>
<td>Inorganic</td>
<td>Potassium Silicate</td>
<td>Lithium-Alumina Silicate</td>
<td>Li-Al-SiO$_4$/K$_2$SiO$_4$</td>
<td>LMSC</td>
</tr>
<tr>
<td>Inorganic</td>
<td>Potassium Silicate</td>
<td>Zinc Oxide</td>
<td>ZnO/K$_2$SiO$_4$</td>
<td>IITRI</td>
</tr>
<tr>
<td>Inorganic</td>
<td>Aluminum Phosphate</td>
<td>SnO$_2$ overlay</td>
<td>SnO$_2$/AlPO$_4$</td>
<td>AI</td>
</tr>
<tr>
<td>Inorganic</td>
<td>Potassium Silicate</td>
<td>Aluminum Silicate</td>
<td>Al-SiO$_4$/K$_2$SiO$_4$</td>
<td>Hughes</td>
</tr>
<tr>
<td>Organic</td>
<td>Methyl Silicone</td>
<td>Zinc Oxide</td>
<td>ZnO/Silicone</td>
<td>IITRI</td>
</tr>
<tr>
<td>Organic</td>
<td>Methyl Silicone</td>
<td>Titanium Dioxide</td>
<td>TiO$_2$/Silicone</td>
<td>LMSC</td>
</tr>
<tr>
<td>Organic</td>
<td>Polyvinyl Butyral</td>
<td>Titanium Dioxide</td>
<td>TiO$_2$/Butyral</td>
<td>American Cyanamid</td>
</tr>
<tr>
<td></td>
<td>Optical Solar Reflector</td>
<td></td>
<td>OSR-TP-060</td>
<td>LMSC</td>
</tr>
</tbody>
</table>
Table 2-3
EFFECT OF ULTRAVIOLET RADIATION

<table>
<thead>
<tr>
<th>Pigment/Binder</th>
<th>Initial $\alpha_s$</th>
<th>Final $\alpha_s$</th>
<th>Exposure (sun-hr)</th>
<th>Temperature ($^\circ$K)</th>
<th>Reference</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZrSiO$_4$/K$_2$SiO$_4$</td>
<td>0.13</td>
<td>0.42</td>
<td>7200</td>
<td>530</td>
<td>(69)</td>
<td>LMSC</td>
</tr>
<tr>
<td></td>
<td>0.11</td>
<td>0.21</td>
<td>600</td>
<td>292</td>
<td>(9)</td>
<td></td>
</tr>
<tr>
<td>Li-Al-SiO$_4$/Na$_2$SiO$_4$</td>
<td>0.16</td>
<td>0.49</td>
<td>280</td>
<td>530</td>
<td>(20)</td>
<td>LMSC</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
<td>0.19</td>
<td>600</td>
<td>292</td>
<td>(9)</td>
<td></td>
</tr>
<tr>
<td>Li-Al-SiO$_4$/K$_2$SiO$_4$</td>
<td>0.12</td>
<td>0.32</td>
<td>7200</td>
<td>530</td>
<td>(69)</td>
<td>LMSC</td>
</tr>
<tr>
<td></td>
<td>0.11</td>
<td>0.15</td>
<td>440</td>
<td>292</td>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td>ZnO/K$_2$SiO$_4$</td>
<td>0.17</td>
<td>0.33</td>
<td>7200</td>
<td>530</td>
<td>(69)</td>
<td>IITRI</td>
</tr>
<tr>
<td></td>
<td>0.16</td>
<td>0.18</td>
<td>1050</td>
<td>305</td>
<td>(21)</td>
<td></td>
</tr>
<tr>
<td>SnO$_2$/AlPO$_4$</td>
<td>0.40</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>(b)</td>
<td>AI</td>
</tr>
<tr>
<td>AlSiO$_4$/K$_2$SiO$_4$</td>
<td>0.17</td>
<td>0.22</td>
<td>1000</td>
<td>292</td>
<td>(8)</td>
<td>Hughes</td>
</tr>
<tr>
<td>ZnO/Silicone</td>
<td>0.18</td>
<td>0.27</td>
<td>7200</td>
<td>530</td>
<td>(69)</td>
<td>IITRI</td>
</tr>
<tr>
<td></td>
<td>0.23</td>
<td>0.26</td>
<td>440</td>
<td>335</td>
<td>(69)</td>
<td></td>
</tr>
<tr>
<td>TiO$_2$/Silicone</td>
<td>0.18</td>
<td>0.39</td>
<td>320</td>
<td>530</td>
<td>(69)</td>
<td>LMSC</td>
</tr>
<tr>
<td></td>
<td>0.18</td>
<td>0.22</td>
<td>3500</td>
<td>292</td>
<td>(60)</td>
<td></td>
</tr>
<tr>
<td>TiO$_2$/Butyral</td>
<td>0.19</td>
<td>0.27</td>
<td>2700</td>
<td>292</td>
<td>(c)</td>
<td>American Cyanamid</td>
</tr>
<tr>
<td>OSR-TP-060</td>
<td>0.05</td>
<td>0.05</td>
<td>430</td>
<td>292</td>
<td>(63)</td>
<td>LMSC</td>
</tr>
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</table>

(a) 13826A
(b) 14630A
(c) 17306AA

LMSC Thermophysics Materials Investigation Reports
<table>
<thead>
<tr>
<th>Pigment/Binder</th>
<th>Predicted Ultraviolet and Nuclear Radiation Stability</th>
<th>Reliability and Reproducibility</th>
<th>Adhesion Compatibility</th>
<th>Thermal Stability</th>
<th>390'K</th>
<th>530'K</th>
<th>( \alpha_s/\epsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{ZrSiO}_4/\text{K}_2\text{SiO}_4 )</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>0.11 (0.85 0.13)</td>
</tr>
<tr>
<td>( \text{Li-Al-SiO}_4/\text{Na}_2\text{SiO}_4 )</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>0.13 (0.85 0.15)</td>
</tr>
<tr>
<td>( \text{Li-Al-SiO}_4/\text{K}_2\text{SiO}_4 )</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>0.11 (0.85 0.13)</td>
</tr>
<tr>
<td>( \text{ZnO/AlPO}_4 )</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>0.16 (0.85 0.19)</td>
</tr>
<tr>
<td>( \text{Al-SiO}_4/\text{K}_2\text{SiO}_4 )</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>0.40 (0.85 0.47)</td>
</tr>
<tr>
<td>( \text{ZnO/Silicone} )</td>
<td>Good</td>
<td>Good</td>
<td>(a)</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>0.17 (0.85 0.20)</td>
</tr>
<tr>
<td>( \text{TiO}_2/\text{Silicone} )</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>0.18 (0.85 0.21)</td>
</tr>
<tr>
<td>( \text{TiO}_2/\text{Butylal} )</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>0.19 (0.85 0.22)</td>
</tr>
</tbody>
</table>

(a) 1100-0 Aluminum only
The Atomic International coating is believed to be the most highly developed coating of this type. This coating has a subcoat of chromium-cobalt-nickel spinel bonded with aluminum phosphate to a 1100-0 aluminum substrate and a top coat of stannic oxide bonded with aluminum phosphate. The 1100-0 substrate has to be used instead of 6061-T6 to produce a representative coating. An initial solar absorptance of 0.3 may be attainable with this coating, but a solar absorptance of 0.40 for a 2-mil thick layer has been measured (Table 2-3).

The sodium silicate coating should be eliminated because of its poor stability in ultraviolet radiation of elevated temperature, as shown in Fig. 2-3 and Table 2-3. Also, the TiO$_2$/Polyvinyl Butyral coating should be eliminated because of its marginal ultraviolet stability even at room temperature and lower. The remaining eight coatings are listed in Table 2-5 as recommended candidate coatings for the 390° to 530° K range and the 295° to 390° K range. The order of listing reflects the relative potentials of these coatings for this study at this time. Further development and testing may lead to a change in this evaluation.
Table 2-5
RECOMMENDED COATINGS

<table>
<thead>
<tr>
<th>Thermal Stability 390° to 530°K</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc Oxide/Potassium Silicate</td>
<td>IITRI</td>
</tr>
<tr>
<td>Zirconium Silicate/Potassium Silicate</td>
<td>LMSC</td>
</tr>
<tr>
<td>Aluminum Silicate/Potassium Silicate</td>
<td>Hughes</td>
</tr>
<tr>
<td>Lithium-Aluminum Silicate/Potassium Silicate</td>
<td>LMSC</td>
</tr>
<tr>
<td>Stannic Oxide over Cr, Co, Ni Spinel/Aluminum Phosphate</td>
<td>AI</td>
</tr>
<tr>
<td>Zinc Oxide/Methyl Silicone</td>
<td>IITRI</td>
</tr>
<tr>
<td>Titanium Dioxide/Silicone</td>
<td>LMSC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermal Stability 295° to 390°K</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc Oxide/Methyl Silicone</td>
<td>IITRI</td>
</tr>
<tr>
<td>Titanium Dioxide/Silicone</td>
<td>LMSC</td>
</tr>
<tr>
<td>Zinc Oxide/Potassium Silicate</td>
<td>IITRI</td>
</tr>
<tr>
<td>Zirconium Silicate/Potassium Silicate</td>
<td>LMSC</td>
</tr>
<tr>
<td>Aluminum Silicate/Potassium Silicate</td>
<td>Hughes</td>
</tr>
</tbody>
</table>
Section 3
SAMPLE PREPARATION

The candidate coatings are applied to disk substrates of 6061-T6 aluminum. The disks are nominally 1 in. in diameter and 0.050 in. thick and are polished on one side and edge to obtain an emittance of 0.03 ± 0.01. The emittance of each disk is inspected using a Lion Research Corporation Optical Surface Comparator to ensure conformance to the established standard. The surface to be painted is machined to a 30 ± 3 rms finish. A number of disks have been randomly selected and the surface roughness measured using a Micrometrical Manufacturing Company Proficorder. The results indicate that the machine surfaces are well within tolerance. The disks are instrumented for temperature measurement by inserting 1/4-in.-long, 26-gage pins of constantan and chromel into the edge. The constantan-chromel combination was selected for its high thermoelectrical emf and stability in the temperature range of interest (Ref. 88). The pins are inserted 1/8 in. into the disks, which are peened to ensure mechanical and electrical integrity. The pins are placed 90 deg apart to give the sample stability when it is suspended in the chamber.

The mechanical and electrical acceptability of this method has been verified by thermal cycling tests over the temperature span of interest to this program. The prime advantage of this technique is that all required mechanical work on the substrate may be performed prior to application of the candidate coating.
Section 4
EXPERIMENTAL APPARATUS

4.1 TEMPERATURE CYCLING APPARATUS

Separate temperature cycling evaluations of the candidate coating materials will be made by alternately heating and cooling the specimens from test temperature, 390° and 530°K, to cryogenic temperature, approximately 80°K, in the apparatus shown in Fig. 4-1. A pressure of not greater than \(10^{-5}\) Torr is maintained during testing. The apparatus consists of a vacuum system, temperature controller, specimen holder, and recorder. The vacuum system comprises a stainless steel hose plate with pyrex enclosure, liquid nitrogen cold trap, 4-in. oil diffusion, and 5-cfm mechanical face pump. The specimen holder is a machined copper block having six flat surfaces for mounting of the specimen. An electric cartridge heater is centrally located in the block, and passages are provided for circulation of a coolant. Instrumentation is provided for automatic temperature control and cycle time and for continuous measurement and recording of sample temperature.

4.2 SPECTRAL-REFLECTANCE MEASUREMENT APPARATUS

4.2.1 Cary Spectrophotometer

Normal spectral reflectance for hemispherical illumination will be measured before and after exposure using a Model 14 Cary double-beam spectrophotometer with an integrating sphere attachment (Fig. 4-2). Measurements will be over a wavelength range of 0.27 to 1.8 μ. Solar absorptances will be calculated from these data using Johnson's extraterrestrial specular irradiance curve (Ref. 89).
Fig. 4-1a Temperature Cycling Apparatus

Fig. 4-1b Sample Holder
4.2.2 Hohlraum Reflectometer

The near-normal spectral reflectance for wavelengths between 2.0 and 20.0 μ will be measured using an LMSC-constructed hohlraum reflectometer (Fig. 4-3) with an associated Perkin-Elmer Model 13 double-beam spectrometer. These measurements will be made on control samples. The infrared emittance of these samples will be calculated using standard blackbody radiation curves.

4.3 TOTAL HEMISPHERICAL EMITTANCE CALORIMETER

The total hemispherical emittance of the coatings selected for Phase II evaluation will be measured using a total hemispherical emittance calorimeter (Fig. 4-4), consisting of an outer vacuum shell and an inner liquid nitrogen cold wall. Chamber pressure is not greater than 10^{-5}. The emittance is calculated from the measured temperature and electrical power required to maintain a coated cylindrical sample at a specified temperature. A complete description of the apparatus is given in Ref. 90.

4.4 LION RESEARCH CORPORATION OPTICAL SURFACE COMPARATOR

The Optical Surface Comparator (Fig. 4-5) will be used to establish a similarity of emittance between the actual test samples and the control samples. This device measures the emittance of a surface by comparison with a known reference standard using a radiometric technique.

4.5 EXPOSURE APPARATUS

The exposure apparatus (Fig. 4-6) consists of four major components:

- A vacuum chamber with LN₂ cold walls
- An electronic vacuum pump
- An ultraviolet source with controls
- A tungsten heat source with controls

The entire system with associated instrumentation is mounted on a 3- by 6-ft table.
Fig. 4-3 Hohlraum Schematic
Fig. 4-4 Total Hemispherical Emittance Test Chamber
Fig. 4-5 Lion Research Corporation Optical Surface Comparator
4.5.1 Vacuum Chamber

The vacuum chamber is a cylinder 12 in. in diameter and 25 in. long mounted with its major axis in a horizontal plane. It is capped with removable end plates sealed with "O" rings. Two 2-in.-diameter Suprasil windows are provided, one in each end on the centerline of the cylinder, to transmit the ultraviolet irradiation and the energy from a tungsten lamp source to maintain the sample at the required temperature. The Suprasil windows were selected for stability in the long-term ultraviolet environment. Exterior shutters are provided to allow the energy to be removed from the samples without disturbing the energy source controls. In addition, the chamber is equipped with 2-in.-diameter quartz inspection windows in the center of the cylinder and perpendicular to its centerline. Inside the vacuum chamber is a split copper liquid-nitrogen reservoir, the halves of which may be separated to allow insertion of the test sample. The interior of the cold wall is painted black to ensure an absorbing diffuse heat sink. The paint is a Finch Paint and Chemical Co. "Cat-a-lac" flat black, Code 463-3-8, consisting of a carbon pigment in an epoxy binder. The \( \text{LN}_2 \) reservoir will be maintained nearly full automatically by use of a timer-controlled fill system. The sample, suspended by the 0.003-in.-diameter thermocouple leads, is installed through a vacuum lock on the chamber with the cold wall in the separated position.

4.5.2 The Vacuum System

The vacuum system consists of a Varian Vacsorb forepump and a Varian 140 liter/second Vacion main pump. An ion gage is provided to measure chamber pressure. In addition, the electronic pump power control unit has a calibrated output for monitoring of pump pressure. The system operates at a pressure of not greater than \( 1 \times 10^{-7} \) Torr.

4.5.3 Ultraviolet Source

This ultraviolet source is a 900-watt xenon lamp in an Orion Optics Corporation Model C-60-50-S-15 lamp housing. The housing contains the necessary collecting and focusing optics to produce uniform irradiation over the test specimen. The
The intensity of the lamp is controlled by an Engelhard Hanovia Model 27801 1,000-watt dc power system, which includes both a current regulating power supply and a high-voltage RF starter. The power supply is capable of varying the light intensity of each lamp from maximum rated lamp current to minimum holding current. The lamp current is maintained within ±1 percent of the set value for a ±10 percent change in the input line voltage. The amount of energy incident upon the sample in the solar spectrum will be monitored using a calibrated Sol-A-Meter silicon cell pyrheliometer manufactured by Yellott Solar Energy Laboratory. The spectral and total radiation intensity of the xenon lamp source as modified by the optical system will be measured. This will give a spectral and total radiant intensity incident on the sample surface. The total radiation of the source will be determined using an Eppley thermopile. The thermopile will be calibrated using known radiant intensities from a Model 101, 1000°C blackbody source manufactured by Infrared Industries. The output of the thermopile is measured with a Leeds & Northrup K3 potentiometer. The spectral radiant intensity of this source is measured by comparison with that of a tungsten iodide lamp which has been calibrated against an NBS certified calibrated lamp. The output of the source and the standard are alternately focused on the entrance slit of a Bausch & Lomb grating monochromator. Since the two sources of radiation are being compared, the results are not dependent upon the spectral reflectance of the mirrors, monochromator transmission characteristics, the spectral sensitivity of the detector, slit widths, or slit area provided that the slit is uniformly filled with energy in both cases.

4.5.4 Tungsten Source

A 900-watt tungsten lamp will provide the additional energy necessary to maintain the samples at the required 390° or 530°K temperature levels. The tungsten source will be controllable and programmable. Thus, the sample can be maintained at a given temperature or thermally cycled automatically. A control system and power supply consists of four major interconnected components (Fig. 4-7): a recorder, a set point controller, an SCR power package, and a programmer. The recorder selected, a Leeds & Northrup Speedomax W AZAR, will provide a continuous record of sample
Fig. 4-7 Schematic of Tungsten Lamp Control System
temperature. A slide wire output from the recorder will be fed into a Leeds & Northrup current adjusting type set point controller. The controller regulates the power output from a Leeds & Northrup SCR, which in turn controls the intensity of the tungsten lamp. When the sample is to be temperature cycled, an RI Controls Data-Track Card Programmer is used to provide the desired reference signal. The energy supplied to the sample will be monitored using a calibrated Eppley thermopile.
Section 5
TEST PLAN

5.1 INTRODUCTION

The experimental program will investigate the optical and physical properties of candidate radiator coatings exposed to ultraviolet irradiation at test temperatures of 390° and 530°K. Investigation will be conducted in a vacuum of at least $1 \times 10^{-7}$ Torr. Experimental observations will be made to determine the solar absorptance and infrared emittance of sample coatings prior to, during, and following exposure. Phase I of this program will study four coatings in duplicate which will be exposed to ultraviolet irradiation at a test temperature of 390°K and four coatings in duplicate which will be exposed at a test temperature of 530°K. The exposure will be for 500 hr at an intensity of 1 sun in the 0.2 to 0.4 μ range. Phase II will consist of selecting two candidates from Phase I to be exposed to ultraviolet irradiation at 390° and 530°K, respectively, for 5000 hr. Temperature cycling will be accomplished during exposure. In addition, separate thermal cycling tests will be conducted to expose the candidate coatings to temperature cycles which simulate a maximum cycling rate of a gas radiator in space. The sequence of tests is presented in Fig. 5-1. The various candidate coatings will, in general, be tested in the order received. Temperature cycling tests will be conducted after all candidates are received.

<table>
<thead>
<tr>
<th>Test</th>
<th>1965</th>
<th>1966</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>N</td>
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<tr>
<td>Phase I 500-hr Screening Tests</td>
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<td></td>
</tr>
<tr>
<td>Thermal Cycling Tests</td>
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<td></td>
</tr>
<tr>
<td>Phase II 5,000-hr Tests</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5-1 Sequence of Tests
5.2 TEMPERATURE CYCLING

The eight candidate coatings will be thermally cycled, in duplicate, four times from
the maximum test temperature to near liquid nitrogen temperature. The rate of tem-
perature change will simulate the cooling of a gas radiator with heat source removed
in space when the radiator is in the earth's shadow. The samples will be cycled in
two groups corresponding to their maximum test temperatures. The test specimen
will be identical to the samples used for the ultraviolet exposure, and the temperature
response of each will be recorded during the test. The criterion for acceptability of
a coating on the basis of the above test will be that no cracking or spalling is evident
to the unaided eye.

The data to be obtained from this test will be (1) pre- and post-test photographs of
each sample, at 1× and 60× magnifications; (2) a record of the temperature history of
each sample; and (3) a written description of any change noted in the sample after
testing.

5.3 500-HR EXPOSURE TEST

The 500-hr screening test will evaluate eight candidate radiator coatings in duplicate,
four at a temperature of 390° K and four at 530° K. The evaluation will be on a basis
of measurement of the solar absorptance and infrared emittance during exposure to a
1-sun level of ultraviolet irradiation in the 0.2 to 0.4 μ range (Ref. 89). The exposure
will be at a pressure of $1 \times 10^{-7}$ Torr or less. The optical properties of the test
specimen and a control sample will be measured prior to the start of the ultraviolet
exposure using reflectance apparatus. The solar absorptance of both the test specimen
and the control will be measured using the Cary spectrophotometer. The total normal
and total hemispherical emittance of the control specimen will be calculated from the
near-normal reflectance data measured using the LMSC hohlraum reflectometer
(Ref. 91).
The design of the hohlraum sample holder is such that the back and edge of the sample disc could be damaged during measurement. Although this does not affect the accuracy of the reflectance data on the front face, it would preclude further use of the sample in the exposure device. To avoid damage to the test specimen, the total emittance of the test sample will be obtained using the Optical Surface Comparator to evaluate any difference in emittance between the test specimen and the control sample.

The test specimen will be installed in the exposure device and the pressure reduced to $1 \times 10^{-7}$ Torr or less. The $\alpha_s$ and $\epsilon$ of the sample will then be measured in situ as a function of temperature. The method used will be the dynamic technique discussed in detail in Ref. 92. Basically, the method entails computing the optical properties from the slopes of the heating and cooling curves and a knowledge of the terminal capacity of the specimen. The energy balance is described by the following:

For a disk sample having one side painted while the edge and other side have aluminized surfaces it is possible to describe its thermal behavior with the following equation:

$$\rho V_c \frac{dT}{d\theta} = G_s A_s \alpha_s + G_T A_T \alpha_T - \epsilon_s A_s \sigma T^4 - (A_e + A_T) \epsilon_T \sigma T^4 - C_{A_w} T \quad (1)$$

where

- $\rho V_c$ = sensible heat of the sample
- $G_s A_s \alpha_s$ = solar energy absorbed by painted surface $A_s$ with solar absorptance $\alpha_s$
- $G_T A_T \alpha_T$ = tungsten lamp irradiation $G_T$, absorbed by sample back surface having area $A_T$ and absorptance $\alpha_T$
- $\epsilon_s A_s \sigma T^4$ = energy emitted by painted surface area $A_s$ at temperature $T$ with surface emittance $\epsilon_s$
- $(A_e + A_T) \epsilon_T \sigma T^4$ = energy emitted by back surface area $A_T$ and edge surface area $A_e$ at temperature $T$ with surface emittance $\epsilon_T$
- $C_{A_w} T$ = power transferred from sample to thermocouple lead wires
- $\frac{dT}{d\theta}$ = rate of change of absolute temperature with time
The overall energy balance given in Eq. (1) describes the sample behavior during transient periods with full lamp illumination for both sides of the sample. Suspension of the sample with 0.003-in.-diameter thermocouple wires reduces the conduction losses to a negligible level (approximately 0.2% of emitted energy), which permits simplification of the equation to the form

$$\rho Vc \frac{dT}{d\theta} = G_s A_s \alpha_s + G_T A_T \alpha_T - \epsilon_s A_s \sigma T^4 - (A_e + A_T) \epsilon_T \sigma T^4$$

(2)

The test surface emittance is established by blanking off the incident beams ($G_s = G_T = 0$), and recording the temperature response of the sample. The emittance may then be determined by measurement of the slope $dT/d\theta$, or by integration of Eq. (2) with $G_s = G_T = 0$. Integrating Eq. (2) gives

$$\epsilon_s = \frac{\rho Vc}{3(\theta_2 - \theta_1) \sigma A_s} \left[ \frac{1}{T_2^3} - \frac{1}{T_1^3} \right] - \epsilon_T \frac{(A_e + A_T)}{A_s}$$

(3)

This relationship permits computation of $\epsilon_s$ from the temperature history recorded during cooling and knowledge of $\rho Vc$. The use of polished aluminum on $A_T$ and $A_e$ provides a very low value of $\epsilon_T$, and thereby makes the first relation of Eq. (3) the governing term. Since polished aluminum has an inherently low emittance which is unchanged by the conditions of this test program, it may be confidently stated that this source of error will be no more than 2 percent.

Determination of $\alpha_s$ will be accomplished using a procedure similar to that described above. The sample will be intermittently heated and cooled by opening and closing a shutter which blocks entry of simulated solar energy to the chamber. During this time the sample will continue to receive energy at a constant level (within ±1 percent) from the tungsten source. The slope of the heating and cooling curves will be measured as the sample passes through a given temperature, and this slope will be used to compute $\alpha_s$. From Eq. (1), the cooling response is given by
\[
\rho V_c \left( \frac{dT}{d\theta} \right)_c = G_T A_T \alpha_T - \epsilon_s A_s \sigma T^4 - (A_e + A_T) \epsilon_T \sigma T^4 - C A_w T
\]

while the heating response is given by

\[
\rho V_c \left( \frac{dT}{d\theta} \right)_h = G_s A_s \alpha_s - \epsilon_s A_s \sigma T^4 - (A_e + A_T) \epsilon_T \sigma T^4 - C A_w T + G_T A_T \alpha_T
\]

Since the slopes \( \left( \frac{dT}{d\theta} \right)_c \) and \( \left( \frac{dT}{d\theta} \right)_h \) are taken at the same sample temperature \( T \), subtraction of these equations gives

\[
\rho V_c \left[ \left( \frac{dT}{d\theta} \right)_h - \left( \frac{dT}{d\theta} \right)_c \right] = G_s A_s \alpha_s
\]

The solar absorptance \( \alpha_s \) is then computed from the known slopes, knowledge of \( \rho V_c \), and measurement of \( G_s A_s \). The sample irradiation \( G_s \) will be available from the monitoring pyroheliometer whose calibration was previously described.

The sample will be exposed to the 1-sun level of ultraviolet radiation for 500 hr. During exposure, the optical properties will be measured near the test temperature every 50 hr and the sample will be temperature cycled every 5 hr. The temperature cycle will be from the test temperature to ambient. The rate of change of temperature will be that obtained by removing incident energy from the specimen and allowing it to radiate to a liquid-nitrogen cold wall. At the completion of the 500-hr exposure, the optical properties will again be evaluated in situ as a function of temperature. The sample will then be removed from the chamber and the optical properties measured using reflectance methods. The data to be obtained from this test will be:

- Pre- and post-test room-temperature values of solar absorptance and infrared emittance, in air, obtained by reflectance techniques
• Pre- and post-test values of solar absorptance and infrared emittance as a function of temperature, in vacuum, obtained by the dynamic technique

• Values of solar absorptance and infrared emittance as a function of time in a vacuum during exposure to a 1-sun level of ultraviolet irradiation obtained by the dynamic technique

5.4 5,000-HR EXPOSURE TEST

The 5,000-hr test will be similar to the 500-hr test previously described except for duration and frequency of thermal cycling. The thermal cycles will be accomplished every 50 hr for the 5,000-hr test program. The same data will be obtained from the 5,000-hr test as from the 500-hr test, with one addition: initial total hemispherical emittance will be measured as a function of temperature using the calorimetric emittance apparatus.
Section 6
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