167-34625

20 JUNE 1967

LMSC-A847882, Vol. III

HANDBOOK OF OPTICAL PROPERTIES FOR THERMAL CONTROL SURFACES

FINAL REPORT, VOLUME III

OF

HIGH-PERFORMANCE INSULATION THERMAL DESIGN CRITERIA

NAS 8-20353

CRYOGENIC STAGE PROGRAMS

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Section 1 INTRODUCTION

The Handbook of Optical Properties for Thermal Control Surfaces was prepared under Contract NAS 8-20353 for the NASA George C. Marshall Space Flight Center (MSFC). This volume is the third in a series of three that constitutes the final report on work conducted under the MSFC contract. The technical manager of this contract at MSFC are Mr. G. Comer and Mr. J. Vaniman, Propulsion Division, R-P & VE-PTP. The prime intent in assembling the enclosed data is to provide a sourcebook of consistent data on the optical properties of thermal control surfaces in order that accurate prediction of spacecraft temperatures may be made.

The data contained in this handbook have been limited to those materials for which qualified space environmental stability and production and quality control data are available. These guide lines have eliminated a substantial amount of data generated in the LMSC Thermophysics laboratory, and of data published in the open literature. In particular, recent developments in methods of obtaining environmental stability data have precluded incorporation of data generated throughout the industry within the last few years. For example, a number of studies of the effects of ultraviolet radiation on thermal control coatings previously have been carried out in the laboratory by exposing materials to this simulated environment. The evaluation of coating performance was based upon pre- and post-exposure reflectance measurements made in air using conventional optical instrumentation. However, it has been discovered recently that the ultraviolet damage to many coating systems is more extensive than previously measured in such laboratory tests. It is found that the damage has been masked by the recovery of the system when returned to an atmospheric environment for measurement of solar absorptance. This effect is clearly shown in Fig. 1-1. Thus, "in situ" measurements (measurements made in place in a vacuum) are necessary to provide accurate knowledge of optical damage to many thermal control coatings. Techniques for "in situ" measurements are relatively new and are described in this handbook. Also, while limited data are available, this handbook presents a thorough compilation of these data.



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It is noted that for certain coatings included in this handbook, there is at present no "in situ" optical property data available. Further, it is felt that some of these data will show a definite response to the "in situ" measurement techniques. However, these data are the latest available and the materials cited are presently in use and approved at Lockheed as thermal control materials. In addition to the optical property data, complete specifications are presented on the application of the thermal control coating to various substrates. These include substrate surface preparation, primer required (if applicable), minimum thickness required to achieve proper optical properties, and type and length of cure cycle. Further, specifications are given for proper protection of the thermal control surface in the pre-launch and ascent environments. Specifications are complete such that engineering drawing callouts can be made.

The primary consideration in the selection of an engineering material is the extent to which that material exhibits the physical characteristics dictated by applicable design requirements. In the case of spacecraft thermal control, materials are chosen for their thermophysical properties – especially thermal radiation characteristics – and for the stability and predictability of these properties in the total spacecraft environment. This handbook contains the design data and information required for the specification of thermal design materials on the basis of the above criteria. The materials were chosen on the basis of the following criteria:

- The material exhibits properties and environmental stability required for spacecraft thermal control. Engineering design data are available.
- The material fulfills requirements, dictated by space-vehicle design, which are not presently fulfilled by other approved thermal-control materials.
- There is an existing capability for reproducible production of the material.

Sections 2 through 4 are written for the layman unfamiliar with the basic concepts of thermal design. Section 2 contains a definition of terms; Sections 3 and 4 review the nature of the thermal-control problem and give the bare outlines of the procedures of thermal design.

Sections 5 through 7 are directed to the thermal designer. Parameters affecting the thermal behavior of a surface are described; the effects of the spacecraft environment are discussed; and the experimental methods used to obtain design data are reviewed. The purpose of these three sections is to supplement the data sheets of Section 8, giving the designer greater insight into the full meaning and proper qualification of the data. Also included as Section 9 is information on promising research coatings presently under intensive investigation at LMSC.

All data throughout this handbook were obtained from the LMSC Thermophysics Research Laboratory unless otherwise noted.

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Section 2 DEFINITION OF TERMS

Effective use of this handbook requires definition of the basic concepts, quantities, and qualifying terms used. These are defined in this section.

2.1 BASIC CONCEPTS

<u>Thermal Radiation</u>. Thermal radiation is defined as radiation emitted from a body by virtue of its temperature.

<u>Blackbody</u>. The blackbody or ideal radiator absorbs all incident radiant energy and radiates energy at the maximum rate possible per unit area at each wavelength for any given temperature.

<u>Stefan-Boltzman Law</u>. The functional relationship between the radiation emitted by a blackbody and its temperature is defined by the Stefan-Boltzman Law. This states that the total radiant emission of a blackbody is proportional to the fourth power of its absolute temperature.

Emittance. Emittance, ϵ , of a body is the ratio between the energy emitted by the body and that which would be emitted by a blackbody at the same temperature.

<u>Kirchhoff's Law</u>. This may be stated as follows. The emittance of a body at thermal equilibrium with its total environment is equal to the absorptance, α , of the body for energy incident upon it from the environment; i.e., $\epsilon_{equil} = \alpha_{equil}$. When radiation of a given wavelength is considered, the emittance of a body at a given temperature for radiation of that wavelength is equal to absorptance of the body at the same temperature and for radiation of the same wavelength, i.e., $\epsilon(T, \lambda) = \alpha(T, \lambda)$.

For monochromatic energy, the restriction to equilibrium conditions is not necessary.

The above statements are true only where the emittance refers to energy emitted in all directions from the body of interest and the absorptance to energy incident from all directions.

2.2 QUANTITIES

Emittance. Defined in 2.1

<u>Emissivity</u>. Emissivity is a fundamental property of the material and is measured as the emittance of a material specimen that has an optically smooth, clean, surface, sufficiently thick to be opaque.

<u>Reflectance and Absorptance</u>. These terms refer to the fraction of radiation incident on a body which is respectively reflected, or absorbed and transformed into internal thermal energy of the body.

<u>Transmittance</u>. Transmittance is the fraction of radiation incident on a body which is transmitted through the body.

2.3 MODIFYING TERMS

<u>Total and Spectral</u>. These terms qualify the wavelength of radiation. Total values include all wavelengths and thus all radiant energy. Spectral values refer to monochromatic radiation of a given wavelength.

The radiative behavior of a surface element of a body is directionally dependent; see Fig. 2-1. Note that surfaces with anisotropy, such as the striations on rolled metal, have properties dependent on both polar (ϕ, ϕ') and azimuth (θ, θ') angles of incidence. Rather than enumerate every possible combination of terms, we cite only a few commonly encountered designations.





Normal Reflectance and Normal Absorptance. These terms refer to the reflectance and absorptance of a body for normally incident radiation (zero polar angle of incidence, ϕ) and are special cases of reflectance and absorptance where all energy from the incident beam is accounted for. Except for perfectly diffuse (Lambertian) surfaces, both reflectance and absorptance are functions of the polar and azimuth angles of incidence.

Specular Reflectance. Specular reflectance is the ratio between energy incident in a given direction (ϕ, θ) and energy reflected in a given direction, such that $\phi = \phi'$ and $\theta' = \theta + \pi$. The solid angles of incident and reflected energy, d Ω and d Ω' , are considered to be equal. Except for perfectly specular surfaces, specular reflectance is not the fraction of incident radiation which is reflected. Energy reflected outside d Ω' in the above geometrical description is not accounted for.

Total Hemispherical Emittance. This is generally taken to be equivalent to the unmodified term, emittance. Total indicates that emitted energy of all wavelength is accounted

for; <u>hemispherical</u> means that all energy emitted into the hemispherical space above the surface element of interest is accounted for.

<u>Normal Emittance</u>. Normal emittance is the ratio of thermal radiation emitted in a direction normal to the surface of interest to that emitted normally by a blackbody at the same temperature. Normal emittance is thus a special case of directional emittance.

2.4 GENERAL REMARKS

The absorptance, reflectance, and transmittance of a given body at a given temperature are functions of both the directional and spectral nature of the incident energy. The spectral absorptance, spectral reflectance, and spectral transmittance of a given body at a given temperature, however, are functions only of the direction of incident energy.

The terms specular and diffuse are also used to describe the directional radiative behavior of surfaces. Optically polished metals generally reflect specularly. With a perfectly specular surface, all energy incident in solid angle $d\Omega$ would be reflected into solid angle $d\Omega'$, where $d\Omega = d\Omega'$, $\phi = \phi'$, $\theta' = \theta + \pi$. A perfectly diffuse (Lambertian) surface with energy incident in solid angle $d\Omega$ would reflect the energy uniformly in all directions into the hemispherical space above the surface element.

The term diffuse is also used to characterize the emission of thermal energy; the emitted intensity of a diffuse emitter is equal in all directions.

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Section 3 THE THERMAL-CONTROL PROBLEM

3.1 SPACECRAFT-COMPONENT TEMPERATURES

All spacecraft contain certain elements – mechanical, electronic, or living – which operate only if maintained within specific temperature ranges. The temperatures of these components are influenced directly by the net thermal energy exchange with the spacecraft environment, regardless of the vehicle design and the type of temperature control system employed. Typical requirements for spacecraft components are shown in Fig. 3-1.



Fig. 3-1 Temperature Tolerances of Typical Spacecraft Components

3.2 SPACECRAFT THERMAL ENVIRONMENT

Figure 3-2 depicts a satellite orbiting the earth, and indicates the sources of energy which are external to the satellite. Except during ascent from, or entry into planetary atmospheres, the spacecraft constitutes a system which may exchange thermal energy with its surroundings only through thermal radiation. Convection, which is the prime method of heat transfer for aircraft, is negligible since there is no atmosphere in the usual sense. Even at an altitude of only 200 miles above the earth, atmospheric pressures and densitites are such that aerodynamic heat-transfer effects may generally be neglected.



Fig. 3-2 Satellite Heat Balance

The energy exchange of an earth satellite with its surroundings can be considered to have four constitutents: (1) direct solar radiation (insolation), (2) solar radiation reflected from nearby planets (the albedo), (3) the thermal energy radiated by nearby planets (planetary emission), and (4) the radiation to space from the satellite surface. When the space vehicle is not near a planetary object, the albedo and planetary-emission terms become trivial and the energy balance is reduced to only two terms: direct solar radiation and radiation from the satellite surface.

Besides the above four energy terms, the spacecraft itself will generally have components on board which act as sources of thermal energy, such as electronic components thermally dissipating internal power, or nuclear engines. All heat dissipated in this way is consolidated in our simplified treatment as a fifth category of thermal energy; internal power.

3.3 THERMOPHYSICAL PARAMETERS GOVERNING ENERGY EXCHANGE

Temperatures experienced by the components of a given vehicle are controlled largely by the ability of the external surfaces to absorb, reflect, transmit, and emit thermal radiation. In most spacecraft designs, the two properties of predominant importance in describing these abilities are emittance and solar absorptance.

- Solar absorptance, α_s , is that fraction of the incident solar energy which is absorbed by a surface.
- Emittance, ∈, is the ratio of the energy emitted by the surface under consideration to that which would be emitted by an ideal radiator (blackbody) at the same temperature

Note that both $\alpha_{\rm g}$ and ϵ are, by definition, properties which vary from 0 to 1.0. From the ratio of these two properties, $\alpha_{\rm g}/\epsilon$, for a given vehicle's surface, one can then estimate vehicle equilibrium temperatures at specific points in space. A vehicle with low $\alpha_{\rm g}/\epsilon$ external surfaces experiences relatively low temperatures, since it does not absorb solar energy very effectively (low $\alpha_{\rm g}$) in comparison to its ability to lose energy to space by thermal radiation (high ϵ). Conversely, high $\alpha_{\rm g}/\epsilon$ surfaces

tend to become hot. This is illustrated in Fig. 3-3, which represents the average temperature of a cylindrical earth satellite orbiting in a stabilized nosedown position at an altitude of 300 miles. The three curves are for three different types of orbits; β is the angle between plane of the satellite's orbit and the earth-sun line. It is apparent from this figure that the temperature increases with increasing $\alpha_{\rm s}/\epsilon$.

The table given below may be used as a general rule of thumb.



Fig. 3-3 Average Satellite Surface Temperature

Type of Material	Approximate α_{s}/ϵ
White paints and ceramics	0.3
Black paints and ceramics	1.0
Metallic paints	0.8-1.2
Bare metals	> 2

Section 4 THERMAL-DESIGN TECHNIQUES

4.1 THERMAL-CONTROL SURFACES

The basic method of controlling spacecraft temperature is through use of materials that exhibit the necessary thermal radiation characteristics (α_s, ϵ) ; these materials cause the various surface areas of the vehicle to emit and absorb the correct amount of energy to ensure that the design temperatures of the interior of the vehicle are maintained. The four basic thermal-control surfaces are shown in Fig. 4-1, where monochromatic absorptance is plotted as a function of wavelength. Note that 94 percent



Fig. 4-1 Ideal Representation of Four Basic Surfaces

4-1

of the solar radiation is of wavelengths less than 2μ . The definitions of these surfaces follow:

- Solar Reflector a surface which is highly reflective to solar energy and emits very well at spacecraft temperatures (low α_s/ϵ ratio).
- Solar Absorber a surface which absorbs solar energy far more effectively than it emits energy at satellite temperatures (high α_{c}/ϵ).
- Flat Reflector a surface which reflects all thermal energy incident upon it, including solar $(\alpha_s/\epsilon \approx 1.0)$.
- Flat Absorber a surface which absorbs all thermal energy incident upon it, including solar $(\alpha_{g}/\epsilon \approx 1.0)$.

There are two techniques for controlling spacecraft temperatures: passive thermal control and active thermal control. Passive control is the basis (as defined in Section 4.2) of all thermal control. Passive control may be the sole means of control-ling the amounts of energy absorbed and emitted. Active control generally is used in varying degrees to supplement passive control.

4.2 PASSIVE THERMAL CONTROL

Passive control of the thermal behavior of a system and its components is attained wholly through geometrical design and the selection of materials with the requisite thermophysical properties. This method includes the static employment of temperatureinduced physical changes in materials. Neither power nor moving parts are employed. Techniques for passive thermal control include use of:

- Materials with desired thermal radiation properties
- Geometrical design
- Materials with desired values of thermal conductivity
- Thermal behavior of materials at a change of phase, utilizing the materials as heat sinks
- Self-thermostatic surfaces

4-2

4.3 ACTIVE THERMAL CONTROL

Active thermal control of a system and its components is attained through a feedback control system, with temperature as the controlled variable. This method includes the dynamic employment of temperature-induced physical changes in materials. Generally, either power or moving parts are employed. Techniques for active thermal control include the use of:

- Thermostats and heaters
- Bimetallic strips to control variable α_{s}/ϵ shutter system
- Fluid transport refrigeration systems
- Variable thermal-resistance techniques
- Thermoelectric cooling

4.4 RELATIVE MERITS OF ACTIVE VERSUS PASSIVE CONTROL SYSTEMS

Passive thermal control systems have certain advantages over active systems in regard to reliability. They employ no moving parts or switches which may malfunction because of such factors as the cold-welding of bearing surfaces in the low pressures of space. Also, the passive solution to a design problem generally requires less weight.

Active thermal control systems, on the other hand, can correct for environmentally induced alterations in the thermal behavior of a vehicle. An example of such an alteration is the increase in the solar absorptance of an exterior surface due to the influence of extraterrestrial solar ultraviolet energy. These systems can also accept changes in the thermal environment, such as the increase in the solar constant experienced by a Venus probe. Extremely accurate knowledge of external thermal-radiation **charac**teristics is not mandatory for active systems, as it is for passive. Among other things, this means that successful operation of a given vehicle is less likely to be jeopardized by the various factors of the prelaunch environment. In addition, active control can provide much more precise control of temperature than is possible with passive control. The choice of whether to use an active or a passive thermal-control system depends on the particular application. The great majority of LMSC vehicles to date have utilized passive thermal control; some have used active systems in conjunction with passive. It should be noted that the design of active thermal-control systems presupposes a knowledge of passive-design techniques. The thermal environment and the fundamental analytical approaches are the same. The greater the accuracy with which one can predict the behavior of materials used for spacecraft thermal control, the smaller the heating and cooling capacities needed, and consequently, the less power and weight are required to solve a given design problem through active thermal control.

4.5 SPACECRAFT THERMAL-DESIGN PROCEDURES

A detailed review of procedures involved in the thermal design of a spacecraft is beyond the scope of this outline. A brief resume of the parameters which must be considered is in order, however, to illustrate the complexity of the problem.

4.5.1 Temperature Requirements

The first consideration of the designer is to ascertain the component temperature which must be maintained if the vehicle is to perform its intended function. The upper and lower temperature limits for the various components are established on the basis of the materials being used or on component-performance test results. It is the thermal designer's job to see that these temperature limits are not exceeded while the vehicle is performing its mission. The same vehicle might carry equipment which requires cryogenic temperatures and other equipment which must operate at refractory temperatures.

4.5.2 Energy Sources

The direct solar insolation, planetary albedo radiation, and planetary emission incident on each portion of the vehicle is then determined by the thermal designer for all possible positions in all possible orbits. The portion of this energy which the vehicle will absorb depends on vehicle geometry and surface thermal-radiation characteristics (α_s and ϵ).

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From this information and a knowledge of the internal power dissipation, a gross energy balance for the vehicle may be written which yields a bulk temperature as a function of α_s and ϵ .

4.5.3 Selection of Temperature-Control System

If thermal-control surface materials with radiation characteristics which will result in a satisfactory vehicle temperature are not available, the thermal designer must consider use of active thermal control. If suitable thermal-control materials are available, however, the possible necessity of an active thermal-control system is not precluded. The thermal designer must analyze, in detail, the heat transferred within the vehicle (using thermal-control surfaces which he believes will yield the desired temperatures). This analysis involves determining the conduction and radiation heat-transfer paths from every component to every other component. Separate energy balances are then written for each component of interest. Component temperatures are variables in these energy balances; consequently, each separate equation includes parameters which appear in at least several of the similar energy balances written for other components. Thus, an equation describing the thermal behavior of component A could include, as variables, the temperature of components B, C, D, and E. These energy balances are in the form of nonlinear partial differential equations and are generally solved simultaneously by digital or analog computer. Their solution yields a temperature history for each component.

Figure 3-3 somewhat oversimplifies the thermal-design problem. Among other aspects, orbital temperature oscillations are not shown. An idea of the oscillations which could be experienced by vehicle skin sections may be gained from Figs. 4-2, 4-3, and 4-4. These figures display the temperature oscillations experienced by different faces in an oriented cube (Fig. 4-5) following a 300-sm altitude circular noon orbit (i.e., earth-sun line is in the satellite orbit plane). Each cube face is assumed to be isolated from its fellows and to have an insulated interior surface. The effect of the thermal-capacity parameter, $mC_p\delta$, is clearly displayed. The symbol m represents the density of the skin material, C_p , the specific heat, and δ , the skin thickness. The quantity



Fig. 4-2 Satellite Skin-Temperature Oscillations – Vertical Surfaces of Cubical Satellite

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Fig. 4-5 Position of Cube-Shaped Satellite Surfaces With Respect to Earth and Insolation

 $mC_p\delta$ is then a measure of the "heat storage" capacity of a skin section of unit area. In general, the fluctuations experienced by internal components are much less than those of the vehicle skin.

If the individual temperature histories obtained above indicate that the components of interest will remain within their allowable temperature ranges, no changes need to be made in the design. If this is not the case, the designer must try to vary such factors as thermal-control surfaces, equipment locations, and conduction paths. If none of these changes are possible or yield satisfactory results, an active thermal-control system must be utilized. The completed design will generally have a number of different thermal-control surfaces on the various sections of the vehicle. Occasionally, some components may be controlled through an active thermal-control system, while the remainder of the vehicle utilizes a passive thermal-control system.

The foregoing has ignored all but the thermal constitutents of the spacecraft environment. Reliable thermal design, however, necessitates knowledge of the behavior of the selected thermal-control materials in the entire space environment. A general summary of the present status of this knowledge is the subject of Section 6.

Section 5 PARAMETERS DEFINING OPTICAL BEHAVIOR OF SOLIDS

5.1 INTRODUCTION

A major problem encountered in obtaining usable radiation-characteristic data lies in adequately describing the surface measured.

On the basis of our limited understanding of radiative heat transfer from real surfaces, some criteria for describing surfaces are presented. Unless otherwise mentioned, the following remarks apply to "opaque" solids. As used here, opaque refers to materials or surface systems of sufficient thickness to transmit less than 1 percent of incident thermal radiation.

The radiative behavior of all real materials is governed in part by their intrinsic optical properties. In general, however, other characteristics modify and often override this intrinsic behavior. For example, it is known that such factors as surface roughness, work hardening, surface films, paint vehicle and pigment contamination, and pigment-to-vehicle ratio affect radiation characteristics. A large amount of work remains to be done, however, before a complete quantitative account of the effects of these various factors can be achieved. At present it is necessary to combine physical description with preparation information in order to adequately specify either a surface measured or one to be manufactured.

In the physical description of radiative surfaces, as well as in the theoretical description of the mechanism of thermal radiation, it is convenient to group materials as electrical conductors, semiconductors, or dielectrics. This section reviews information required for material specification as well as available data of intrinsic properties.

5.2 ELECTRICAL CONDUCTORS

Surface profile can exercise an overriding influence on the radiative behavior of conducting materials. A surface may be thought of as made up of minute hills and valleys; it may be described in terms of the average diameters, \bar{x} , and depths, \bar{y} , of the valleys, together with a parameter or parameters defining the slope or shape of the valley walls. The presence of any surface anisotropy and its orientation during the measurements should be included in any description. These surface irregularities generally have the greatest effect on radiative behavior if their dimensions are of the same order as the wavelengths of the incident and emitted radiation.

Such a description, however, may not be sufficient. The possible presence of such factors as an extremely thin film on chemically polished surfaces may make it necessary to include preparation information. Typical production parameters are shown in Table 5-1. Any foreign matter on the surface should be completely described, if possible, in such terms as substance and particle size. It should be clear from this discussion that it is highly desirable that the surfaces be completely clean both for measurements and for thermal control of spacecraft. Any special cleaning procedures employed should be included in the surface description.

Work hardening is also known to have an effect on the radiative behavior of metal surfaces. At the present time, however, no quantitative relationships between degree of work hardening and radiation properties have been established.

5.3 SEMICONDUCTORS AND DIELECTRICS

The same criteria apply for the characterization of semiconducting and dielectric materials as do for the metals, with several important additions. With semiconductors, the radiative behavior can be profoundly influenced by the impurities present. With both dielectrics and semi conductors, extinction coefficients are much lower than for metals; therefore particulate or void structure can be expected to be more important to radiative behavior than the surface profile proper.

Table 5-1 presents a summary of important material parameters. If thermal radiation were better understood, it would be theoretically possible to completely characterize

Table 5-1

PARAMETERS CONTROLLING THE RADIATIVE CHARACTERISTICS OF ENGINEERING MATERIALS

Intrinsic Material Properties	Index of refraction Extinction coefficient Scattering coefficient
Typical Production and	Metals
Application Parameters	Polishing: polishing solutions; polishing compounds, polishing wheels, surface speeds
	Sandblasting, Vapor Blasting, Vapor Honing: Grit, propellant pressure, gun-to-target distance
	Machining
	Heat Treatment
	Vacuum Deposition: deposition rate, degree of vacuum, nature of residual gas, substrate tem- perature, thickness of any oxide layer present
	Paint and Ceramic Coatings
	Viscosity (paints)
	Catalyst (paints)
	Spray-gun pressure
	Gun-to-target distance
	Rate of gun traverse
	Power input (flame and plasma spraying)
	Substrate surface preparation
Composition Parameters	Materials
	Purity (nature and degree of contamination)
	Uniformity
Geometrical Parameters	Surface profile
	Particle size, shape, distribution
	Pore size, shape, distribution
	Pigment-vehicle ratio
	Porosity and void volume
	Coating thickness

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a material's radiative behavior from the intrinsic properties of the pure materials and the composition and geometrical parameters of the final surface system. As has been mentioned, however, information of the intermediate preparation procedures must supplement and often supplant the more basic data if an adequate description is to be obtained. The general tenor of these remarks apply equally to the specification of transparent materials. In addition to those radiation data required for opaque solids, determination of diffuse and specular transmittance and information on scattering coefficient are needed. The surface conditions of all material boundaries or interfaces, such as the glass-aluminum interface of a second-surface mirror, become important.

The implications of these remarks are summarized in the following statements:

- At present, with few exceptions, the designer must obtain new measurements to insure reliable data on a given engineering material.
- Comprehensive specification and production control of thermal control surfaces is mandatory.

Section 6

EFFECTS OF THE SPACECRAFT ENVIRONMENT ON THERMAL-CONTROL MATERIALS

6.1 GENERAL

In this section factors of the spacecraft total environment, which are either known or thought to be significant sources of optical and/or physical damage for thermal-control materials, are discussed in terms of present estimates of their effects on these substances. The general remarks of this section are supplemented by the discussions of the stability of specific materials found in Section 8.

6.2 PRELAUNCH ENVIRONMENTAL EFFECTS

The prelaunch environment of a space-vehicle material includes its entire history up to launch. Major problems of manufacturing and quality control, handling techniques, and protection of thermal-control surfaces have become increasingly obvious. These difficulties are intensified in the case of large satellites. The production of the thermalcontrol surface must be carefully controlled, whether the surface be a paint or ceramic film, polished metal, or conversion coating. If the bulk radiative characteristics of a given paint or ceramic coating are to be achieved by a coated surface, care must be taken to assure that adequate film thicknesses are obtained. For the materials it has been found that thicknesses required for opacity varies from 0.001 in. or less for some black paints (flat absorbers) up to 0.008 in. for some white paints. In the case of metals used as solar absorbers, the surface condition achieved is as important as the material. These remarks are amplified in Section 5.

Once the desired thermal-control surface is achieved, still more problems are encountered. Fingerprints have been known to cause localized corrosion of aluminum and gold-plated surfaces which resulted in a doubling of emittance. Atmospheric corrosion and contamination of bright metal surfaces involve so many different
parameters (time, salinity, temperature, moisture condensation or precipitation, wind current, and dirt) that it is preferable to protect a surface rather than attempt to predict its behavior.

For indoor protection, tapes are used to either cover the coating of interest directly or to hold protective wrapping on the optical surfaces. Out-of-door protection requires that the tapes and the wrapping be weatherproof. In all cases the protective materials must be qualified as to their effect on the optical properties of the surfaces to be protected. Residue which can be deposited by some protective systems can result in appreciable degradation when the optical surface is subsequently exposed to the ascent and space radiation environments.

In summary, the prelaunch environment merits the same detailed consideration as the ascent and space environments. Practical manufacturing considerations must be included in the selection and development of spacecraft thermal-control materials.

6.3 ASCENT ENVIRONMENT

As the space vehicle enters the ascent phase of its history, it is exposed simultaneously to aerodynamic heating and aerodynamic pressure and shear forces, to the possible presence of ionized and dissociated gases, and to vibration and shock forces arising mainly from engine-ignition shocks, acoustic pressures, aerodynamic forces, and stage-separation shocks. Of these factors, aerodynamic heating apparently has the most significant effect on the thermal-control problem. Many surfaces which are external during ascent must perform as thermal-control surfaces upon reaching space. Such surfaces may be subjected to temperature histories as those in Fig. 6-1; the peak temperatures shown are followed by a slow radiative decay. The exact temperature history experienced depends primarily on ascent trajectory, vehicle geometry, vehicle material properties, and location of the surface of interest on the vehicle. This thermal behavior is accompanied by a rapid decrease in local air pressure and density. A typical local pressure history for the cylindrical section is 5 mm Hg at 100 sec after liftoff, 10^{-1} mm Hg at 160 sec, and 10^{-2} mm Hg at 180 sec.



Figure 6-1 Representative Agena Ascent-Temperature Histories

The ascent heating damage most difficult to circumvent is the degradation of white paints which result in increased α_s . Inorganic films generally possess stability in ascent heating environment superior to that of organic materials.

In addition to the direct effect on thermal control materials, a secondary source of damage in the ascent environment results from the outgassing, volatilization, or pyrolysis of materials during ascent and subsequent recondensation on and contamination of adjacent thermal-control and optical materials. The most noteworthy example is damage which might be caused by thermal decomposition/volatilization of such materials as adhesives, wire insulation, or potting compounds located in a space vehicle nose cone.

The other important constituents of the ascent phase are shear and vibration. However, tests performed to date indicate damage caused by these constituents to be of second order as compared to the effects of heating and reduced pressure.

In summary, the most serious effects of the ascent environment on thermal control materials are the discoloration of white paints, the bubbling and adhesion failures experienced by paints in general, and the potential contamination of optical surfaces through recondensation of substances evolved from adjacent materials.

6.4 SPACE ENVIRONMENT

In the space environment, the vehicle encounters a large assortment of environmental constituents. Only those potentially damaging to thermal control materials are discussed.

6.4.1 Planetary Atmospheres – Vacuum

Planetary atmospheres at artificial-satellite altitudes are best described in terms of particles species, kinetic energies, and concentrations, rather than by the continum concept of pressure. Johnson, in a description of the earth's atmosphere (Ref. 3), estimates that concentrations at solar maximum of $\sim 10^9$ particles/cm³ exist at an altitude of 200 miles above the earth, with the particles consisting of approximately 75 percent atomic oxygen, 18 percent molecular nitrogen, and the remainder molecular oxygen helium, and atomic nitrogen. This corresponds to a pressure of roughly 10^{-7} mm Hg. Lower concentrations are estimated for greater altitudes. Due to the large mean free paths of the particles of these pressures, particles leaving a surface will not return; volatilization is therefore a potential problem. In addition, participation in reactions by the atmospheric constituents, particularly oxygen, is considerably reduced.

Volatilization of metals is not an expected source of damage to thermal design because evaporation at modest temperatures of all metals except tin, cadmium, and zinc will be insignificant. The question of the stability of dielectric materials in a vacuum has not proved to be amenable to so simple an answer (Refs. 3 and 4). Mechanisms of

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degradation are generally more complex than those of metals. An an example of this complexity, a substance can decompose to simpler materials, which may subsequently volatilize; and the loss of more volatile components of a complex material may be governed by diffusion rates rather than the subsequent volatilization process. Organic compounds are generally less stable in vacuum than are inorganic ones. Organic coatings used for thermal control of LMSC spacecraft are the acrylics (Kemacryl), silicones, and silicates as discussed in Section 8. These coatings have been extensively studied under vacuum conditions in various environmental tests; no indications of vacuum instability at temperature levels to be encountered in service have been noted.

It must be remarked that for thermal-control surfaces operating at elevated temperatures, with $600-1400^{\circ}$ F nuclear reactor radiators, for example, the volatilization problem must be reexamined.

One phenomenon caused by the presence of atmospheric particles is physical sputtering, which is the removal or ejection of one or more atoms from a surface due to collision with a high-velocity particle. Most calculations of the rate of removal of a satellites surface have been made by determining the threshold (for sputtering) to be the heat of sublimation divided by the energy transfer factor. Large rates of removal are usually obtained from these calculations. A more qualified number to use for the threshold for physical sputtering is the energy associated with the displacement threshold for radiation damage (roughly four times the heat of sublimation). Using this threshold energy and correcting for mass inequality and angular effects, it is found that the constituents of the atmosphere do not have sufficient energy relative to the spacecraft to initiate physical sputtering. Sputtering can, therefore, hardly play a role in damaging the optical surface of satellites in circular orbits. However, since the relative energy of the upper atmosphere constituent can be as much as a factor of two greater for the parabolic case of an eccentric orbit, further investigations are warranted for these applications. Also, flights which would orbit or fly by other planets with significant atmospheres may also warrant additional attention.

6.4.2 Solar Electromagnetic Radiation

Solar radiation is considered to be the primary source of degradation of the optical properties of thermal control surfaces. Present knowledge of extra-terrestrial solar radiation is summarized in Refs. 3 and 4. The solar constant (the total solar irradiance at the Earth's mean distance from the sun) is equal to 443 Btu/hr-ft². The visible and infrared portion of the solar spectrum is well approximated in spectral quality by the radiation from a 10,800°R black body, whereas the total amount of electromagnetic radiation from the sun is equivalent to that from a 10,440°R black body. Only 0.02 percent is estimated to be of wavelengths shorter than 2200 Å, while 9 percent of the energy is in the 2200 to 4000 Å range.

Although more than 90 percent of the extraterrestrial solar energy is in the wavelength region beyond 4000 Å, these photons are not, in general, considered sufficiently energetic to significantly alter the optical properties of common thermal control materials. However, these photons should be considered for possible synergistic and/or annealing effects when in combination with charged particle exposure. For an ultraviolet-only environment in vacuum, the near ultraviolet region (2200 to 4000 Å) is regarded as the most significant source of environmental degradation.

The effects of solar ultraviolet radiation are most pronounced in low surfaces (solar reflectors) and, in particular, those with "white paint" system. The phenomenological effect of ultraviolet radiation on organic materials is, in general, a tendency toward an increased value of solar absorptance (darkening). For polymeric materials, absorption of sufficiently energetic photons can lead to cross-linking, chain fission, and molecular elimination. Proliferation of such structural alterations leads to degradation of both optical and physical properties. Pigments and other inorganic materials also undergo changes in their optical properties. Ultraviolet irradiation of white oxide pigment materials leads to the loss of oxygen with the creation of defect centers. For some typical pigments (zinc oxide, titanium dioxide) the solar absorptance has been found to double after extended irradiation in vacuum (Ref. 27). For paint systems composed of pigments dispersed in organic or inorganic binders, performance is complicated by the fact that the pigments conventionally absorb a large portion of the

potentially damaging near-ultraviolet radiation, effectively screening the binders from energetic photons. Metals appear to be unaffected by ultraviolet radiation although the oxide films on certain metals may be altered.

The effects of temperature on the damage due to solar electromagnetic energy must also be considered. In general, ultraviolet radiation-induced degradation of materials is accelerated at elevated temperatures in vacuum and deaccelerated at temperatures less than room temperature.

6.4.3 Penetrating Radiation

A summary of the penetrating radiation environment of space is presented in Table 6-1. The specific effects of any particular environment must take into consideration the angular intensity and energy distribution of the radiation, the orbit or trajectory of the satellite, the positioning of the optical surface relative to the radiation angular distributions, combinations of environments, and the mission thermal design lifetimes. Most of these parameters are well defined for a given satellite. However, there is a lack of ground-based experimental and theoretical data which relate all of the aforementioned considerations. It is, therefore, not possible at the present time to reliably predict the optical degradation of surfaces which must perform in these adverse environments.

There has been, however, an adequate number of exploratory experiments on the effects of the various environments which has allowed the identification of these environments on which detailed studies must continue in order to allow the reliable prediction of optical property degradation. Those portions of the total space environment which are considered of importance in the definition of optical damage in space-craft optical surface materials are as follows:

- Auroral electrons
- Artificial electron belt
- Van Allen electrons
- Van Allen protons
- Solar wind protons

Table 6-1

SPACE RADIATION ENVIRONMENT

NATURAL

Particle Radiation	
Protons	Galactic
	Van Allen
	Solar Flare
	Solar Wind
	Auroral
Electrons	Van Allen
	Auroral
Alpha Particles	Solar Wind
	Solar Flare
Electromagnetic	Solar Emissions
Physical Impact	Atmospheric Particles
	Micrometeoroid

ARTIFICIAL

Persistent

Electrons

Neutron/gamma

Electron/gamma

Transient

Burst Products

High-Altitude Nuclear Detonations

Spacecraft-Borne Nuclear Reactors

Spacecraft-Borne Isotope Power Supplies

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Weapons

These environments which may be damaging but have not been defined adequately to date include auroral and low-energy solar flare protons. Additional environments, such as radiation from spacecraft-borne nuclear sources and ground and orbital environments of other panets, must also be considered if the space vehicle is required to function in these specific environments.

Studies are presently in progress on the effects of combined Van Allen protons-plussolar electromagnetic radiation and combined artificial electron belt-plus-solar electromagnetic radiation electrons with the coating substrates maintained at cryogenic temperatures (AF33(615)-5066). The results of these studies will answer many questions in regard to the vulnerability of candidate "state-of-the-art" thermal control surfaces which could be used for thermal protection of cryogenic gases and fluids in space. An important effect in determining the change in α_s/ϵ of coatings for cryogenic temperature substrate applications is the large decrease in total hemispherical emittance that occurs for most of the common solar reflector materials; the emittance decreases for decreasing material temperatures.

None of the presently known penetrating radiation environments of space will cause physical sputtering damage of any importance.

6.4.4 Meteoroids

The available information on size, mass, velocity, spatial distribution, and number densities of meteoroids has been presented in Refs. 3, 4, 5, 12, 13, and 14. The various values of particle fluxes presented in each reference vary by at least four orders of magnitude. Estimates of damage are generally theoretical, since particles with meteoric mass and velocity have not been produced in the laboratory in a controlled fashion. Jaffe and Rittenhouse (Ref. 5), among others, have estimated the effect on aluminum over a period of one year, based on the work of Bjork (Ref. 12). The general conclusion is that thermal-control surfaces of deep-space vehicles with lifetimes of two years or less will not be significantly affected by meteoroid impact. Surfaces of vehicles in earth orbits of less than 300-mile altitude may experience some minor degradation. If care is not exercised in design, penetration may seriously damage active thermal-control systems.

6.4.5 Cryogenic Temperatures

Candidate thermal control coatings have been evaluated for possible application to cryogenic temperature substrates. The stability of the coatings under a simulated solar ultraviolet environment and the coating's physical properties were evaluated with substrate temperatures of 139[°]R (Ref. 28) and is presented below. The results showed that the near-ultraviolet stability and, in general, the physical properties of the coatings are improved at cryogenic temperatures. A follow-on program to this initial study is presently in progress at LMSC and is concerned with optical stability of the coatings at 139[°]R in combined environments, with the solar reflectance measured "in situ" (Ref. 29). Another portion of this activity is the determination of the total hemispherical emittance of the coatings from 126 to 530⁰R. These measurements are performed calorimetrically and indications are that there is, in general, a large decrease in the total hemispherical emittance of typical solar reflector coatings. This trend in data has significant implications for the thermal design of cryogenic systems, where α_s/ϵ must be reliably predicted in order to design the system. A limited amount of this data is available and given in Section 8 for the Optical Solar Reflector (OSR) coatings.

6.4.5.1 <u>Flexibility Tests</u>. The flexibility characteristics of the candidate coatings were determined by subjecting the coating-substrate combinations to bending while the sample was held at either room or cryogenic temperature in a vacuum. The samples were coated on one side only (except for the RTD anodized aluminum coating which was coated on both sides) and placed in curvilinear deformation. The coating surfaces were placed in either tension or compression.

Some physical damage was incurred by four of the thirteen coatings tested (Table 6-2); the four were damaged in tension only. Based on these tests, it appears that damage may be enhanced somewhat at cryogenic tempteratures.

6.4.5.2 <u>Adhesive Tests</u>. The butt tensile adhesion characteristics of the candidate coatings were determined both at room and cryogenic temperatures. The forces required to pull the coatings from their substrates or the forces required for the coating structures to fail were determined.

Table 6-2

FLEXIBILITY TESTS

Sample Spe	cification					
Coating Description	LMSC Number	Panel Number	Flexi- bility Test	Tempera- ture (°F)	Status of Coating After Flexure	Results
LMSC Ematal-type conversion coating- K_2 TiO(C_2O_4) ₂ bath	14814-AE 14814-AA 14814-AB 14814-AG		12 13 10 11	-310 ~315 70 70	In tension In compression In tension In compression	No change noted
LMSC Lithafrax coating - room- temperature cure	14684-AA 14684-AB 14684-AD 14684-AC		2 3 4 5	-300 -294 70 70	In tension In compression In tension In compression,	No change noted
LMSC Lithafrax coating — high- temperature cure	14685-A 14685-AA 14685-AB 14685-AC		2 3 4 5	-300 -294 70 70	In tension In compression In tension In compression	No change noted
LMSC Ultrox coating - room- temperature cure	14686-A 14686-AA 14686-AB 14686-AC		2 3 4 5	-300 -294 70 70	In tension In compression In tension In compression	No change noted
LMSC Ultrox coating - high- temperature cure	14687-A 14687-AA 14687-AB 14687-AC		2 3 4 5	-300 -294 70 70	In tension In compression In tension In compression	No change noted
LMSC Synthetic LiAlSiO4 Coating spray application	14688-A 14688-AA 14688-AB 14688-AC		6 7 8 9	-298 -297 70 70	In tension In compression In tension In compression	No change noted
RTD Anodized Aluminum coating -	14752-A		6	-298	In tension and compression	Coating cracked in tension along 1-in. portion bent around copper block; crack density ~75 in. ⁻¹ no change in coating side flexed in compression
20-mil 1199 Al substrate	14752-AA		7	-297	In tension and compression	Same as 14752-A
	14752-AB		8	70	compression In tension and	density increased
	14752-AC		12	-910	compression	Same as 14752-AB
LMSC Thermatrol 6A-100 Silicone coating	14896-AA 14896-AB 14896-AC		13 10 11	-315 70 70	In compression In tension In compression	No change noted
American Cyanamid	14756-A	1	6	-298	In tension	Coating cracked along 0.75-in. portion bent around copper block; crack density ~40 in. ⁻¹
S7094-3 coating	14756-AA 14756-AB 14756-AC	2 3 4	7 8 9	-297 70 70	in compression In tension In compression	No change noted No change noted No change noted
American Cyanamid	14760-A	1	6	-298	In tension	Coating wrinkled rather than cracked along 1-in. portion bent around copper block
of the formation of the second	14760-AA 14760-AB 14760-AC	2 3 4	7 8 9	-297 70 70	In compression In tension In compression	No change noted Same as 14760-A No change noted
MANE TiO ₂ - Acrylic coating	17332-A 17332-AA 17332-AB 17332-AC		15 15 14 14	-305 -305 70 70	In tension In compression In tension In compression	No change noted
IITRI S-13 Silicone coating	14795-A 14795-AA 14795-AB 14795-AC	S-1 S-2 S-3 S-4	12 13 10 11	-310 -315 70 70	In tension In compression In tension In compression	Coating cracked along 0.5-in. portion bent around copper block No change noted No change noted No change noted
IITRI Z-93 coating	14791-A 14791-AA 14791-AB 14791-AC	1 2 3 4	12 13 10 11	-310 -315 70 70	In tension In compression In tension In compression	No change noted



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When compared with the expected tensile forces to be encountered in the ascent and space environment, all coatings tested displayed more than adequate butt tensile adhesive properties. The results are shown in Table 6-3.

6.4.5.3 <u>Calorimetric Absorptance Measurements</u>. Because of the critical nature of the α_s/ϵ ratio in controlling the boiloff rate of an insulated vessel in space, it is necessary to obtain values of α_s which are as accurate as possible. Most solar absorptance determinations of thermal control coatings are based upon radiometric measurements determined in air and at room temperature. However, on insulated vessels thermal control coatings will be exposed to solar irradiation at temperatures below 70°F. Therefore, the absorptances of thermal control coatings were determined calorimetrically in vacuum and between nominal temperatures of 173 and 463°R (Tables 6-4, 6-5, and 6-6). The purpose of these measurements was twofold:

- To determine the absolute absorptance for simulated solar irradiation of the thermal control coatings.
- To determine the effect of cryogenic temperature on the absorptance of the coatings.

The measurements were made with the LMSC calorimetric absorptance apparatus. A xenon lamp was used to simulate extraterrestrial solar energy. The results of these measurements indicate the following:

- Absorptance of simulated solar irradiation was a very weak function of coating temperature between 173 and 463[°]R.
- Values of coating absorptance determined calorimetrically and radiometrically at or near room temperature were approximately equal for most of the coatings.

6.5 CONCLUDING REMARKS

Results of investigations on effects of the spacecraft environment indicate the most important sources of damage to thermal control materials to be ascent heating, solar ultraviolet energy, penetrating radiation, and the entire prelaunch environment.

Table 6-3

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ADHESION TESTS

Coating Description	LMSC Number	Substrate Tempera- ture (°F)	Apparent Butt Pressure (psi)	Results
LMSC Ematal-type conversion coating- K ₂ TiO(C ₂ O4)2 bath	14892-B 14892-AA	-259 70 70	1360 1360 1180	No failure occurred No failure occurred Adhesive failed
LMSC Lithafrax coating- room-temperature cure	17252-AG	$\begin{cases} -250\\ 70 \end{cases}$	$\begin{array}{c} 2260\\ 1270\end{array}$	No failure occurred Adhesive failed
	17252-AF	70	1380	Adhesive failed together with a small amount of paint structure
LMSC Lithafrax coating- high temperature cure	17259-AB 17259-AC	-230 70 70	$\begin{array}{r} 1400\\ 470\\ 960 \end{array}$	No failure occurred Adhesive failed Adhesive failed
LMSC Ultrox coating – room-temperature cure (See Figure 13)	17266-AB 17266-A	$\begin{cases} -275 \\ 70 \\ 70 \end{cases}$	$1400 \\ 1420 \\ 770$	No failure occurred Adhesive failed Failure over 75% of the paint-
	17266-AA 17266-AH	70 70	470 790	substrate interface area Adhesive failed Failure over 40% of the paint- substrate interface area
LMSC Ultrox coating – high temperature cure	17272-AC 17272-AA	-260 70 70	1380 1360 1420	No failure occurred No failure occurred No failure occurred
LMSC Synthetic LiAlSiO ₄ coating - spray application	17279-AG	-260 70	$\begin{array}{c} 1410 \\ 540 \end{array}$	No failure occurred Failure over 75% of the paint- substrate interface area
	17279-A	70	560	Failure over 75% of the paint- substrate interface area
RTD Anodized Aluminum coating – 1199 Al sub- strate	14916-A 14916-AA	-272 70 70	1360 1360 1380	No failure occurred No failure occurred Adhesive failed
LMSC Thermatrol 6A-100 silicone coating	17291-B, AI 17291-A, BC	$\begin{cases} -250\\70 \end{cases}$	180 18	Adhesive failed Adhesive failed

Table 6-3 (Cont'd)

Coating Description	LMSC T Number ta	ubstrate empera- ure (°F)	Apparent Butt Pressure (psi)	Results
American Cyanamid S7094-3 coating	17298-BD 17298-BA	$\begin{cases} -240\\70\\70 \end{cases}$	1420 1420 1830	No failure occurred No failure occurred Adhesive failed
American Cyanamid S7094-4 coating	17305-AD 17305-AA	$ \begin{bmatrix} -240 \\ 70 \\ -250 \end{bmatrix} $	$1420 \\ 1420 \\ 1150$	No failure occurred No failure occurred Adhesive failed together with
	17305-A	70	1230	a small amount of paint structure Adhesive failed together with a small amount of paint structure
MANE TiO ₂ -Acrylic	17336-AH	{-250 70	1440 1440	No failure occurred Adhesive failed together with a small amount of paint structure
	17336-AG	70	790	Adhesive failed together with approximately 20% of paint structure
	17336-AI	70	1020	Adhesive failed together with approximately 10% of paint structure
IITRI S-13 Silicone coating	17493-AF, A 17493-AE, A	G-250 H 70	230 9	Adhesive failed Adhesive failed
IITRI Z-93 coating (See Figure 13)	17486-AC	-270	1220	Approximately 50% of paint structure failed; adhesive failed on remainder of surface
	17486-A	70	690	Approximately 50% of paint structure failed; adhesive failed on remainder of surface
	17486-AF	70	790	Approximately 50% of paint structure failed; adhesive failed on remainder of surface
		1	4	

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RESULTS FOR NEAR-ULTRAVIOLET EXPOSURE AT CRYOGENIC TEMPERATURE Table 6-4

During Exposure(d) $\Delta^{lpha}_{
m L}$ Determined 0.150.170.110.100.040.050.01Change (c) Absorp-0.050.020.06Solar tance 0.020.010.010.01Absorptance Exposure^(b) 0.150.160.22 Solar 0.230.145226After .0 0. $tance(\bar{b})$ Absorp-Solar 0.16 Initial 0.220.140.140.11 25500 0. Exposure Nominal Density (suns) Flux 131313 13 13 1314 Exposure (hr) 204201 201 201 201 201 201 Exposure(a) Ultraviolet (sun-hr) 26802790 Near 26802680268026802680Substrate Tempera-Nominal -235 -240 -230 -230 -230 -230 ture -190 (°F) (Figs. C-10 (Figs. C-13 (Figs. C-16 (Figs. C-19 (drawdown application) and C-48) (Figs. C-4 17260-AD (Figs. C-7 17267-AB and C-45) 17273-AD and C-46) 17285-AB and C-47) (Figs. C-1 and C-44) 17253-AA and C-42) and C-43) 17636-A LMSC Number 14889-A **Coating Description** [K2TiO(C204)2 bath] conversion coating-LMSC Ematal-type (spray application) temperature cure) temperature cure) temperature cure) temperature cure) LiAlSiO₄ coating LiAlSiO4 coating LMSC Lithafrax LMSC Synthetic LMSC Synthetic LMSC Lithafrax coating (roomcoating (roomcoating (highcoating (high-LMSC Ultrox LMSC Ultrox

 6×10^{-8} to 1×10^{-1} (a) Chamber Pressure

(b) Determined with Cary spectrophotometer; accuracy = ± 0.02 . (c) Accuracy = ± 0.01 . (d) Determined on thumbtack calorimeter; accuracy = ± 0.02 . ium H⊊

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Coating Description	LMSC	Nominal Substrate Tempera- ture (°F)	Near Ultraviolet Exposure(a) (sun-hr)	Expo- sure (hr)	Nominal Exposure Flux Density (suns)	Initial Solar Absorp- tance(b)	Solar Absorptance After Exposure(b)	Solar Absorp- tance Change(c)	$\Delta \alpha_{\mathrm{L}}$ Determined During Exposure(d)
RTD anodized aluminum coating (1199 Al substrate	14915-AD (Figs. C-21 and C-49)	-205	2790	204	14	0.14	0. 25	0. 11	0.31
LMSC Thermatrol 6A-100 silicone coating	17292-AF (Figs. C-24 and C-50)	-225	2790	204	14	0.21	0.21	0.01	0.03
American Cyanamid S7094-3 coating	17299-A (Figs. C-27 and C-51)	-225	2790	204	14	0.20	0.24	0.04	0.12 (see section 6-4)
American Cyanamid S7094-4 coating	17306-AB (Figs. C-30 and C-52)	-225	2790	204	14	0.20	0. 23	0.03	0.08
MANE TiO ₂ -acrylic coating	17337-AD (Figs. C-33 and C-54)	-210	2790	204	14	0. 22	0. 29	0.08	0.17
IITRI Z-93 coating	17487-AB (Figs. C-36 and C-54)	-230	2790	204	14	0.18	0.18	0.00	0.06
IITRI S-13 silicone coating	17494-A (Figs. C-35 and C-55)	-215	2790	204	14	0.18	0. 19	0.01	0.06

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Table 6-4 (Cont'd)

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(a) Chamber pressure = 6 × 10⁻⁸ to 1 × 10⁻⁷ mm Hg.
(b) Determined with Cary spectrophotometer; accuracy = ±0.02.
(c) Accuracy = ±0.01.
(d) Determined on thumbtack calorimeter; accuracy = ±0.02.

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Table 6-5

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RESULTS FOR NEAR-ULTRAVIOLET EXPOSURE WITH SIMULTANEOUS TEMPERATURE CYCLING BETWEEN CRYOGENIC AND ROOM TEMPERATURES

Δ ^α L ermined Muring osure(d)	0.11	0.14	0.14	0.12	0.14	0. 22
ar hrp- Det, ce L ge(c) Exp	05	90			8	
e Abso tan	0.0	0.0	0.0).0 	0.0	0.1
Solar Absorptanc After Exposure(b	0. 55	0.26	0.24	0.20	0. 22	0.29
Initial Solar Absorp- tance(b)	0.50	0.20	0.19	0.13	0.14	0.18
Number of Tempera- ture Cycles	332	332	332	332	332	332
Nominal Exposure Flux Density (suns)	13	13	13	13	13	13
Expo- sure (hr)	243	243	243	243	243	243
Near Ultraviolet Exposure(a) (sun-hr)	3130	3130	3130	3130	3130	3130
Nominal Maximum Substrate Tempera- ture (°F)	+80	+75	+75	+75	+ 80	+ 80
Nominal Minimum Substrate Fempera- ture (°F)	-190	-225	-230	- 235	- 235	-225
LMSC	14889-AB (Figs. C-2 and C-42)	17253-A (Figs. C-5 and C-43)	17260-AC (Figs. C-8 and C-44)	17267-AD (Figs. C-11 and C-45)	17273-A (Figs. C-14 and C-46)	17402-A (Figs. C-17 and C-47)
Coating Description	LMSC Ematal- type conversion coating - [K2TiO(C2O4)2 bath]	LMSC Lithafrax coating (room - temperature cure)	LMSC Lithafrax coating (high - temperature cure)	LMSC Ultrox coating (room- temperature cure)	LMSC Ultrox coating (high - temperature cure)	LMSC Synthetic LiAlSiO4 (spray application)

(a) Chamber pressure = 3×10^{-8} to 6×10^{-8} mm Hg. (b) Determined with Cary spectrophotometer; accuracy = ± 0.02 . (c) Accuracy = ± 0.01 . (d) Determined on thumbtack calorimeter; accuracy = ± 0.02 .

Table 6-5 (Cont'd)

		Nominal Minimum	Nominal Maximum	Near		Nominal	Number	Initial	Solar	Solar	<u>Δ</u> α1,	
Coating Description	LMSC Number	Substrate Tempera- ture (° F)	Substrate Tempera- ture (°F)	Ultraviolet Exposure(a) (sun-hr)	Expo- sure (hr)	Exposure Flux Density (suns)	of Tempera- ture Cycles	Solar Absorp- tance(b)	Absorptance After Exposure(b)	Absorp- tance Change(c)	Determined During Exposure(d)	
RTD anodized aluminum coating (1199 Al substrate)	14915-A (Figs. C-2 and C-49)	2 -210	+75	2560	211	12	275	0.14	0.32	0.18	0.40	
LMSC Thermatrol 6A-100 silicone coating	17292-AC (Figs. C-2 and C-50)	-215	+75	2560	211	12	275	0.20	0.24	0.04	0.08	
American Cyanamid S7094-3 coating	17299-AC (Figs. C-2 and C-51)	-215	+75	2560	211	12	275	0.19	0.27	0.08	0.11	
American Cyanamid S7094-4 coating	17306-AA (Figs. C-3 and C-52)	-215	+75	2560	211	12	275	0.19	0.27	0.08	0.10	
MANE TiO ₂ - acrylic coatings	17337-A (Figs. C-3 and C-53)	-200	+75	2560	211	12	275	0.21	0.35	0.14	0. 24	
I ITRIZ-93 coating	17487-A (Figs. C-3 and C-54)	-215	+75	2560	211	12	275	0.18	0.19	0.01	0.09	
IITRI S-13 silicone coating	17494-AA (Figs. C-4 and C-55)	-220	+75	2560	211	12	275	0.20	0. 23	0.03	0. 08	
(a) Chamber pre (b) Determined v (c) Accuracy $= \pm$ (d) Determined c	ssure = 3 vith Cary s 0.01. n thumbtac	× 10 ⁻⁸ to pectrophoto k calorime	6 × 10 ⁻⁸ r ometer; acc eter; accura	nm Hg. curacy = ±0. acy = ±0.02.	02.							

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RESULTS FOR NEAR-ULTRAVIOLET EXPOSURE AT ROOM TEMPERATURE Table 6-6

Coating Description	LMSC Number	Average Substrate Tempera- ture (° F)	Near Ultraviolet Exposure(a) (sun-hr)	Exposure (hr)	Nominal Exposure Flux Density (suns)	Initial Solar Absorp- tance(b)	Solar Absorptance After Exposure(b)	Solar Absorptance Change(c)
LMSC Ematal-type conversion coatings [K ₂ TiO(C ₂ O ₄) ₂ bath]	14815-AE (Fig. C-3)	+ 80	2530	226	II	0.51	0. 58	0.07
LMSC Lithafrax coating (room- temperature cure)	17256-AA (Fig. C-6)	02+	2530	226	Ħ	0.25	0. 29	0.05
LMSC Lithafrax coating (high- temperature cure)	17263-A (Fig. C-9)	+ 80	2530	226	11	0.24	0.28	0.05
LMSC Ultrox coat- ing (room- temperature cure)	17269-AA (Fig. C-12)	0'2 +	2530	226	11	0.13	0.20	0.08
LMSC Ultrox coat- ing (high- temperature cure)	17276-A (Fig. C-15)	+75	2530	226	11	0.12	0.20	0.07
l MSC Synthetic LiAlSiO4 coating (spray application)	17403-AF (Fig. C-18)	+ 75	2530	226	11	0.18	0.26	0.08
LMSC Synthetic Li AlSiO4 coating (drawdown application)	17635-A (Fig. C-20)	+ 75	2530	226	11	0.16	0.27	0.11
 (a) Chamber pressu: (b) Determined with (c) Accuracy = ± 0.0 	$re = 4 \times 10$ Cary spectro 1.) ⁻⁸ mm Hg. pphotometer	; accuracy = -	±0.02.				

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Coating Description	LMSC Number	Average Substrate Tempera- ture (°F)	Near Ultraviolet Exposure(a) (sun-hr)	Exposure (hr)	Nominal Exposure Flux Density (suns)	Initial Solar Absorp- tance(b)	Solar Absorptance After Exposure(b)	Solar Absorptance Change ^(c)
RTD anodized aluminum coating (1199 Al substrate)	14915-AB (Fig. C-23)	+ 85	2530	226	11	0.14	0.32	0.18
LMSC Thermatrol 6A-100 silicone coating	14811-AB (Fig. C-26)	+ 75	2530	226	11	0.19	0. 25	90 0
American Cyanamid S7094-3 coating	17302-AB (Fig. C-29)	LL+	2530	226	11	0.21	0.28	0.07
American Cyanamid S7094-4 coating	17309-AA (Fig. C-32)	+72	2530	226	11	0.20	0.30	0.10
MANE TiO ₂ - acrylic coating	17334-A (Fig. C-35)	+72	2530	226	11	0.21	0.35	0.14
IITRI Z-93 coat- ing	17490-AB (Fig. C-38)	+72	2530	226	11	0.18	0.18	0.01
I ITRI S-13 silicone coating	17497-AB (Fig. C-41)	+ 70	2530	226	11	0.19	0.21	0.02

Table 6-6 (Cont'd)

(a) Chamber pressure = 4 × 10⁻⁸ mm Hg.
(b) Determined with Cary spectrophotometer; accuracy = ±0.02
(c) Accuracy = ±0.01.

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The materials most susceptible to damage during ascent are the white dielectric films used as solar reflectors; these generally tend to darken and suffer increases in α_s .

In addition, secondary damage can be caused during ascent through the contamination of surfaces due to recondensation of substances evolved by the outgassing, volatilization, or pyrolysis of adjacent materials.

For practical thermal-control purposes, solar ultraviolet energy produces the same macroscopic effect on white materials as does ascent heating, i.e., turning brown with resulting increases in α_s . The behavior of candidate thermal materials in penetrating radiation fluxes is in many cases as important to damage predictions as is the stability of surfaces in the ultraviolet environment. However, as a consequence of the results of the ascent and ultraviolet tests and the results of radiation exposures, inorganic materials are recommended where a highly stable solar reflector is desired for use on a spacecraft with a desired lifetime of one to two years.

Information is needed on the behavior of materials in the total spacecraft environment. An attempt is being made to infer such information from experimental and theoretical studies of the effects of individual and combined constituents. It is desirable, however, to base stability estimates upon data of material behavior in space in conjunction with the ground-based data. For this reason, the utilization of spacecraft-borne experiments designed for this specific purpose is urgently needed. (See Section 7.2.3).

Since the space environment cannot be controlled, concentration on the selection or development of stable materials with predictable characteristics is necessary to achieve reliable thermal design. The prelaunch environment of a thermal-control surface, on the other hand, is potentially controllable. The approach adopted at LMSC, therefore, is to concentrate on prelaunch protection, enforced by inspection. An inspection device and protective handling procedures and devices have been developed; production personnel are receiving indoctrination in the handling and care of thermal-control surfaces.

Section 7 METHODS FOR OBTAINING DESIGN DATA

This section contains a summary of the experimental methods employed to obtain design values. Following the discussion of property measurements and environmental behavior studied, some guidelines for interpretation of thermal-design data are provided.

7.1 THERMOPHYSICAL PROPERTY MEASUREMENT

7.1.1 Calorimetric Radiation Characteristic Determinations

With this technique, the material of interest is placed in a known thermal environment, generally in vacuum. From observation of the thermal behavior of the object via temperature measurements and by applying the law of conservation of energy, emittance or absorptance can be deduced.

Two calorimetric techniques are in use by LMSC Thermophysics; these differ primarily in the method for supplying external power to the sample.

In the first technique, the sample is located in an evacuated enclosure, the wall absorptance of which is known (usually $\alpha \approx 1.0$). The walls are maintained at a uniform temperature different from that of the sample, generally much lower. Electrical power is applied to a heater element within the sample. When a steady-state thermal condition has been established, the total herispherical emittance may be computed from an energy balance which is based on knowledge of sample and wall temperatures and power dissipated within the sample. In transient measurements, a temperature difference between the sample and the enclosure walls is achieved, usually through cooling the enclosure walls. The temperature response of the sample and wall temperature, and from knowledge of the sample mass and specific heat, an energy balance can be performed, from which emittance is determined.

Three LMSC apparatus are based upon the general principles outlined above, each covering a different temperature range: 40-400 ^OR, 400-1000 ^OR, 1000-2000 ^OR. Data obtained with these apparatus are coded "C" in the data sheets. Uncertainties range from less than three percent in the low-temperature device (Ref. 15) and 1 percent in the middle-temperature range (Ref. 16) to 5-10 percent for elevated temperatures (Ref. 17).

A second calorimetric technique allows the direct measurement of the ratio of solar absorptance to infrared emittance. The device used with this technique consists of an evacuated chamber with black cryogenic walls, which are cooled to liquid-nitrogen temperature. The sample with the surface finish of interest is a disk which is much smaller than the enclosure volume.

Radiant energy simulating solar radiation is introduced into the chamber through a small window; this energy is incident upon the sample face and elevates the sample temperature. Steady-state temperature is attained when the rate at which the sample absorbs the incident energy equals the rate at which it emits energy. Upon attaining this steady-state condition, the temperature of the sample is directly related to the α_1/ϵ ratio, where α_1 is the absorptance of the sample for the source energy. After the steady-state temperature is recorded, the externally incident radiation is blocked from the sample. The sample temperature then decays exponentially with time, and this temperature history is recorded.

Data analysis will yield values of emittance as a function of temperature throughout the temperature range experienced by the sample. Thus, this device is capable of determining α_1^{ϵ} at the steady-state temperature found above, from which α_s^{ϵ} is deduced. In addition, determinations of ϵ are made throughout the temperature range obtainable with a given sample. Data obtained with this device is coded "D" in the data sheets (Refs. 16 and 18).

7.1.2 Radiometric Radiation Characteristic Determinations

The radiant energy emitted by the surface of interest is detected and usually compared to that emitted by a blackbody standard or known reference surface at the same temperature. From a comparison of these two measurements, the desired value of emittance is obtained.

Three such devices are used in Thermophysics. One is the Optical Surface Comparator (Lion Research Corp.) which is in use as a production-line thermal control surface inspection device. The emissometer unit of this device is a radiometric comparison instrument. The detector of the emissometer head views an area on the test surface about 3/4 in. in diameter. Energy emitted by the surface is sensed through a KRS-5 infrared window with a thermoelectrically cooled (~ 0 ^OF) thermopile mounted in an evacuated chamber. Before the specimen to be measured is viewed, the energy emitted by three standards ($\varepsilon = 0.04, 0.5, 0.97$) is detected and the thermopile output is calibrated. A correction must be applied to the ε measurement obtained if specimen and standards are not at the same temperature. As a comparison instrument, the uncertainty in the emissometer is less than 5 percent. Data obtained with the emissometer is coded "E" on the data sheets (Refs. 19 and 20).

A second radiometric device measures the total hemispherical, total directional, and spectral directional emittance at high temperatures (700 to 3,500 ^OF). The device consists of a water-cooled evacuated chamber in which a sample formed into a modified Mendenhall wedge enclosure is heated electrically by its own resistance. The vertically mounted sample can be rotated about a vertical axis while being viewed externally through a double-slit collimating optical system. Total or spectral emittance is determined by comparing emitted radiation from the surface to radiation emitted from the enclosure as detected by a vacuum thermocouple used with or without a monochromator. The modified Mendenhall wedge approximates a blackbody; its departure from this condition is estimated and corrections are applied. Uncertainties with this device are on the order of 10 percent. Data obtained with this device is coded "F" in the data sheets (Ref. 21).



The third radiometric device measures total normal emittance in air for 500-1800 ^OF samples. In this system, a sample is mounted at the opening of a rectangular muffle furnace where it is heated by the radiating furnace walls. The sample temperature is measured with surface thermocouples, and the radiant energy rate from the front surface is detected with a Gier-Dunkle directional radiometer. These determinations permit computation of the sample emittance. Data from this apparatus is coded "G".

7.1.3 Reflectance Radiation Characteristic Determinations

Energy of a known intensity is incident upon the surface of interest. The amount reflected is detected, usually spectrally, and compared to the incident energy; from this comparison reflectance is obtained. Emittance and absorptance are then inferred from the law of conservation of energy and Kirchhoff's Law, i.e., $1 - \rho_{\lambda} = \alpha_{\lambda} = \varepsilon_{\lambda}$ for opaque bodies.

Three apparatus are in use at LMSC. Each measures the energy reflected in a nearnormal direction from a diffusely illuminated sample, which is equivalent to a determination of near-normal reflectance.

Near-normal spectral reflectance from 0.24 to 1.8 μ is obtained with a Model 14 Cary double-beam spectrophotometer equipped with an integrating sphere reflectance attachment. The source energy is introduced through an aperture into a sphere with a diffuse inner surface of high reflectance. A sample place in the wall of this inner sphere is illuminated diffusely. Energy reflected from the sample is detected, compared to that reflected from a surface of known reflectance, and the sample reflectance is computed. This reflectance curve is then multiplied by the solar spectral flux-density curve of Johnson (Ref. 3) and integrated; solar reflectance, ρ_s , is obtained by dividing the result of the above integration by the solar constant. Finally, we have $1 - \rho_s = \alpha_s$. A Gier-Dunkle directional integrating sphere is also used to obtain information on the angular dependence of surface reflection. Data obtained in this manner is coded "A" (Refs. 22 and 23). Near-normal spectral reflectance, $\rho_{\lambda n}$, from 1.4 to 25.0, is obtained with a Gier-Dunkle constructed hohlraum and associated Perkin-Elmer Model 13 ratio-recording spectrophotometer. A hohlraum is essentially a heated-cavity reflectometer with walls at uniform temperature. In the device under discussion, the cooled sample forms part of one wall. With the exception of the solid angle subtended by the cavity aperture, the sample is irradiated uniformly from hemispherical space. Energy from the sample in a near-normal direction passes out of the hohlraum aperture and is compared monochromatically to the radiosity of the hohlraum wall.

From a reciprocity theorem of Helmholtz (Refs. 2 and 3), the ratio of reflected energy to the radiosity of the hohlraum wall is equal to the reflectance of the sample for similar near-normal incident unidirectional irradiation. This quantity will be referred to as near-normal spectral reflectance. The reflectance thus obtained is subtracted from 1.0 to obtain near-normal spectral absorptance $(1 - \rho_{\lambda n})^{=\alpha} = \alpha_{\lambda n}$. The absorptance surve is integrated with the blackbody curve for the temperature, of interest, T, used as a weighting function. Total near-normal absorptance for blackbody energy from a source at temperature T is thus obtained. The result is corrected to total hemispherical absorptance, α_h , by the relationships developed by Eckert and given by Jakob, unless there is reason to suspect the surface of interest does not behave in accordance with the Eckert relationship. In any case, the best possible estimate of α_h is obtained. This is assumed equal to the total hemispherical emittance of the surface of interest, when that surface is at the temperature of the blackbody for which α_h was computed. However, see Section 7.3.1 for dangers inherent in this practice. This data is coded "B" (Refs. 22 and 24).

7.2 ENVIRONMENTAL-BEHAVIOR DATA

Two fundamental methods are used to evaluate environmental stability:

- Direct exposure to the actual environmental conditions
- Exposure to laboratory environmental simulation tests

7.2.1 Prelaunch Environment

The effects of conditions encountered during manufacturing, assembly, systems test, shipment, captive-engine test, and at the launch pad are evaluated pragmatically by direct exposure to the environment rather than by laboratory test.

7.2.2 Post-Launch Environment – Laboratory Investigations

<u>Ascent-heating tests</u>. Ascent-heating tests of pertinent materials are currently being conducted. Radiant heating in a reduced-pressure environment is employed to produce the desired heat pulse; specimen temperature is the controlled parameter. A given vehicle-skin temperature history may be achieved with a variety of vehicle configuration-trajectory combinations which result in a variety of pressure histories. For this reason, and also because of the difficulties involved in achieving a controlled reproducible pressure decay with the present apparatus, constant pressures are used during the tests. However, each material is subjected to the same temperature history twice, once with 5 mm Hg (the pressure found at the beginning of the temperature rise) and again with 10^{-3} mm Hg (the pressure found after the ascent-temperature pulse). This repetition is expected to yield data that is conservative, whether the damage is enhanced by the presence of oxygen or the absence of pressure (Ref. 25).

<u>Near-ultraviolet radiation in vacuum</u>. Thermal-control surface specimens are being exposed to near-ultraviolet radiation in a vacuum varying from 10^{-7} to 10^{-8} mm Hg (Ref. 6). The source of ultraviolet energy is either a mercury-argon high-pressure AH-6 lamp, held in a water-cooled quartz envelope, or a xenon high-intensity lamp. Optical property determinations are both pre- and post-test and "in situ".

<u>Thermal Cycling</u>. Specimens are cycled in the temperature range of -240 to $+350^{\circ}$ F with a 12- to 18-min. cycling period; tests are performed in a vacuum of 10^{-5} torr. Materials failing this test are given tests of reduced severity to ascertain their operational limits.

<u>Penetrating radiation</u>. The LMSC combined-environments apparatus is used for these studies. Selected environments are simulated in the laboratory both alone and in combination with simulated solar radiation. Pressures are in the 10^{-8} -torr range, and optical property determinations are performed "in situ". The following environments are being investigated on a routine basis: Low-energy geomagnetically trapped electrons and protons; artificial electron belt electrons; auroral electrons and protons; and solar wind protons. Heavy gas ion bombardment (i. e., A, Xe, Kr) is also being used to aid in the elucidation of optical damage mechanisms. Results are used to define future studies, to guide material development programs, and to give estimates of the space degradation of materials.

7.2.3 Post-Launch Environment – Satellite-Borne Experiments

Effects of the post-launch environment are evaluated most satisfactorily through spacecraft-borne experiments. Many flight experiments have been proposed and used to assess the stability of candidate thermal-control surfaces in the space environment.

Common to such flight test programs is a thermal-control surface specimen, thermally isolated from the parent space vehicle, and coupled to the space environment by primarily radiative heat transfer. The specimen temperature history is controlled by its spatial coordinates, thermal capacitance, and radiation characteristics (α_s and ε). Ephermeris and temperature profile data are used to determine surface damage (i.e., changes in α_s and ε).

Surface-stability experiments were successfully flown by the National Aeronautics and Space Administration (NASA), Ames Research Center on OSO-1 (Ref. 30). The flight data were compared with laboratory simulation testing, thereby furnishing an exceed-ingly valuable example of correlation between flight and ground-base data.

The OSO-2 thermal flight experiment (Ref. 31) conducted by the same research laboratory investigated more surfaces and conducted a round-robin study at many different thermophysics laboratories on four coatings in order to obtain closer correlation between flight and laboratory test results. A Mariner-4 thermal flight experiment (Ref. 32) extended coating research into deep space. Four coatings were investigated

under prolonged exposure conditions by researchers at Jep Propulsion Laboratory (JPL) during the Mars mission.

A series of Explorer thermal flights were designed by NASA-Marshall Space Flight Center for investigation of the effects of ascent and/or space environments on the optical properties of thermal-control surfaces (Ref. 33). A thermal-surface environmental effect sensor was used to measure changes in the thermal profile after extended space exposure.

In addition, NASA-Marshall included a thermal control coatings experiment on Pegasus 1, 2, and 3 (Ref. 34). Each experiment consisted of a package containing four thermally-isolated discs, all of which were coated with a thermal control surface of interest.

General Dynamics/Astronautics designed a calorimetric experiment as part of the ARENTS Program (Ref. 35) to test six coating materials. The satellite was to be in a synchronous Earth orbit for a period greater than six months.

Future thermal flight experiments planned for launch during early 1967 are a third NASA-Ames OSO-3 flight containing 12 specimens and a Lockheed Missiles & Space Company/Air Force flight test experiment, which is part of the ASTEC Program (Ref. 36). The ASTEC thermal flight experiments utilize a reflectance degradation instrument using an integrating sphere principal to provide in-flight data on changes in specular, diffuse, and hemispherical reflectance of highly specular reflective coatings. In addition, a set of segregated environment calorimeters will expose test samples to various controlled combinations of the space environmental components.

7.3 INTERPRETATION OF DATA

7.3.1 Emittance Data Based on Hohlraum Reflectance Determinations

Although the spectral characteristics of a given material with a given surface condition and internal structure are only slightly dependent upon temperature, the spectral data

should only be used to obtain approximations of the total radiation characteristics at temperatures near the temperature at which the measurement was performed. This is true because such factors as the formation of thick oxide films on many substances at elevated temperatures and the changes of crystalline structure of phase may not be taken into account.

7.3.2 Normal Solar Absorptance

The values of α_{g} given in Section 8, based on Cary integrating sphere data, are for near-normal solar absorptance. Incident solar energy is collimated; for maximum precision in calculating satellite energy balances, α_{g} as a function of angle of incidence is required. For many vehicle geometries (such as spheres and cylinders), solar energy is normally or nearly normally incident on the external surface element absorbing most of the incident energy. For specialized shapes such as a 15-deg cone with the apex directed toward the sun, on the other hand, all energy will be at high angles of incidence. Errors in temperature predictions on the order of 30^oF can occur from use of normal solar-absorptance values in analysis (Ref. 26).

An additional problem is engendered by surface anisotropy, such as striations on metal sheet. This causes a variation in solar absorptance with the azimuthal angle of incidence. Due to asymmetry in the Cary Model 14 integrating sphere, data for surfaces with large azimuthal variations are difficult to interpret. The α_s/ϵ device and the Gier-Dunkle directional reflectance device are used to resolve this problem.

7.3.3 Ascent-Heating Data

Ascent-heating data are reported in terms of α_s versus the peak temperature encountered during a given temperature history. The designer must note that the ascentheating histories used as design criteria are for the maximum-heating case of a given vehicle. It is improbable, however, that any given vehicle will experience a maximum-heating trajectory. Consider material X with $\alpha_s = \alpha_{s_2}$ for the predicted peak temperature and $\alpha_s = \alpha_{s_1}$ initially. Generally, for orbital predictions, the designer must consider α_{s_1} to α_{s_2} as a range of possible values and add to this range the normal uncertainties given in Section 8 for material X.

7.3.4 Space-Degradation Data

Near-ultraviolet degradation information is given as curves of α_{s} versus exposure to near-ultraviolet energy. The exposure is measured in "sun-hours," a sun-hour being the product of the flux density incident upon the sample measured in "suns" and the number of hours exposed. Here a sun is defined as that flux density of solar energy in the wavelength region from 2,000 Å to 4,000 Å, which is incident upon a flat plate perpendicular to the solar vector at a distance of one astronomical unit from the sun.

The majority of ultraviolet degradation data contained in this handbook are based upon measurement of degradation after readmitting air into the exposure chamber.

A recent analysis of laboratory and flight-based data has shown that some thermal control coatings will incur damage rapidly upon exposure of the coatings to air. Discovery of this phenomenon has led to "in situ" reflectance measurements where the optical damage is recorded before admitting air into the apparatus. A limited amount of "in situ" data is included in this handbook. "In situ" measurements are planned, however, on all of the production thermal control coatings.

Caution must be exercised on the interpretation of any ground-based degradation data. For example, neglect of allowing for damage recovery effects can result in significant errors in the thermal design of specesystems. Figure 7-1 is included to illustrate this point. This figure indicates the degradation curves for LMSC Thermatrol 2A-100 resulting from pre- and post-test measurements and from "in situ" measurements. Conventional data indicates a nominal maximum change in α_s of +31 percent, while in actuality the maximum change for the material in solar ultraviolet environment is +93.5 percent.

Care must also be taken in interpreting ultraviolet data which is generated at simulated solar intensities of greater than one sun. "In situ" studies of LMSC Thermatrol 2A-100 have indicated that there is a rate dependence of damage for this coating (i.e., optical damage at 10 "suns" for 5 hours is not equivalent to the optical damage resulting from 1 "sun" intensity for 50 hours). This effect can be seen by comparing Figures 7-1 and 8-11.



7-11

LMSC-A847882 Vol. III <u>Combined Environments.</u> Care must also be exercised in specifying the optical properties of surfaces which must function in combined environments of space. "In situ" studies are in progress to define the extent of combined environmental damage to surfaces. However, even as the basis of pre- and post-test measurements, synergistic effects of engineering importance have been recorded (Ref. 37). Without detailed information at the present time on combined environmental effects, it is a recommended practice to use a nondegrading coating if the satellite must have reliable thermal response in space. (Important environments to consider for damaging combined effects are detailed in Section 6). The LMSC Optical Solar Reflector (OSR) coating is at present the only solar reflector coating qualified for such applications. The OSR has been subjected to extensive charge particle, ultraviolet, and combined environmental tests and has yet to be damaged.

Application of data in design. View factors of surfaces for direct insolation and for albedo radiation are commonly obtained in predicting satellite temperatures (Ref. 4). Care must be exercised, however, in applying these view factors to determine exposures to ultraviolet energy. Time-averaged view factors must be obtained for carefully selected increments of area rather than for large-curved surfaces or entire satellites. In general, areas receiving the largest exposure to ultraviolet are also the areas that most strongly affect satellite temperature through the absorption of solar and albedo energy. It is not permissible, therefore, to calculate exposures through the use of view factors averaged over an entire satellite. Consider a flat plate with normally incident solar energy, where the anticipated effect is an alteration in $\alpha_{\!\!\!\!\!S}$. The average view factor of the entire plate surface for solar energy is one-half, but clearly the correct value to use in calculating exposure for the side absorbing solar energy is unity. A further complication is introduced by the difference between the spectral distribution of the sun and that of albedo (Ref. 4); this could be of importance for some near-Earth satellites. A method of accounting for these factors in determing ultraviolet exposure has been outlined by Camack (Ref. 4).

The results of a sample calculation giving conservative results for extent of ultraviolet damage incurred by vertical satellite surfaces (such as the external surface of an Earth-oriented stabilized vertical cylinder) are shown below.

Consider a flat plate placed in a twilight ($\beta = \pm 90^{\circ}$) 2,000-mile altitude circular polar orbit with the plate oriented such that its normal is parallel to the Earth-Sun line. After 1,200 hours (50 days) in space, the α_s of the plate will increase to 0.325 if the surface is coated with LMSC Thermatrol 2A-100.

Now consider the plate to be in a noon ($\beta = 0^{\circ}$) 2,000-mile altitude circular polar orbit with the plate oriented such that its normal is parallel to its velocity vector. The α_s will increase to the above value after 4,540 hours (189 days) in space.

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Section 8 THERMAL-DESIGN MATERIALS DATA

The thermophysical property data contained in this section were obtained in the LMSC Thermophysics Laboratory.

The thermal designer is reminded of the qualifying remarks of Subsection 7.3 regarding proper interpretation of the data. Special care must be exercised in the use of near-ultraviolet degradation information.

The following code is used on the data sheets to specify the source of radiation property data (the equipment is described in Subsection 7.1):

- A. Cary integrating sphere and spectrophotometer
- B. Hohlraum and spectrophotometer
- C. Standard calorimetric emittance devices
- D. Direct α_{e}/ϵ device
- E. Emissometer unit of Optical Surface Comparator (Lion Research Corporation)
- F. Elevated temperature directional emittance device
- G. Radiometric total normal emittance apparatus
- H. Reflectometer unit of Optical Surface Comparator (Lion Research Corporation)

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8.1 THERMAL CONTROL SURFACE - SOLAR ABSORBER

8.1.1	
MATERIAL	6061 Aluminum Alloy
SUBSTRATE	Not applicable
MATERIAL DESCRIPTION	6061 Aluminum sheet (nonclad); forging and weld area chemically cleaned per PB-35 Method I
DRAWING CALLOUT	6061 Aluminum Alloy. Clean per PB-35 Method I. Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance	Data Source	Remarks
530	Sun	0.16 ^(a)	±0.04	Α	Nonclad sheet, as proc- essed per PB-35 Method I (C)
530	Sun	0.19 ^(b)	±0.06	A	Sheet sanded before processing(c)
530	Sun	0. 18 ^(b)	±0.06	A, H	Agena fuel tank. Sanded before processing per PB-35 Method I(C,d)

Sample Temperature (° R)	E	Tolerance	Data Source	Remarks
530	0.06 ^(a)	±0.03	B, E	Nonclad sheet, as processed per PB-35 Method I (C)
530	0.08 ^(b)	+0.03 -0.05	В, Е	Sheet or Agena fuel tanks. Sanded before processing per PB-35 Method (^c , d)
500	0.09	±0.06	В	Forging
600	0.10	±0.06		
400	0.10	±0.06		
500	0.10	±0.06	В	Weld Area
600	0.11	±0.06		

(a) Values of $\alpha_8 = 0.12$ to 0.27 and $\epsilon \le 0.12$ have been observed on samples improperly processed.

(b) Values of $\alpha_{\rm s} = 0.13$ to 0.33 and $\epsilon \le 0.18$ have been observed on samples sanded and improperly processed.

(c)Surfaces that are critical for thermal control purposes must be inspected with the Lion Optical Surface Comparator.

(d)Agena fuel tanks must be sanded before processing per PB-35 Method I. If external surfaces are to be thermal-control surfaces, the Optical Surface Comparator inspection is required.

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Aluminum surface is very susceptible to increases in α_{g} and ϵ caused by contamination. The surface must be protected from physical abuse, atmospheric exposure, and caustic contaminants; cleanliness must be assured.

POSTLAUNCH

There are no known restrictions, other than structural.

REMARKS

The surface characteristics of the sheet materials are subject to variations depending on fabricating operations.
8.1.2	
MATERIAL	6061 Aluminum Alloy
SUBSTRATE	Not applicable
MATERIAL DESCRIPTION	6061 Aluminum sheet (nonclad); chemically cleaned per PB-35 Method II
DRAWING CALLOUT	6061 Aluminum alloy sheet (nonclad). Clean per PB-35 Method II. Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance		Data Source	Remarks
530	Sun	0. 16 ^(a)	±0.05		Α	(b)
Sample Temperature (° R)	E	Tolerance		Data Source		Remarks
530	0.06	±0.03	В		В, Е	(b)

(a) Values of 0.11 to 0.40 for α_s have been observed where the instructions of PB-35 were not followed or were improperly applied.

(b)Surfaces that are critical for thermal control purposes must be inspected with the Lion Optical Surface Comparator.

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Aluminum surface is very susceptible to increases in α_s and ϵ caused by contamination. The surface must be protected from physical abuse, atmospheric exposure, and caustic contaminants; cleanliness must be assured.

POSTLAUNCH

There are no known restrictions, other than structural.

REMARKS

The surface characteristics of the sheet materials are subject to variations depending on fabricating operations. These values are given for the as-rolled condition.

8.1.3

MATERIAL	2024 Aluminum Alloy Sheet (nonclad)					
SUBSTRATE	Not applicable					
MATERIAL DESCRIPTION	2024 Aluminum alloy sheet (nonclad); chemically cleaned per PB-35 Method II					
DRAWING CALLOUT	2024 Aluminum Sheet. Cleaned per PB-35 Method II. Protec per LAC 1002.					

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance	Data Source	Remarks
535	Sun	0.20 ^(a)	±0.05	A	(b)
Sample Temperature (° R)	E	Тс	olerance	Data Source	Remarks
535	0.00	6	±0.03	В, Е	(b)

(a) Values of 0.15 to 0.36 for α_s have been observed where the instructions of PB-35 were not followed or were improperly applied.

(b)Surfaces that are critical for thermal control purposes must be inspected with the Lion Optical Surface Comparator.

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Aluminum surface is very susceptible to increases in α_s and ϵ caused by contamination. The surface must be protected from physical abuse, atmospheric exposure, and caustic contaminants; cleanliness must be assured.

POSTLAUNCH

There are no known restrictions, other than structural.

REMARKS

The surface characteristics are subject to variations depending on prior fabrication operations. These values are given for the as-rolled condition.

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8.1.4

MATERIAL	2024 Aluminum Alloy Sheet (Clad)
SUBSTRATE	Not applicable
MATERIAL	2024 Aluminum alloy sheet (clad); chemically cleaned per
DESCRIPTION	PB-35 Method II
DRAWING	2024 Aluminum alloy sheet (clad). Clean per PB-35 Method II.
CALLOUT	Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance	Data Source	Remarks
535	Sun	0.22 ^(a)	±0.05	A	(b)
Sample Temperature (° R)	E	Т	olerance	Data Source	Remark s
535	0.06		±0.03	B, E	(b)

(a) Values of $\alpha_{\rm B} \leq 0.28$ have been observed where the instructions of PB-35 were not followed or were improperly applied.

(b)Surfaces that are critical for thermal control purposes must be inspected with the Lion Optical Surface Comparator.

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Aluminum surface is very susceptible to increases in α_s and ϵ caused by contamination. The surface must be protected from physical abuse, atmospheric exposure, and caustic contaminants; cleanliness must be assured.

POSTLAUNCH

There are no known restrictions, other than structural.

REMARKS

The surface characteristics are subject to variations depending on prior fabrication operations. The cladding can be removed by abrasives, caustics, etc. These values are given for the as-rolled condition with cladding intact.

8.1.5

MATERIAL	Fasson Foil
SUBSTRATE	Any clean rigid surface
MATERIAL DESCRIPTION	Adhesive-backed bright aluminum foil. Type I has a clear protective coating, Type II is bare
DRAWING CALLOUT	LAC 24-4051 Type II. Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (* R)	Radiant Source	α	Tolerance		Data Source		Remarks
530	Sun	0.12	±0.04		A, D		This is Type II with no protective film on the surface
Sample Temperature (°R)	E	Tolerance D So		Dat Sour	A Ce	Remarks	
530	0.04	+ 0. 02 -0. 01		B, C, 1	D,E	This tect. Typ erly equi surf air laye alun	a is Type II with no pro- ive film on the surface. e I with the film prop- removed is essentially valent. The aluminum face has been exposed to and has the thin oxide r characteristic of minum.

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

The surface of Type II or Type I with the film removed is very susceptible to increases in α_s and ϵ caused by contamination. The surface must be protected from physical abuse, atmospheric exposure, and caustic contaminants; cleanliness must be assured.

POSTLAUNCH

This material should be used only in areas where the peak ascent temperatures are not expected to exceed 375° F; it must not be external during ascent. The method of obtaining data on ascent stability is described in Subsection 7.2.2.

REMARKS

Type II fasson foil is supplied bare, with nothing to protect the bright surface from handling and application damage to the thermal properties. Any film, such as oil or fingerprints, may increase ϵ to 0.15 or higher. Type I fasson foil, with the nitrocellulose lacquer protection, may be used in place of Type II, provided the lacquer is completely removed prior to application of the foil. The coating may be removed by wiping with a soft clean cloth, using the following solvents in this order:

- a) Lacquer thinner or methyl-ethyl-ketone (MEK)
- b) Isopropyl or ethyl alcohol

To avoid localized lifting of the foil from the substrate in vacuum or hightemperature applications due to gas evolved from the underlying adhesive, the foil should be perforated. Holes approximately 1/32 in. in diameter on 1/2 in. centers are recommended.

Cleaning and removing of the protective lacquer must be done prior to perforation of the foil to avoid introducing solvents within the adhesive.

The lacquer coating on Type I fasson is almost invisible to the eye. If any doubt exists whether the fail is Type I or Type II, or whether the lacquer has been removed, the following technique is recommended. Place the probes of ohmeter <u>lightly</u> against the foil surface; if electrical continuity is observed, the foil is bare; if electrical resistance is indicated, the probes are on the dielectric lacquer coating. Fasson foil for spacecraft or missile use should be ordered with S-277 adhesive. Nylon gloves should be worn by all persons working on or near this thermal-control surface, as specified in LAC 1002.

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8.1.6

MATERIAL	Dry Annealed Aluminum Foil (MIL-A-148C)
SUBSTRATE	Not applicable (Amendment II, $3-8-61$)
MATERIAL DESCRIPTION	MIL-A-148C Aluminum Foil; vapor degreased per LAC 0170
DRAWING CALLOUT	MIL-A-148C Aluminum Foil; vapor degrease per LAC 0170. Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance	Data Source	Remarks
530	Sun	0.12	±0.04	A, D	

Sample Temperature (° R)	E	Tolerance	Data Source	Remarks
530	0.04	+0.02 -0.01	B, C, D, E	_

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Foil surface is very susceptible to increases in $\alpha_{\rm s}$ and ϵ caused by contamination. The surface must be protected from physical abuse, atmospheric exposure, and caustic contaminants; cleanliness must be assured.

POSTLAUNCH

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There are no known restrictions, other than structural.

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8.1.7

MATERIAL	Mystik 7402 Pressure-Sensitive Aluminum Foil					
SUBSTRATE	Any clean rigid surface					
MATERIAL DESCRIPTION	Aluminum foil tape with a pressure-sensitive silicone adhesive					
DRAWING CALLOUT	LAC 24-4199. Protect per LAC 1002.					

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance	Data Source	Remarks
530 530	Sun	0.12	±0.04	A,D	
000	1200° blackbody	0.07	± 0.05	В	

Sample Temperature (° R)	Ę	Tolerance	Data Source	Remark s
530 0.04 +0 -0		+0.02 -0.01	B, C, D, E	

ENVRIONMENTAL BEHAVIOR

PRELAUNCH

Aluminum surface is very susceptible to increases in $\alpha_{\rm g}$ and ϵ caused by contamination. The surface must be protected from physical abuse, atmospheric exposure, and caustic contaminants; cleanliness must be assured.

POSTLAUNCH

The tape, if applied externally, should have mechanical fastening on both ends to prevent ascent forces from peeling the tape away from its substrate. This tape may be used internally where peak temperatures of up to 800° F are anticipated and externally for temperatures up to 750° F.

8.1.8	
MATERIAL	Chemically Polished Beryllium
SUBSTRATE	Not applicable
MATERIAL DESCRIPTION	The beryllium tested to date is known as QMV which is a Brush Co. designation that refers to the processing technique. QMV is a sintered product and is supplied in four different minimum purities (87, 98, 98.5 and 99.0 percent). Lockheed-purchased beryllium has a minimum purity of 98 percent.
DRAWING CALLOUT	QMV Beryllium. Process per PB-59, Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	R	adiant ource	α	Toler	ance	Data Source	Remarks		
530		Sun	0.50	±0.	06	A			
530	2100° F	l blackbody	0.18	±0.	05	В			
530	1500° F	l blackbody	0.15	±0.	05	В	PB-59		
530	800° F	l blackbody	0.11 ±0.06		В				
530	Sun		0.50	±0.	06	A	Not chemically polished. As machined, but free of corro- sion and fingerprints		
Sample	ε	Tolerance	Da	ita	Bemarks				

Temperature (° R)	E	Tolerance	Source	Remarks
530	0.10	±0.06	B,E	PB-59
530	0.10	±0.06	В	Not chemically polished. As machined, but free of corro- sion and fingerprints
530	0.10	±0.06	В	A previously chemically polished piece of beryllium wet sanded with #400 silicone carbide paper

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Oxidation in air at room temperature is negligible due to formation of a nonporous protective oxide film approximately 10^{-6} cm thick. In this respect, beryllium is similar to aluminum. Samples have been left outdoors in the Palo Alto environment for an entire month (June 1961) with no observable changes in optical properties. However, similar samples left out in the San Francisco environment (10 blocks from the ocean) for the same month suffered permanent corrosive damage. Following residue removal, α_s increased by 0.10 and ϵ by 0.05. Corrosion damage due to fingerprints has been observed, although the chemically polished surfaces appear to be less susceptible to this type of damage than are as-machined surfaces.

POSTLAUNCH

Normal ascent temperatures do not affect the optical properties of this material. Oxidation rates below 1400° F are negligible. Heating to 1600° F within 3 minutes followed by normal cooling in a one-atmosphere environment resulted in an increase of ϵ of only 0.04. Heating to 1700° F within five minutes in a 0.05-mm Hg environment resulted in a 0.01 increase in ϵ .

REMARKS

As the above measurements indicate, machined or sanded beryllium surfaces have the same nominal optical properties as the chemically polished surfaces. However, it is not always possible to adequately protect as-machined surfaces, and sanding can be a health hazard. The PB-59 chemical polishing process is not difficult and will ensure a surface finish with known optical properties. Additionally, the chemically-polished surfaces appear to resist corrosion better than the machined surfaces, although there is no quantitative data to support this observation.

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MATERIAL Inconel Foil (Hitco Specification Number TPS-0101B, H. Thompson Company)	Inc. The	el Foil (Hitco Spec pson Company)	eification Number	TPS-0101B,	H.	I.
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SUBSTRATE Not applicable

MATERIAL Nickel-chrome alloy, a nonmagnetic heat- and corrosion-resisting alloy which will withstand temperatures up to 2200° F with high-temperature strength and resistance to progressive oxidation and fatigue. This foil has been "quilted." The general appearance is of a foil that has been corrugated twice, with the directions of the corrugations perpendicular to each other.

DRAWINGASM 5540, MIL N-6840.Solvent clean per LAC 0170.CALLOUTProtect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (°R)	Radiant Source		α	Tolerance	Data Source	Remarks
530 530	Sun 800° R blackbody		0.38 0.32	±0.05 ±0.05	A B	_
Sample Temperature (° R)	E	Tolerance		Data Source	e	Remarks
400 500 600	0.11 0.12 0.13	±0.05 ±0.05 ±0.05		B, F	e	

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Highly polished foil is very susceptible to increases in α_s and ϵ by fingerprinting and oxidation of surface. Permanent damage may ensue unless contamination is removed immediately and the surface protected per LAC 1002.

POSTLAUNCH

Ascent heating is very likely to increase α_s and ϵ . Measurements performed on samples scorched during a test-engine firing have given α_s values as high as 0.91 and room-temperature emittances as high as 0.27.

REMARKS

Chemical polish may be performed on sheet material only; it is not suitable for completed assemblies.

8.1.10	
MATERIAL	Inconel X Foil
SUBSTRATE	Not applicable
MATERIAL DESCRIPTION	Age-hardened nickel-chromium alloy which has high strength and low creep rate at temperatures up to 1500° F, after suitable thermal treatment. The material has high resistance to chemical corrosion and oxidation.
DRAWING CALLOUT	ASM 5542, MIL-N-7786. Clean per PB-38. Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	α Tolerance		Data Source	Remarks
530	Sun	0.66	±0.09		A	
530	800° R blackbody	0.18				_
	1800° R blackbody	0.25	±0.04		В	
·····	2100° R blackbody	0.27				
Sample Temperature (° R)	E	Tolerance D So		Da Sou	ata irce	Remarks
500	0.15	±0.05			E	
900-2,000° R	see Fig. 8-1					-

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

The highly polished foil is very susceptible to increases in α_s and ϵ by fingerprinting and oxidation of surface. Permanent damage may ensue unless contamination is removed immediately and the surface protected per LAC 1002.

G

POSTLAUNCH

Ascent heating is very likely to increase α_{g} and ϵ by 100 percent or more. Results of total normal-emittance measurements performed in air are shown in Fig. 8-1. Data were obtained with the Radiometric Total Normal Emittance apparatus "G." Each ϵ value was obtained with the sample held at constant temperature for over one hour. The figure shows data from the first test-cycle

ascent with progressive increases in temperature and a second successive cycle descent with progressive decreases in temperature.

Note that the lowest data point in Fig. 8-1 ($\epsilon = 0.16$) is not an initial roomtemperature value but a value of ϵ for Inconel X after more than one hour at 900° R in air. The primary cause for the increased ϵ values for Inconel X in air is oxidation. At a given temperature in air, 85 percent or more of the expected change in emittance will occur within the first hour of exposure.

REMARKS

Chemical polish PB-38 may be performed on sheet material only; it is not suitable for completed assemblies.



Fig. 8-1 Normal Emittance of Inconel X Foil



8.2 THERMAL CONTROL SURFACE - SOLAR REFLECTOR

8.2.1					
MATERIAL	Tinted White Kemacryl Lacquer (Sherwin-Williams M49WC17) ^(a)				
SUBSTRATE	Any clean, rigid substrate; primer required				
MATERIAL DESCRIPTION	White acrylic flat paint, room-temperature cured				
DRAWING CALLOUT	Finish per PB-55 (see Remarks). Material per LAC 37-4033 Class I for topcoat and LAC 37-4036 Class I for primer. Protect per LAC 1002.				

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance	Data Source	Remarks
530	Sun	0.28 ±0.04		A, D	Tinted ^(a)
Sample Temperature (° R)	E	Tolerance		Data Source	Remarks
530	0.86	±0.03		B, C, D, E	_

(a)Only tinted Kemacryl is approved for thermal control use.

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

The surface is porous and requires protection from contamination per LAC 1002.

POSTLAUNCH

This material requires a minimum of 14 days of room-temperature curing to remove volatile materials sufficiently to minimize blistering during ascent heating.

<u>Ascent</u>. The affect of ascent heating is shown in Fig. 8-2, where α_{g} at room temperature is plotted as a function of the peak temperature experienced during ascent heating. Time held at peak temperatures and ambient pressures are as indicated. At peak temperatures less than $450-500^{\circ}$ F, the most serious stability problem results from outgassing or bubbling of the surface. Bubble height was < 0.04 in.; bubble diameter 0.1 in. Bubbling commenced at peak temperatures of 205° F and above. This material may be used in locations where maximum

temperatures encountered during ascent are less than 450° F, provided the alterations in surface finish and solar absorptance due to the bubbling discussed herein and shown in Fig. 8-2 can be tolerated. If no change in surface finish or solar absorptance is allowable, the maximum temperature encountered must be less than 200° F. Method of obtaining these data is described in Subsection 7.2.2. <u>Orbital.</u> The primary source of degradation appears to be the near-ultraviolet portion of incident solar and albedo radiation. Presently available data on ultraviolet damage are summarized in Fig. 8-3. The methods of obtaining and interpreting the data are described in Subsection 7.2.2.

The following half-cylinder specimens successfully survived 385 temperature cycles between 150° F and 70° F with a 12–15 min. cycling period in a vacuum of 10^{-5} mm Hg:

• White Kemacryl Lacquer (Sherwin-Williams M49WC17); 3.0 to 4.0 mil thick; over one coat pretreatment primer P40GCI; on Dow-17 coated HM21 magnesium alloy

• The same coating system as above on a 6061-aluminum alloy substrate The equipment is described in Subsection 7.2.2. No serious flaking, cracking, or loss of adhesion was observed.

The results are interpreted as demonstrating the behavior of Kemacryl-base paints on the substrates specified above during orbital temperature cycling.

REMARKS

For internal applications, where emittance is the value of interest, a minimum thickness of 1.0 mil should be maintained (PB-55 Method I Class A). For external surfaces, where both α_s and ϵ are important, the minimum thickness for opacity is 5.0 mil (PB-55 Method II Class A).





8-25





8-26

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8.2.2	
MATERIAL	Fuller Gloss White Silicone Paint (517-W-1)
SUBSTRATE	HM21A-T3 magnesium annealed (-0) magnesium and aluminum,
	titanium, stainless steels and super alloys, and any other rigid
	substrate capable of withstanding the cure cycle.
MATERIAL	TiO_2 pigment in silicone-modified alkyd vehicle. Cured by baking
DESCRIPTION	at 465°F (see PB-55).
DRAWING CALLOUT	Finish per PB-55 (see Remarks). Material per LAC-37-4038 Class IV. Protect per LAC 1002

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance		Data Source	Remarks
530	Sun	0.25 ±0.03		A	_	
Sample Temperature (° R)	ε	Tolerar	ice	l Se	Data Durce	Remarks
530	0.90	+ 0.03 - 0.00	3 6	E	9, E	

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

The surface must be handled and protected per LAC 1002.

POSTLAUNCH

<u>Ascent</u>. The effect of ascent heating is shown in Figs. 8-4 and 8-5, where α_s at room temperature is plotted as a function of the peak temperature experienced during ascent. Time held at peak temperatures and ambient pressures are as indicated. This paint is not recommended for general use in locations reaching temperatures above 650° F during ascent, for at temperatures from 690° F to 775° F, the paint surface cracks. The method of obtaining the data is described in Subsection 7.2.2.

<u>Orbital.</u> The primary source of degradation appears to be the near-ultraviolet portion of incident solar and albedo radiation. Presently available data on

ultraviolet damage are summarized in Fig. 8-6. The methods of obtaining and interpreting this data are described in Subsection 7.2.2, as is the equipment used in performing simulated orbital thermal cycling tests. The results recorded in Table 8-1 were observed during cycling tests with 12 to 15-minute periods at a vacuum of 10^{-5} mm Hg.

Table 8-1

THERMAL CYCLING RESULTS FOR GLOSS WHITE SILICONE PAINT (FULLER 517-W-1)

Material	Temperature Range	Number of Cycles	Results
517-W-1 White Silicone on Dow 17-coated flat plate of HM21A mag- nesium alloy, $1-1/4$ in. $\times 2-1/2$ in. \times 0.060 in.	-240° F + 70° F	170	Severe cracking occurred on first cycle. As test progressed, cracks increased both in number and se- verity. Testing was terminated at the 170th cycle because large sec- tions of paint ($\approx 1/8$ in.strips) be- gan to peel back.
517-W-1 White Silicone on Dow-17 coated half cylinder of HM21A mag- nesium alloy, 2-1/2 in. long, 5/8 in. radius	– 240° F + 70° F	1210	Three fine cracks extending around circumference appeared after 45 cycles. After 170 cycles, six cracks were visible. At 332 cycles, the surface had become covered with cracks ranging from hairline to fairly wide, through which the substrate was visible. At 433 cycles two small specks fell off the surface. No major visual change occurred from this point to the end of the test.

REMARKS

These results are interpreted as demonstrating the behavior of all approved Fuller silicone thermal-control paints during orbital thermal cycling. Evaluation is continuing.

For internal applications, where emittance is the value of interest, a minimum thickness of 1.0 mil should be maintained (PB-55 Method 5, Class C). For external surfaces, where both $\alpha_{\rm g}$ and ϵ are important, the minimum thickness for opacity is 5.0 mil, (Method 6, Class C).



Fig. 8-4 Effect of Ascent Heating on Solar Absorptance of Fuller Gloss White Silicone Paint on 6061 Aluminum





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8.2.3

MATERIAL	White Skyspar Enamel (A. Brown A423 Color SA 9185)
SUBSTRATE	Any rigid substrate
MATERIAL DESCRIPTION	TiO ₂ pigmented epoxy-base paint, room-temperature cured
DRAWING CALLOUT	Finish per PB-55 (see Remarks). Material per LAC 37-4036 Class I and LAC 37-4037 Class I. Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source α		Т	olerance	Data Source	Remarks	
530	Sun	Sun 0.22		-0.04	A, D	-	
Sample Temperature (° R)	ε	Tolerance		e	Data Source		Remarks
530	0.91		+ 0.03 -0.06		В,С	, D, E	~

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

The resistance to ultraviolet degradation is low. Sufficient ultraviolet energy is radiated by the common flourescent lights used throughout the fabrication areas to measureably change the $\alpha_{\rm g}$ values after several months of exposure. Samples exposed within six inches of these lights for 60 days displayed an increase in $\alpha_{\rm g}$ of 0.06. Epoxy paints are generally resistant to most chemical environments anticipated. LAC 1002 protection from contamination is required.

POSTLAUNCH

<u>Ascent</u>. The effect of ascent heating is shown in Fig. 8-7, where α_s at room temperature is plotted as a function of the peak temperature experienced during ascent. Time held at peak temperatures is two minutes; ambient pressure is 10^{-3} mm Hg. This paint is not recommended for general use in locations reaching temperatures above 450° F during ascent. The method of obtaining the data is described in Subsection 7.2.2.



<u>Orbital</u>. The primary source of degradation appears to be the near-ultraviolet portion of incident solar and albedo radiation. Presently available data on ultraviolet damage are summarized in Fig. 8-8. The method of obtaining and interpreting the data is described in Subsection 7.2.2.

REMARKS

For internal application, where emittance is the value of interest, a minimum thickness of 1.0 mil should be maintained (PB-55 Method 3, Class B). For external surfaces where both α and ϵ are important, the minimum thickness for opacity is 4.0 mil (PB-55 Method 4, Class B).



Fig. 8-7 Effect of Ascent Heating on Solar Absorptance of White Skyspar Enamel on Dow-15 Coated HM21A Magnesium



solar absorptance, a

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MATERIAL Optical Solar Reflector (OSR) Silver Coated, Fused, Silica, Second Surface Mirror

SUBSTRATEAluminum alloys per Surface Preparation LAC 3013, PrimerLAC 30-4325 and Adhesive RTV-615 per LAC 30-4324.

MATERIALVapor-deposited silver on Corning No. 7940 fused silica with an
overcoating of vapor-deposited inconel. Recommended standard
mirror size approximately 1 in. x 1 in. x .008 in. thick.

DRAWINGSecond Surface Mirrors per LAC 42-4322. Application perCALLOUTLAC 3801. Clean and protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (^O R)	Radiant Source	a	Tolerance	Data Source	Remarks
325-530	Sun	0.050	±0.005	A, D	_
Sample Temperature (^O R)	£	To	lerance	Data Source	Remarks
260 360 460 560 660	0.744 0.800 0.807 0.795 0.795	L) 7 5)	±.01 ±.01 ±.015 ±.02 ±.02	C C C C C C	.008-In. Fused Silica .008-In. Fused Silica .008-In. Fused Silica .008-In. Fused Silica .008-In. Fused Silica

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Optical Solar Reflectors are fragile and should be protected from mechanical damage during storage and shipping. Surface contamination including fingerprints, oil, dust, and atmospheric weathering does not cause permanent degradation after application. However, temporary contaminants must be removed prior to launch per LAC 3801.

POSTLAUNCH

This surface requires a minimum of 14 days of room-temperature curing to minimize outgassing of the adhesive during ascent.



<u>Ascent.</u> The effect of ascent heating on OSR is unknown. However, no significant change in α_s is anticipated up to the approximate 500[°]F limit of the adhesive. Availability of improved adhesives may extent this temperature limt. Future experiments are planned to investigate adhesive outgassing, mirror optical properties at higher temperatures and mirror thermal shock capabilities.

<u>Orbital.</u> Presently available data on ultra-violet damage reveal no measurable change in a_s due to near-ultraviolet radiation as summarized in Fig. 8-9. The methods of obtaining the data is described in Subsection 7.1.3. The coating is also stable for extended missions of up to two years in all charged particle environment and combined environments of space; this coating has been extensively investigated and has never been damaged.

REMARKS

OSR panels have successfully passed sinusoidal and random vibration tests per "Lockheed Aircraft Corporation General Environmental Specification For Agena Satellite Programs" - LMSD 6117-D.



Fig. 8-9 Effect of Near-Ultraviolet Radiation on Solar Absorptance of Silver-Coated Optical Solar Reflectors

8-39

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MATERIAL Optical Solar Reflector (OSR) Aluminum Coated, Fused, Silica, Second Surface Mirror

SUBSTRATE Aluminum alloys per Surface Preparation LAC 3013, Primer LAC 30-4325 and Adhesive RTV-615 per LAC 30-4324.

MATERIALVapor-deposited aluminum on Corning No. 7940 fused silica withDESCRIPTIONan overcoating of vapor-deposited silicon monoxide. Recommended
standard mirror size approximately 1 in. x 1 in. x .008 in. thick.

DRAWING Second Surface Mirrors per LAC 42-4322. Application similar to LAC 3801. Clean and protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (⁰ R)	Radiant Source	a	Tolerand	e Data Source	Remarks
325-530	Sun	0.100	0.100 ±0.005 A,		-
Sample Temperature (⁰ R)	e	Tol	lerance	Data Source	Remarks
260 360 460 560 660	$\begin{array}{c} 0.744 \\ 0.800 \\ 0.807 \\ 0.795 \\ 0.790 \end{array}$	E E E E	=.01 =.01 =.015 =.02 =.02	C C C C C	.008–In. Fused Silica .008–In. Fused Silica .008–In. Fused Silica .008–In. Fused Silica .008–In. Fused Silica

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Optical Solar Reflectors are fragile and should be protected from mechanical damage during storage and shipping. Surface contamination including fingerprints, oil, dust and atmospheric weathering does not cause permanent degradation after application. However, temporary contaminants must be removed prior to launch per LAC 3801.

POSTLAUNCH

This surface requires a minimum of 14 days of room-temperature curing to minimize outgassing of the adhesive during ascent.

<u>Ascent</u>. The effect of ascent heating on OSR is unknown. However, no significant change in a_s is anticipated up to the approximate 500^oF limit of the adhesive. Availability of improved adhesives may extend this temperature limit. Future experiments are planned to investigate adhesive outgassing, mirror optical properties at higher temperatures and mirror thermal shock capabilities.

<u>Orbital</u>. Presently available data on ultraviolet damage reveal no measurable change in a_s due to near-ultraviolet radiation as summarized in Fig. 8-10. The methods of obtaining the data is described in Subsection 7.1.3. This coating is also stable in all important combined environments of space.

REMARKS

OSR panels have successfully passed sinusoidal and random vibration tests per "Lockheed Aircraft Corporation General Environmental Specification For Agena Satellite Programs" - LMSD 6117-D.



Fig. 8-10 Effect of Near-Ultraviolet Radiation on Solar Absorptance of Aluminum-Coated Optical Solar Reflectors

8-43

8.2.6	
MATERIAI	•

MATERIAL Thermatrol (2A-100) White Air Drying Silicone Paint

SUBSTRATE Any clean substrate (rigid and non-rigid); primer required; may also be applied onto PBSS paints and primers, and onto Mystik No. 7402 aluminum tape.

MATERIALTiO2 pigment in elastomeric silicone (di-methyl siloxane) vehicle.DESCRIPTIONRoom temperature cured requiring atmospheric moisture and solvent evaporation.

DRAWING Finish per PB-105-101. Materials per LAC 37-4294-101. Protect CALLOUT per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (^O R)	Radiant Source	a	Tolerand	Data Source	Remarks
500-700	Sun	0.16	±0.03	A, G	_
Sample Temperature (^O R)	e	Tole	rance	Data Source	Remarks
530	0.95	+0 -0	.02 .03	B, D, E	-

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

The surface is soft and rubbery and should be protected from abrasion or scratches. This material is electrostatic and requires protection from con-tamination per LAC 1002.

POSTLAUNCH

This material requires a minimum of 24 hours of room-temperature cure to remove volatile materials sufficiently to avoid blistering during ascent heating.

<u>Ascent</u>. Ascent heating histories with peak temperatures $\leq 650^{\circ}$ F cause an increase in a_{s} of 0.03 or less; ε is unaffected. The method of obtaining the data is described in Subsection 7.2.2.

Orbital. The primary source of degradation appears to be the near-ultraviolet portion of incident solar and albedo radiation. Presently available data on ultraviolet damage are summarized in Fig. 8-11. The methods of obtaining and interpreting this data are described in Subsections 7.2.2 and 7.3.

REMARKS

For internal application, where emittance is of primary interest, a minimum thickness of 1.0 mil should be maintained. For external surfaces, where both a_s and ε are important, the minimum thickness for opacity is 3.5 to 5.0 mils (PB 105-101).

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8.3 THERMAL CONTROL SURFACE - FLAT ABSORBER

8.3.1

MATERIAL	Black Kemacryl Lacquer (Sherwin-Williams M49BC12)
SUBSTRATE	Any clean, rigid substrate; primer required
MATERIAL DESCRIPTION	Room-temperature cured black acrylic flat paint
DRAWING CALLOUT	Finish per PB-55 (see Remarks). Material per LAC 37-4033 Class II for topcoat and LAC 37-4036 Class I for Primer. Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance		Data Source	Remarks
530	Sun	0.93	±0.03		A	-
Sample Temperature (° R)	ε	Toler	ance	l Sc	Data Durce	Remarks
530 _.	0.88	± 0.03		B, E		-

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

The surface is porous and requires protection from contamination per LAC 1002.

POSTLAUNCH

<u>Ascent</u>. This paint requires a minimum of 14 days of room-temperature curing to remove volatile materials sufficiently to minimize blistering during ascent heating. It is not recommended for general use in locations reaching temperatures above 450° F; at temperatures less than this, $\alpha_{\rm g}$, ϵ , and adhesives are unaffected. At peak temperatures above 470° F, the paint blisters. The method of testing is described in Subsection 7.2.2.

<u>Orbital.</u> No orbital degradation has been observed in tests of the natural space environment. The following half-cylinder specimens successfully survived 385 temperature cycles between -150° F and 70° F with cycling periods of from 12 to 18 minutes in a vacuum of 10^{-5} mm Hg.

- White Kemacryl Lacquer (Sherwin-Williams M49WC12); 3.0 to 4.0 mil thick; over one coat pretreated primer P40GC1; or Dow 17 on HM21 magnesium alloy
- The same coating system as above on a 6061 aluminum alloy substrate. The equipment is described in Subsection 7.2.2. No serious flaking, cracking, or loss of adhesion was observed.

These results are interpreted as demonstrating the behavior of Kemacryl-base paints on the substrate specified above, during orbital temperature cycling.

REMARKS

For both internal and external applications, the minimum thickness for opacity is 1.5 mil (PB-55 Method, Class A).

8.3.2					
MATERIAL	Fuller Black Silicone Paint (517-B-2)				
SUBSTRATE	HM21A-T8 Magnesium, annealed (-0) magnesium and aluminum, titanium, stainless steels and superalloys, and any other rigid substrate capable of withstanding the cure cycle				
MATERIAL DESCRIPTION	Lamp black pigment in silicone vehicle; cured by baking at 465° F (see PB-55)				
DRAWING CALLOUT	Finish per PB-55 (see Remarks). Material per LAC 37-4038 Class V. Protect per LAC 1002.				

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance		Data Source	Remarks
530	Sun	0.89	±0.05		A	-
Sample Temperature (° R)	€	Tolera	nce Dat Sour		a ce	Remarks
530 ·	0.88	±0.05		B, E		-

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Handle and protect per LAC 1002

POSTLAUNCH

<u>Ascent</u>. Adhesion, $\alpha_{\rm g}$ and ϵ are unaffected by ascent-heating histories with peak temperatures $\lesssim 1070^{\circ}$ F. The material has not been evaluated at higher temperatures. The method of obtaining the data is described in Subsection 7.2.2.

<u>Orbital</u>. In tests simulating exposure to extraterrestrial solar near-ultraviolet energy in vacuum, changes in $\alpha_{\rm g}$ of 0.05 or less were observed after 600 "sunhours." It is suspected that even changes as small as 0.05 may not be real. Simulated orbital thermal-cycling tests were performed on white silicone paint (Fuller 517-W-1) with the equipment described in Subsection 7.2.2. Results observed during cycling tests with 12 to 15-minute periods in a vacuum of 10^{-5} mm Hg are shown in Table 8-1 on p. 8-28.
REMARKS

These results are interpreted as demonstrating the behavior of all approved Fuller silicone thermal-control paints during orbital thermal cycling. For both internal and external application, the minimum thickness for opacity is 1.0 mil (PB-55 Method 5, Class C).

8-52

8.3.3	
MATERIAL	Rokide C
SUBSTRATE	René 41 with a two-mil coating of nichrome
MATERIAL DESCRIPTION	Rokide C is essentially chromic oxide (85 percent Cr_2O_3), flame-sprayed by Norton Abrasive Company.
DRAWING CALLOUT	Flame spray coat per PB-41. Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α Tolerance		e Data Source	Remarks
530	Sun	0.90	±0.04	A	
530	2100° R blackbody	0.84	±0 .04	В	
530	1500° R blackbody	0.84	±0.04	В	
530	800° R blackbody	0.82	±0.04	В	
Sample Temperature (° R)	E	Tolerance		Data Source	Remarks
400	0.85	±	0.04	С, В	See Fig. 8-12
600	0.85	±	0.04	С, В	
800	0.85	±	0.04	С, В	
1,000	0.86	±	0.04	С	
1,300	0.86	±0.04		С	
1,600	0.86	±0.04		С	
1,900	0.86	±0.04		С	
2, 100	0.86	±0.04		С	

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

The Rokide-C coating is extremely hard and is very inert chemically. Consequently, no problem with the prelaunch environment is anticipated.

POSTLAUNCH

There is no degradation of optical properties resulting from ultraviolet exposure. Because of the differential in thermal expansion between typical oxide coating and metal substrates, there is always concern about the adhesion of such coatings during rapid changes of temperature. The René 41-nichrome-Rokide C combination thermal control system has been checked for possible thermal shock damage. Heating complex shapes to 2100° R within 5 minutes followed by a 5-minute cooling period has resulted in no coating failures.

REMARKS

The bonding between the substrate material, nichrome, and the Rokide C is purely mechanical. Rokide C may be used on other metallic substrates; however, thermal shock stability should always be checked experimentally for any new substrate. Because of the mechanical bonding requirement, all substrates must be grit blasted before coating application.



Fig. 8-12 Emittance of Rokide C

8-54

8.3.4	
MATERIAL	Platinum Black
SUBSTRATE	QMV Beryllium
MATERIAL DESCRIPTION	The platinum-black thermal control surface is essentially a deposit of finely divided platinum on Beryllium. It is deposited from a solution of chloroplatinic acid (H ₂ PtCl ₆). Application is by spraying.
DRAWING CALLOUT	Platinum-black coating per PB-59. Protect per LAC 1002.

Sample Temperature (° R)	Radiant Source		α Το		olerance	Data Source	Remarks
530	Sun		0.94		±0.03	A	· · ·
530	2100° R black	cbody	0.85		±0.05	В	
Sample Temperature (° R)	E	Tolerance		Data Source	Remarks		
360	0.80		±0.07		С	Uncertainty reflects	
500	0.80		±0.07		B, C	process variables rather	
540	0.85	±0.07			С	than measurement	
720	0.88	±0.07		С	accuracy		
900	0.90	±0.07		С			
1,080	0.90		±0.07		С		
500	0.77	±0.07			С	After heati	ng to 1500° F
						for 3 hr in	a 10 ⁻⁵ mm
						Hg environ	ment
500	≥0.45	-			В	Value obtai	inable if PB-59
						is not follo	wed

THERMOPHYSICAL PARAMETERS

Curves displaying effects of elevated temperatures on platinum black are shown in Figs. 8-13 through 8-18.

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

No corrosive effects resulting from normal storage and/or atmospheric exposure have been observed. However, the platinum-black surface has not been tested in a more corrosive environment, such as a salt spray. The surface is porous and must be carefully protected from contamination per LAC 1002.

POSTLAUNCH

Ascent heating (short-duration heating) temperatures of less than 1200° F will not change the optical properties of the surface. Effects of elevated temperature are shown in Figs. 8-15 and 8-18. It is believed that above 390° F (200° C), some sintering of the finely divided platinum particles occurs. The following review of recent platinum black investigations gives a graphic picture of thermal stability of this surface.

1. The spectral normal emittances for two high-quality platinum black coatings are shown in Figs. 8-13 and 8-14 by the curves labeled A. The spectral curves from samples with poorer quality coatings deviated from these curves primarily in the long-wavelength region beyond 8μ . For low-quality coatings, the emittance decreased with wavelength to values as low as 0.40 at 20 μ .

Curves B and C on Fig. 8-13 show the effect of heating samples to 1173° K in a vacuum of 10^{-6} mm Hg, Curve B shows the spectral emittance after a 2-hr exposure, Curve C after a 6-hr exposure. As shown, the principal effect on spectral emittance occurred in the wavelength region between 8 and 16 μ . The increase in reflectance at 13 μ appeared in all samples which were heated above 773° K in either vacuum or air.

2. The total normal emittance of platinum black as a function of its temperature is shown in Fig. 8-15. These curves are obtained by integrating the spectral reflectance data after it has been appropriately adjusted for the blackbody curve for each temperature. Curve A was obtained from the spectral data from an as-received sample (Curve A of Fig. 8-13). Curve B was obtained from the spectral data from a sample which had been aged at 1173° K for 2 hr in vacuum (Curve B of Fig. 8-13). As shown, the difference between the two curves decreases as the temperature is increased from about 14 percent at 200° K to less than 3 percent at 1000° K.

3. The variation of the total hemispherical emittance of platinum black as a function of its absolute temperature in vacuum is shown in Figs. 8-16 and 8-17. These values were determined directly by the calorimetric steady-state method.

The sample of Fig. 8-16 was thermal cycled five times, with the emittance decreasing slightly after each cycle to the high temperature. The main decreases in emittance occurred at the low temperatures (less than 400°K). This corresponds to the formation of the decreasing emittance band at 13μ at the high temperature. A slight visible change in the quality of the surface was observed at the end of the test. The surface was smoother. as if the original diffuse surface had fused. The total hemispherical emittance of the platinum-black coating remained stable above 400°K. The two high-emittance values obtained at the temperatures above 900° K are suspected to be the result of thermocouple error rather than of change in emittance. Long-term stability tests (Fig. 8-17) have shown the emittance of platinum black on beryllium to be stable for 30-day periods in vacuum at temperatures of 600° F and 1000° F. At 1500° F, the emittance was found to be unstable, apparently due either to reactions between the platinum black and the beryllium, or to sintering of the platinum black. In X-ray diffraction studies made after the 30-day exposure, the platinum diffraction pattern was no longer evident.

4. In Fig. 8-18, the total normal emittance as derived from integrated spectral data is shown in comparison with the calorimetrically determined total hemispherical emittance of Fig. 8-16. Close agreement is observed in the temperature range 300 to 850°K. In this temperature range, both curves show the same general character. Relatively large deviations between the two curves occur only at the low and high temperatures. It is at these extremes that changes in the surface quality occur which affect the surface emittance. The integrated spectral data is based upon a room-temperature measurement and is extrapolated to other temperatures. Thus it does not reflect changes in surface quality which occur with temperature.

5. The room-temperature spectral normal emittance as a function of wavelength is shown in Curve A of Fig. 8-14. Curve B shows the spectral emittance of the sample after exposure to air at a temperature of 1270°K, for 5 minutes. This emittance decreased at wavelengths greater than 7μ . After the exposure, the sample surface had a greyish color and the total normal emittance decreased from 0.85 to 0.80. Exposure at this temperature for longer periods of time produced severe oxidations of the beryllium substrate; at the end of one hour the substrate was oxidized beneath the coating. After exposure for 20 minutes to air at a temperature of 970°K, the spectral emittance shown by Curve C was obtained. No visible change in the surface quality was observed. Very little oxidation of the beryllium substrate occurred at these temperatures. The total normal emittance decreased from 0.89 to 0.77. No further changes in emittance were observed for exposures of up to 5 hours. The characteristic reflection band at 13 μ was observed for all samples heated in air above 850° K.



Fig. 8-13 Spectral Normal Emittance of Platinum Black on Beryllium





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cance of Platinum Black on Beryllium

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MATERIAL	Dow-17 Anodize on HM21A Magnesium Alloy			
SUBSTRATE	HM21A-T8 Magnesium Alloy Sheet			
MATERIAL DESCRIPTION	An anodic conversion coating for magnesium alloys – a proprietary process of the Dow Chemical Company			
DRAWING CALLOUT	Anodize per PB-72. Protect per LAC 1002.			

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	Q	Tolerance		Data Source	Remarks
530	Sun	0.78	±0.08		A	PB-72
Sample Temperature (° R)	ε	Tolerance		Data Source		Remarks
530	0.70	±0.06		В,	E	PB-72

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

The surface is porous and requires the necessary protection per LAC 1002 if used as a thermal control surface.

POSTLAUNCH

There are no unusual restrictions other than structural requirements of the substrate. Thermal stability above 500° F is in doubt.

REMARKS

The surface can be cleaned with most inert solvents. PB-72 must be followed to obtain the above design values.

8.4 THERMAL COI 8.4.1	NTROL SURFACES – FLAT REFLECTOR
MATERIAL	Fuller Aluminum Silicone Paint (172-A-1)
SUBSTRATE	HM21A-T8 Magnesium, annealed (-0) magnesium and aluminum, titanium, stainless steels and super alloys, and any other rigid substrate capable of withstanding the cure cycle
MATERIAL DESCRIPTION	Leafing aluminum pigment in silicone vehicle; baked on at 465° F
DRAWING CALLOUT	Finish per PB-55 (see Remarks). Material per LAC 37-4054, Class II. Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance	Data Source	Remarks
530	Sun	0.25	±0.07	A, D	-
Sample Temperature (° R)	€	Tolerance		Data Source	Remarks
530 ·	0.28	±0.07		B,C,D,E	

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Handle and protect per LAC 1002

POSTLAUNCH

<u>Ascent</u>. No change was observed in α_s and ϵ as a result of ascent heating with peak temperatures $\leq 885^{\circ}$ F. The methods of obtaining the data are described in Subsection 7.2.2.

<u>Orbital</u>. The primary source of degradation appears to be the near-ultraviolet portion of incident solar and albedo radiation. Present data indicate that α_{s} increases by $\Delta \alpha_{s} = 0.09 \pm 0.04$ after 600 "sunhours"; ϵ is unaffected. The methods of obtaining and interpreting the data are described in Subsection 7.2.2. Simulated orbital thermal-cycling tests were performed on white silicone paint (Fuller 517-W-1) with the equipment described in Subsection 7.2.2. The results observed during cycling tests with 12 to 15-minute periods at a vacuum of 10^{-5} mm Hg are shown in Table 8-1 on p. 8-28.

REMARKS

These results are interpreted as showing the behavior of all approved Fuller silicone thermal-control paints during orbital thermal cycling. For internal applications, where emittance is the value of interest, a minimum thickness of 1.0 mil should be maintained (PB-55 Method 5, Class C). For external sources, both $\alpha_{\rm g}$ and ϵ are important. The minimum thickness for opacity is 3.0 mil (PB-55 Method 6, Class C).



8.4.2	
MATERIAL	Fuller Aluminum Silicone Paint (171-A-152)
SUBSTRATE	HM21A-T8 Magnesium, annealed (-0) magnesium and aluminum titanium, stainless steels, and super alloys, and any other rigid substrate capable of withstanding the cure cycle
MATERIAL DESCRIPTION	Leafing aluminum pigment in silicone vehicle; baked on at 465° F
DRAWING CALLOUT	Finish per PB-55 (see Remarks). Material per LAC 37-4054 Class I. Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (° R)	Radiant Source	α	Tolerance		Data Source	Remarks
530	Sun	Sun 0.22 ±0.04		4	A,D	
Sample Temperature (° R)	E	Tolerance		Da Sou	ta rce	Remarks
530	0.24	±0.04		В,С	, D, E	

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

Handle and protect per LAC 1002.

POSTLAUNCH

<u>Ascent</u>. Ascent heating histories with peak temperatures $\leq 880^{\circ}$ F cause an increase in α_{s} of 0.01 or less; ϵ is unaffected. The method of obtaining the data is described in Subsection 7.2.2.

<u>Orbital.</u> The primary source of degradation appears to be the near-ultraviolet portion of incident solar and albedo radiation. Present data indicate that $\alpha_{\rm g}$ increases by $\Delta \alpha_{\rm g} = 0.09 \pm 0.04$ after 600 "sunhours"; ϵ is unaffected. The methods of obtaining and interpreting the data are described in Subsection 7.2.2. Simulated orbital thermal-cycling tests were performed on the equipment described in Subsection 7.2.2. The results observed during cycling tests with 12 to 15-minute periods at a vacuum of 10^{-5} mm Hg are shown in Table 8-1 on p. 8-28.

REMARKS

These results are interpreted as showing the behavior of the stability of all approved Fuller silicone thermal-control paints during orbital thermal cycling.

For internal application, where emittance is the value of interest, a minimum thickness of 1.0 mil should be maintained (PB-55 Method 5, Class C). For external surfaces, where both α_s and ϵ are important, the minimum thickness for opacity is 3.0 mil (PB-55 Method 6, Class C).

8.4.3	
MATERIAL	Nonleafing Aluminum Acrylic Paint
SUBSTRATE	Any clean substrate; primer required
MATERIAL DESCRIPTION	Room-temperature cured flat acrylic-based aluminum paint
DRAWING CALLOUT	Finish per PB-55 (see Remarks). Material per LAC 37-4033 Class V for top coat vehicle, LAC 37-4098 Class II for pigment, and LAC 37-4036 Class I for primer. Protect per LAC 1002.

THERMOPHYSICAL PARAMETERS

Sample Temperature (°R)	Radiant Source	α	Tolerance		Data Source	Remarks		
530	Sun	0.38- 0.52	-		A, D	Prepared per PB-55		
530	Sun	0. 41	±0.03		±0.03		Α	Prepared per PB-55 controlled with $OSC^{(a)}$
Sample Temperature (°R)	ε	Tolera	ance D So		ta rce	Remarks		
530	0.36-0.58	-		B, D, E		Prepared per PB-55		
530	0.48	±0.0	5	E		Prepared per PB-55 controlled with OSC ^(a)		

(a)OSC = Optical Surface Comparator (Lion Research Corp.)

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

The surface is porous and requires protection from contamination per LAC 1002

POSTLAUNCH

<u>Ascent</u>. This material requires a minimum of 14 days of room-temperature curing to remove volatile materials sufficiently to minimize blistering during ascent heating. The affect of ascent heating is shown in Fig. 8-19, where α_s at room temperature is plotted as a function of the peak temperature experienced during ascent heating. Time held at peak temperatures and ambient pressures

are as indicated. At peak temperatures less than 650° F, the most serious stability problem is caused by outgassing or bubbling of the surface. Bubble height ≤ 0.015 in.; bubble diameter ≤ 0.04 in. Bubbling commenced at temperatures of 245°F and above. The material may be used in locations where maximum temperatures encountered during ascent are less than 650° F, provided the alteration in surface finish and solar absorptance due to bubbling discussed herein and shown in Fig. 8-19 can be tolerated. If no change in surface finish or solar absorptance is allowable, the maximum temperature allowable must be less than 240° F.

The following half-cylinder specimens successfully survived 385 temperature cycles between 150 and 70°F with an 18-minute cycling period in a vacuum of 10^{-5} mm Hg.

- White Kemacryl Lacquer (Sherwin-Williams M49WC17) 3.0 to 4.0 mil thick over one coat pretreatment primer P40GC1; or Dow 17 on HM21 magnesium alloy
- The same coating system as above on a 6061-aluminum alloy substrate

The equipment is described in Subsection 7.2.2. No serious flaking, cracking, or loss of adhesion was observed.

The results are interpreted as demonstrating the behavior of Kemacryl-base paints on the substrates specified above, during orbital temperature cycling.

REMARKS

For internal applications, where emittance is the value of interest, a minimum thickness of 1.0 mil should be maintained (PB-55 Method I, Class A). For external surfaces where both α_s and ϵ values are important, the minimum thickness for opacity is 3.0 mil (PB-55 Method II Class A). This material is mixed at LMSC per PB-55. The base is Sherwin-Williams Kemacryl clear acrylic vehicle, LAC 37-4033 Class V. The pigment is aluminum paste, LAC 37-4098 Class II.



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- 8.5 THERMAL CONTROL SURFACE LOW SOLAR ABSORPTANCE WITH WIDE EMITTANCE RANGE
- MATERIAL Optical thin films by vapor disposition; metal films (silver, aluminum, gold) with dielectric overlay (silicon dioxide, aluminum oxide); solar absorptance controlled by choice of metal film; emittance determined by thickness of dielectric layer.
- SUBSTRATE Any clean rigid substrate. Surface finish of substrate affects optical properties of coating. Lowest solar absorptance requires polished metal or glass substrate.

Sample Temperature (^o R)	Radiant Source	۵ _S		Data Source	Remarks
530 Sun 0.05 (silver) $\frac{\pm 0}{-0}$			2 1	A	a dependent upon metal film, sub-
		0.14 (aluminum) ±	0.02		strate finish, and deposition param-
		0.20 (gold) ±0.02		eters. See Figs. 8-20 and 8-21.	
Sample Temperature (^o R)		E So	Data urce	Remarks	
530	0.03 (overla (60,00	o 500 A dielectric ay) to 0.66 00 A dielectric)	В,	E,F	Emittance varies with dielectric thickness. Nor- mal emittance lower than total hemispherical. See Figs. 8-20 and 8-21.

THERMOPHYSICAL PARAMETERS

ENVIRONMENTAL BEHAVIOR

PRELAUNCH

The surfaces are hard and abrasion resistant. They may be cleaned by conventional techniques without deterioration of optical properties.

POSTLAUNCH

These coatings do not require a curing treatment, will not blister, and are capable of repeated thermal cycling between 30° F- 500° F, providing that the substrates are compatible with the coatings.



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LMSC-A847882 Vol. III <u>Ascent.</u> No deterioration is observed due to vacuum or thermal effects up to 500° F for silver or aluminum films. Gold films on aluminum substrates fail at these temperatures. The use of thermal diffusion barriers between the coating and substrate should provide stability up to 2000° F.

<u>Orbital.</u> No significant degradation has been observed for these systems due to simulated solar ultraviolet irradiation at 70° F and 500° F for periods up to 2000 equivalent sun horns, with the exception of the aluminum alloy/gold/silica system and the aluminum alloy/silver/alumina system at 500° F. Presently available ultraviolet exposure data are shown in Tables 8-2, 8-3, and 8-4. The results are interpreted as indicating extreme stability for the systems employing dielectric overlays up to 60,000 Å thick.

Table 8-2

RESULTS OF SCREENING TEST --250 EQUIVALENT SUN-HOURS OF ULTRAVIOLET AT 500°F 10 THERMAL CYCLES (70°F-500°F)

Substrate	Motal	Overcoat	Ab	sorptance ^(a)	Emittance ^(b)		
	metan	1000 Ă	Initial	Final	Initial	Final	
Glass ^(c)	Gold Silver Aluminum	Silica	0.187 0.051 0.126	0.178 0.051 0.122	0.03 0.04 0.07	0.045 0.035 0.06	
	Gold Silver Aluminum	Alumina	0.181 0.056 0.139	0.180 0.060 0.128	0.03 0.04 0.06	0.045 0.04 0.06	
Polished ^(d) Aluminum	Gold Silver Aluminum	Silica	0.199 0.061 0.181	Sample Failure 0.061 0.185	0.03 0.04 0.06	Sample Failure 0.03 0.05	
Aluminum Alloy	Gold Silver Aluminum	Alumina	0.183 0.070 0.129	$\begin{array}{c} 0.186 \\ 0.074 \\ 0.134 \end{array}$	0.03 0.04 0.07	0.035 0.03 0.05	
Mill ^(d) Finish	Gold Silver Aluminum	Silica	0.206 0.085 0.184	Sample Failure 0.080 0.177	0.03 0.04 0.06	Sample Failure 0.035 0.04	
Aluminum Alloy	Gold Silver Aluminum	Alumina	0.215 0.105 0.163	0.217 0.101 0.149	0.04 0.04 0.07	0.04 0.04 0.06	
Stainless ^(e)	Gold Silver Aluminum	Silica	0.202 0.071 0.164	0.202 0.061 0.169	0.02 0.04 0.06	$0.04 \\ 0.035 \\ 0.04$	
Steel	Gold Silver Aluminum	Alumina	0.199 0.076 0.141	0.204 0.077 0.135	$0.03 \\ 0.04 \\ 0.07$	$\begin{array}{c} 0.035 \\ 0.03 \\ 0.04 \end{array}$	
OSR	TP-60		0.045	0.042	0.76	0.76	

(a) Solar absorptance values valid within ± 0.005 .

(b) Emittance values from Lion emissometer valid within ± 0.01 .

(c) Corning No. 7059.

(d) 6061-T6 Aluminum Alloy.

(e) Type 430, Republic Steel No. 2 Bright Annealed.

Table 8-3

EFFECT OF ULTRAVIOLET IRRADIATION ON SILICA/ALUMINA-ALUMINUM ALLOY SYSTEMS – 2000 SUN-HOURS OF ULTRAVIOLET AT 70°F

Substrate	Metal	Dielectric	Overcoat	Absorptance ^(a) ^α s		${ m Emittance}^{(\!b)}$	
	Film	Thickness					
		о (А)	Material	Initial	Final	Initial	Final
Polished Aluminum Alloy	Silver	1,000	Silica	0.084	0.108	0.03	0.03
	Silver	2,000	Silica	0.067	0.077	0.04	0.04
	Silver	3,000	Silica	0.063	0.078	0.07	0.06
Mill-Finish Aluminum Alloy	Silver	1,000	Alumina	0.074	0.076	0.03	0.03

Table 8-4

EFFECT OF ULTRAVIOLET IRRADIATION ON SILICA/ALUMINA-ALUMINUM ALLOY SYSTEMS -2000 SUN-HOURS OF ULTRAVIOLET AT 500°F

	Metal	Dielectric	Overcoat	Absorptance (a)		Emittance ^(b) ε_{-}		
Substrate	Film	Thickness		~	S			
		(Ă)	Material	Initial	Final	Initial	Final	
Polished Aluminum Alloy	Silver	1,010	Silica	0.087	0.109	0.03	0.03	
	Silver	2,000	Silica	0.063	0.068	0.04	0.04	
	Silver	3,000	Silica	0.072	0.076	0.07	0.07	
Mill-Finish	Silver	1,000	Alumina	0.074	0.125	0.03	0.04	
Aluminum Alloy	•					0.00	0 00	
Titanium Alloy (Polished)	Aluminum	60,000	Alumina	0.144	0.152	0,60	0.60	

(a) Solar absorptance values valid within ± 0.005 .

(b) Emittance values valid within ± 0.01 .

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8.6 CONCLUDING REMARKS

In general, a thin film optical coating system is specified only when the desired thermophysical properties cannot be obtained by mechanical or chemical treatment of the substrate or by application of conventional coatings. The limitations of the conventional coatings can be their degradation in a high-temperature environment (greater than 1000° R), ultraviolet stability, high energy particle irradiation stability, high values of solar absorptance, and weight. A painted thermal control coating or tape is much more economical in initial application as well as repair or modification.

The specification of an optical-thin-film coating system cannot be justified on an economic basis for those applications in which paints, tapes, or other surface treatments are suitable. The cost is high in equipment and processing. Results are highly dependent on technique and operator's skill. In optical-thin-film systems, consideration should be given to the design of small planar panel sections that can be coated with a uniform film thickness.

The optical thin films have great advantages, in spite of cost, over conventional coated surfaces for many applications in which the paints are limited. These advantages are:

- High-temperature environment stable optical properties in excess of 1000^oR; possible applications at temperature of 2000-2500^oR if thermal diffusion barriers are used
- Ultraviolet stability
- Low values of solar absorptance (.05)
- Variable emittance from . 03 to . 66 by varying dielectric film thickness
- Resistance to high energy particle radiation damage
- Good abrasion resistance in film surfaces with dielectric overlay; readily cleaned surfaces; good corrosion resistance in prelaunch environment

- Fabrication capability of structures from small panels an alternative is to fabricate large area panels or form compound-curved surfaces from precoated stock sheets. Low-emittance surface panels (with dielectric thickness in the order of 1000 Å) can be bent 180° with a 5-sheet-thickness bend radius without failure. High emittance surfaces (3-micron dielectric films thickness) can tolerate 90° bends at approximately 10-sheet-thickness bend radius.
- Low weight by virtue of their thin film configuration, it can result in considerable payload increase.

The thermophysical parameters to be specified by the designer are substrate material and finish, desired solar absorptance and emittance of the metal, and dielectric coating. Cases in which minimum solar absorptance is desired, mechanical finishing (such as polishing) of the substrate may be necessary. Surface finish typical of commercial mill finishes is suitable for low-emittance surfaces.

The predominant controlling process parameters are dielectric film thickness for varying emittance, and deposition rate for achieving minimum absorptance. Other deposition parameters have minor effects on optical properties as long as good processing techniques are employed. If such is not the case, there can be orders of magnitude variations in optical properties.

Section 9 ADDITIONAL COATING DATA

The data presented in this section summarizes the properties and application techniques for a number of more commonly used solar reflector coatings. Special emphasis should be placed on Figs. 9-2, 9-5 and 9-8 which indicate space environmental stability and under ultraviolet exposure of these coating systems. This data has been taken "in situ" with the samples exposed to a xenon lamp ultraviolet source with a 1-sun intensity at the sample in the 0.2 to 0.4μ wavelength region. All solar absorptance data for these samples was obtained using calorimetric techniques. The accuracy of these data is attested by the fact that data obtained on Thermatrol-A100 using calorimetric techniques for determining α_s is identical within the limits of experimental error to the previously discussed data on Thermatrol-A100 obtained using bidirectional reflective techniques.

9-1 S-13 MODIFICATION II (ZnO/SILICONE)

Source

IIT Research Institute.

Method of Application

<u>Preparation of paint for application</u>. The paint is furnished without the SRC-05 catalyst. The catalyst is added as 1 part SRC-05 in 20 parts of toluene per 670 parts of S-13 (as formulated). This concentration represents 0.76% catalyst based on polymer solids. A lower concentration is recommended in order to ensure optimum stability to ultraviolet irradiation in vacuum. A concentration of 0.4% based upon RTV-602 provides optimum stability without greatly sacrificing terminal cure properties, although a coating prepared at this concentration represents the lower limit without sacrificing cure and physical properties. Somewhat better physical properties are obtained with a

catalyst concentration of 0.5% based on RTV-602. A catalyst concentration of 0.4% of resin solids corresponds to 1 part SCR-05 per 1275 parts of S-13; 0.5% catalyst requires 1 part catalyst per 1020 parts of S-13. The catalyst should be added as a 20:1 reduction in toluene. The catalyst solution is added only as the paint is used and only to the amount that can be applied in about 30 minutes. The bulk paint was furnished in 5-gal epoxy-lined metal pails. The paint should be thoroughly stirred before transfer to other containers or before addition of catalyst. Allow the catalyst paint to set for 10 minutes before application to the primed surfaces.

<u>Preparation of surfaces for painting</u>. Standard surface cleaning procedures should be used to prepare the surface for application of the S-13 paint. S-13 paint can, in general, be applied to any surface to which the required primer can be applied. The primer, General Electric's proprietary SS-4044, can be applied to either anodized or zinc chromate-primed surfaces. It is preferable that it be applied to clean bare metal or to anodized surfaces, however. Greasy surfaces should be cleaned with standard detergent and water prior to priming; they should be thoroughly dry.

Application of paint. The primer can be spray-applied (Binks model 18 or comparable gun) at about 30 psi. Only about 0.5 mil of primer is required (just enough to provide a base for the S-13 paint). The primer should be allowed to air-dry for 1 hour before application of the S-13 paint.

The S-13 paint can be spray-applied with a Binks model 18 spray gun (or comparable gun) at a gas pressure of about 60 psi. Unless clean, dry air is available, prepurified nitrogen or prepurified air must be used. The S-13 paint should be allowed to aircure for 16 hours. It is imperative that dust and debris be kept off the surface during the curing process.

The wet film thickness of the paint can be measured by either the Pfund or the Interchemical wet-film thickness gage, or a suitable bridge-type gage. Dry film thickness can be measured with a Fischer Permascope nondestructive thickness tester, type ECTH.

<u>Reapplication</u>. Soiled or damaged areas can be recoated. Soiled areas must be cleaned thoroughly with detergent and water and dried before application of additional S-13 paint. Damaged or gouged areas can be recoated by making a paste of S-13 in which the bulk of the solvent is omitted. Such a material can be trowelled or brushed over the damaged areas and cures can be tack-free within a few hours.

Coating Thickness

3.5 to 5.5 mils.

Weight Loss During Vacuum Testing

Not stated by supplier.

Final Composition

Not stated by supplier.

Initial Optical Properties

The solar absorptance α_s and infrared emittance ϵ of the S-13 samples were measured at room temperature in air. These data are reported in Table 9-1. Total emittance measurements were carried out using the Lion Optical Surface Comparator. Solar absorptances were calculated using spectral reflectance data obtained from measurements made using a Cary Model 14 spectrophotometer with integrating sphere and a Gier-Dunkel integrating sphere with a Perkin-Elmer Model 98 monochrometer. A typical spectral reflectance curve is presented in Fig. 9-1.

"In Situ" Optical Property Data

Results of the calorimetric "in situ" measurements of the S-13 coatings are given in Table 9-2. Figure 9-2 illustrates the changes in solar absorptance as a function of exposure time. This coating showed an increase in solar absorptance of 0.08 during the exposure period. Also, this increase occurred during the first 300 hr of exposure and $\boldsymbol{\alpha}_{s}$ remained essentially constant after that time.

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Fig. 9-1 Typical Spectral Reflectance of ZnO/Silicone Coating







Table 9-1

Sample	Solar Ab	Emittance	
	Cary	Gier-Dunkle	(Optical Surface Comparator)
1	0.19 ±0.02	0.20 ± 0.01	0.79 ±0.03
2	0.19 ± 0.02	0.20 ± 0.01	0.79 ± 0.03
3	0.19 ± 0.02		0.81 ± 0.03
4	0.19 ± 0.02		0.80 ± 0.03
5	0.19 ± 0.02		0.81 ± 0.03
6	0.19 ± 0.02		0.87 ± 0.03
7	0.19 ± 0.02		0.85 ± 0.03
8	0.19 ± 0.02		0.80 ± 0.03

INITIAL ROOM TEMPERATURE OPTICAL PROPERTIES OF ZnO/SILICONE (S-13) COATING

Pre- and post-exposure test room temperature reflectance data are shown for the S-13 coating in Fig. 9-3. Comparison of these data with those shown in Table 9-2 shows the recovery phenomena associated with the S-13 system in the near infrared region.

9.2 S-13G

Source

IIT Research Institute.

Method of Application

<u>Preparation of Paint for Application</u>. The paint is furnished without the SRC-05 catalyst. The catalyst is added as 1 part SRC-05 in 10 parts of toluene. The catalyst solution is added to the paint through stirring. A low catalyst concentration is recommended in order to ensure optimum stability to ultraviolet irradiation in vacuum. A concentration of 0.4% based upon RTV-602 provides optimum stability without greatly sacrificing

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Table 9-2

CALORIMETRIC TOTAL HEMISPHERICAL EMITTANCE AND "IN SITU" ABSORPTANCE DATA FOR S-13 COATING, ZnO/SILICONE AT 710°R

Hour	Cycle	Temp.	E	$\alpha_{\rm H}^{(a)}$						
		°R	TH	Total	0.2 - 0.41	0.41-0.6	0.6-0.85	0.85-	Total	
0	1	529	0.86	0.21		_		-	-	
0	1	610	0.87	0.21	-	- -		_		
0	2	710	0.86	0.21	-	-	-	-	-	
4	3	710	0.85	0.21	0.65	0.08	0.06	0.24	0.21	
53	15	710	0.86	0.23	0.65	0.10	0.06	0.27	0.23	
61	27	710	0.86	0.24	0.65	0, 15	0.06	0.28	0.24	
113	42	710	0,85	0.27	0. 70	0.15	0.08	0.30	0.26	
158	52	710	0.86	0.26	0.70	0.19	0.08	0.28	0.26	
230	82	710	0.86	0.27	0.75	0.21	0.09	0.28	0.27	
280	94	710	0.86	0.27	0.75	0.25	0.08	0.29	0.28	
330	105	710	0.87	0.26	0.70	0.26	0.10	0.28	0.28	
402	125	710	0.87	0.27	0.65	0.26	0.08	0.28	0.28	
450	136	710	0.87	0.27	0.65	0.27	0.08	0.30	0.28	
500	147	710	0.86	0.27	0.70	0.27	0.10	0.28	0.28	
	Before Exposure ^(C)		0.18	0.65	0.08	0.10	0.14	0.18		
	After Ex	xposure ⁽	c)	0.26	0.76	0.31	0.15	0.17	0.28	

(a) Absorptance for xenon source.(b) Absorptance for solar source.

(c) From Cary room temperature reflectance measurements.

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Fig. 9-3 Room Temperature Spectral Reflectance of S-13 Coating
thermal-cure properties, although a coating prepared at this concentration represents the lower limit without sacrificing cure and physical properties. Somewhat better physical properties are obtained with a catalyst concentration of 0.5% based on RTV-602 and still better properties are obtained at 0.75% SRC-05. The SRC-05 catalyst-topaint ratio is 1 part SRC-05 in 10 parts of toluene to 1030 parts of S-13G (by weight). The catalyst solution is added only as the paint is used and to only the amount that can be applied in a 30-minute period. Allow the catalyzed paint to set for 10 to 15 minutes before application to the primed surfaces. The paint should be thoroughly stirred before addition of catalyst.

<u>Preparation of Surfaces for Painting</u>. Standard surface cleaning procedures should be used to prepare the surface for application of the S-13G paint can, in general, be applied to any surface to which the required primer can be applied. The primer, General Electric's proprietary SS-4044, can be applied to either anodized or zinc chromate-primed surfaces. It is preferable that it be applied to clean bare metal or to anodized surfaces, however. Greasy surfaces should be cleaned with standard detergent and water prior to priming; they should be thoroughly dry.

<u>Application of Paint.</u> The primer can be spray-applied (Binks model 18, Paasche Autch, or comparable gun) at about 30 psi. Only about 0.5 mil of primer is required (just enough to provide a base for the S-13G paint). The primer should be allowed to air-dry for 1 to 2 hours before application of the S-13G paint.

The S-13G paint can be spray-applied with a Binks model 18 spray gun (or comparable gun) at a gas pressure of about 60 psi. Unless clean, dry air is available, prepurified nitrogen or prepurified air must be used. The S-13G paint should be allowed to aircure for 16 hours before handling. It is imperative that dust and debris be kept off the surface during the curing process.

The wet film thickness of the paint can be measured by either the Pfund or the Interchemical wet-film thickness gage, or a suitable bridge-type gage. Dry film thickness can be measured with a Fischer Permascope nondestructive thickness tester, type ECTH.

<u>Reapplication.</u> Soiled or damaged areas can be recoated. Soiled areas must be cleaned thoroughly with detergent and water and dried before application of additional S-13G paint. Damaged or gouged areas can be recoated by making a paste of S-13G in which the bulk of the solvent is omitted. Such a material can be trowelled or brushed over the damaged areas and cures tack-free within a few hours.

Coating Thickness

5.0 to 8.0 mils is recommended with actual thickness not determined. Coating weight is 0.006 lb/ft^2 as measured from test specimens.

Weight Loss During Vacuum Testing

Not stated by supplier.

Final Composition

Not stated by supplier.

Initial Optical Properties

The solar absorptance α_s and total emittance ϵ_T of a number of S-13G samples have been measured at room temperature in air. These data are reported in Table 9-3. Total emittance measurements were carried out using the Lion Optical Surface Comparator. Solar absorptances were calculated using spectral reflectance data obtained from measurements made using a Cary Model 14 spectrophotometer with integrating sphere and a Gier-Dunkel integrating sphere with a Perkin-Elmer Model 98 monochrometer. A comparison of typical spectral reflectance curves are presented in Fig. 9-4.



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Table 9-3

	Solar Ab	Emittance	
Sample	Cary	Gier-Dunkle	(Optical Surface Comparator)
1	0.19 ±0.02	0.20 ±0.01	0.85 ± 0.03
2	0.20 ± 0.02	0.20 ± 0.01	0.85 ± 0.03
3	0.20 ± 0.02	0.20 ±0.01	0.85 ± 0.03
4	0.20 ± 0.02	-	0.85 ± 0.03
5	0.19 ±0.02	-	0.85 ± 0.03
6	0.16 ± 0.02	-	0.86 ±0.03
7	0.20 ± 0.02	-	0.84 ± 0.03
8	0.19 ± 0.02	-	0.86 ± 0.03

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INITIAL ROOM TEMPERATURE OPTICAL PROPERTIES OF ZnO/SILICONE (S-13G) COATING

"In Situ" Optical Property Data

The results of the calorimetric "in situ" measurements of the S-13G coatings are given in Table 9-4. Figure 9-5 illustrates the changes in solar absorptance as a function of exposure time. This coating showed an increase in solar absorptance of 0.08 during the exposure period. This is identical to the change experienced by the S-13 coating. The increase occurred during the first 300 hours of exposure, and α_{s} remained essentially constant after that time.

Pre- and post-exposure test room-temperature reflectance data are shown for the S-13G coating in Fig. 9-6. Comparison of these data with those shown in Table 9-4 indicate the recovery phenomena associated with the S-13G coating in the near infrared region. It should be noted that the degradation measured in the 0.20 to 0.85μ region was greater for the S-13G than for S-13.

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Table 9-4

Hour	Cycle	Temp.	$\epsilon_{ m TH}$		$\alpha_{\rm H}^{(a)}$				$\alpha_{\rm s}^{(b)}$
ļ		(10)		Total	0.2 - 0.41	0.41-0.6	0.6-0.85	0.85-	Total
0	0	529	0.86	0.23	-	_	_	-	_
0	0	610	0.89	0.21	_	-	-	—	
0	1	710	0.90	0.21	-	-	_		-
0	L	710	0.90	0.20	0.85	0.12	0.05	0.15	0.20
4	1	710	0.93	0.21	0.90	0.12	0.05	0.16	0.21
51	13	710	0.92	0.23	0.90	0.17	0.08	0.17	0.24
149	46	710	0.92	0.24	0.90	0.21	0.09	0.17	0.25
195	58	710	0.92	0.26	0.92	0.27	0.10	0.17	0.27
248	70	710	0.90	0.26	0.90	0.28	0.10	0.17	0.27
296	81	710	0.92	0.26	0.90	0.32	0.09	0.17	0.28
344	92	710	0.92	0.26	0.85	0.35	0.11	0.17	0.28
392	104	710	0.90	0.26	0.85	0.35	0.11	0.17	0.28
500	125	710	0.91	0.26	0.85	0.35	0.10	0.18	0.28
Before Exposure ^(C)			0.19	0.70	0.10	0.10	0.13	0.19	
After Exposure ^(C)			0.28	0.82	0.37	0.20	0.15	0.31	

CALORIMETRIC TOTAL HEMISPHERICAL EMITTANCE AND "IN SITU" ABSORPTANCE DATA FOR S-13G COATING ZnO/SILICONE, AT 710° R

(a) Absorptance for xenon source.

(b) Absorptance for solar source.

(c) From Cary room temperature reflectance measurements.



Fig. 9-5 Solar Absorptance of S-13G Thermal Control Coating as a Function of Exposure Time at a One-Sun Level (0.2 to 0.4 μ Xenon) and $710^0 \rm R$





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9.3 Z-93 (ZnO/K_2SiO_3)

Source

IIT Research Institute

Method of Application

<u>Application</u>. The formulation is applied by spray-painting. The carrier gas should be clean; prepurified nitrogen is a good source. Aluminum or plastic substrates should be abraded, i.e., with No. 60 Aloxite metal cloth, and thoroughly washed with detergent and water.

The application technique consists of spraying at a distance of 6 to 12 in. until a reflection due to the liquid is apparent. This is followed by air-drying until the gloss is practically gone, at which time the spraying-drying cycle is repeated. A thickness of about 1 mil is achieved per cycle. Coating dimensions can therefore be predictably applied. However, hand-spraying is inherently an art and not a science, and experience must be gained by the individual painter to determine the most satisfactory technique for him.

<u>Reapplication</u>. The porous nature of a cured coating necessitates heavy spraying upon application of a second coat to achieve a satisfactory, finished texture. If the area to be repainted has been contaminated, it should be scrupulously cleaned with detergent and water. If desired, the paint can be removed simply by abrasion, since it is somewhat soft.

<u>Curing.</u> Satisfactory physical properties are obtained by an air-drying cure. Improved hardness is obtained by heat-curing at 745°R. Strict adherence to cleanliness should be observed during this step as in all the other steps. The presence of impurities can greatly decrease the stability of paints to the space environment.

Coating Thickness

4.5 to 6.0 mils.

Weight Loss During Vacuum Testing

Not stated by supplier.

Final Composition

Not stated by supplier.

Initial Optical Properties

The solar absorptance α_s and infrared emittance ϵ of several Z-93 samples were measured at room temperature in air. These data are reported in Table 9-5 Total emittance measurements were carried out using the Lion Optical Surface Comparator. Solar absorptances were calculated using spectral reflectance data obtained from measurements made using a Cary Model 14 spectrophotometer with integrating sphere and a Gier-Dunkel integrating sphere with a Perkin-Elmer Model 98 monochrometer. A typical spectral reflectance curve is presented in Fig. 9-7.

Table 9-5

INITIAL ROOM TEMPERATURE OPTICAL PROPERTIES OF Z-93 (ZnO/K₂SiO₃) COATING

Samplo	Solar Ab	Emittance		
Sample	Cary	Gier-Dunkle	(Optical Surface Comparator)	
1	0.14 ± 0.02	0.15 ±0.01	0.92 ±0.03	
2	0.14 ± 0.02	0.14 ± 0.01	0.96 ±0.03	
3	0.14 ± 0.02		0.96 ±0.03	
4	0.14 ± 0.02		0.91 ±0.03	
5	0.14 ± 0.02		0.96 ±0.03	
6	0.14 ± 0.02		0.96 ±0.03	
7	0.14 ± 0.02		0.97 ±0.03	
8	0.14 ± 0.02		0.95 ± 0.03	





LOCKHEED MISSILES & SPACE COMPANY

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"In Situ" Optical Property Data

Calorimetric "in situ" data measured with the sample at 960° R are tabulated in Table 9-6. Solar absorptance of the sample as a function of exposure time is shown in Fig. 9-8. At 960° R the solar absorptance increased from 0.12 to 0.25. Practically all this increase occurred during the first 300 hours. Room-temperature spectral reflectance data taken before and after exposure testing are shown by Fig. 9-9.

9.4 LP 10A ($\operatorname{ZrSiO}_4/\operatorname{K}_2\operatorname{SiO}_3$)

Source

Lockheed Missiles & Space Company

Method of Application

Standard spray gun techniques are used, and base coat reacts with substrate and serves as primer; the room temperature cure is approximately for 12 hours.

Coating Thickness

3.0 to 5.0 mils.

Density

 4.0 gm/cm^3

Weight Loss During Vacuum Testing

Less than 5.0%.

Table 9-6

CALORIMETRIC TOTAL HEMISPHERICAL EMITTANCE AND "IN SITU" ABSORPTANCE DATA FOR Z-93 COATING, ZnO/K_2SiO_3 , AT 960°R

Hour	Cycle	Temp.	E	$\alpha_{\rm H}^{(a)}$					$\alpha_{\rm s}^{(b)}$
	- Joie	(° R)	TH	Total	0.2-0.41	0.41-0.6	0.6-0.85	0.85-	Total
0	0	529	0.93	0.12	_	-		_	-
0	0	610	0.94	0.12	_	-	-	-	-
0	0	710	0.91	0.11	_	-	_	_	_
0	1	960	0.81	0.11	_	-		-	-
0	1	960	0.81	0.11	0.60	0.03	0,05	0.08	0.12
12	5	960	0.80	0.16	0.55	0.20	0.08	0.09	0.16
60	16	960	0.80	0.20	0.55	0.27	0.10	0.12	0.20
140	33	960	0.80	0.21	0.55	0.28	0.13	0.16	0.22
181	43	960	0.82	0.22	0.55	0.27	0.15	0.17	0.23
256	61	960	0.82	0.23	0.55	0.25	0.20	0.16	0.24
304	72	960	0.82	0.23	0.55	0.25	0.20	0.18	0.24
356	83	960	0.81	0.23	0.50	0.25	0.20	0.18	0.24
404	94	960	0.81	0.24	0.50	0.25	0.23	0.19	0.25
426	99	960	0.82	0.24	0.55	0.26	0.22	0.19	0.25
502	120	960	0.81	0.24	0.55	0.26	0.23	0.19	0.25
Before Exposure ^(C)			0.13	0.64	0.05	0.05	0.07	0.14	
After Exposure ^(c)			0.25	0.70	0.28	0.19	0.16	0.26	

(a) Absorptance for xenon source.

(b) Absorptance for solar source.

(c) From Cary room temperature reflectance measurements.

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Fig. 9-8 Solar Absorptance of Z-93 Thermal Control Coating as a Function of Exposure Time at a One-Sun Level (0.2 to 0.4 μ Xenon) and 960^OR

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Fig. 9-9 Room Temperature Spectral Reflectance of Z-93

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Final Composition

Zirconium silicate-potassium silicate composite (exact chemical composition not known).

Initial Optical Properties

The initial optical properties, the solar absorptance (α_s) , and the infrared emittance (ε) of a number of samples of LP 10A have been determined and are tabulated in Table 9-7. Typical spectrum reflectance curves for these coatings are presented in Fig. 9-10. Data obtained by use of the Cary spectrophotometer and the Gier-Dunkle intergrating sphere are presented for comparison. The emittance values reported were obtained by use of the Lion Research Corp. Optical Surface Comparator.

Table 9-7

Sample	Solar Ab	Emittance	
	Cary	Gier-Dunkle	(Optical Surface Comparator)
1	0.11 ± 0.02	0.11 ± 0.01	0.91 ± 0.03
2	0.11 ± 0.02		0.87 ± 0.03
3	0.14 ± 0.02	0.15 ± 0.01	0.90 ± 0.03
4	0.11 ± 0.02		0.90 ± 0.03
5	0.13 ± 0.02		0.91 ± 0.03
6	0.11 ± 0.02	0.11 ± 0.01	0.90 ± 0.03
7	0.14 ± 0.02		0.90 ± 0.03
8	0.10 ± 0.02		$0 90 \pm 0.03$
1		1	

INITIAL ROOM TEMPERATURE OPTICAL PROPERTIES LP-10 ($ZrSiO_4/K_2SiO_3$)



"In Situ" Optical Property Data

The results of the calorimetric "in situ" measurements made during the exposure test on this sample at $960^{\circ}R$ are tabulated in Table 9-8. Solar absorptance as a function is. at exposure time, shown graphically by Fig. 9-11. Solar absorptance increased from 0.11 to 0.42 with almost all of the change occurring in the first 150 hours of exposure. Pre- and post-exposure room temperature spectral reflectance data are shown in Fig. 9-12.

9.5 HUGHES INORGANIC WHITE COATING (Al SiO_4/K_2SiO_3)

Source

Hughes Aircraft Co.

Substrate

1-in. diameter disc, 0.050 in. thick of 6061 T-6 aluminum machined to 30 rms finish.

Method of Application

The coating is applied in three coats, each coat being baked for 1 hour at $225^{\circ}F$ and the final coating baked for 1 hour at $260^{\circ}F$. An air brush is used for painting.

Coating Thickness

6.0 to 8.0 mils after curing.

Weight Loss During Vacuum Testing

The procedure is covered by Hughes Materials and Process Specification, HMS 15-1374 and HP 4-135. A typical weight loss is 0.02% when exposed to vacuum at 250° F; the weight loss is water vapor.

Table 9-8

Hour	Cycle	Temp.	ε _{тн}	$\alpha_{\rm H}^{(a)}$					$\alpha_{\rm s}^{(b)}$
		(10)		Total	0.2 - 0.41	0.41-0.6	0.6-0.85	0.85-	Total
0	0	529	0.87	0.16	-	-	-	_	-
0	0	610	0.87	0.15	_	-	—	—	-
0	0	710	0.87	0.14	_	_	—	-	-
0	1	960	0.71	0.12	0.30	0.12	0.10	0.08	0.12
12	5	960	0.71	0.23	0.50	0.30	0.23	0.15	0.25
24	10	960	0.71	0.31	0.50	0.31	0.35	0.23	0.31
75	22	960	0.71	0.38	0.50	0.39	0.43	0.29	0.37
127	33	960	0.71	0.39	0.50	0.45	0.48	0.33	0.40
171	44	960	0.70	0.39	0.50	0.46	0.46	0.34	0.41
196	49	960	0.71	0.38	0.50	0.39	0.45	0.34	0.40
267	65	960	0.72	0.38	0.50	0.38	0.50	0.34	0.40
315	77	960	0.72	0.40	0.55	0.39	0.50	0.37	0.41
380	92	960	0.72	0.40	0.55	0.37	0.49	0.39	0.41
432	104	960	0.70	0.42	0.55	0.40	0.47	0.40	0.43
500	120	960	0.71	0.41	0.55	0.45	0.48	0.43	0.42
Before Exposure ^(C)			0.11	0.23	0.10	0.09	0.10	0.12	
After Exposure ^(C)			0.48	0.61	0.60	0.55	0.40	0.51	

Calorimetric total hemispherical emittance and "in situ" absorptance data for ${\rm ZrSiO}_4/{\rm K_2SiO}_3$ coating at 960° r

(a) Absorptance for xenon source.
(b) Absorptance for solar source.
(c) From Cary room temperature reflectance measurements.

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b

Fig. 9-11 Solar Absorptance of $ZrSiO_4/K_2SiO_3$ Thermal Control Coating as a Function of Exposure Time at a One-Sun Level (0.2 to 0.4 μ Xenon) and 960^OR



Fig. 9-12 Room Temperature Spectral Reflectance of $ZrSiO_4/K_2SiO_3$ Coating

Final Composition

Not known.

Initial Optical Properties

The solar absorptance α_s and infrared emittance ε of the Hughes (Al-SiO₄/K₂SiO₃) samples were measured at room temperature in air. These data are reported in Table 9-9. Total emittance measurements were carried out using the Lion Optical Surface Comparator. Solar absorptances were calculated using spectral reflectance data obtained from measurements made using a Cary Model 14 spectrophotometer with integrating sphere and a Gier-Dunkel integrating sphere with a Perkin-Elmer Model 98 monochrometer. A typical spectral reflectance curve is presented in Fig. 9-13.

Table 9-9

Sample	Solar Ab	Emittance		
	Cary	Gier-Dunkle	(Optical Surface Comparator)	
1	0.14 ± 0.02	0.14 ± 0.01	0.90 ± 0.03	
2	0.14 ± 0.02	$0.\ 14\ \pm\ 0.\ 01$	0.88 ± 0.03	
3	0.14 ± 0.02		0.90 ± 0.03	
4	0.14 ± 0.02		0.90 ± 0.03	
5	0.14 ± 0.02		0.89 ± 0.03	
6	0.14 ± 0.02		0.88 ± 0.03	
7	0.14 ± 0.02		0.90 ± 0.03	
8	0.13 ± 0.02		0.90 ± 0.03	

INITIAL ROOM TEMPERATURE OPTICAL PROPERTIES OF HUGHES INORGANIC WHITE COATING $(Alsio_4/K_2SiO_3)$

"In Situ" Optical Property Data

Not yet available for this paint system.



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