

ESA PSS-03-108 Issue 1
November 1989



Spacecraft thermal control design data

Volume 2

STCDDAT 972

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8-10, rue Mario-Nikis, 75738 PARIS 15, France



Published by ESA Publications Division,
ESTEC, Noordwijk, The Netherlands

Printed in The Netherlands

ESA price code: E4

ISSN 0379 - 4059

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ABSTRACT

The aim of the present handbook is to assist the thermal design engineer by presenting him in a single document with all the information relevant to spacecraft thermal-control design.

This handbook has been compiled by the School of Aeronautics of the Polytechnic University of Madrid (ETSI-A) under several ESA contracts.

REVISION PROCEDURE

It is intended to issue revisions and additions to this handbook as they become available. It is hoped that in this way it will remain up-to-date as regards state-of-the-art information and recent developments in the field of spacecraft thermal control.

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DISCLAIMER

The description in this handbook of thermal-control components and systems is intended to be purely illustrative, and the use of tradenames of specific products, which is essential to a proper understanding of the data presented herein, in no way implies any approval, endorsement or recommendation of these products by the European Space Agency.

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THERMAL CONTROL SURFACES

1 COATINGS

2 ADHESIVE TAPES



THERMAL CONTROL SURFACES

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THERMAL CONTROL SURFACES

List of Symbols

LIST OF SYMBOLS

- A , Area of the Sensor. [m^2].
- C , Conductive Thermal Coupling Constant between Sensor and Tray. [$W.K^{-1}$].
- D , Irradiation Dose. [GY/particle].
- F , View Factor from the Sun.
- F , Adhesive Force. [N].
- F_a , View Factor for Albedo.
- F_{SP} , View Factor for Earth Infrared Radiation.
- K , Radiative Thermal Coupling Constant between Sensor and Tray. [$W.K^{-4}$].
- P , Earth Infrared Radiation. [$W.m^{-2}$].
- Q , Heat Transfer Rate through Sensor Insulation from External Sources. [W].
- Q_i , Internal Dissipated Power or Heat Load. [W].
- R , Sheet Electrical Resistance. [Ω per square, Ω/\square].
- S , Solar Flux. [$W.m^{-4}$].
- T , Temperature. [K].
- T_R , Equilibrium Temperature for an Isothermal Sphere at 1 AU. [K].
- T_c , Tray or Sample-Housing Temperature. [K].
- T_s , Equivalent Surrounding Temperature. [K].
- T_{max} , Maximum Temperature. [K].
- T_{min} , Minimum Temperature. [K].
- X_d , Irradiation Penetration Range. [$kg.m^{-2}$].
- X_u , Photon Absorption and Scattering Range. [$kg.m^{-2}$].

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List of Symbols

- a , Mean Albedo of the Earth.
 c , Specific Heat of a Sample. [$J.kg^{-1}.K^{-1}$].
 c , Resin Concentration in an Adhesive.
 p , Pressure. [Pa].
 t , Thickness. [m].
 t_c , Coating Thickness. [m].
 t , Time. [h] or [ESH].
 n , Number of Experimental Data Points.
 w , Width. [m].
 α , Hemispherical Total Absorptance.
 α_p , Earth Infrared Radiation Absorptance.
 α_s , Solar Absorptance.
 $\alpha'_\lambda(\lambda, \beta, \theta)$, Directional-Hemispherical Spectral Absorptance.
 β , Angle between Surface Normal and Direction of Incident Flux. [Angular Degrees].
 β' , Angle between Surface Normal and Direction of Emitted, Reflected or Transmitted Flux. [Angular Degrees].
 ϵ , Hemispherical Total Emittance.
 $\epsilon'(\beta', \theta')$, Directional Total Emittance.
 θ , Azimuthal Angle of Incident Flux. [Angular Degrees].
 θ' , Azimuthal Angle of Emitted, Reflected or Transmitted Flux. [Angular Degrees].
 λ , Wavelength. [m].
 ρ , Electrical Resistivity. [$\Omega.m$].
 ρ_c , Specific Electrical Cross Resistance. [$\Omega.m^2$].

THERMAL CONTROL SURFACES

List of Symbols

- ρ_s , Solar Reflectance.
- ρ_{sIR} , Solar Reflectance in the Infrared Range.
- ρ_{sUV} , Solar Reflectance in the UV Range.
- ρ_{sV} , Solar Reflectance in the Visible Range.
- $\rho'_\lambda(\lambda, \beta, \theta)$, Directional-Hemispherical Spectral Reflectance.
- σ , Stefan-Boltzmann Constant. $\sigma = 5.6697 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4}$.
- σ , Standard Deviation.
- ω , Solid Angle of Incident Radiation Beam.
[Steradians].
- ω' , Solid Angle of Emitted, Reflected or Transmitted Radiation Beam. [Steradians].

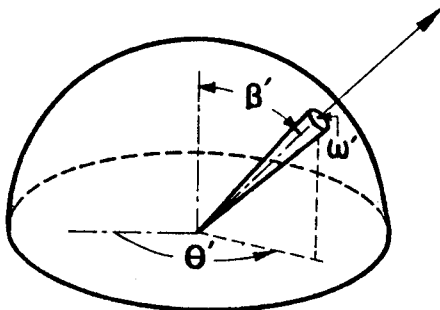
Subscripts

- o , Refers to Initial Values.
- f , Refers to After-Exposure Values.

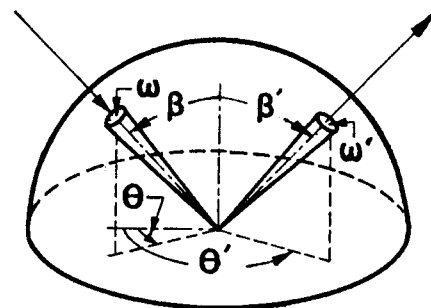
Superscripts

- , Mean Value.

Angles used to define directional emittance.



Angles used to define bidirectional reflectance.



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THERMAL CONTROL SURFACES

List of Symbols

Acronyms

AU	, Astronomical Unit. 1 AU = 1.495×10^{11} m.
CC	, Conductive Coated.
COP	, Coprecipitation.
CVCM	, Collected Volatile Condensable Materials.
ESH	, Equivalent Sun Hours.
EWH	, Equivalent (Solar) Wind Hours.
GY	, Gray. 1 GY = 1 J.kg^{-1} .
IR	, Infrared.
ITO	, Indium-Tin Oxide.
LDEF	, Long Duration Exposure Facility.
MLI	, Multilayer Insulation.
MOX	, Mixed Oxalate Process.
OSR	, Optical Solar Reflector.
PBR	, Pigment to Binder Ratio by Weight.
RML	, Remainder Mass Loss.
RMS	, Root Mean Square.
RTV	, Room Temperature Vulcanizing.
SCATHA	, Spacecraft Charging at High Altitudes.
SSM	, Second Surface Mirror.
SSR	, Solid State Reaction.
TML	, Total Mass Loss.
TWL	, Total Weight Loss.
UV	, Ultra-Violet.
VCM	, Volatile Condensable Materials.

Other symbols are introduced when used.

THERMAL CONTROL SURFACES

General Introduction

GENERAL INTRODUCTION

A coating consists of a layer (or layers) of any substance (s) upon a substrate.

Optical coatings have been used to control the temperature of satellites since the first successful orbital flight in 1958. Since then coating materials have been developed to the point where reasonably stable coatings are available that give any desired value of the hemispherical total emittance, ϵ , between .1 and .9 for any desired value of the solar absorptance, α_s , between .1 and .9.

According to Touloukian, DeWitt & Hernicz (1972) three types of coatings can be identified:

- 1) Pigmented coatings which are mixtures of a pigment and a vehicle.
- 2) Contact coatings, formed by layers of a substance coated on a substrate without chemical reaction occurring between the coating material and the substrate.
- 3) Conversion coatings which are layers of compounds formed by the chemical reaction of the substrate with another material.

Fig 0-1, from Touloukian et al. (1972) is a plot of solar absorptance, α_s , vs. hemispherical total emittance, ϵ . For each ray from the origin two values are given. The first one, T_R , is the equilibrium temperature for an isothermal sphere at 1 AU; the second value is the ratio α_s/ϵ .

Fig 0-2, from the same source, indicates how to obtain the various types of surfaces exhibiting the characteristics shown in the previous figure.

THERMAL CONTROL SURFACES

General Introduction

The basic requirement for a coating to be used in spacecraft is long-term space stability for periods of months and even of years. This objective, however, has not yet been achieved in many instances.

The problem of selecting the specific coating for a given α_s/ϵ is somewhat circumvented by the use of mosaics or coating patterns, normally combining white and black paints. Nevertheless, the possibility of using a single paint should not be lay aside; for example, Triolo (1973) reports that encouraging results have been obtained by using green paints to take the place of white and black paint patterns.

This data item, which is intended to give information on several pigmented and contact coatings, has two clearly different parts. In the first one data concerning several coating materials are gathered. These coatings are classified according to their thermal radiation characteristics.

The second part deals with coated foils and tapes. The main characteristic of these coatings is that they are flexible and can be applied to a surface by mere pressure, although a double-faced adhesive tape must be used in several case. Since ease of application and removal is the peculiar feature of these coatings, particular emphasis has been placed on their adhesive characteristics.

No attempt has been made to classify foils and tapes according to their thermal radiation properties. On the other hand,

THERMAL CONTROL SURFACES

General Introduction

this classification is by no means obvious in several cases. For example: Series Emittance Tapes are coatings whose emittance is controlled by the thickness of a Teflon Type A film, and their solar absorptance by a metallic second surface. By choosing the proper Teflon thickness and the appropriate metal it is possible to specify a thermal control surface within a wide range of α_s/ϵ values.

In addition to the data collected here, information concerning aluminium coatings can be found in G, Section 1.2.

THERMAL CONTROL SURFACES
General Introduction

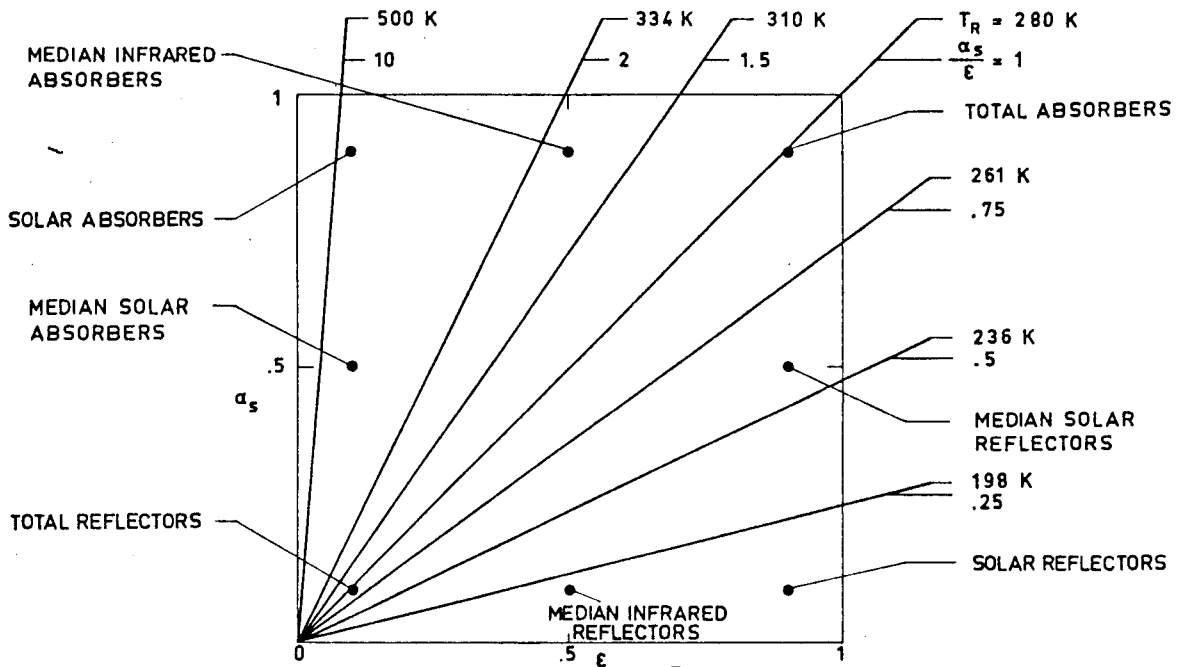


Fig 0-1. Basic types of thermal control coatings. T_p [K] is the equilibrium temperature of a coated isothermal sphere at 1 AU. From Touloukian, DeWitt & HERNICZ (1972).

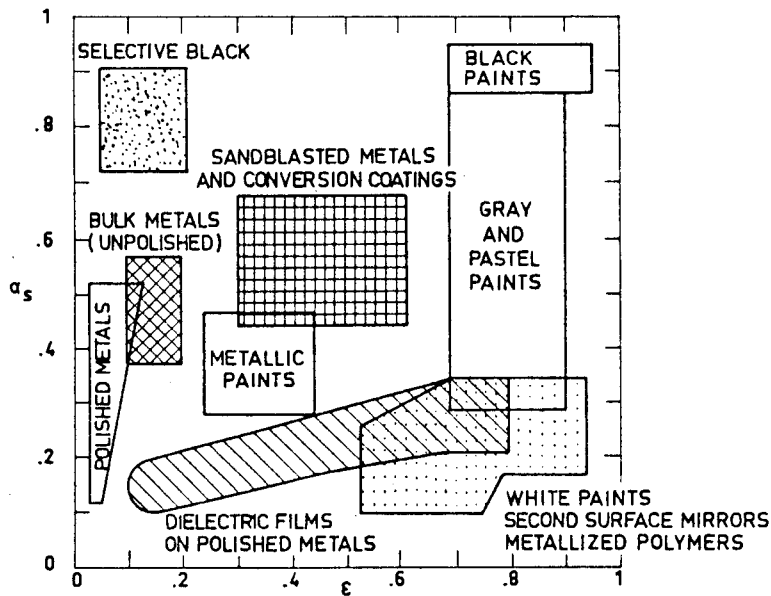


Fig 0-2. Range of solar absorptance, α_s , and hemispherical total emittance, ϵ , covered by available thermal control coatings. From Touloukian, DeWitt & HERNICZ (1972).

COATINGS

General

1. COATINGS1.1 GENERAL

The data concerning each coating have been arranged, whenever possible and meaningful, as indicated below. When no data on a given property are available the corresponding heading has been normally omitted.

1. COMPOSITION2. FORMULATION3. USUAL DESIGNATION4. SUBSTRATE5. METHOD OF APPLICATION5.1. Preparation of paint for application5.2. Preparation of surfaces for painting5.3. Application of paint5.4. Coating thickness5.5. Curing process6. SOLVENTS RESISTANCE7. PHYSICAL PROPERTIES7.1. Density7.2. Outgassing7.3. Thermal radiation properties

7.3.1. Emittance

7.3.1.1. Hemispherical total emittance

7.3.1.2. Variation of hemispherical total emittance with coating thickness

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7.3.1.3. Effects of the Space Environment on hemispherical total emittance

7.3.1.3.1. Ultra-Violet Radiation

7.3.2. Absorptance

7.3.2.1. Solar absorptance

7.3.2.2. Variation of solar absorptance with coating thickness

7.3.2.3. Variation of solar absorptance with incidence angle

7.3.2.4. Earth Albedo normal absorptance

7.3.2.5. Effects of Space Environment on absorptance

7.3.2.5.1. Ultra-Violet Radiation

7.3.2.5.2. Gamma Radiation

7.3.2.5.3. Protons only exposure

7.3.2.5.4. Electrons only exposure

7.3.2.5.5. Contamination

7.3.2.5.6. Combined exposure

7.3.2.6. Effects of the Space Environment on solar absorptance to emittance ratio

7.3.3. Reflectance

7.3.3.1. Normal-hemispherical spectral reflectance

7.3.3.2. Effects of the Space Environment on reflectance

7.3.3.2.1. Ultra-Violet Radiation

7.3.3.2.2. Gamma Radiation

7.3.3.2.3. Protons only exposure

7.3.3.2.4. Electrons only exposure

7.3.3.2.5. Contamination

7.3.3.2.6. Combined exposure

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General

7.4. Electrical resistance

7.4.1. Effects of Temperature on electrical resistance

7.4.2. Effects of the Space Environment on electrical resistance

7.4.2.1. Ultra-Violet Radiation

7.4.2.2. Gamma Radiation

7.4.2.3. Protons only exposure

7.4.2.4. Electrons only exposure

7.4.2.5. Contamination

7.4.2.6. Combined exposure

7.4.3. Charging

8. ENVIRONMENTAL BEHAVIOR

8.1. Prelaunch

8.2. Postlaunch

8.2.1. Ascent

8.2.2. Orbital

9. THERMAL CYCLING

10. SOURCE

11. COST

12. PAST SPATIAL USE

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COATINGS
Solar Reflectors

1.2. SOLAR REFLECTORS

1.2.1. TITANIUM DIOXIDE-POLYMETHYL VINYL SILOXANE

1. COMPOSITION

Pigment: Titanox Ra-NC, Titanium Pigment Corp. proprietary, calcined rutile TiO_2 , 93% TiO_2 .

Vehicle: Dow-Corning proprietary, Q 92-007. 33% nonvolatile content by weight after 24 h at 343 K.

From Cunnington, Grammer & Smith (1969), Cunnington (1974).

2. FORMULATION

1:1 by weight of pigment and vehicle (Cunnington et al. (1969)).

3. USUAL DESIGNATION

LMSC/Dow-Corning Thermatrol 2A-100.

4. SUBSTRATE

Any clean substrate, either rigid or non-rigid (Breuch (1967)).

5. METHOD OF APPLICATION

5.2. Preparation of surfaces for painting. The entire surface is primed with one coat of silicone primer, Dow Corning Corp. A-4094 or equivalent, to a thickness of approximately 5×10^{-6} m. The primer is air cured 30 min minimum prior to application of top coats.

5.3. Application of paint. By spray techniques.

5.4. Coating thickness. For internal application, where emittance is of primary interest, a minimum thickness of 2.54×10^{-5} m should be maintained. For external surfaces, where both α_s and ϵ are

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Solar Reflectors

important, the minimum thickness for opacity is $.9 \times 10^{-4}$ to 1.3×10^{-4} m.

- 5.5. Curing process. 24 h minimum at room temperature and normal pressure, after final coat.

From Breuch (1967), Cunnington, Grammer & Smith (1969).

6. SOLVENTS RESISTANCE

The following data, concerning resistance of elastomeric silicons to chemical attack, have been reported by the producer of the vehicle.

<u>Solvents and Fuels</u> (after 7 d at room temperature)	<u>Volume Variation</u> (per cent)
Acetone	15 to 25
Carbon tetrachloride	above 150
Ethyl alcohol	0 to 20
Isooctane	above 150
Xylene	above 150
B type fuel	above 150
JP-4 jet fuel	above 150
 <u>Oils</u> (after 70 h at T=423 K)	
ASTM No. 1 Oil	5 to 10
ASTM No. 3 Oil	35 to 60
Hydraulic fluid Mil-0-5606 (Univis J-43)	above 150
Oronite 8200 (silicate ester)	above 150

From DOW-CORNING (1970).

7. PHYSICAL PROPERTIES

- 7.1. Density. $1\ 500\ \text{kg}\cdot\text{m}^{-3}$ after curing (Cunnington et al. (1969)).

COATINGS
Solar Reflectors

7.2. Outgassing. Negligible after coating has been fully cured (Cunnington, Grammer & Smith (1969)).

7.3. Thermal radiation properties

7.3.1. Emittance.

7.3.1.1. Hemispherical total emittance.

T [K]	ϵ^a	ϵ^b
295	.86 ± .03	.84
395	.86 ± .02	.84

^a Determined calorimetrically. Chamber pressure: 1.33×10^{-5} Pa.

^b From spectral reflectance data in the range 2×10^{-6} to 2.5×10^{-5} m and the blackbody function corresponding to the temperatures quoted.

From Cunnington et al. (1969).

7.3.1.3. Effects of the Space Environment on hemispherical total emittance.

7.3.1.3.1. Ultra-Violet Radiation.

t [h]	.25	5	69	117	168	250	360	410	457	486	550
ϵ	.87	.87	.87	.85	.88	.88	.87	.85	.86	.85	.85

Degrading Source: 2×10^{-7} to 4×10^{-7} Xenon Lamp, 1 Sun level.

Method of obtaining data: Calorimetric. Chamber pressure: 1.33×10^{-5} pa.

Probe temperature 395 K.

t, exposure time.

From Cunnington et al. (1969).

7.3.2. Absorptance.

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COATINGS

Solar Reflectors

7.3.2.1. Solar Absorptance.

T [K]	α_s
278	.16 ± .03 ^a
295	.15 ± .02 ^b
389	.16 ± .03 ^a
395	.18 ± .01 ^b

^a From Breuch (1967).^b From Cunnington, Grammer & Smith (1969).

7.3.2.5. Effects of the Space Environment on absorptance.

7.3.2.5.1. Ultra-Violet Radiation. Laboratory data concerning the effects of UV radiation on spectral absorptance are given in Table 1-1. Calculated values of α_s are also included.

Table 1-1

Ultra-Violet Radiation Effects on Spectral
Absorptance of Thermatrol 2A-100

T [K]	t [h]	α for Xenon Lamp					α_s
		Range of $\lambda \times 10^7$ [m]					
		2-4.1	4.1-6	6-8.5	8.5 -	Total	
395	.25	.70	.12	.07	.13	.18	.18
395	5	.70	.17	.07	.19	.21	.21
395	69	.85	.25	.16	.22	.29	.29
395	117	.85	.24	.18	.26	.30	.31
395	168	.85	.25	.18	.28	.31	.32
395	360	.80	.24	.17	.27	.29	.31
395	410	.85	.25	.18	.26	.30	.31
395	457	.85	.24	.18	.26	.30	.31
395	486	.90	.25	.18	.27	.31	.32
395	550	.90	.25	.19	.27	.31	.32
Before Exposure ^a		.69	.08	.06	.07	.14	.15
After Exposure ^a		.79	.27	.15	.13	.24	.26

^a Values deduced from spectral reflectance data.

(Continued onto next page)

COATINGS

Solar Reflectors

Degrading Source: 2×10^{-7} to 4×10^{-7} m Xenon lamp, 1 Sun level.

Method of obtaining data: Calorimetric in situ absorptance.

Chamber pressure: 1.33×10^{-5} Pa.

From Cunnington, Grammer & Smith (1969).

Similar laboratory data are compared with those corresponding to orbital flight in Fig 1-1.

The influence of different radiation conditions on the degradation of solar absorptance is represented in Fig 1-2. It can be deduced from this figure that the intensity of the radiating source does not affect significantly the results, since the difference between the curves labeled 5 Suns and 10 Suns seems to be smaller than the experimental error.

7.3.3. Reflectance.

7.3.3.1. Normal-hemispherical spectral reflectance: Fig 1-3.

7.3.3.2. Effects of the Space Environment on reflectance.

7.3.3.2.1. Ultra-Violet Radiation: Fig 1-4.

8. ENVIRONMENTAL BEHAVIOR

8.1. Prelaunch. The surface is soft and rubbery and should be protected from abrasion or scratches. Since this paint is electrostatic, contamination must be avoided.

8.2. Postlaunch. In order to avoid blistering during ascent heating, the paint must be cured, at room temperature, at least for 24 h. In this manner, volatile materials are removed.

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COATINGS
Solar Reflectors

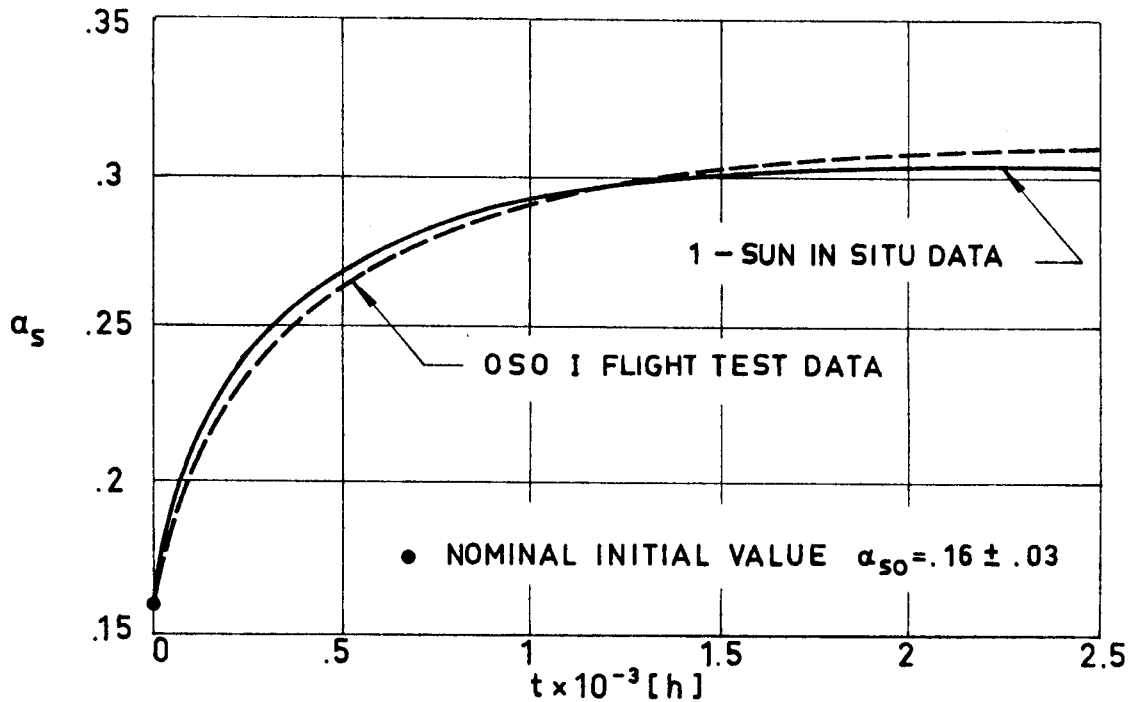


Fig 1-1. UV radiation effects on solar absorptance, α_s , of Thermatrol 2A-100 vs. exposure time, t . From Breuch (1967).

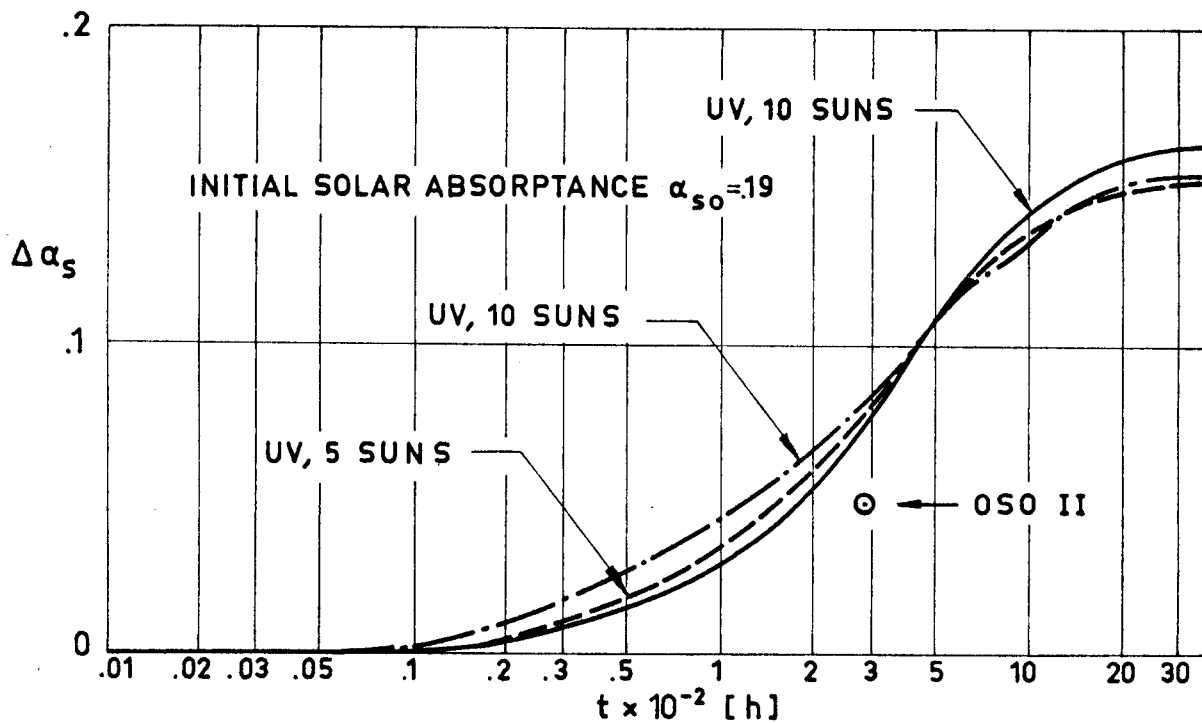


Fig 1-2. Change in solar absorptance, $\Delta\alpha_s$, of Thermatrol 2A-100, under various radiation conditions, vs. exposure time, t . From McCargo et al. (1971).

COATINGS
Solar Reflectors

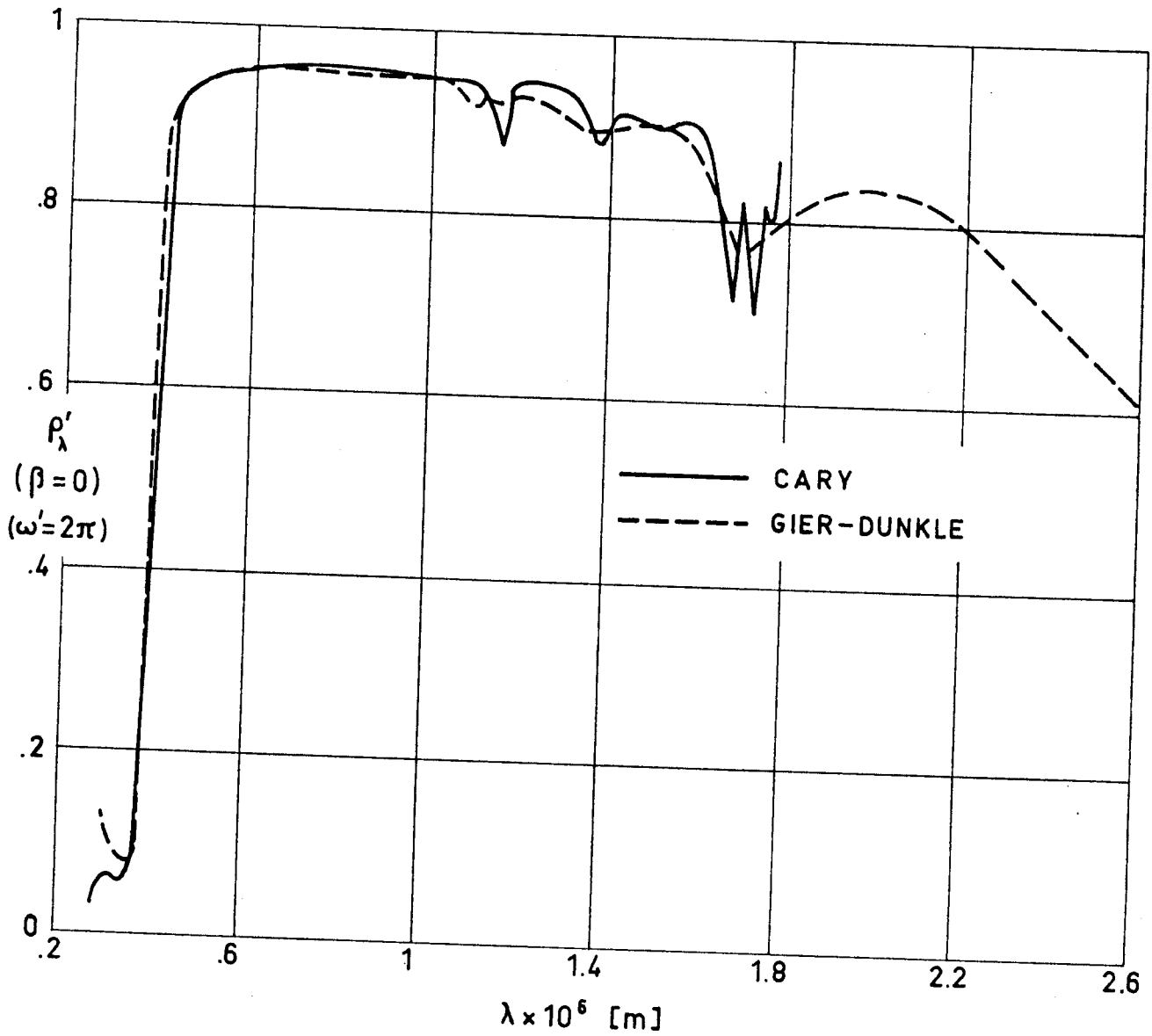


Fig 1-3. Normal-hemispherical spectral reflectance, ρ'_λ , of Ther-matrol 2A-100, measured by two different methods, vs. wavelength, λ . From Cunningham, Grammer & Smith (1969).

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COATINGS
Solar Reflectors

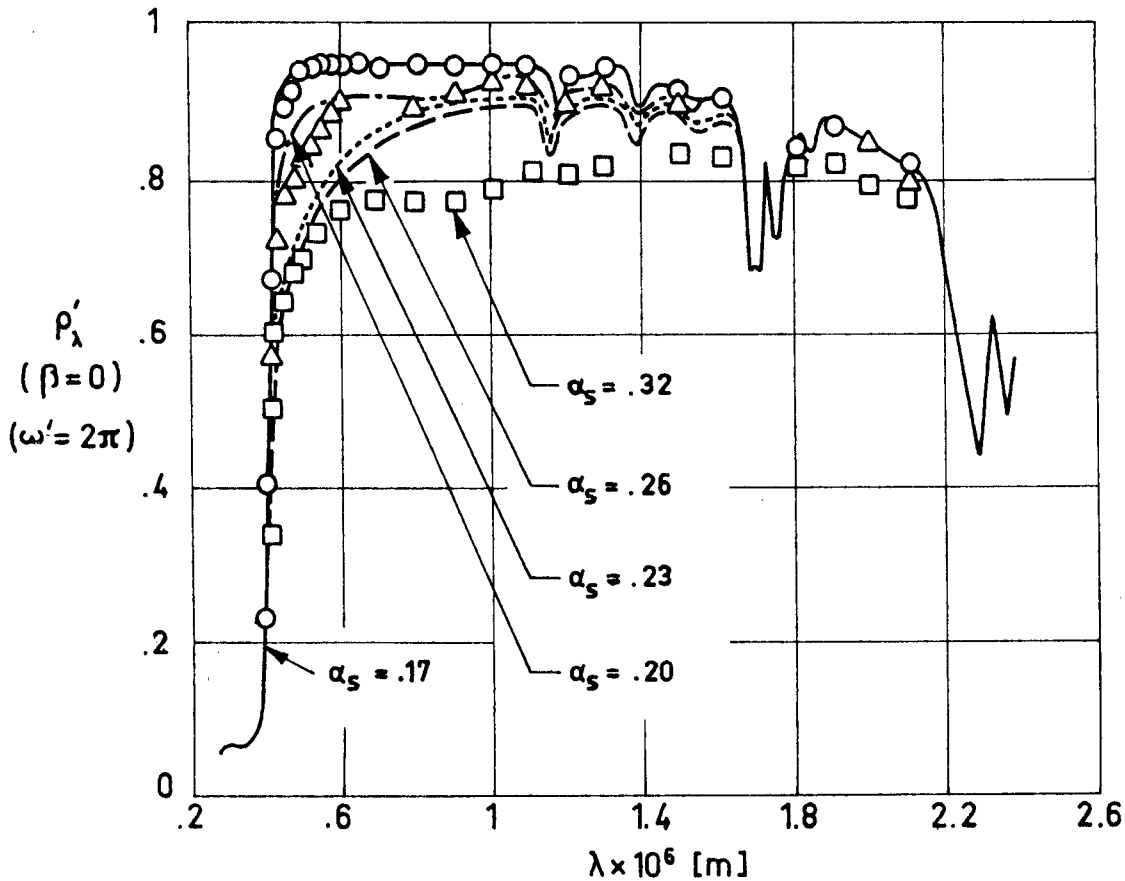


Fig 1-4. Effect of Ultra-Violet Radiation on spectral reflectance, ρ'_λ , of Thermatrol 2A-100 vs. wavelength, λ . Most of the data, concerning bidirectional reflectance, are from Rittenhouse & Singletary (1969), while ——— and - - - - - , normal-hemispherical reflectance, are from Cunnington, Grammer & Smith (1969).

Explanation

Key	Description	Comments
—		T=313 K. Near-normal reflectance (Cary).
○		T=313 K. Measured in vacuum (6.65×10^{-5} Pa).
□		Same as ○ except exposed to UV radiation (PEK Type C(A-H6) lamp, 20 Suns). ESH 1330. During exposure $p=9.3 \times 10^{-5}$ Pa.
△		Same as □ except sample in air at 40 Pa for 24 h after exposure.
- - - -		Same as — except exposed to the same radiation as □ .
- - - -	6061-T6 Al substrate polished and then machined to a $(30 \pm 3) \times 10^{-6}$ m RMS finish.	T=395 K. Exposed to UV radiation (900 W Hanovia, Xenon lamp, 1 Sun) ESH 550. Sample in air for 5 min after exposure.
.....	Same as - - - - .	Same as - - - - . Sample in air for 30 min.

COATINGS

Solar Reflectors

8.2.1. Ascent. Ascent heating histories with peak temperatures below 615 K cause an increase in α_s of .03 or less, while ϵ is unaffected.

8.2.2. Orbital. The primary source of degradation appears to be the near-ultra-violet portion of incident solar and albedo radiation.

From Breuch (1967).

9. THERMAL CYCLING

The maximum and minimum temperatures at which the paint has been tested without major changes in properties were:

$$T_{\min} = 211 \text{ K}$$

$$T_{\max} = 366 \text{ K}$$

(Rittenhouse & Singletary (1969)).

10. SOURCE

Lockheed Missiles and Space Company Inc. 3251 Hanover Street.
Palo Alto, California 94304.

11. COST

Varies depending on quantity; Cunnington et al. (1969) indicate that the nominal price is 16 US \$ per litre.

12. PAST SPATIAL USE

Thermatrol 2A-100 has been used for thermal control in Explorer 33 (launched July 1, 1966), Rittenhouse & Singletary (1969). According to Neel (1967), this paint has been tested on board OSO I (launched March 7, 1962) and OSO II (Feb. 3, 1965). The results obtained have been presented in Figs 1-1 and 1-2.

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1.2.2. ZINC OXIDE-POTASSIUM SILICATE

1. COMPOSITION

Pigment: New Jersey Zinc Co., SP500 zinc oxide; calcined at 873 to 973 K for 16 h. (Heating and cooling rates are not critical).

Binder: Sylvania Electric Products Corp., PS7 potassium silicate. From Cunnington, Grammer & Smith (1969).

2. FORMULATION

4.3:1 by weight of pigment and binder (Cunnington et al. (1969)).

3. USUAL DESIGNATION

Z-93. IIT Research Institute.

4. SUBSTRATE

All metals except noble; Aluminium is preferred (IITRI (1974)).

5. METHOD OF APPLICATION

5.1. Preparation of paint for application. The components are mixed in a pigment to binder ratio of 4.3 with a solids content of 56.9%. A typical batch may be .1 kg of ZnO, 50 cm³ of PS7 (35% solution), and 50 cm³ distilled water.

The paint should be prepared just before use. Shelf life is limited. Actual shelf life should exceed 24 h. The mixture should be shaken to maintain the pigment in suspension (Cunnington et al. (1969)).

5.2. Preparation of surfaces for painting. The substrate should be abraded and thoroughly washed with detergent and water.

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According to the supplier, chromate treatments are not permissible.

- 5.3. Application of paint. By spray-painting. Because of the porous nature of the cured coating, heavy spraying upon application of a second coat is required to achieve a satisfactory finished texture (Breuch (1967)).

For process specification see Stevens (1971).

- 5.4. Coating thickness. A thickness of about 2.54×10^{-5} m is achieved per cycle. Total thickness should be of the order of 1.1×10^{-4} to 1.5×10^{-4} m.

- 5.5. Curing process. Satisfactory physical properties are obtained by an air-drying cure for 4 h. The supplier recommends, as optional, a cure at 366 K for 16 h, while Cunnington et al (1969) indicate that improved hardness is obtained by heat curing at 413 K.

6. SOLVENTS RESISTANCE

Not attacked by the solvents.

7. PHYSICAL PROPERTIES

- 7.2. Outgassing. Initial weight loss in 20 h: 8.0×10^{-4} kg.m⁻².

Stationary loss rate: 5.6×10^{-10} kg.m⁻².s⁻¹ (McCargo, Spradley, Greenberg & McDonald (1971)).

7.3. Thermal radiation properties

- 7.3.1. Emittance.

- 7.3.1.1. Hemispherical total emittance.

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T [K]	ϵ^a	ϵ^b	Ref.
295	.90±.05	.87	c
310	.96		d
394		.88	c
533		.88	c

- a Determined calorimetrically. Chamber pressure: 1.33×10^{-5} Pa.
- b From spectral reflectance data in the range 2×10^{-6} m to 2.5×10^{-5} m and the blackbody function corresponding to the temperatures quoted.
- c From Cunningham, Grammer & Smith (1969).
- d From Westcott (1968).

7.3.1.3. Effects of the Space Environment on hemispherical total emittance.

7.3.1.3.1. Ultra-Violet Radiation. The following table has been prepared using data given by Cunningham et al. (1969).

T [K]	t [h]	n	ϵ_o	ϵ_f	$\bar{\epsilon}$	σ
300	2001	28	.90	.88	.882	.012
366	2024	33	.89	.88	.887	.007
422	10517	140	.88	.87	.878	.010
450	1004	19	.87	.87	.871	.004
534	502	12	.81	.81	.811	.009

Degrading Source: 2×10^{-7} to 4×10^{-7} m Xenon Lamp, 1 Sun level.

Method of obtaining data: Calorimetric. Chamber pressure: 1.33×10^{-5} Pa.

t, total exposure time. [h].

n, number of data points given in the source.

ϵ_o , ϵ_f , initial and after-exposure values of the hemispherical total emittance.

$\bar{\epsilon}$, mean value.
$$\bar{\epsilon} = \frac{\sum_1^n \epsilon_i \Delta t_i}{t}$$

σ , standard deviation.
$$\sigma = \sqrt{\frac{\sum_1^n (\epsilon_i - \bar{\epsilon})^2 \Delta t_i}{t-1}}$$

7.3.2. Absorptance.

7.3.2.1. Solar absorptance: Table 1-2.

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Table 1-2

Solar Absorptance of Zinc Oxide-Potassium Silicate Paint

No	T [K]	α_s	Comments
1	278	.114	Measured in vacuum (1.2×10^{-4} Pa).
2	278	.112	Similar to above specimen and conditions.
3	279	.153	Air dried at 100% relative humidity; measured in vacuum (1.3×10^{-4} Pa).
4	279	.168	Similar to above specimen and conditions except air dried at 0% relative humidity.
5	279	.161	Similar to No. 3 specimen and conditions except air dried at 35% relative humidity.
6	279	.147	Spray application; measured in vacuum (1.3×10^{-4} Pa); fresh preparation.
7	279	.150	Similar to above specimen and conditions except measured in vacuum (6.7×10^{-4} Pa).
8	279	.150	Similar to No. 6 specimen and conditions except measured in vacuum (4.7×10^{-4} Pa).
9	279	.138	Spray application; measured in vacuum (1.3×10^{-4} Pa); preparation aged 120 d.
10	279	.119	Above specimen and conditions except heat-treated at 773 K for 2 h.
11	279	.131	Similar to No. 9 except measured at pressure of 6.7×10^{-4} Pa.
12	279	.126	Above specimen and conditions except heat-treated at 773 K for 2 h.
13	279	.140	Similar to No. 9 specimen and conditions except measured at pressure of 4.7×10^{-4} Pa.
14	279	.119	Above specimen and conditions except heat-treated at 773 K for 2 h.
15	279	.120	Spray application; measured in vacuum (1.3×10^{-4} Pa); preparation aged 120 d.
16	279	.133	Similar to above specimen and conditions except measured in vacuum (6.7×10^{-4} Pa).
17	279	.124	Similar to No. 15 specimen and conditions except measured at pressure of 4.7×10^{-4} Pa.
18	298	.164	Substrate abraded with No. 60 Aloxite cloth. Sample cured at 413 K for 18 h.
19	298	.158	Above specimen and conditions except heat-treated (418 K for 16 h); time lapse, 1 d.
20	298	.149	Similar to No. 18 specimen and conditions except heat-treated (773 K for 2 h); time lapse, 6 h.
21	298	.160	Similar to No. 18 specimen and conditions except after time lapse of 90 d.
22	298	.165	Abraded magnesium silicate substrate.
23	298	.158	Similar to above specimen and conditions except heat-treated (418 K for 16 h); time lapse, 1 d.
24	298	.158	Similar to No. 22 specimen and conditions except heat-treated (973 K for 2 h); time lapse, 1 d.
25	298	.159	Similar to No. 22 specimen and conditions except heat-treated (1073 K for 2 h); time lapse, 6 h.
26	298	.161	Similar to No. 22 specimen and conditions except after time lapse of 90 d.
27	298	.168	Abraded alumina substrate.
28	298	.159	Similar to above specimen and conditions except heat-treated (418 K for 16 h); time lapse, 1 d.
29	298	.160	Similar to No. 27 specimen and conditions except heat-treated (973 K for 2 h); time lapse, 1 d.
30	298	.160	Similar to No. 27 specimen and conditions except heat-treated (1073 K for 2 h); time lapse, 6 h.
31	298	.165	Similar to No. 27 specimen and conditions except after time lapse of 90 d.
32	298	.153	Measured in vacuum (4×10^{-3} Pa).
33	298	.120	Aluminium substrate; supplied by IITRI.
34	298	.220	Similar to above specimen and conditions except supplied by ESRO I Project Group; coating thickness 8.9×10^{-5} m.
35	298	.260	Similar to above specimen and conditions except soiled.
36	298	.184	Property calculated from reflectance; lab data taken on sample to be tested on Lunar Orbiter V.
37	293	.14 ± .02	Substrate abraded with No. 60 Aloxite cloth. ^a
38	289	.14 ± .02	Same as above ^a .
39	533	.14 ± .02	Same as above ^a .

^a From Breuch (1967).

All data, unless otherwise stated, are from Touloukian, DeWitt & Hearnicz (1972).

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7.3.2.2. Variation of solar absorptance with coating thickness: Fig 1-5

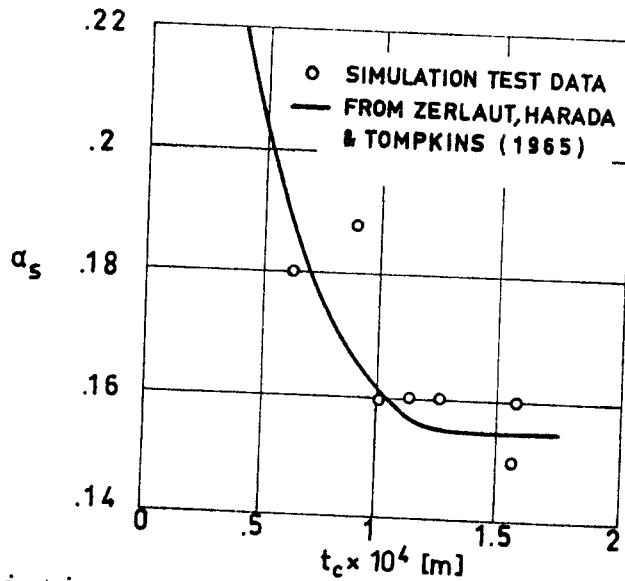


Fig 1-5. Variation of solar absorptance, α_s , with thickness, t_c .

From Stevens (1971).

7.3.2.4. Earth Albedo normal absorptance. The value $\alpha = .26$ has been obtained by Westcott (1968) from spectral data. Albedo radiation is approximated by the solar spectrum truncated below 3.5×10^{-7} m. Aluminium substrate.

7.3.2.5. Effects of the Space Environment on absorptance.

7.3.2.5.1. Ultra-Violet Radiation. Fairly detailed laboratory data on the effects of UV radiation on spectral absorptance are given in Table 1-3. Table 1-4 has a broader scope, it is intended to illustrate how the experimental conditions influence the results.

Changes in solar absorptance during the total mission profile for a near-Earth orbit, as estimated by McCargo, Spradley, Greenberg & McDonald (1971) are shown in Fig 1-6.

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Table 1-3

Ultra-Violet Radiation Effects on Spectral Absorptance of Zinc Oxide-Potassium Silicate Paint

T [K]	t [h]	α for Xenon Lamp					α _s
		Range of λ x 10 ³ [μm]					
		2-4.1	4.1-6	6-8.5	8.5 -	Total	
300	0	.72	.10	.05	.08	.14	.14
300	43	.70	.09	.05	.09	.14	.14
300	293	.67	.11	.06	.08	.15	.14
300	365	.67	.15	.04	.09	.14	.15
300	461	.66	.15	.05	.09	.15	.15
300	509	.65	.14	.06	.09	.15	.15
300	605	.69	.14	.06	.09	.15	.16
300	701	.70	.16	.07	.09	.15	.16
300	773	.67	.19	.09	.08	.16	.16
300	821	.71	.18	.05	.09	.15	.17
300	869	.70	.19	.08	.09	.16	.17
300	941	.65	.19	.08	.09	.15	.17
300	989	.70	.15	.09	.08	.16	.17
300	1039	.65	.19	.09	.08	.15	.17
300	1109	.66	.20	.08	.08	.16	.17
300	1157	.73	.19	.10	.08	.16	.17
300	1205	.69	.20	.09	.08	.16	.18
300	1277	.68	.20	.07	.09	.16	.17
300	1325	.63	.23	.07	.09	.16	.18
300	1373	.65	.22	.10	.08	.16	.17
300	1445	.66	.23	.10	.08	.16	.18
300	1545	.65	.22	.08	.09	.16	.18
300	1617	.68	.22	.10	.08	.16	.19
300	1665	.67	.24	.08	.08	.16	.18
300	1713	.67	.22	.08	.09	.16	.18
300	1785	.69	.22	.09	.09	.17	.18
300	1953	.69	.21	.09	.08	.17	.18
300	2001	.68	.21	.09	.09	.17	.18
After Exposure ^a		.75	.17	.06	.08	.16	.17
366	0	.84	.05	.04	.08	.14	.14
366	17	.88	.10	.06	.08	.16	.16
366	70	.89	.14	.08	.08	.17	.18
366	93	.89	.16	.06	.08	.17	.18
366	161	.90	.14	.09	.08	.17	.18
366	233	.90	.16	.07	.08	.18	.18
366	329	.91	.16	.10	.08	.18	.19
366	377	.90	.16	.10	.08	.18	.19
366	425	.90	.16	.09	.08	.18	.19
366	497	.89	.16	.09	.09	.18	.19
366	545	.85	.17	.10	.09	.17	.19
366	593	.85	.20	.09	.09	.18	.20
366	665	.82	.18	.08	.09	.18	.18
366	713	.87	.18	.10	.09	.19	.20
366	761	.87	.19	.10	.09	.19	.20
366	833	.85	.19	.11	.09	.18	.20
366	881	.85	.18	.11	.09	.18	.19
366	939	.80	.20	.12	.09	.19	.20
366	1011	.80	.19	.10	.09	.17	.20
366	1059	.83	.19	.10	.09	.18	.19
366	1179	.84	.18	.09	.09	.17	.19
366	1227	.85	.19	.13	.09	.19	.20
366	1275	.82	.21	.12	.08	.181	.19
366	1347	.84	.21	.11	.09	.183	.20
366	1395	.84	.19	.13	.09	.187	.20
366	1443	.85	.18	.11	.09	.173	.19
366	1575	.85	.18	.10	.09	.173	.19
366	1621	.82	.19	.12	.09	.183	.20
366	1693	.82	.19	.12	.09	.183	.20
366	1741	.81	.22	.11	.09	.187	.20
366	1909	.80	.22	.11	.09	.183	.20
366	1957	.80	.22	.12	.085	.183	.20
366	2024	.80	.22	.11	.085	.185	.20
After Exposure ^a		.75	.25	.12	.10	.18	.21

T [K]	t [h]	α for Xenon Lamp					α _s
		Range of λ x 10 ³ [μm]					
		2-4.1	4.1-6	6-8.5	8.5 -	Total	
422	0	.75	.11	.05	.05	.126	.137
422	22	.90	.16	.05	.05	.15	.16
422	46	.92	.16	.07	.07	.17	.18
422	144	.87	.17	.07	.07	.16	.18
422	192	.80	.20	.07	.07	.16	.18
422	264	.80	.18	.10	.07	.16	.19
422	312	.78	.20	.07	.08	.16	.18
422	360	.80	.17	.08	.09	.16	.18
422	432	.76	.19	.07	.08	.16	.18
422	480	.76	.20	.09	.08	.16	.18
422	528	.76	.19	.08	.08	.16	.18
422	600	.80	.17	.10	.08	.16	.19
422	648	.80	.19	.09	.08	.16	.19
422	768	.77	.18	.07	.08	.15	.18
422	816	.80	.17	.08	.08	.15	.19
422	864	.75	.18	.07	.08	.14	.17
422	936	.78	.16	.08	.08	.14	.17
422	984	.78	.18	.08	.08	.15	.18
422	1032	.78	.18	.08	.08	.14	.18
422	1152	.70	.16	.08	.08	.14	.17
422	1200	.72	.17	.09	.08	.15	.17
422	1272	.73	.17	.08	.08	.14	.17
422	1320	.72	.18	.08	.08	.14	.17
422	1488	.70	.19	.08	.08	.14	.17
422	1536	.68	.21	.09	.09	.15	.18
422	1608	.66	.18	.09	.09	.15	.17
422	1656	.65	.18	.10	.08	.15	.17
422	1704	.67	.18	.10	.08	.15	.17
422	1776	.68	.20	.09	.08	.15	.18
422	1824	.70	.18	.11	.08	.16	.18
422	1872	.70	.19	.09	.09	.16	.18
422	1944	.70	.18	.09	.09	.16	.18
422	2016	.68	.19	.10	.08	.16	.18
422	2256	.69	.19	.09	.08	.16	.17
422	2424	.69	.17	.11	.08	.15	.17
422	2472	.66	.19	.10	.08	.15	.17
422	2560	.68	.17	.11	.08	.15	.18
422	2644	.67	.18	.10	.09	.15	.17
422	2736	.68	.18	.10	.08	.15	.17
422	2784	.68	.18	.11	.09	.15	.18
Xenon Lamp off 2832 to 3335 h.							
422	3336	.66	.17	.10	.09	.16	.17
422	3408	.64	.16	.11	.09	.15	.17
422	3508	.64	.18	.10	.09	.15	.17
422	3580	.64	.18	.11	.09	.15	.17
422	3678	.62	.16	.12	.09	.16	.17
422	3676	.64	.20	.11	.09	.16	.18
422	3798	.63	.17	.12	.09	.16	.18
422	3866	.66	.17	.11	.09	.16	.18
422	3914	.64	.20	.12	.09	.16	.18
422	3962	.61	.17	.13	.09	.16	.17
422	4034	.65	.20	.12	.09	.17	.18
422	4082	.66	.21	.12	.09	.17	.18
422	4202	.65	.20	.13	.09	.16	.19
422	4298	.66	.20	.12	.09	.17	.19
422	4370	.65	.20	.12	.09	.17	.18
422	4466	.63	.20	.13	.09	.17	.18
422	4530	.62	.21	.13	.09	.17	.19
422	4634	.61	.20	.13	.10	.17	.19
422	4706	.61	.25	.12	.09	.17	.19
422	4754	.66	.22	.12	.09	.17	.19
422	4802	.65	.23	.12	.09	.17	.19
422	4874	.62	.21	.12	.10	.17	.20
422	4921	.63	.22	.11	.10	.17	.19

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Table 1-3 (Continued)

Ultra-Violet Radiation Effects on Spectral Absorptance of Zinc Oxide-Potassium Silicate Paint

T [K]	t [h]	α for Xenon Lamp					α _s
		Range of λ × 10 ³ / [m]					
		2-4.1	4.1-6	6-8.5	8.5 -	Total	
422	4969	.66	.20	.11	.10	.17	.19
422	5089	.62	.22	.10	.11	.17	.18
422	5137	.59	.24	.11	.09	.17	.18
422	5209	.63	.24	.10	.10	.17	.19
422	5329	.60	.25	.11	.10	.17	.19
422	5401	.61	.25	.11	.11	.17	.19
422	5449	.64	.25	.13	.09	.17	.20
422	5497	.59	.26	.12	.09	.17	.20
422	5617	.62	.25	.12	.10	.18	.20
422	5665	.58	.25	.11	.10	.17	.19
422	5737	.59	.26	.12	.09	.17	.19
422	5785	.58	.26	.14	.09	.17	.20
422	5833	.59	.25	.11	.10	.17	.19
422	5905	.58	.22	.14	.10	.17	.19
422	5953	.58	.25	.11	.10	.17	.19
422	6001	.61	.25	.11	.10	.17	.19
422	6073	.62	.22	.11	.10	.17	.19
422	6121	.60	.26	.09	.10	.17	.19
422	6169	.63	.22	.11	.09	.17	.19
422	6241	.64	.23	.09	.10	.17	.19
422	6289	.64	.22	.08	.10	.16	.19
422	6457	.68	.20	.10	.10	.17	.19
422	6505	.64	.23	.08	.10	.17	.19
422	6577	.63	.22	.11	.09	.17	.19
422	6625	.65	.20	.11	.10	.17	.19
422	6673	.62	.24	.10	.09	.17	.19
422	6745	.62	.22	.11	.10	.16	.19
422	6793	.62	.22	.10	.09	.16	.19
422	6913	.62	.23	.10	.09	.16	.19
422	6961	.62	.23	.10	.10	.16	.19
422	7009	.62	.20	.10	.10	.16	.19
422	7081	.66	.19	.10	.10	.16	.18
422	7129	.63	.19	.09	.10	.16	.19
422	7177	.65	.21	.09	.10	.16	.18
422	7249	.65	.18	.10	.10	.16	.18
422	7345	.60	.18	.11	.10	.16	.18
422	7417	.62	.18	.10	.10	.16	.18
422	7465	.63	.19	.09	.10	.16	.18
422	7513	.65	.20	.11	.10	.16	.19
422	7585	.62	.22	.10	.10	.16	.19
422	7633	.65	.20	.10	.10	.16	.19
422	7681	.63	.17	.10	.10	.16	.18
422	7753	.64	.18	.12	.10	.16	.18
422	7801	.60	.19	.10	.10	.16	.18
422	7849	.62	.20	.11	.09	.17	.18
422	7921	.63	.20	.09	.09	.17	.18
422	8017	.62	.21	.09	.10	.16	.18
422	8029	.62	.20	.10	.10	.16	.18
422	8125	.62	.20	.10	.10	.16	.18
422	8251	.57	.17	.12	.10	.16	.18
422	8301	.56	.17	.12	.10	.16	.18
422	8349	.57	.18	.11	.10	.16	.18
422	8421	.55	.17	.13	.10	.16	.18
422	8517	.54	.17	.12	.10	.16	.18
422	8589	.57	.17	.12	.10	.16	.18
422	8781	.59	.19	.13	.10	.16	.18
422	9021	.54	.21	.11	.11	.17	.18
422	9093	.57	.19	.11	.10	.16	.17
422	9189	.50	.20	.09	.10	.15	.17
422	9285	.53	.21	.11	.10	.16	.18
422	9357	.54	.23	.14	.10	.17	.19

T [K]	t [h]	α for Xenon Lamp					α _s
		Range of λ × 10 ³ / [m]					
		2-4.1	4.1-6	6-8.5	8.5 -	Total	
422	9424	.54	.21	.12	.10	.17	.18
422	9501	.52	.20	.09	.10	.16	.17
422	9597	.54	.19	.13	.10	.16	.18
422	9645	.52	.21	.11	.10	.15	.18
422	9693	.52	.19	.11	.10	.16	.18
422	9789	.54	.19	.09	.11	.16	.18
422	9861	.50	.19	.11	.11	.15	.17
422	9885	.53	.20	.12	.10	.15	.18
422	9975	.50	.18	.11	.11	.16	.17
422	10071	.48	.19	.10	.11	.15	.17
422	10143	.50	.17	.13	.10	.14	.17
422	10239	.49	.19	.12	.10	.15	.17
422	10431	.49	.21	.11	.10	.15	.17
422	10454	.49	.19	.12	.10	.14	.17
422	10517	.45	.19	.13	.10	.15	.17
422	10517	.62	.22	.14	.12	.17	.19
Before Exposure ^a		.60	.06	.06	.07	.13	.15
After Exposure ^a		.66	.23	.14	.10	.20	.21
450	0	.50	.10	.04	.08	.12	.12
450	20	.75	.15	.07	.08	.16	.16
450	58	.80	.17	.08	.08	.18	.18
450	106	.84	.23	.09	.09	.18	.20
450	154	.85	.23	.10	.10	.19	.20
450	226	.91	.23	.12	.10	.20	.22
450	274	.90	.23	.11	.11	.21	.22
450	322	.94	.29	.10	.11	.21	.24
450	394	.95	.27	.10	.11	.20	.24
450	488	.87	.28	.13	.11	.22	.24
450	560	.87	.24	.14	.12	.20	.23
450	606	.85	.30	.14	.13	.22	.24
450	656	.88	.28	.18	.13	.22	.24
450	728	.85	.31	.16	.13	.24	.26
450	776	.80	.31	.16	.14	.25	.25
450	824	.75	.35	.20	.14	.25	.26
450	896	.80	.30	.20	.14	.25	.26
450	944	.80	.30	.19	.14	.25	.25
450	1004	.85	.30	.20	.14	.25	.26
Before Exposure ^a		.60	.05	.05	.07	.12	.14
After Exposure ^a		.90	.25	.15	.10	.21	.23
534	0	-	-	-	-	.11	-
534	0	.60	.03	.05	.08	.11	.12
534	12	.55	.20	.08	.09	.16	.16
534	60	.55	.27	.10	.12	.20	.20
534	140	.55	.28	.13	.16	.21	.22
534	181	.55	.27	.15	.17	.22	.23
534	256	.55	.25	.20	.16	.23	.24
534	304	.55	.25	.20	.18	.23	.24
534	356	.50	.25	.20	.18	.23	.24
534	404	.50	.25	.23	.19	.24	.25
534	426	.55	.26	.22	.19	.24	.25
534	502	.55	.26	.23	.19	.24	.25
Before Exposure ^a		.64	.05	.05	.07	.13	.14
After Exposure ^a		.70	.28	.19	.16	.25	.26

^a Values deduced from spectral reflectance data.

Degrading Source: 2x10⁻⁷ to 4x10⁻⁷ m Xenon Lamp, 1 Sun level.

Method of obtaining data: Calorimetric in situ absorptance. Chamber pressure: 1.33x10⁻⁵ Pa.

From Cunningham, Grammer & Smith (1969).

COATINGS

Solar Reflectors

Table 1-4

Ultra-Violet Radiation Effects on Solar Absorptance of Zinc Oxide-Potassium Silicate Paint

T [K]	Intensity Suns	Exp. Time ESH	$\Delta\alpha_s$	Comments
258-280		0 310 444 661 881 1194 1629 1995	.003 .022 .029 .038 .047 .058 .071 .081	Calculated from sample temperature; flight data of Lunar Orbiter I. Data from smooth curve.
278	3.9	1020	.010	Sample No. 1 of Table 1-2
279	10	2160	.006	Sample No. 3
279	10	2160	.006	Sample No. 4
279	10	2160	.004	Sample No. 5
279	4.8	300	.003	Sample No. 6
279	6.1	4500	.024	Sample No. 7
279	5.8	7900	.049	Sample No. 8
279	4.8	300	.005	Sample No. 10
279	6.1	4500	.026	Sample No. 12
279	5.8	7900	.053	Sample No. 14
279	4.8	300	.005	Sample No. 15
279	6.1	4500	.024	Sample No. 16
279	5.8	7900	-.004	Sample No. 17
293	11.7	1000	.006	Sample No. 32
298		800	.010	UV from a G.E.AH-6 lamp in vacuum, Absorptance calculated from reflectance measured in situ.
~298	6	100 500 1000 3000	.000 .005 .009 .019	UV from a AH-6 lamp in vacuum; property measured in situ. Data from smooth curve.
~298	1	100 500 1000 1800	.083 .129 .152 .155	UV from Xenon lamp in vacuum at 460 K, property measured in situ. Data from smooth curve.
~298	1	100 500 1000 2100	.000 .012 .024 .041	UV from Xenon lamp in vacuum; property measured in situ. Data from smooth curve.
unknown		100 500 650 1000 2650	.010 .046 .050 .068 .118	Calculated from flight data of Mariner IV.
unknown		.46 1.1 3.9 4.0 4.3 4.9 5.2 7.1 7.4 7.7 8.1 8.5	.002 -.001 -.004 -.001 -.001 -.001 .002 -.003 .001 -.001 .000 -.004	Calculated from temperature of substrate from flight data of OSO III.

(Continued onto next page)

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Table 1-4 (Continued)

Ultra-Violet Radiation Effects on Solar Absorptance of Zinc Oxide-Potassium Silicate Paint

T [K]	Intensity Suns	Exp. Time ESH	$\Delta\alpha_s$	Comments
unknown		8.7	.001	Calculated from temperature of substrate from flight data of OSO III.
		721	-.004	
		717	.000	
		727	.002	
		751	.000	
		1336	-.004	
		1336	-.001	
		1336	.000	
		1336	.003	
		1513	.005	
		1577	.002	
		1577	.003	
1577	.005			
unknown		.1	.000	Calculated from temperature of substrate from flight data of Pegasus II. Data from smooth curve.
		1.0	.000	
		10	.000	
		100	.000	
		1000	.000	
		2500	.000	
unknown		.1	.000	Calculated from temperature of substrate from flight data of OSO III. Data from smooth curve.
		1.0	.000	
		10	.000	
		100	.000	
		1000	.000	
		2500	.000	

From Touloukian, DeWitt & HERNICZ (1972).

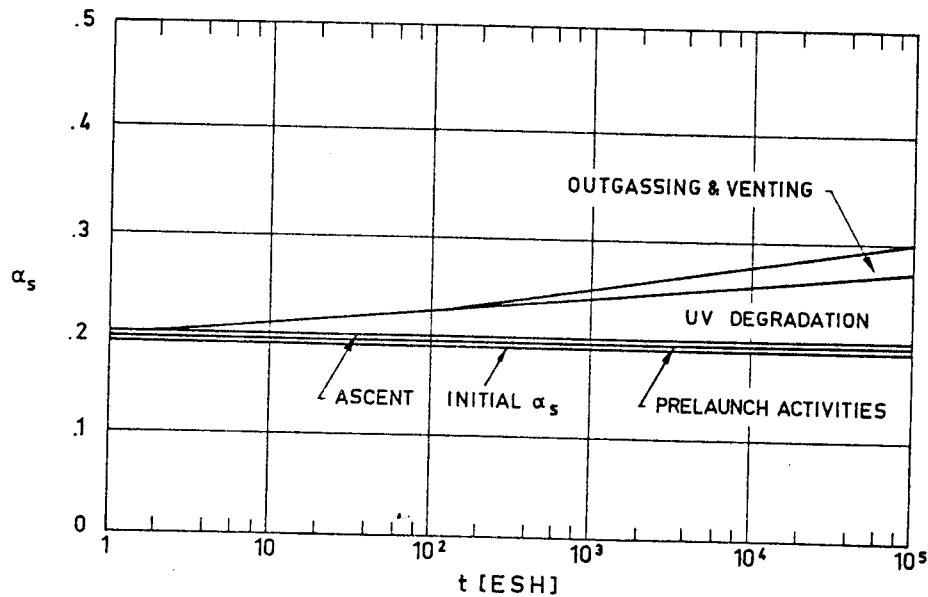


Fig 1-6. Estimated changes in the solar absorptance, α_s , of Z-93 during the total mission profile for a near-Earth orbit. From McCargo, Spradley, Greenberg & McDonald (1971).

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7.3.2.5.3. Protons only exposure. The available data are given in the following table.

Radiation Exposure		α_{so} Initial	$\Delta\alpha_s$	Comments
Intensity [keV]	Integrated Flux [protons.m ⁻²]			
150	1×10^{18}	.17	.02	Protons in situ Solar wind protons Solar wind protons
20	1×10^{20}	.17	.13	
2	5×10^{20}		.26	
1	4.2×10^{21}	.15	.35	
1	1.9×10^{22}	.15	.67	

From Rittenhouse & Singletary (1969).

7.3.2.5.4. Electrons only exposure.

Radiation Exposure		α_{so} Initial	$\Delta\alpha_s$	Comments
Intensity [keV]	Integrated Flux [electrons.m ⁻²]			
2×10^3	1×10^{20}	.17	.03	

From Rittenhouse & Singletary (1969).

7.3.2.5.6. Combined exposure.

Near UV ESH	Lyman ESH	Protons		T [K]	α_{so} Initial	$\Delta\alpha_s$
		[keV]	[protons.m ⁻²]			
375-450	750	10	1.4×10^{19}	304	.139	.019
375-450	750	-	-	304	.139	.004
-	-	-	-	304	.139	.002
375-450	750	10	1×10^{19}	301	.143	.023
375-450	750	-	-	301	.144	.005
-	-	10	1×10^{19}	290	.147	.020
-	-	10	1×10^{19}	291	.142	.026
750	750	10	2×10^{19}	300	.145	.030
750	750	-	-	300	.145	.007
-	-	-	-	300	.148	.001
750	750	10	2×10^{19}	304	.144	.035
750	750	-	-	304	.146	.014
750	750	10	2×10^{19}	295	.144	.029
750	750	-	-	295	.144	.011

From Stevens (1971).

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Solar Reflectors

7.3.2.6. Effects of the Space Environment on solar absorptance to emittance ratio.

T [K]	ESH	α_s/ϵ	Comments
~298	1160	.183	Data taken from flight of Pegasus II. Values deduced from the temperature of the substrate.
	1169	.226	
	1178	.199	
	1198	.231	
	1258	.212	
	1291	.240	
	1308	.208	
	1537	.259	
	2048	.188	
	2070	.200	
	2089	.221	
	2100	.200	
	2110	.173	
	2133	.254	
	2141	.282	
	2243	.245	
	2246	.229	
	2260	.243	
	2291	.173	
	2300	.234	
2300	.279		
2423	.173		
2431	.240		
2431	.270		
2442	.216		
258-280	0	.185	Data taken from flight of Lunar Orbiter V. Values deduced from the temperature of the substrate. Data stracted from smooth curve.
	54	.226	
	120	.251	
	214	.285	
	346	.309	
	783	.336	
	2038	.416	

From Touloukian, DeWitt & HERNICZ (1972).

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7.3.3. Reflectance.

7.3.3.1. Normal-hemispherical spectral reflectance: Fig 1-7.

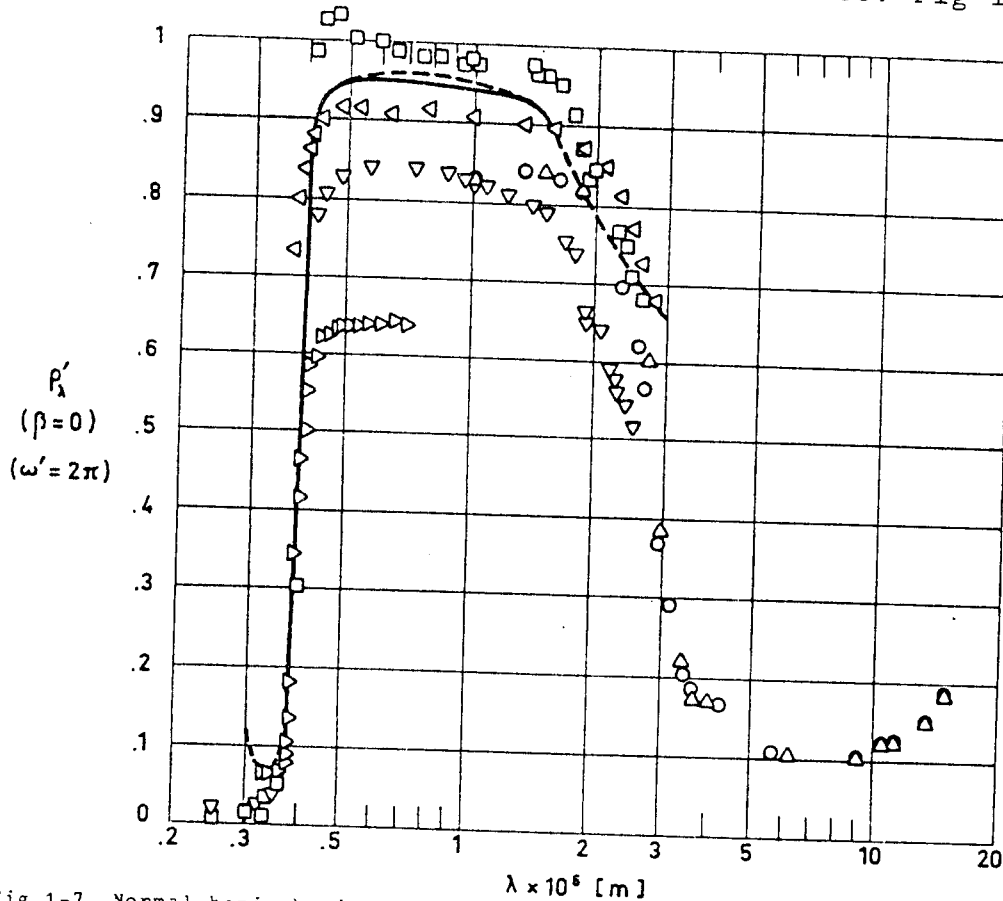


Fig 1-7. Normal-hemispherical spectral reflectance, ρ'_λ , of Z-93 vs. wavelength, λ . All data are from Touloukian, DeWitt & HERNICZ (1972) except \square and \triangle which are from Cunningham, Grammer & Smith (1969).

Explanation

Key	Description	Comments
○	Sprayed onto a 1.27×10^{-3} m thick aluminium substrate.	$T \sim 300$ K. Measured in vacuum (1.33×10^{-4} Pa). Data from smooth curve.
□	Sprayed on an aluminium substrate.	$T \sim 298$ K. Measured relative to MgO. Data from smooth curve.
△	Same as □.	Same as □. Not referenced to MgO.
▽		$T \sim 298$ K. Data from smooth curve.
▷		$T \sim 298$ K. Measured in vacuum. Data from smooth curve.
◁		$T \sim 298$ K. Exposed to vacuum. Measured in situ.
—	Applied to disc substrates of 6061-T6 aluminium. The discs, 2.54×10^{-2} m diameter by 1.27×10^{-3} m thick, were polished on one side and edge. The surface to be coated was machined to a $(30 \pm 3) \times 10^{-6}$ m RMS finish.	$T \sim 298$ K. Measured in vacuum (1.33×10^{-5} Pa) by using an integrating sphere attached to a Cary Model 14 spectrophotometer. Reported error 2%.
---	Same as —.	Same as — except measured using a Gier-Dunkle reflectometer. Reported error $\pm 1\%$.

COATINGS
Solar Reflectors

7.3.3.2. Effects of the Space Environment on reflectance.

7.3.3.2.1. Ultra-Violet Radiation: Fig 1-8.

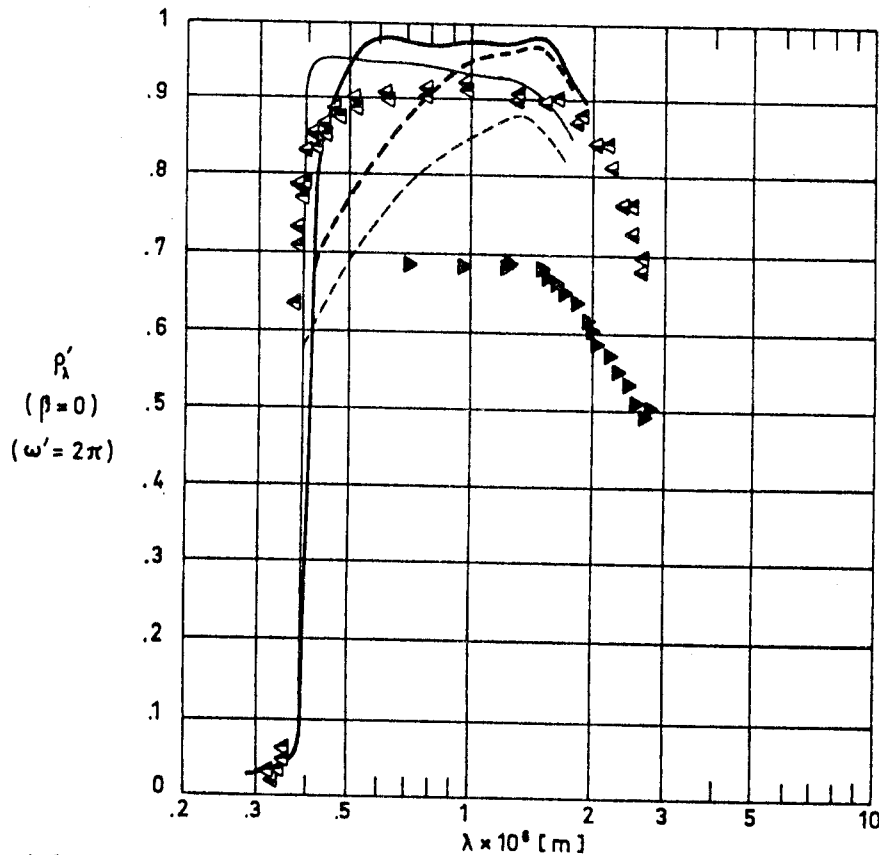


Fig 1-8. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of Z-93 vs. wavelength, λ . Data points are from Touloukian, DeWitt & HERNICZ (1972), while smooth curves are from CUNNINGTON, GRAMMER & SMITH (1969).

Explanation

Key	Description	Comments
▶		Tv298 K. Exposed in vacuum to 200 ESH. Measured in situ. Data from smooth curve.
◀		Tv298 K. Exposed to UV radiation (from a GE AH-6 lamp) in vacuum. ESH 800. Measured in situ.
◀		Same as ◀ except measured in air after UV exposure.
—	Applied to disc substrates of 6061-T6 Aluminium. The discs, 2.54×10^{-2} m diameter by 1.27×10^{-3} m thick, were polished on one side and edge. The surface to be coated was machined to a $(30 \pm 3) \times 10^{-6}$ m RMS finish.	Tv422 K. Measured in vacuum (1.33×10^{-5} Pa) by using an integrating sphere attached to a Cary Model 14 spectrophotometer. Reported error 2% (Calibrations made using a Gier-Dunkle reflectometer).
---	Same as —.	Same as — except exposed to UV radiation (from a 900 W Hanovia xenon lamp, 1 Sun level). ESH 10014.
—	Same as —.	Same as — except Tv534 K.
---	Same as —.	Same as — except exposed to UV radiation (from a 900 W Hanovia xenon lamp, 1 Sun level). ESH 502.

COATINGS
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7.3.3.2.3. Protons only exposure: Fig 1-9.

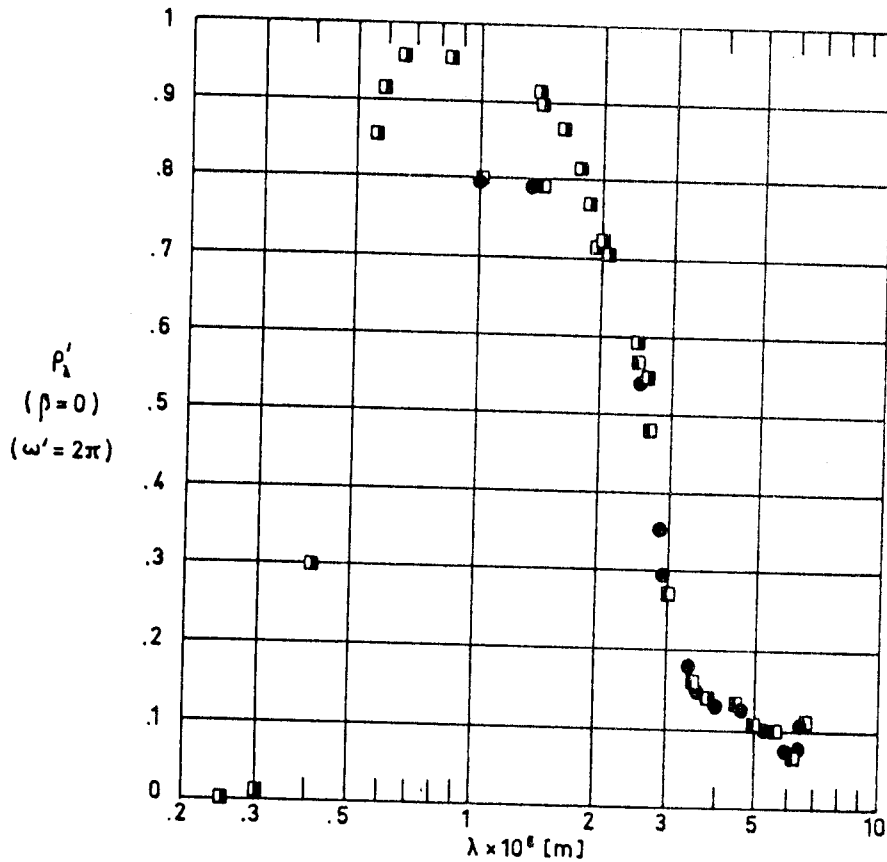


Fig 1-9. Effect of Protons Radiation on normal-hemispherical spectral reflectance, ρ_{λ}' , of Z-93 vs. wavelength, λ . From Touloukian, DeWitt & HERNICZ (1972).

Explanation

Key	Description	Comments
●	Sprayed onto a 1.27×10^{-3} m thick aluminium substrate.	T \sim 298 K. Exposed to 10^{20} p.m $^{-2}$.
□	Sprayed on an aluminium substrate.	T \sim 298 K. Irradiated in vacuum at 300 K with 7.7×10^3 eV protons to a total dose of 10^{20} p.m $^{-2}$. Measured in vacuum (1.33×10^{-4} Pa). Measured relative to MgO. Data from smooth curve.
□	Same as □.	Same as □ except not referenced to MgO.

COATINGS

Solar Reflectors

8. ENVIRONMENTAL BEHAVIOR

8.1. Prelaunch. The coating is brittle, hard to apply and maintain (Scollon & Carpitella (1970)).

8.2. Postlaunch. Blistering during ascent heating can be avoided by curing appropriately the paint (Stevens (1971)).

8.2.1. Ascent. Ascent heating histories with peak temperatures below 645 K do not cause increase in α_s and ϵ (Rittenhouse & Singletary (1969)).

8.2.2. Orbital. The primary source of degradation appears to be the near ultraviolet portion of incident solar and albedo radiation.

The presence of impurities can greatly decrease the stability to the space environment of this coating (Cunnington, Grammer & Smith (1969)).

9. THERMAL CYCLING

The maximum and minimum temperatures at which the paint has been tested without major changes in properties were:

$$T_{\min} = 211 \text{ K}$$

$$T_{\max} = 366 \text{ K}$$

(Rittenhouse & Singletary (1969)).

10. SOURCE

IIT Research Institute. 10 West 35 Street, Chicago, Illinois 60616.

11. COST

Pigment: 165 US \$.kg⁻¹ (Minimum order 2 lb).

Potassium Silicate: 22 US \$.kg⁻¹.

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These prices are FOB Chicago. 35 US \$ per shipment for prepaid should be added.

Effective July 1, 1974

(IITRI 1974).

12. PAST SPATIAL USE

This coating has been widely tested and used in spacecraft. The table below gives several precedents.

Spacecraft	Launching Date	Used or Tested	References
Mariner IV	Nov. 28, 1964	Tested	Lewis & Thostesen (1965).
Pegasus II	May 25, 1965	Tested	Schafer & Bannister (1967).
Pegasus III	July 30, 1965		
Lunar Orbiter V	Aug. 1, 1967	Tested	Caldwell y Nelson (1968).
SERT II (Space Electric Rocket Test)	Feb. 3, 1970	Used	Stevens (1971), Stevens & Smolak (1971).
OSO III (Orbiting Solar Observatory)	March 8, 1967	Tested	Millard & Pearson (1973).

COATINGS

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1.2.3. ZINC ORTHOTITANATE - POTASSIUM SILICATE1. COMPOSITION

Pigment: IIT Research Institute, Zn_2TiO_4 .

Binder: GTE Sylvania Incorporated, PS7 potassium silicate.

Distilled water.

From Harada & Wilkes (1979).

Details on pigment preparation are given overleaf. These details, which are not very relevant to the user of the coating, could be essential to the proper understanding of this data item.

2. FORMULATION

As given in the following table. PBR is the pigment to binder ratio by weight.

PBR	Components		
	Zn_2TiO_4 [kg]	PS7 [m^3]	H_2O [m^3]
4.3	.1	50×10^{-6}	30×10^{-6}
5.3	.1	40×10^{-6}	35×10^{-6}
6.1	.1	35×10^{-6}	40×10^{-6}
7.1	.1	30×10^{-6}	45×10^{-6}
8.5	.1	25×10^{-6}	50×10^{-6}
10.6	.1	20×10^{-6}	55×10^{-6}

From Harada & Wilkes (1979).

High PBR values provide both higher reflectance and greater stability.

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PREPARATION OF THE PIGMENT

Three processes have been considered at IITRI for the synthesis of Zn_2TiO_4 . All of them involve calcination and reaction of zinc and titanium precursors.

Solid State Reaction (SSR)

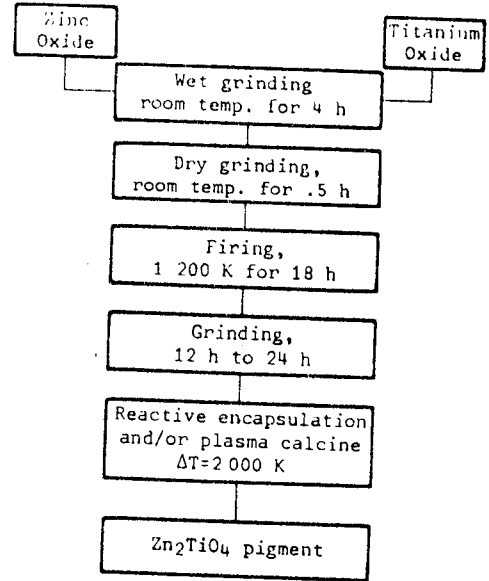
New Jersey Zinc Co., SP500 zinc oxide, ZnO , and E.I. DuPont de Nemours Co., R900 anatase, TiO_2 , are grinded and mixed at low temperature for a total of 4 h of wet grinding and .5 h of dry grinding. The aim of these grinding and mixing operations is to assure good particle to particle contact, and hence, reactivity of the two oxides.

Zn_2TiO_4 pigment is formed by firing at 1 200 K for 18 h, additional 12 h to 24 h of grinding followed by reactive encapsulation and/or induction plasma calcining to obtain a stable product.

Reactive encapsulation aims at stabilizing pigments against ultra-violet space damage. Encapsulating a pigment also avoids the possibility of a radiation-induced change in surface state. A number of reactive encapsulants can be used as, sodium acid phosphate, potassium hexafluorosilicate, ferro-ferricyanide, PS7 potassium silicate, ... The last is the most widely used.

Plasma heat treatment basically consists in passing an Ar/O_2 aerosol of the pigment through a plasma reactor with temperature jumps across the boundary layer close to 2 000 K. This annealing of the reactively encapsulated pigment results in enhanced ultra-violet behavior of both pigment alone and coating.

The solid state reaction process is time consuming, presents the danger of introducing degradable contaminants and does not allow an appropriate control of the pigment size. Because of these limitations, studies on the use of salt precursors for Zn and Ti were conducted in order to improve the pigment.

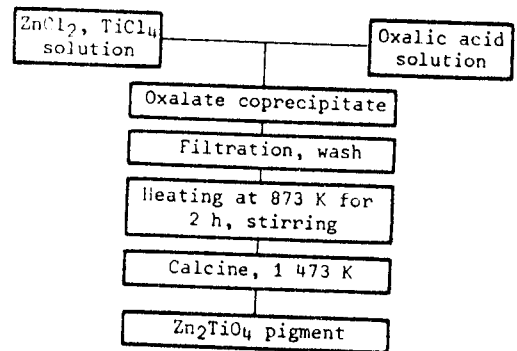


Coprecipitation (COP)

A mixed solution of zinc and titanium chlorides is added to a solution of oxalic acid. The resulting solution is then heated to 873 K and held at this temperature during 2 h, being continuously stirred while the Zn_2TiO_4 precipitate is formed.

Calcination and firing at 1 473 K are performed in standard atmospheric Globar furnaces (bonded silicon carbide resistance elements).

No grinding is required for obtaining pigment particles amenable to incorporation to a paint. Ultra-violet irradiation in vacuum of these powders resulted in minimal change in reflectance after 1 000 ESH, although damage resulted when the powders, incorporated in a silicone binder, were irradiated as coating. The particles showed a tendency toward agglomeration which can be avoided by use of the third process, below.



Mixed Oxalate Process (MOX)

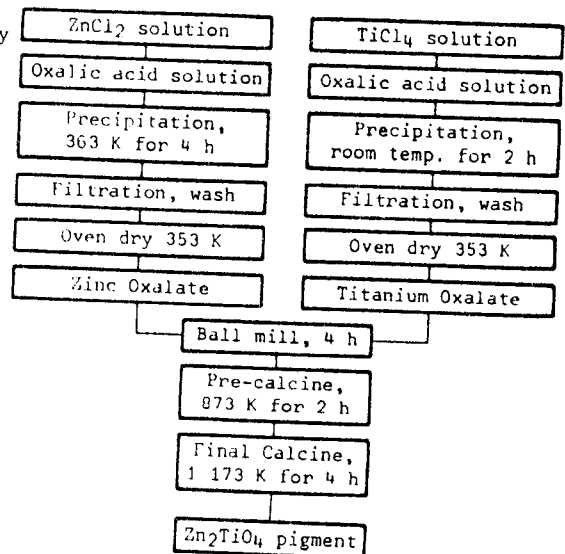
Zinc and titanium oxalates are produced from the corresponding chlorides through two independent steps which can be separately established and controlled to produce an optimum precipitated product.

The resulting titanium and zinc oxalates are mixed and ball milled for 4 h, pre-calcined at 873 K for 2 h and, finally, calcined at 1 173 K for 4 h.

Fine particle size zinc orthotitanate is achieved using very fine precursors.

The product obtained by this method can be utilized as a pigment with no grinding.

This is the most current state of the art pigment preparation process. Most of the information given below refers to a coating based on MOX prepared pigment.



References: Zerlaut, Gilligan & Ashford (1972), Gilligan & Zerlaut (1973), Gilligan, Harada & Gates (1974), Harada & Wilkes (1979).

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3. USUAL DESIGNATION

Zinc Orthotitanate (ZOT). IIT Research Institute.

Coating corresponding to PBR=7.1, which is the most current, is known as YB-71 (Harada (1981)).

4. SUBSTRATE

Most surfaces (IITRI (1974)).

5. METHOD OF APPLICATION

- 5.1. Preparation of paint for application. The components are mixed in a porcelain ball mill with porcelain balls for 4 h.
- 5.2. Preparation of surfaces for painting. The surface should be chemically etched or abraded and then cleaned with an alkaline detergent and rinsed with distilled water.
- The complete surface must be water-break free after the abrasion and cleaning process. By observing the above practices, excellent adhesion on metal surfaces is achieved.
- 5.3. Application of paint. By spray-painting, using standard paint spray guns. The coating is applied as a continuous, wet film. This film is permitted to dry until the gloss has almost disappeared and then the next coat is sprayed on. The process is repeated until the desired thickness is achieved.
- 5.4. Coating thickness. A thickness of .004" to .006" (10^{-4} m to 1.5×10^{-4} m) is recommended by the supplier (IITRI (1974), which concerns a silicone binded coating). Minimum solar absorptance is achieved with a coating thickness close to .010" (2.5×10^{-4} m), Fig 1-11.

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5.5. Curing process. According to Harada & Wilkes (1979) the YB-71 coating can be air-dried, or can be baked at 390 K for complete water removal.

The curing process indicated in IITRI (1974), also given in Gilligan, Harada & Gates (1974), is for a silicone binded coating.

6. SOLVENTS RESISTANCE

Not attacked by the solvents.

7. PHYSICAL PROPERTIES

7.1. Density. 2.460 kg.m^{-3} for the YB-71 formulation. This value has been deduced by Harada & Wilkes (1979) from a plot of coating mass vs. coating thickness for several samples.

7.2. Outgassing. No data available. Water is the only volatile component of these inorganic coatings.

7.3. Thermal radiation properties. The optical properties of these coatings depend upon pigment purity, stoichiometry, particle size and ZnO content. Stability also relates to the last three mentioned variables. In addition, the influence of the binder on the ultra-violet damage of the coating has been noted by Zerlaut, Gilligan & Ashford (1972), Gilligan & Zerlaut (1973), and Gilligan, Harada & Gates (1974). Since these coatings are evolving from many years of research effort and apparently conflicting data have been reported, emphasis should be placed on the correct identification of both pigment preparation process and binder used. Table 1-5 has been devised to this aim.

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Table 1-5

Literature Search for Thermal Radiation Properties of ZOT Coatings

Reference	Pigment		Binder	Available Data	Data in this Item
	Process	Encapsulation			
Zerlaut, Gilligan & Harada (1964) quoted by Touloukian, DeWitt & Hencicz (1972).	Solid State Reaction (SSR).	Not given. Pigment calcined at 973 K for 16 h.	PS7 Potassium Silicate. Silvania, Inc.	α_s and $\Delta\alpha_s$ after 690 ESH, UV radiation.	Tables 1-6 and 1-7.
		Not given.		α_s .	
		Not given. Pigment calcined at 973 K for 4 h.		α_s and $\Delta\alpha_s$ after 170 ESH, UV radiation.	
Zerlaut, Noble & Rogers (1968).	SSR.	None. Phosphated. Phosphated and recalcined at 925 K for 18 h. None but recalcined at 925 K for 18 h.	OI-650 Polymonomethylsiloxane, Owens Illinois, Inc.	α_s and $\Delta\alpha_s$ after 300, 550, 1 200 ESH, UV radiation and after Air exposure. ρ'_λ vs. λ before and after the above exposures.	Not given.
Gilligan & Zerlaut (1971).	SSR.	None. Plasma calcined.	None.	ρ'_λ vs. λ before and after proton exposure.	Not given.
		Ferro-ferricyanide treated.	OI-650.	ρ'_λ vs. λ before and after the following exposures: proton, UV radiation (600, 1 300 ESH), combined UV and proton (1 300 ESH + 972 EWH) and O ₂ bleach. $\Delta\alpha_s$ after the above exposures.	
		Phosphated.	PS7.	ρ'_λ vs. λ before and after 1 300 ESH and O ₂ bleach. ρ'_λ vs. λ before and after proton exposure. $\Delta\alpha_s$ after UV radiation (600, 1 300 ESH), combined UV and proton (1 300 ESH + 972 EWH) and O ₂ bleach.	
Zerlaut, Gilligan & Ashford (1972).	SSR.	Several treatments with soluble alkali salts were tested, among them: Potassium silicate, Lithium silicofluoride, Potassium silicofluoride.	None.	UV effect on ρ'_λ after 970 or 1 010 ESH (depending on the case) at selected values of λ . ρ'_λ vs. λ for the mentioned encapsulants, before and after 970 or 1 010 ESH (depending on the case), UV radiation.	Not given.
		Untreated, plasma calcined (several plasma temperatures).	None.	UV effect on ρ'_λ after 1 010 or 2 500 ESH (depending on the case) at selected values of λ . α_s and $\Delta\alpha_s$ after 1 010 or 2 500 ESH (depending on the case), UV radiation. ρ'_λ vs. λ before and after 2 500 ESH, UV radiation. $\Delta\alpha_s$ after proton exposure.	
		Phosphated and silicated, plasma calcined (several plasma temperatures).	None.	UV effect on ρ'_λ after 2 500 ESH, UV radiation at selected values of λ . α_s and $\Delta\alpha_s$ after 2 500 ESH, UV radiation. ρ'_λ vs. λ before and after 2 500 ESH, UV radiation.	

(Continued onto next page)

COATINGS

Solar Reflectors

7.3.1. Emittance.

7.3.1.1. Hemispherical total emittance. Fig 1-10.

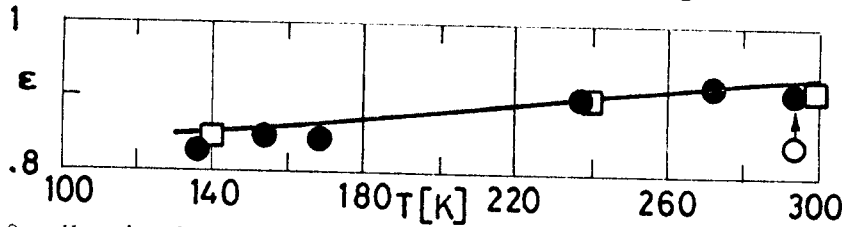


Fig 1-10. Hemispherical total emittance, ϵ , of Zinc Orthotitanate-Potassium Silicate Coatings vs. temperature, T.
 ○ SSR pigment, phosphated. From Keyte (1975).
 ● MOX pigment, YB-71. From Harada & Wilkes (1979).
 □ YB-71. AESC. From Ahern & Karperos (1983).

7.3.2. Absorptance.

7.3.2.1. Solar absorptance. Table 1-6. See also p. 1-40.2.

7.3.2.2. Variation of solar absorptance with coating thickness.

Fig 1-11. Differently prepared coatings. Partial removal of ZnO from the pigment decreases α_s .

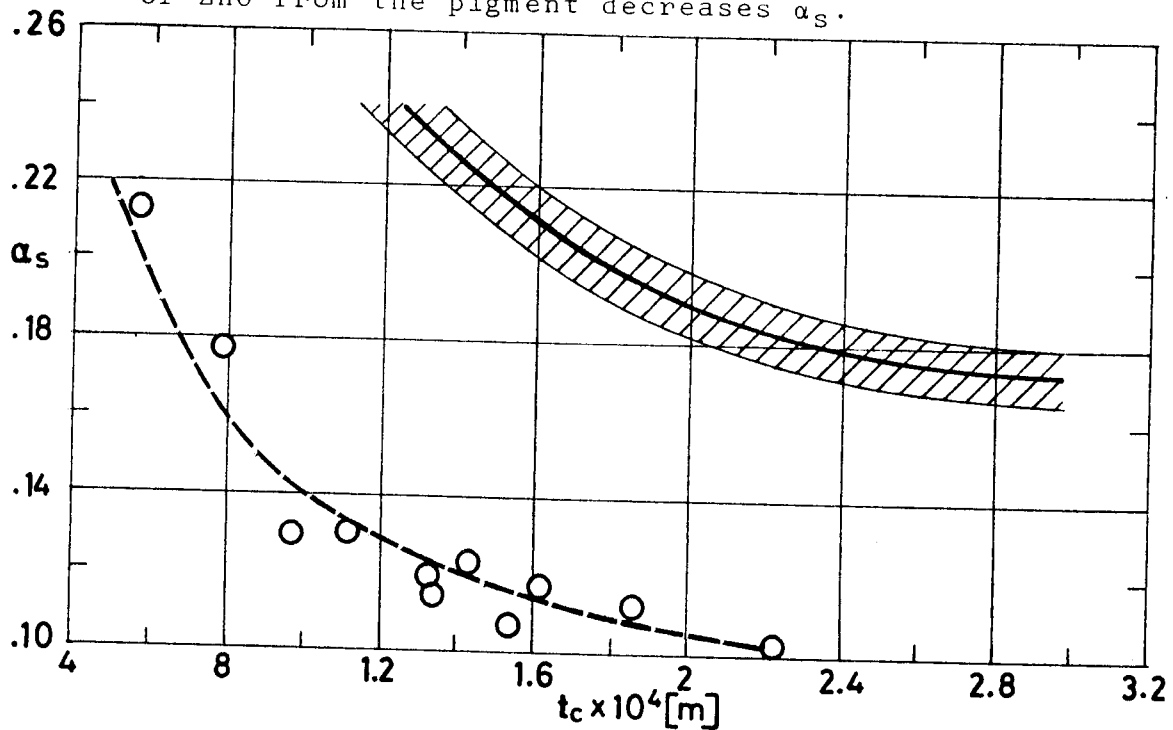


Fig 1-11. Solar absorptance, α_s , of YB-71 vs. thickness, t_c .
 ○ From Harada & Wilkes (1979).
 ▨ From measurements on 16 panels by AESC. Scatter is due to t_c variation. From Ahern & Karperos (1983).

COATINGS

Solar Reflectors

Table 1-6
Solar Absorptance of Zinc Orthotitanate-Potassium Silicate Coatings^a

No.	SAMPLE							TEST CONDITIONS			α_s	References															
	Process	Zn/Ti Stoichiometric Ratio	Encapsulation	Calcination		PBR	Coating Curing Process	Author's Designation	Temp. [K]	Pressure [Pa]			Incidence [degrees]														
				Temp. [K]	Time [h]																						
1	Solid State Reaction (SSR).			973	16	4.30	Air dried	Sample No. 7008	298 K	$\beta=0^\circ$.122	Zerlaut, Gilligan & Harada (1964), quoted by Touloukian, DeWitt & Hearnicz (1972).															
2				773	2			Sample No. 7009			.118																
3				973	4	Air dried	Sample No. H-19-53	.139																			
4				773	2		.128																				
5					Silicated			Batch No. B-419			$p=1.3 \times 10^{-4} - 1.3 \times 10^{-5}$ Pa		$\beta=7^\circ$.136	Zerlaut, Gilligan & Ashford (1972). Test Conditions, Zerlaut & Courtney (1967).												
6					Phosphated			Batch No. B-421						.122													
7					Ferro-ferricyanide treated.			Batch No. B-424						.154													
8					Potassium hexa-fluorosilicate treated.	773	7							Batch No. B-563		.120											
9					Phosphated			Surface No. 9 white paint B-303						$p=10^5$ Pa		$\beta=0^\circ$.109	Keyte (1975).									
10	Mixed Oxalate (MOX).	1.95		1 173		4.26						.192		Harada & Wilkes (1979).													
11																					.169						
12																					.153						
13																					.228						
14																		.203									
15																		.205									
16											2.00				1 173		4.26					.190					
17																											.183
18																											.154
19																											.230
20																											.225
21						.198																					

^a Values deduced from spectral reflectance data.

COATINGS

Solar Reflectors

7.3.2.3. Variation of solar absorptance with incidence angle.

Fig 1-12. Solar absorptance deduced from spectral reflectance measured in air. Two different sample sizes were used to assure full sample illumination at all incidence angles. Thence, a discontinuity appears in the curve plotted in Fig 1-12 at $\beta=60^\circ$.

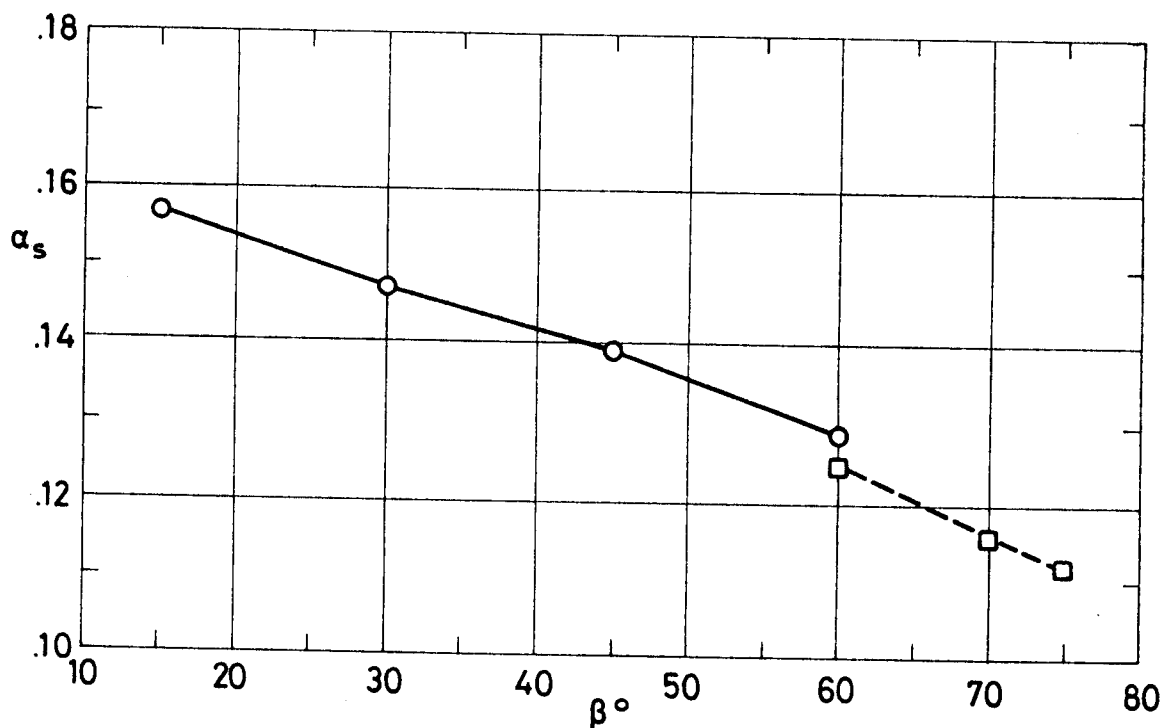


Fig 1-12. Solar absorptance, α_s , of Zinc Orthotitanate-Potassium Silicate coatings vs. incidence angle, β . SSR pigment, phosphated. From Keyte (1975).

7.3.2.5. Effects of the Space Environment on absorptance.

7.3.2.5.1. Ultra-Violet Radiation. Table 1-7.

Low-orbit (UV-only environment) data appear in pp. 1-39 and 1-40. UV, protons and electrons are present in geosynchronous orbit (pp. 1-76 or 1-135). See pp. 1-40.1 and 1-40.2 for several experiments.

COATINGS

Solar Reflectors

Table 1-7
Ultra-Violet Radiation Effects on Solar Absorptance of Zinc Orthotitanate-Potassium Silicate Coatings ^a

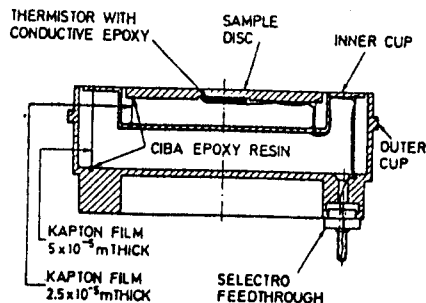
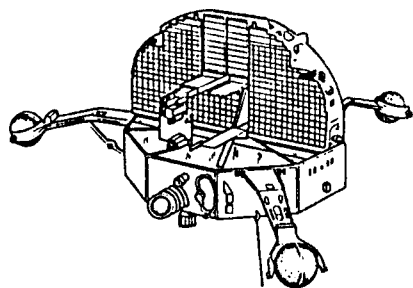
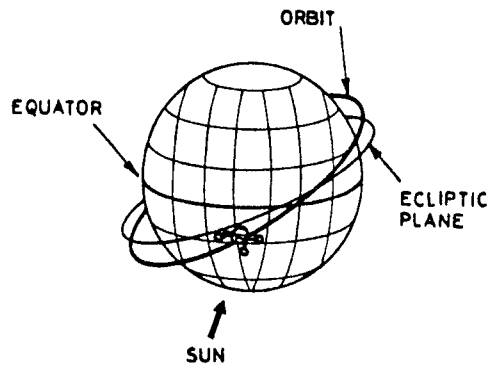
Sample No. ^b	Exposure Time [ESH]	Test Conditions	$\Delta\alpha_s$	References
1	690	Irradiated in vacuum	.019	Zerlaut, Gilligan & Harada (1964), quoted by Toulioukian, DeWitt & Hernicz (1972).
2			.032	
4	170	Irradiated in vacuum (below 1.3×10^{-3} Pa). Intensity 3.5 Suns.	.031	
5	2 400	Irradiated in vacuum (1.3×10^{-4} Pa - 1.3×10^{-5} Pa) with 1 kw General Electric AH-6 Mercury-Argon lamp. Spectral reflectance measured in situ.	.020	Zerlaut, Gilligan & Ashford (1972). Test Conditions, Zerlaut & Courtney (1967).
6	2 000		.010	
7			.011	
8	1 200		.002	
9	700	Irradiated in vacuum (below 1.3×10^{-5} Pa) with 1 kw Thorn Mercury discharge lamp (type LRD 94-0151). Intensity 3.5 Suns. Measured in situ.	.026 to .040	Keyte (1975).
	700+10 min in Air	Same as above except measured after 10 min exposure in Air	.038 to .061	
10	1 000		.006	Harada & Wilkes (1979).
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21		.006		

^a Values deduced from spectral reflectance data.
^b Sample numbers in this Table correspond to those in Table 1-6.

COATINGS

Solar Reflectors

OSO-H

TEST CONDITIONSSpacecraft & Programme

Orbiting Solar Observatory (OSO-H).
Thermal Control Coating Experiments (TCCE).

Orbit

Launched on September 29, 1971 into a 327 km by 560 km near to Earth elliptical orbit with a 33° inclination angle.

Configuration

OSO satellites have two main parts: a lower section, consisting of a nine-sided wheel, which rotates to provide gyroscopic stabilization, and a stabilized semicircular upper section, or sail, aimed at the Sun.

Thermal Test

Twelve samples (Triolo (1973)) were placed in the Sun-oriented, non-spinning sail. Data up to 8 225 orbits for eight of these samples are given by Triolo, Heaney & Hass (1978).

SAMPLESample Description

SSR- processed Zn_2TiO_4 pigment, plasma calcined. PS7 binder.

Sample Mounting

The sample is mounted on a disc 2×10^{-2} m diameter. The disc is supported by a Kapton film cylinder fastened to both the disc and an inner cup. The thermistor and its leads were attached to the underside of the sample disc with conductive silver epoxy. Another Kapton film cylinder was used for attaching the inner cup to the outer cup. The two Kapton cylinders and the film covering the thermistor network were vapor-aluminized during assembly. Dimpled Mylar sheets were placed inside each cylinder for the reduction of radiative losses.

Holes were cut in the cylinders and the bases of both cups for venting when the assembly is exposed to a vacuum environment. In order to prevent contamination during cup fabrication, the coating was applied to the cup once assembled. The aim of the inner cup is to act as a thermal guard for the back of the sample disc and thermistor leads. The inner cup flange has the same area and thermal coating as the sample disc. In addition, the thermal capacity of the disc and the inner cup are made as close as possible, thus the sample disc and the inner cup temperatures are maintained close to each other under both steady and transient conditions.

CALCULATION METHOD

α_s/ϵ is measured calorimetrically from the disc temperature, T . The terms which appear in the heat balance equation are: $c(T)dT/dt$, Sensible heat of the sample and substrate. This term disappears since the sample is in thermal equilibrium when readings are taken.

$\epsilon A \sigma (T_s^4 - T^4)$, Radiation to outer space. The hemispherical total emittance of the sample is measured before launch. The equivalent surrounding temperature, T_s , is assumed to be zero.

$\alpha_s A S$, Radiation from the Sun. Recall that the sail, where the coating is located, remains Sun-oriented.

Q , Heat transfer between the back of the sample and the outer cup. Measured before launch.

Albedo and Earth infrared radiations do not appear since reads were only taken at the Earth subsolar points.

α_s/ϵ is deduced from the resulting simplified equation, assuming that Q/c is equal to its prelaunch value.

RESULTS

$\alpha_s/\epsilon = .17$ Measured in the laboratory.

$\alpha_s/\epsilon = .21$ Deduced from flight data after 20, 780 and 8 225 orbits.

COMMENTS

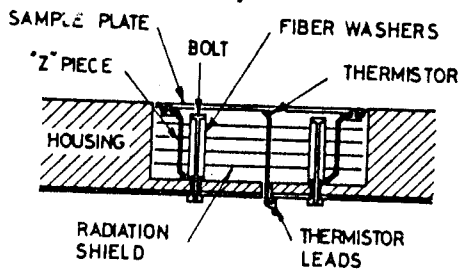
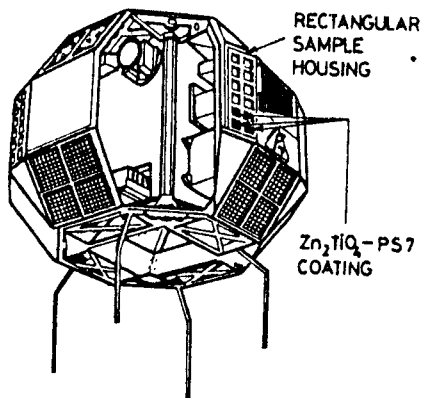
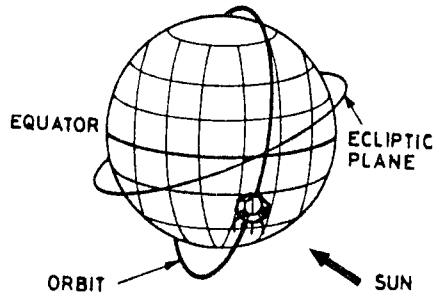
The first usable data point corresponded to the 20th orbit because of malfunction of the tape recorder. Data on a "model coating" (Alzak), previously tested both in the laboratory and in orbit, were used to convert from orbital time to ESH. (1.5 orbital hours = 1 ESH. 1 orbit takes 1.5 orbital hours). The difference between the laboratory and the first in-flight data, (which is common to all the tested coatings) must have been caused by a systematic error in the measurements.

References: Triolo (1973), Triolo, Heaney & Hass (1978).

COATINGS

Solar Reflectors

PROSPERO



TEST CONDITIONS

Spacecraft & Programme
Prospero.

Thermal Control Surface Experiment (TCSE).

Orbit

Launched by the Black Arrow R3 launch vehicle on October 28, 1971. The initial orbit parameters were: Apogee, 1 580 km; Perigee, 547 km; Inclination, 82.06°; Period, 106.5 min (13.53 orbits per day).

Configuration

Prospero is a 26-faced polyhedron, .71 m height and 1.09 m in equatorial diameter. Mass, 65.8 kg. The satellite is spin stabilized and fitted with nutation dampers. The spin axis-Sun angle at launch was approximately 94°, providing roughly normal incidence of solar radiation on most of the coatings. Initial spin rate was 17.8 rad.s⁻¹.

Thermal Test

64 thermal control surfaces were flown, including 7 gold reference surfaces, 6 black gloss reference surfaces and 3 of each of 17 different coatings, among them 9 white paints. Two types of sample housing were used; 4 of rectangular shape each containing 12 samples and mounted in corner fillets parallel to the satellite spin axis, and 4 of triangular geometry, each containing 4 samples and also mounted in corner fillets, but at an angle of about 30° to the spin axis. The 3 samples of this coating were placed in a rectangular housing.

SAMPLE

Sample Description

SSR-processed Zn₂TiO₄ pigment, phosphated. PS7 binder.

Sample Mounting

The coating was applied on an aluminium clad alloy (L72) substrate, goldized on the edges and on the rear side. The sample plate was mounted in a cup, machined in a magnesium alloy housing, by means of four fiber-glass Z pieces. The cup was goldized on both sides. 4 goldized radiation shields were placed between the substrate and the cup. The shields were mutually separated by small fiber-glass washers, and held in position by four bolts. Slots were cut in the radiation shields for passage of the above mentioned Z pieces. The temperature was measured by a YSI precision thermistor attached with Araldite in the center of the rear face of the plate.

CALCULATION METHOD

α_s is measured calorimetrically from the temperature, T, of the plate. The terms which appear in the heat balance equation are: $c(T)dT/dt$, Sensible heat of the sample plate. Since readings were only taken with the surface in thermal equilibrium, this term vanishes. $\epsilon A \sigma (T_s^4 - T^4)$, Radiation to outer space. ϵ measured before launch ($\epsilon = .91$). The equivalent surrounding temperature, T_s , is assumed to be zero. At-

tempts were made to deduce ϵ from in-flight measurements during the eclipse part of the orbit. This effort was unsuccessful because of the many parameters involved.

$\alpha_s A S(t)$, Radiation from the Sun. S is the solar flux, a known function of time, t.

$\alpha_s F_a A a S$, Albedo radiation. F_a view factor, a is the mean albedo of the Earth.

$\alpha_s F_{sp} A P$, Earth infrared radiation. F_{sp} is the view factor, and $F_{sp} P$ the flux of energy on the sample.

The last two terms were deduced from assumed values of α_s and ϵ for a reference surface (gold), using the balance equations for both the eclipse and the sunlit parts of the orbit.

$Q(T, T_c)$, Thermal coupling between the plate, at temperature T, and housing, at temperature T_c . Three methods for calculating Q were explored, none of them was completely successful. These methods were:

- 1) Calibration in a solar simulation vacuum chamber. Attempts to remove the many sources of error failed.
- 2) Thermal modelling of the sensor-housing assembly by a six-node network. Heat input was that on an orbiting-spinning plate. Temperatures for given α_s and ϵ were compared with in-flight data. Correlation was poor.
- 3) Calculation from in-flight data. ϵ was fixed for 4 samples. Only eclipse temperatures were used. Data of Q vs. $T - T_c$ were arranged as $Q = k + w_1(T - T_c) + w_2(T - T_c)^2$ and values of k, w_1 and w_2 for an average housing, as well as values of c(T) for each sample were deduced. The results for the 4 samples were fair, although discrepancies appeared.

Finally, a "best estimate" of Q vs. $T - T_c$ was made by a critical analysis of the above methods.

RESULTS

$\alpha_s = .109$, measured in the laboratory. $\alpha_s = .110$, after 15 days in orbit. $\alpha_s = .141$, after 330 days in orbit.

COMMENTS

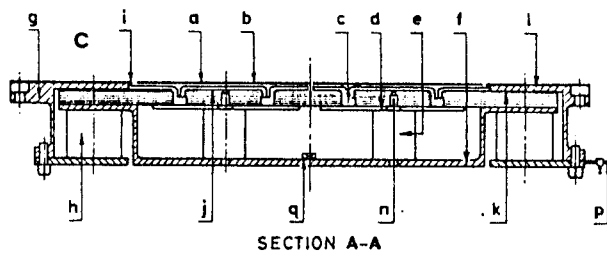
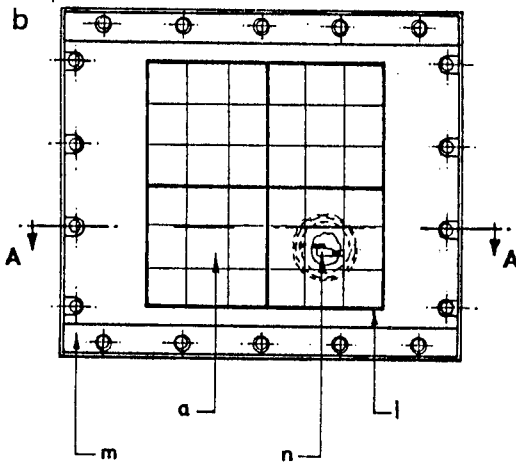
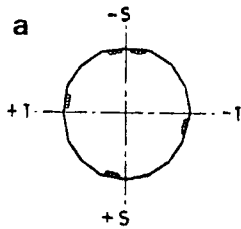
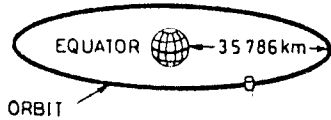
Owing to the design of the sample mounting, Q was 10 times too large for reaching sufficient sensitivity.

References: Adams (1973), Keyte (1975).

COATINGS

Solar Reflectors

SPACECRAFT IN GEOSYNCHRONOUS ORBIT



(j) is held in place between the support discs and the corresponding mounting platform to minimize heat transfer between samples and the housing enclosure. This MLI (see J, § 3.10) is composed of several aluminized mylar sheets and has an aluminized side facing the housing enclosure. The MLI also extends outwards (k) and insulates the housing from the mounting frame, where it overlaps the housing adjacent to the samples. The top of the mounting frame in this overlapping region is covered with SSMs (see H, § 1.2.6 and 1.2.7) to minimize heat absorption adjacent to the samples ((l) in the figure). A strip of silvered teflon (m) serves the same purpose where the mounting frame bolts to the radiator. Attached beneath each sample mounting platform is a thermal sensor (n), the leads of which travel through the fiber-glass cylinders to the terminal board (p). An additional thermal sensor (q) is mounted on the inside housing baseplate to provide data for the heat leak calculations of each individual sample.

CALCULATION METHOD

One of the main aims of the configuration design was simplicity of the computer thermal model. Basically the sample temperature provides α/ϵ , where ϵ , although temperature dependent (Fig 1-10), does not change with time. A typical thermal network for one specimen is shown in the enclosed figure (next page). For the nodes corresponding to external spacecraft surfaces viewing the sample, an AESC-developed Monte Carlo view factor programme was used. The temperatures of these external surfaces were supplied to the programme.

TEST CONDITIONS

Spacecraft & Programme

Different spacecraft in similar orbits.

Orbit

Geosynchronous.

Configuration

No data are given except that the calorimeters holding the samples were all installed in the same clean location (-T axis in the enclosed figure a) on several spacecraft. The calorimeter locations were so chosen as to minimize radiant heat exchange with spacecraft external surfaces. They were mounted in one of the main radiators of the satellite.

Thermal Test

Two set of data from calorimetric tests have been issued, Curran & Millard (1978), Ahern & Karperos (1983). The last set includes, among others, five ZOT coating samples of various thicknesses on different substrates. Calorimeter sample areas were 76×10^{-3} m by 76×10^{-3} m. See figure b.

SAMPLE

Sample Description

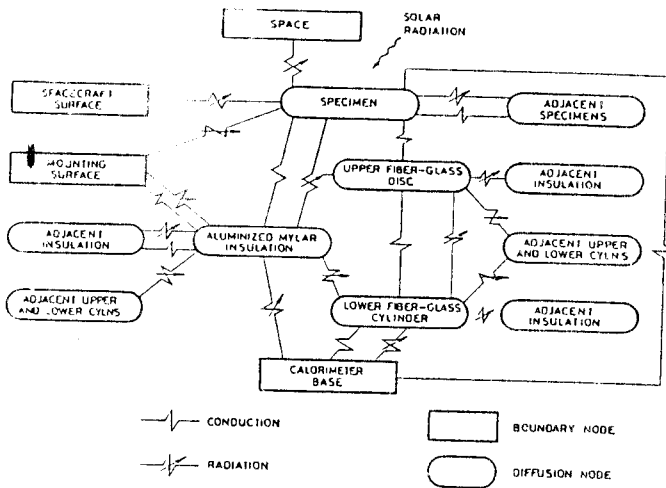
YB-71. Coating characteristics are given in the following Table.

Sample Designation	Thickness $t_c \times 10^4$ [m]	Substrate
9	2.03 - 2.54	Al alloy 6061-T6
10		
14	2.54 - 3.05	Mg alloy AZ31B
18		
20		

Sample Mounting (figures b and c)

Each sample (a) is bonded to a magnesium mounting platform (b) bonded to a series of thin-walled (10^{-4} m to 1.5×10^{-4} m) fiber-glass support cylinders for improved thermal isolation. Shown in the figure are, upper cylinders (c), discs (d) and lower cylinders (e). The lower cylinders are mounted to a magnesium housing (f). The housing is attached to the radiator mounting frame (g) (and thermally isolated from it) by fiber-glass support cylinders (h). All of the fiber-glass support cylinders and discs along with the housing are coated on both sides with vacuum-deposited aluminium ($\epsilon < .1$) to minimize radiation heat transfer between surfaces. Silvered teflon gap seals (i) close the space between samples so that solar energy cannot reach the housing enclosure. An MLI

COATINGS Solar Reflectors



Solar heating of the sample was introduced in the computer model through a diurnal table automatically adjusted for solar angle and heat flux. The diurnal temperatures for the radiating spacecraft nodes (available at 15 min intervals) and the calorimeter base temperature, were introduced into the programme. Temperatures are then calculated on the basis of an assumed α_s value (normally the previous one). The computer then adjusts α_s and iterates until the calculated temperatures match the flight data within 1°F ($.56 \text{ K}$) thus giving the α_s for the day. The analysis was repeated at varying intervals which generally were determined by the temperature rise rate. Usually large rises followed a roll-off trend and, thence, early data were obtained at time intervals of the order of one month, whereas at three years in orbit data were taken at approximately 3 months interval. The measurements of the absolute solar absorptance involves the full calorimeter design errors, the thermal sensor calibration error and the telemetry quantization error. The estimated error in α_s is $+ .009, - .006$.

RESULTS

Laboratory α_s data have been compared to initial flight measurements in the following Table. Laboratory measured hemispherical total emittance at 295 K was $\epsilon = .91$ in any case (see also Fig 1-10).

Sample	Laboratory α_s	Flight α_s
9	.194	.197
10	.181	.185
14	.167	.177
18	.167	.190
20	.167	.199

Among the results for twenty samples reported by Aherns & Karperos (1983), ZOT samples are those giving the worst agreement between laboratory and flight data. The reason for this apparent ground-handling or launching degradation has not been determined.

The flight evolution of α_s with time t is shown in Fig 1-12.1. An exponential expression in t has been fitted to these data as follows:

$$\alpha_s = \alpha_o + (\alpha_m - \alpha_o)(1 - e^{-t/\tau})$$

Values of α_o , α_m and τ , together with the time range of validity of the expression are given in the enclosed Table.

Sample	α_o	α_m	τ ESH	t_{max} ESH
9	.198	.301	2863	5 800
10	.185	.314	2933	5 800
14	.188	.358	5920	3 400
18	$\alpha_s = .190 + 3.65 \times 10^{-5}t$, preliminary			
20	$\alpha_s = .199 + 3.09 \times 10^{-5}t$, preliminary			

COMMENTS

Solar absorptance, α_s , depends on coating thickness as shown in Fig 1-11. Samples 18 and 20 depart from this rule but the reasons for the discrepancy are other hand the rate of degradation seems to be in- tested in the same flight and that on magnesium

Fig 1-12.1. Solar absorptance, α_s , of several YB-71 coatings vs. exposure time, t , as deduced from data of various spacecraft in geosynchronous orbits. Numbers correspond to sample designations.

not clear since the results given are only preliminary. On the dependent of the coating thickness. Samples 14, 18 and 20 were substrate exhibits a slightly larger degradation rate.

References: Curran & Millard (1978), Ahern & Karperos (1983).

COATINGS

Solar Reflectors

7.3.2.5.3. Protons only exposure. The data below refer to a SSR pigment, phosphated.

α_s deduced from spectral reflectance measured in situ.

Radiation Exposure			α_{s0}	$\Delta\alpha_s$	Comments
Intensity [keV]	Integrated Flux [protons.m ⁻²]	Flux [protons.m ⁻² .s ⁻¹]	Initial		
1.2	8.4×10^{19}	5.4×10^{13}	.149	.038	Irradiations performed at 1.3×10^{-5} Pa. Sample temperature, 265 K. Reflectance measured in situ (initially at 8×10^{-6} Pa).

From Zerlaut, Gilligan & Ashford (1972). For a description of the experimental set up see Gilligan & Zerlaut (1971).

7.3.2.5.6. Combined exposure. α_s deduced from spectral reflectance measured in situ.

Chamber pressures and sample temperature as above.

Exposures in the order given from left to right, except those under Combined which are simultaneous.

UV Exposure Time [ESH]	Combined					$\Delta\alpha_s$	$\Delta\alpha_s$ after O ₂ Bleach
	Protons				UV Exposure Time [ESH]		
	Intensity [keV]	Integrated Flux [protons.m ⁻²]	Flux [protons.m ⁻² .s ⁻¹]	Exposure ^a Time [EWH]			
600						.033	
600	1.2	8.3×10^{18}	1.21×10^{13}	927	700	.074	.053
600					700	.019	.010

^a EWH: Equivalent Wind Hours.

From Gilligan & Zerlaut (1971).

7.3.2.6. Effects of the Space Environment on solar absorptance to emittance ratio. See pp. 1-39 and 1-40.

7.3.3. Reflectance.

7.3.3.1. Normal-hemispherical spectral reflectance. See Fig 1-13.

COATINGS
Solar Reflectors

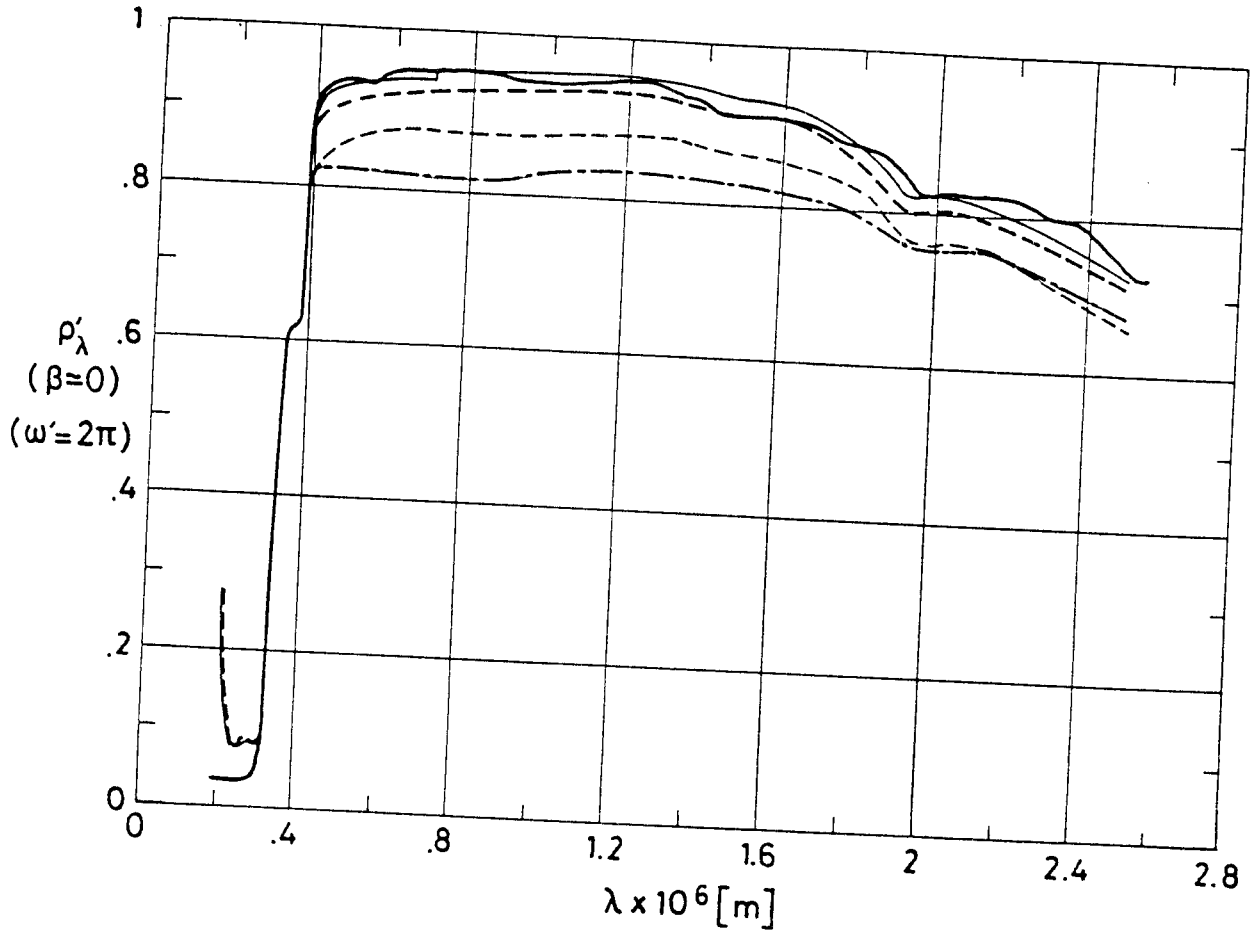


Fig 1-13. Normal-hemispherical spectral reflectance, ρ'_λ , of Zinc Orthotitanate-Potassium Silicate coatings vs. wavelength, λ .

Explanation

Key	Description			Comments	References
	Pigment Process and Encapsulation	Coating Thickness, $t_c \times 10^4$ [m]	α_s		
————	SSR Phosphated		.109	Measured in air with an integrating sphere attached to a Beckman DK2A reflectometer. $\beta=0^\circ$.	Keyte (1975).
————	MOX	1.73	.108	Measured in vacuum (1.3×10^{-5} Pa) with an integrating sphere attached to a Beckman DK2A reflectometer. $\beta=7^\circ$.	Harada & Wilkes (1979). Test Conditions Zerlaut & Courtney (1967).
-----		1.45	.125		
-----		.79	.178		
-----		.56	.214		

COATINGS

Solar Reflectors

7.3.3.2. Effects of the Space Environment on reflectance.

7.3.3.2.1. Ultra-Violet Radiation. The data below refer to coatings based on SSR processed pigments.

a Sample No.	Exposure Time [ESH]	Spectral Reflectance Decrease, $10^2 \times \Delta \rho'_{\lambda} / \rho'_{\lambda}$, at Wavelengths, λ , below				
		$\lambda \times 10^7$ [m]				
		3.62	4.25	7.00	9.25	24.00
5	2 400	4.0	7.0	1.0	1.0	-1.0
6	2 000	7.0	5.5	.2	-.4	-2.2
7	2 000	4.2	5.0	1.8	1.0	-2.2
8	1 200	2.2	2.8	0	0	.5

^a Sample numbers in this Table correspond to those in Tables 1-6 and 1-7.
 Degrading Source: 1 kw General Electric AH-6 Mercury-Argon lamp, 6 Suns level.
 Irradiated in vacuum (1.3×10^{-4} Pa - 1.3×10^{-5} Pa).
 Measured in situ with an integrating sphere attached to a Beckman DK2A reflectometer.

From Zerlaut, Gilligan & Ashford (1972). For a description of the experimental set up see Gilligan & Zerlaut (1971).

Additional information, in graphical form, is given in Fig 1-14.

7.3.3.2.3. Protons only exposure. See Fig 1-15, p. 1-45.

COATINGS
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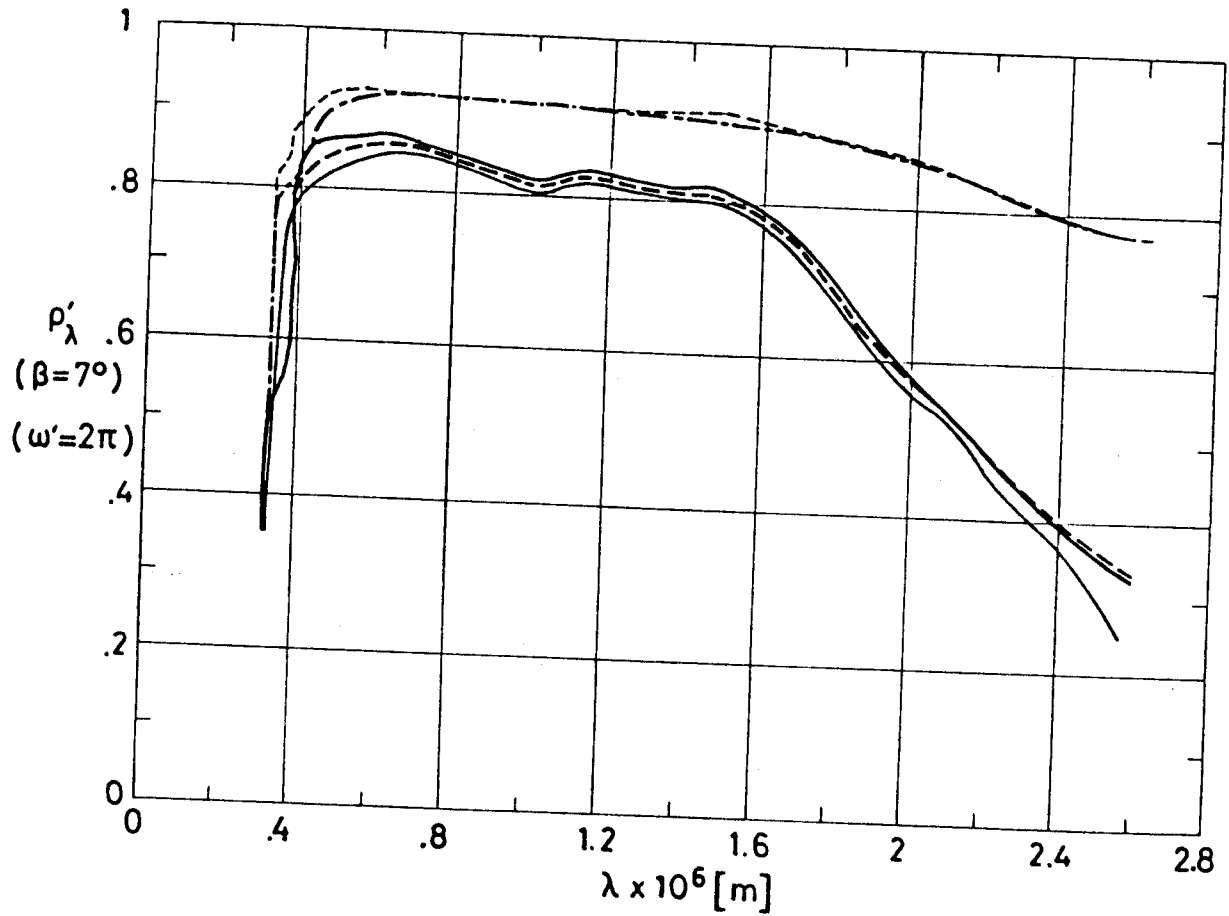


Fig 1-14. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of Zinc Orthotitanate-Potassium Silicate coatings vs. wavelength, λ .

Explanation

Key	Pigment Process and Encapsulation	Comments	References
—	SSR Phosphated.	Measured in vacuum (initially at 8×10^{-6} Pa). Sample temperature, 285 K.	Gilligan & Zerlaut (1971).
—		Same as above but irradiated in vacuum (1.3×10^{-5} Pa). 1 300 ESH.	
- - - -		Same as above. O ₂ bleached. This is the same sample as in the lower Table p. 1-41.	
- - - -	SSR Potassium hexafluorosilicate treated.	Coating cured at 773 K for 7 h. Sample No. 8 in Tables 1-6 and 1-7.	Zerlaut, Gilligan & Ashford (1972).
- - - -		Measured in vacuum (initially at 8×10^{-6} Pa). Same as above but irradiated in vacuum (1.3×10^{-5} Pa). 1 200 ESH.	

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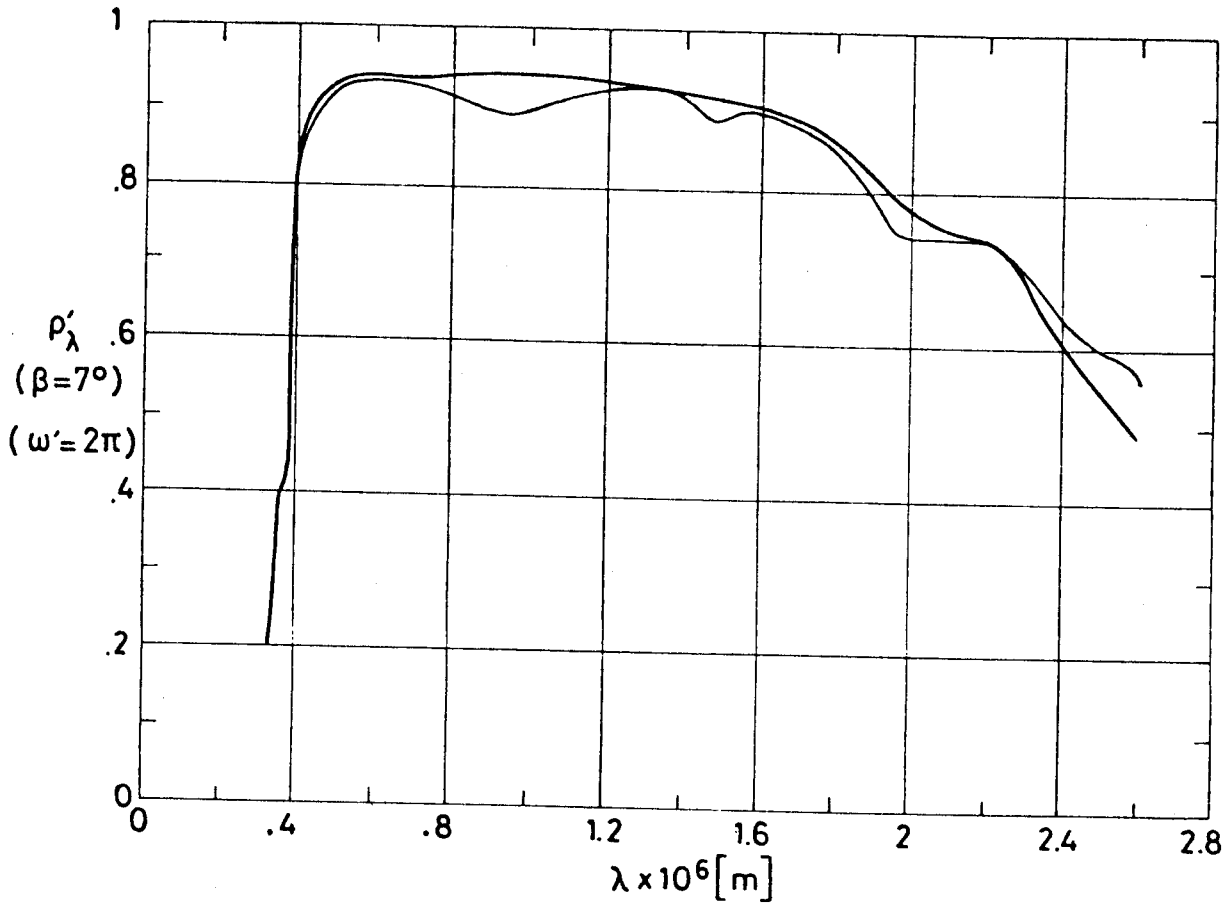


Fig 1-15. Effect of Protons Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of Zinc Orthotitanate-Potassium Silicate coatings vs. wavelength, λ . From Gilligan & Zerlaut (1971).

Explanation

Key	Pigment Process and Encapsulation	Protons Exposure			Comments
		Intensity [keV]	Integrated Flux [protons.m ⁻²]	Flux [protons.m ⁻² .s ⁻¹]	
—	SSR Phosphated.				Measured in vacuum (8x10 ⁻⁶ Pa). Sample temperature, 285 K.
—		1.2	2.7x10 ¹⁹	5.4x10 ¹³	Irradiated in vacuum (1.3x10 ⁻⁵ Pa). Measured in situ (initially at 8x10 ⁻⁶ Pa).

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8. ENVIRONMENTAL BEHAVIOR

8.1. Prelaunch. The adhesion to 6061-T6 aluminium alloy and cohesion of YB-71 coating appears to be similar to that for Z-93 (see § 1.2.2) which is a space-qualified paint. Scratching of the coating with a steel microspatula showed that the material is quite tough and could be removed only by applying strong pressure. Good adhesion was indicated in that after penetration to the substrate, complete removal of the coating at the coating-metal interface could not be effected. Initial conical mandrel bend tests have also revealed good adhesion (Harada & Wilkes (1979)).

According to Keyte (1975), who refers to a SSR pigment, phosphated, the coating is not as strong as Z-93 mechanically.

8.2. Postlaunch. Although this coating has been proposed for use in a number of satellites, actual in orbit performance data is very limited.

8.2.1. Ascent. The coating based on SSR processed pigment, phosphated, exhibits little tendency to change under vacuum (Keyte (1975)).

8.2.2. Orbital. The coating based on SSR processed pigment, phosphated, degrades itself very slightly, by about $\Delta\alpha_s = .03$, under ultra-violet radiation and near-to-Earth flight. (Keyte (1975)).

The initial degradation shown by all coatings tested on OSO-H has not been explained satisfactorily.

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9. THERMAL CYCLING

The maximum and minimum temperatures at which YB-71 has been tested, in a vacuum of 1.3×10^{-5} Pa, without any evidence of deterioration in adhesion were:

$$T_{\min} = 116 \text{ K}$$

$$T_{\max} = 380 \text{ K}$$

Samples have been cooled to the range 33 K to 88 K for 45 min with no apparent loss in bond integrity.

(Harada & Wilkes (1979)).

10. SOURCE

IIT Research Institute, 10 West 35 Street, Chicago, Illinois 60616. Contact person: Mr. Yoshiro Harada.

11. COST12. PAST SPATIAL USE

No information other than that given in pp. 1-39 and 1-40 has been found by the compiler.

Data on the performance of YB-71 coating samples in a geosynchronous orbit is now being collected (Harada (1981)).

A sample of this coating, on aluminium substrate, will be tested, among others, onboard Long Duration Exposure Facility (LDEF) 1st Mission (scheduled for early 1984), Experiment S0010. In this experiment the coating will be examined before flight and after retrieval (Clark (1981)).

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1.2.3.1. ZINC-OXIDE METHYLSILICONE

Three slightly different coatings will be introduced in this data item. For the time being they will be designated a, b and c respectively.

1. COMPOSITION

a) Pigment: New Jersey Zinc Co., SP500 zinc oxide

Binder: General Electric Co., RTV-602, methylsilicone

Solvent: Toluene

b) Pigment: New Jersey Zinc Co., SP500 zinc oxide,
PS7-treated

Binder: General Electric Co., RTV-602, methylsilicone

Solvent: Toluene, USP (US Pharm.)

The pigment is reactively encapsulated to enhance its stability against UV radiation. The zinc oxide (the unstable component) is reacted in slurry with PS7 potassium silicate (Sylvania Electric Products Co.) The details vary from reference to reference. "Sweating" involves sealing in aluminium foil the slurry resulting from hot treatment of a slurry containing 1.7 parts PS7 and 1 part SP500 letting it to stand during 6 h at least. Satisfactory softness, whiteness and protection against UV is achieved with sweating times above 6 h. Paints prepared from 24 h-sweated pigment have extended shelf lives without the use of retarders. Sweating times of 48 h result

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in paints which cannot be easily applied or cured (Zerlaut, Rogers, Noble (1969)).

c) Pigment and solvent as in b

Binder: stripped methylsilicone

Outgassing characteristics are enhanced by devolatilization of the binder at $423 \text{ K} \pm 3 \text{ K}$ and a vacuum of the order of $7 \times 10^{-4} \text{ Pa}$ for 24 h (Seidenberg, Park & Clatterbuck (1972)).

The properties (other than outgassing), application procedures and handling procedures are the same for both b and c coatings.

The silicones of General Electric were originally sold under the name of LTV (Low Temperature Vulcanizing). Sometime in the sixties the name LTV was changed into RTV (Room Temperature Vulcanizing) (Zwaal (1986)). Here either LTV or RTV will be used according to the corresponding source.

In 1982 General Electric Co. discontinued the manufacture of RTV-602. Since then IITRI, manufacturer of the coatings, is engaged in a program to find at least two new suitable replacement binders for RTV-602. See Cull et al (1984) for preliminary results with 21 commercial silicone resins.

2. FORMULATION

a) 2.4:1:1.7 by weight of pigment, binder and solvent

b) 2.4:1:1.75 by weight of pigment, binder and solvent

From Cunningham, Grammer & Smith (1969).

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c)

3. USUAL DESIGNATION

- a) S-13
- b) S-13 G
- c) S-13 G/LO

IIT Research Institute.

4. SUBSTRATE

Any substrate to which the primer (General Electric proprietary S-4044 silane) will adhere. This primer can be applied to either anodized or zinc-chromate-primed surfaces.

From Cunnington, Grammer & Smith (1969).

5. METHOD OF APPLICATION

5.1. Preparation of paint for application

a) S-13. The paint is furnished in 5 gal epoxy-lined metal pails. The paint should be thoroughly stirred before transfer to other containers or before additions of catalyst. The catalyst is SRC-05. The recommended concentration is 1 part SRC-05 in 20 parts of toluene to 670 parts of S-13 (by weight). This is equivalent to .76 % catalyst based on polymer solids. Lower catalyst concentrations are recommended to ensure optimum stability to UV irradiation in vacuum. For example a concentration of 1 part SRC-05 in 20 parts of toluene to 1 275 parts of S-13 (which represents .4 % catalyst based on polymer solids) provides optimum stability to UV irradiation in vacuum without great-

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ly sacrificing terminal-cure properties.

The catalyst solution is added only as the paint is used and only to the amount that can be applied in about 30 min. Allow the catalyst paint to set for 10 min before application to the primed surface.

b) S-13 G and S-13 G/LO. As above but now the recommended concentration of catalyst is 1 part SRC-05 in 10 parts of toluene to 1 030 parts of S-13 G (by weight), which corresponds to .75 % SRC-05. A concentration of .4 % based upon RTV-602 provides optimum stability without sacrificing terminal-cure properties.

The undiluted catalyst has a shelf life of six months and the diluted a shelf life of thirty days (Cull, Stevenson, Harada & Mell (1984)).

From Cunnington, Grammer & Smith (1969) unless otherwise stated.

5.2. Preparation of surfaces for painting. Greasy surfaces should be cleaned with standard detergent and water, and thoroughly dry prior to priming. Primer is SS-4044.

From Cunnington, Grammer & Smith (1969).

5.3. Application of paint. The primer can be spray-applied (Binks model 18 or comparable gun) at about 2×10^5 Pa. Only about 12.7×10^{-6} m thick primer is required. Allow primer to air dry for 1 h before application of the paint. Paint can be spray-applied (Binks model 18 or comparable

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kept off the surface during the curing process.

From Gilligan, Harada & Gates (1974).

There is a minimum time of 10 minutes required between coats and 50 h required before handling.

For the qualification testing, S-13 G/LO is allowed to cure for 7 days prior to testing.

5.6. Reapplication. Soiled or damaged areas can be recoated.

Soiled areas must be cleaned thoroughly with detergent and water, and dried before application of additional paint.

Damaged or gouged areas can be recoated by making a paste of paint in which the bulk of solvent is omitted. Such a material can be troweled or brushed over the damaged areas and cures can be tack free within a few hours.

From Cunnington, Grammer & Smith (1969).

6. SOLVENTS RESISTANCE

See a typical list of solvents in p. 1-4.

Optimum solvent composition based on Toluene (p. 1-48.41).

7. PHYSICAL PROPERTIES

7.1. Density

a)

b) S-13 G. Coating surface density is $.03 \text{ kg.m}^{-2}$ as measured from test specimens (Breuch (1967)).

Paint density is between 1.425 kg.m^{-3} and 1.475 kg.m^{-3} (Cull, Stevenson, Harada & Gates (1984)).

c) Paint density as in b).

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7.2. Outgassing. See table below.

Coating	^a % TML	^b % VCM	Cure Time [h]	Cure Temp. [K]	Vacuum Conditions [Pa]	References
S-13 G	.42	.09	48 16	298 394	^c 10 ⁵ 13x10 ⁻⁵	Campbell, Marriott & Park (1978)
	.26	.03				
	.82	.16	24	298	10 ⁵	
S-13 G/LO	.56	.13	48 24	298 366	^c 10 ⁵ 10 ⁵	
A/B as 100/1 ^d	.54	.10	168	298	10 ⁵	
	.40	.01	1	394	10 ⁵	
No primer	.50	.12				
A/B as 100/1 ^d	.59	.11	168	298	10 ⁵	
S-13 G/LO	^e .40	.05				INTA (1976)

a TML: Total Mass Loss.

b VCM: (Collected) Volatile Condensable Material.

c Each one of these cures was used in the order given.

d A refers to S-13 G/LO and B to SRC-05 catalyst in toluene. See b) in p. 1-48.4.

e Data for this sample have been obtained per Specification ESA PSS-09/QRM-02T (see p. 1-53). % RML = .25 %.

7.3. Thermal radiation properties

7.3.1. Emittance

7.3.1.1. Hemispherical total emittance. The data in the Table 1-7.1 overleaf have been taken from several sources. They correspond to samples under different conditions and have been determined by different procedures.

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Table 1-7.1

Hemispherical Total Emittance of S-13 and S-13 G Coatings

Coating	T [K]	$t_c \times 10^3$ [m]	^a ϵ	^b ϵ	References
S-13	294			^{b1} .87	Cunnington, Grammer & Smith (1969)
	395	.090-.140	^{a1} .87 \pm .02	^{b1} .84	
	300	\sim .127		^{b2} .81	Millard & Pearson (1973)
S-13 G	294			^{b1} .84	Cunnington, Grammer & Smith (1969)
	395	.090-.140	^{a1} .89 \pm .02	^{b1} .85	
	300	\sim .127		^{b2} .81	Millard & Pearson (1973)

a Determined calorimetrically.

a1 6061-T6 Al alloy disc substrate. 25.4×10^{-3} m diameter, 1.27×10^{-3} m thick. Chamber pressure 1.33×10^{-5} Pa.

b From spectral reflectance data and the blackbody function for the quoted temperature.

b1 λ range 2×10^{-6} m to 2.5×10^{-5} m.

b2 OSO III preparation. Substrate primed with G.E. SS-4044.

Hemispherical total emittance vs. temperature is given in Fig 1-48.1 in the following page. The coating is S-13 G, 2×10^{-4} m thick, on molybdenum substrate. Hemispherical total emittance, absorptance and specific heat of the coating have been measured by a calorimetric cyclic radiation method (Spisz & Jack (1971)).

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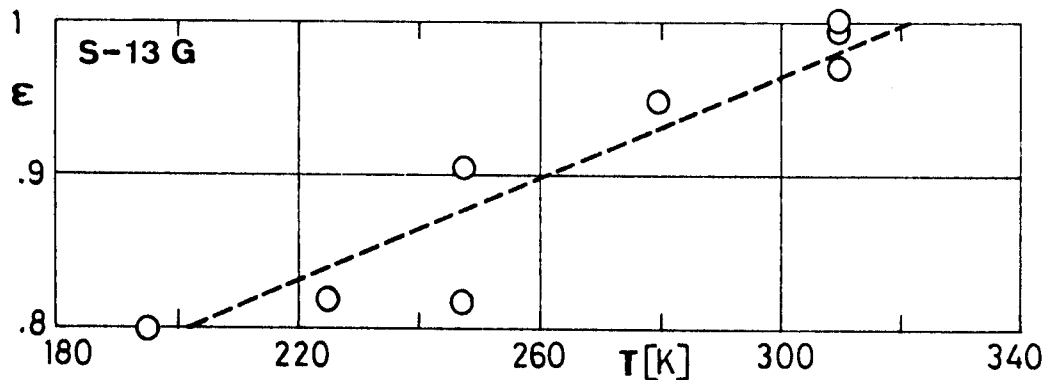


Fig 1-48.1. Hemispherical total emittance, ϵ , of S-13 G coating vs. temperature, T . 2×10^{-4} m thick coating on molybdenum substrate. From Spisz & Jack (1971).

The method consists basically in the following: First the substrate is irradiated in vacuum. After thermal equilibrium is reached, the radiant intensity is varied sinusoidally and the substrate temperature is measured as a function of time. From the temperature variation the properties of the substrate are deduced. The coating is then applied to the bottom side of the substrate and the process is repeated by irradiating the top side. Now the average hemispherical total emittance of both sides, the absorptance of the substrate, and the specific heat of coating plus substrate are deduced. The process is repeated again, irradiating the bottom side. The measurements indicate that the solar absorptance of this coating is practically temperature independent.

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7.3.1.3. Effects of the Space Environment on hemispherical total emittance

7.3.1.3.1. Ultra-Violet Radiation. Table 1-7.2 below has been prepared using data from Cunningham, Grammer & Smith (1969).

Table 1-7.2

Ultra-Violet Radiation Effects on Hemispherical Total
Emittance of S-13 and S-13 G Coatings

Coating	Sample	T [K]	t [h]	n	ϵ_0	ϵ_f	$\bar{\epsilon}$	σ
S-13	27	395	500	12	.86	.86	.862	.006
	28	395	636 ^a	14	.85	.87	.867	.005
S-13 G	43	395	500	10	.90	.91	.914	.008
	44	395	520	11	.91	.91	.911	.005

Degrading Source: 2×10^{-7} m to 4×10^{-7} m Xenon Lamp, 1 Sun level.

Method of obtaining data: Calorimetric. Chamber pressure: 1.33×10^{-5} Pa. 6061-T6 Al disc, 25.4×10^{-3} m diameter, 1.27×10^{-3} m thick.

t, total exposure time. [h]

n, number of data points given in the source at the quoted temperature.

ϵ_0 , ϵ_f , initial and after-exposure values of the hemispherical total emittance.

$\bar{\epsilon}$, mean value, $\bar{\epsilon} = \frac{\sum_{i=1}^n \epsilon_i \Delta t_i}{t}$.

σ , standard deviation, $\sigma = \sqrt{\frac{\sum_{i=1}^n (\epsilon_i - \bar{\epsilon})^2 \Delta t_i}{t-1}}$.

^a Failure during test (electronic pump off, pressure increase to > 6.65 Pa (50×10^{-3} mm Hg) for 2 h).

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Test data have been represented in Fig 1-48.2 below.

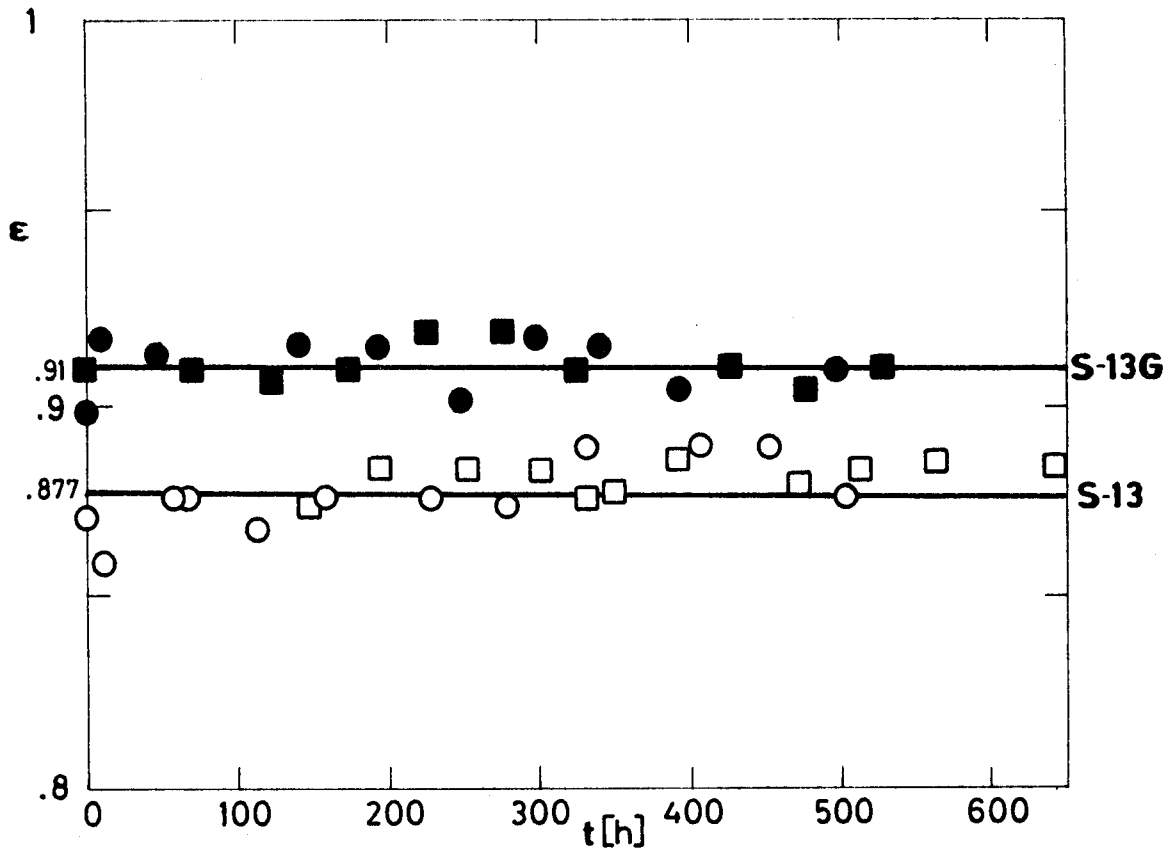


Fig 1-48.2. Hemispherical total emittance, ϵ , of S-13 and S-13 G coatings vs. exposure time, t , at 1-Sun level and 395 K. From Cunningham, Grammer & Smith (1969). Equal symbols correspond to the same sample.

- | | |
|-------------|-------------|
| ○ Sample 27 | ● Sample 43 |
| □ Sample 28 | ■ Sample 44 |

7.3.1.4. Normal total emittance.

See Table 1-7.3 overleaf.

Room-temperature emittance measurements were performed in the past using an infrared spectrophotometer with

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an attached heated cavity. The spectral reflectance data were then used to calculate the emittance. More recent data are being obtained with a Gier-Dunkle portable emissometer, model DB-100 (Henninger (1984)).

Table 1-7.3

Normal Total Emittance of S-13 G and S-13 G-LO Coatings

T [K]	Coating Description	ϵ'	References
311	S-13 G over B-1056 ZnO in methyl silicone binder ($.0508 \times 10^{-3}$ m thick), over ZnO in RTV-602 silicone resin binder substrate ($.254 \times 10^{-3}$ m thick). Property calculated from reflectance. Laboratory data taken on sample to be tested on LO IV.	.860	Touloukian DeWitt & Hernicz (1972)
	Similar to above specimen and conditions except sample to be tested on LO V.	.860	
	S-13 G, ZnO in methyl silicone binder ($.254 \times 10^{-3}$ m thick). Calculated from reflectance. Laboratory data taken on sample to be tested on LO IV.	.879	
	B-1060; SP-500 ZnO in silicone binder ($.264 \times 10^{-3}$ m thick). ZnO silicated. Property calculated from reflectance. Laboratory data taken on sample to be tested on LO IV.	.880	
300	S-13 G. Measured with a Gier-Dunkle portable emissometer. NASA specifications.	$.90 \pm .05$	Henninger (1984)
	S-13 G/LO. As above.	$.90 \pm .05$	Cull et al (1984)

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7.3.2. Absorptance

7.3.2.1. Solar absorptance

a) S-13. Near normal solar absorptance. Coating thickness $t_c = .127 \times 10^{-3}$ m, substrate primed with G.E. S-4044.

$$\alpha_s = .19 , \quad T = 300 \text{ K.}$$

From spectral reflectance data.

From Millard (1969).

b) S-13 G. Near normal solar absorptance.

$t_c = .127 \times 10^{-3}$ m substrate primed with G.E. S-4044.

$$\alpha_s = .23 , \quad T = 300 \text{ K.}$$

From spectral reflectance data.

From Millard (1969).

A recent value for S-13 G is

$$\alpha_s = .20 , \quad T = 300 \text{ K}$$

From spectral reflectance.

Data on absolute reflectance, absorptance and transmittance are presently taken at NASA Goddard with a Beckman DK-2A spectrophotometer with a Gier-Dunkle absolute integrating sphere. The instrument covers the wavelength region from $.3 \times 10^{-6}$ m to 2.4×10^{-6} m. It is coupled to a microcomputer for data reduction. The manufacturer of the instrument lists an accuracy of $\alpha_s \pm .015$ units over the total measurement range. From Henninger (1984).

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7.3.2.2. Variation of solar absorptance with coating thickness.

Data in Fig 1-48.3 are for S-13 coating.

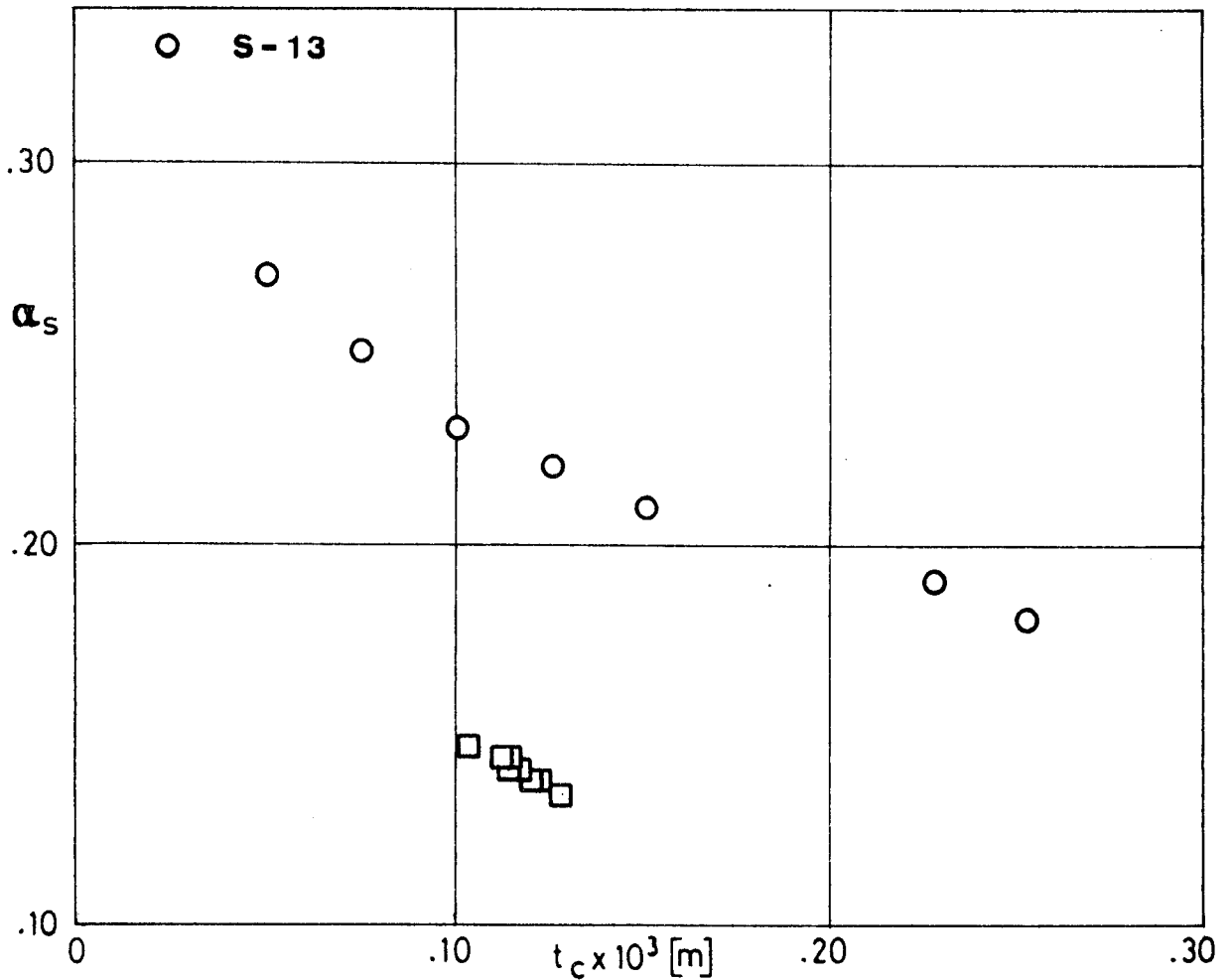


Fig 1-48.3. Variation of solar absorptance, α_s , of S-13 coating with coating thickness, t_c .

- Nominal composition. Sprayed on primed surface. Air dried. T = 298 K. (Designation in the ref.: 119 to 127).
- ZnO in silicone binder. T = 298 K. (Designation in the ref.: 29, 30).

From Touloukian, DeWitt & Hernicz (1972).

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7.3.2.3. Variation of solar absorptance with incidence angle.

Fig 1-48.4. Solar absorptance deduce from spectral reflectance measured in air. Two different sample sizes were used to assure full sample illumination at all incidence angles.

S-13 G coating, silicated pigment in silicone binder applied to aluminium substrate. Sample to be tested on Prospero.

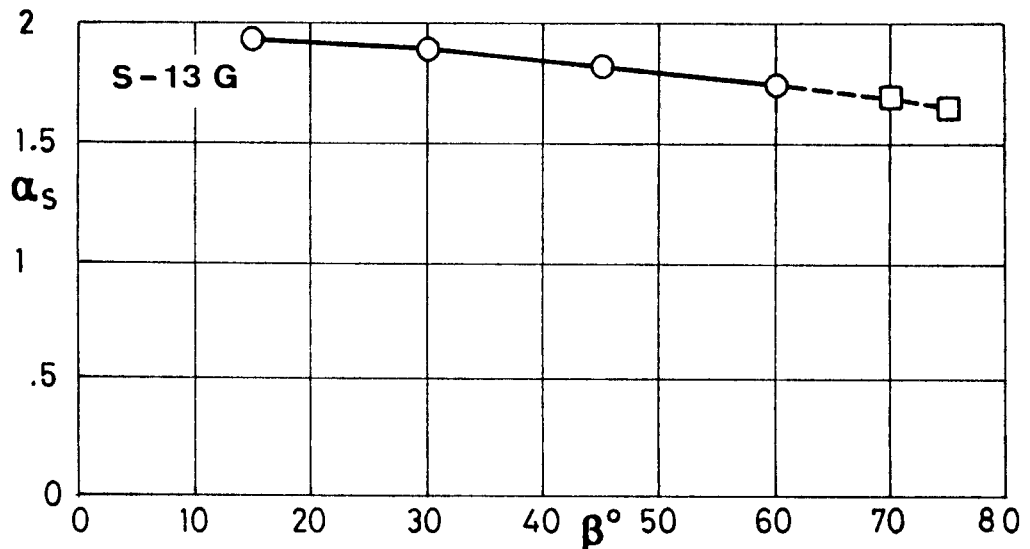


Fig 1-48.4. Solar absorptance, α_s , of S-13 G coating vs. incidence angle, β . From Keyte (1975).

7.3.2.5. Effects of Space Environment on absorptance

7.3.2.5.1. Ultra-Violet Radiation. Detailed laboratory data on the effects of UV radiation on spectral absorptance are given in Table 1-7.4.

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Table 1-7.4

Ultra-Violet Radiation Effects on Spectral Absorptance
of S-13 Coating (Samples 27 & 28)

T [K]	t [h]	α for Xenon Lamp					α_s
		Range of $\lambda \times 10^7$ [m]					
		2-4.1	4.1-6	6-8.5	8.5-	Total	
294	0	---	---	---	---	.21	---
339	0	---	---	---	---	.21	---
395	0	---	---	---	---	.21	---
395	4	.65	.08	.06	.24	.21	.21
395	53	.65	.10	.06	.27	.23	.23
395	61	.65	.15	.06	.28	.24	.24
395	113	.70	.15	.08	.30	.27	.26
395	158	.70	.19	.08	.28	.26	.26
395	230	.75	.21	.09	.28	.27	.27
395	280	.75	.25	.08	.29	.27	.28
395	330	.70	.26	.10	.28	.26	.28
395	402	.65	.26	.08	.28	.27	.28
395	450	.65	.27	.08	.30	.27	.28
395	500	.70	.27	.10	.28	.27	.28
Before Exposure ^a		.65	.08	.10	.14	.18	.18
After Exposure ^a		.76	.31	.15	.17	.26	.28
290	0	---	---	---	---	.21	---
342	0	---	---	---	---	.20	---
395	0	.70	.10	.10	.19	.21	.20
395	4	.70	.10	.10	.23	.22	.21
395	50	.65	.12	.10	.26	.23	.23
395	146	.65	.18	.10	.28	.26	.26
395	196	.65	.23	.08	.32	.27	.28
395	246	.70	.28	.08	.32	.30	.30
395	296	.70	.26	.09	.31	.29	.30
395	328 ^b	.70	.21	.10	.26	.25	.26
395	346	.70	.22	.10	.29	.27	.27
395	396	.70	.22	.10	.31	.28	.28
395	468	.70	.24	.11	.30	.27	.28
395	516	.70	.23	.14	.30	.27	.28
395	564	.70	.24	.14	.30	.27	.28
395	636	.70	.24	.14	.30	.27	.28
Before Exposure ^a		.65	.08	.10	.14	.19	.19
After Exposure ^a		.78	.32	.17	.21	.28	.31

(Continued onto next page)

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Table 1-7.4 (Continued)

Ultra-Violet Radiation Effects on Spectral Absorptance of S-13 G Coating (Samples 43 & 44)

T [K]	t [h]	α for Xenon Lamp					α_s
		Range of $\lambda \times 10^7$ [m]					
		2-4.1	4.1-6	6-8.5	8.5-	Total	
294	0	---	---	---	---	.23	---
339	0	---	---	---	---	.21	---
395	0	---	---	---	---	.21	---
395	0	.85	.12	.05	.15	.20	.20
395	4	.90	.12	.05	.16	.21	.21
395	51	.90	.17	.08	.17	.23	.24
395	149	.90	.21	.09	.17	.24	.25
395	195	.92	.27	.10	.17	.26	.27
395	248	.90	.28	.10	.17	.26	.27
395	296	.90	.32	.09	.17	.26	.28
395	344	.85	.35	.11	.17	.26	.28
395	392	.85	.35	.11	.17	.26	.28
395	500	.85	.35	.10	.18	.26	.28
Before Exposure ^a		.70	.10	.10	.13	.19	.19
After Exposure ^a		.82	.37	.20	.15	.28	.31
294	0	---	---	---	---	.24	---
339	0	---	---	---	---	.22	---
395	0	.80	.10	.08	.14	.19	.19
395	5	.80	.10	.08	.14	.20	.20
395	75	.80	.16	.09	.15	.20	.21
395	123	.80	.16	.08	.16	.21	.22
395	172	.80	.21	.08	.16	.21	.22
395	227	.75	.27	.08	.16	.22	.23
395	274	.75	.27	.08	.16	.22	.23
395	327	.75	.27	.10	.16	.22	.24
395	423	.75	.27	.10	.17	.22	.24
395	471	.75	.27	.10	.17	.22	.24
395	520	.75	.28	.10	.18	.22	.25
Before Exposure ^a		.65	.10	.10	.13	.18	.20
After Exposure ^a		.75	.29	.12	.15	.23	.27

a Values from Cary room temperature reflectance measurements.
 b Electronic pump off, pressure increase to >6.65 Pa (50 μ m Hg).
 Ultraviolet source is a 900 W Hanovia Xenon lamp, Model 538-CL.
 Method of obtaining data: Calorimetric in situ absorptance.
 Chamber pressure: 1.33×10^{-5} Pa.
 From Cunnington, Grammer & Smith (1969).

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The UV radiation induced absorption of zinc oxide pigments is based on a photochemical evolution of oxygen. UV degraded zinc oxide rapidly recovers its initial optical properties upon reexposure to air. Table 1-7.5 (p. 1-48.19) lists results obtained under varied experimental conditions, and deduced from spectral reflectance given in pp. 1-48.41 to 1-48.50.

Data from flight experiments have been grouped in § 7.3.2.5.6 under Combined exposure. Reported measurements correspond to widely different orbits. Effects on solar absorptance of UV exposure and thermal cycling at cryogenic and room temperatures have been reported by Breuch (1967) and are given below. Coating is S-13.

Data Obtained by Cary Reflectometer

Chamber pressure:

For $T = 136 \text{ K}$, $p = 8 \times 10^{-6} \text{ Pa}$ to $13.3 \times 10^{-6} \text{ Pa}$
 For $T = 133\text{-}297 \text{ K}$, $p = 4 \times 10^{-6} \text{ Pa}$ to $8 \times 10^{-6} \text{ Pa}$.

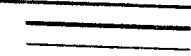
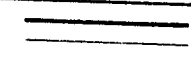
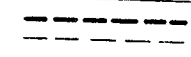
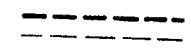
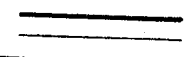
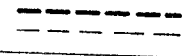
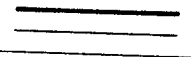
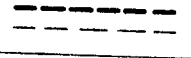
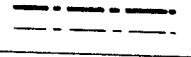

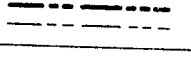
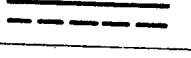
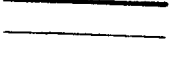
T [K]	t [ESH]	UV [Suns]	α_s	$\Delta\alpha_s$
136	2 790	14	.18	.01
133-297 (275 cycles)	2 560	12	.20	.03

From Breuch (1967).

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Table 1-7.5

Ultra-Violet Radiation Effects on Solar Absorptance of S-13
and S-13 G Coatings

Coating	Spectral Reflectance Data		t [ESH]	α_s	$\Delta\alpha_s$
S-13	p. 1-48.40		800	.21	.08
S-13 G	pp. 1-48.42 & 43		600	.21	.01
	p. 1-48.42		600	.22	.03
	p. 1-48.43		800	.20	.03
	p. 1-48.46		600	.22	.06
			600	.22	.02
	pp. 1-48.47 & 48		1 400	.24	.01
	p. 1-48.48		1 400	.22	.02
			1 400	.22	.03
			1 400	.26	.05
			1 400	.23	.06
	p. 1-48.49		600+700		.039
			600+700+ O ₂ bleaching		.013

7.3.2.5.3. Protons only exposure. Data for coatings S-13 and S-13 G are given in Fig 1-48.5. Data for S-13 have been measured in air after exposure and those for S-13 G in situ (see comments in p. 1-48.36).

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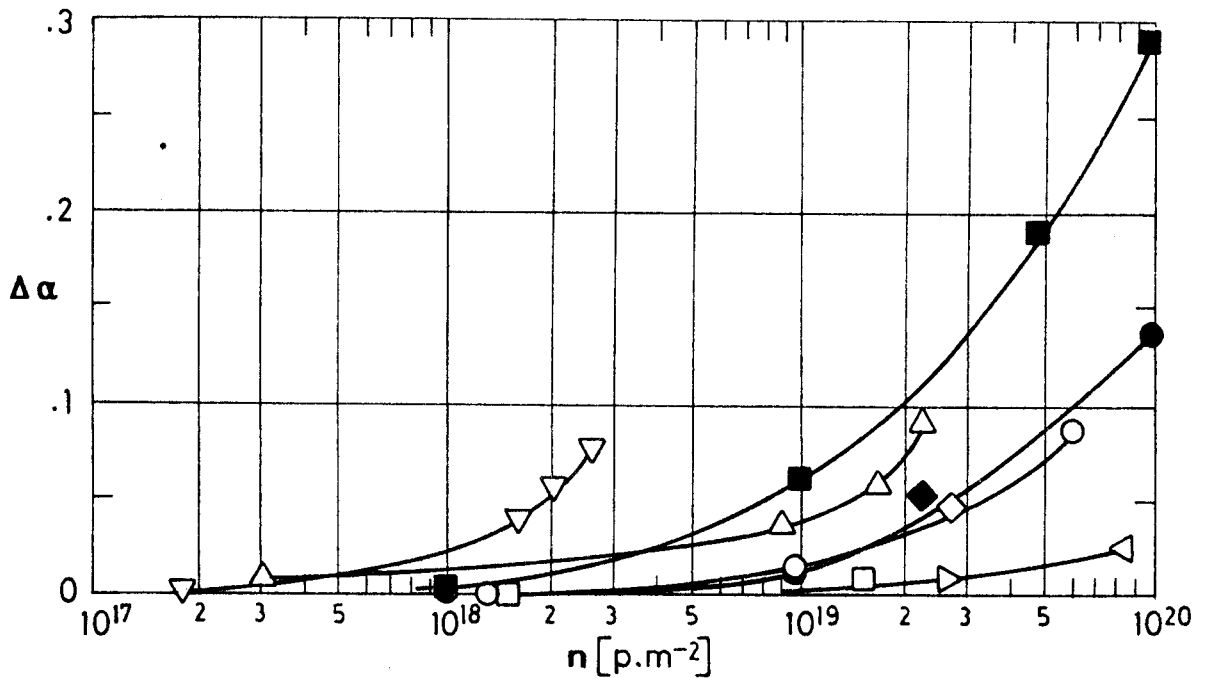


Fig 1-48.5. Change in solar absorptance, $\Delta\alpha_s$, of S-13 and S-13 G coatings due to Protons and Alpha Particles Radiation vs. integrated flux, n .

Explanation

Key	Coating	Intensity [keV]	Comments	References
○	S-13	8 p	$p \sim 10^{-4}$ Pa, $T=303 \text{ K} \pm 5 \text{ K}$. Irradiated in vacuum by a low energy particle accelerator and a Dynamitron. From spectral reflectance measured in air (20 h-40 h delay). Cracking observed.	Gillette, Brown, Seiler & Sheldon (1966)
□		8 p		
△		2.5×10^3 p		
▽		5×10^3 α		
▷	S-13 G	1.2 p	$4.9 \times 10^{13} \text{ p.m}^{-2}.\text{s}^{-1}$. $T=285 \text{ K}$	Compiled by Bourrieau, Pailous & Romero
◁		1.2 p	$5 \times 10^{13} \text{ p.m}^{-2}.\text{s}^{-1}$	
◇		2 & 10 p		
◆		10 & 20 p	$7.3 \times 10^{13} \text{ p.m}^{-2}.\text{s}^{-1}$. $T=288 \text{ K}$	
●		40 p	$T=293 \text{ K}$	
■		40 p	$10^{14}-5 \times 10^{14} \text{ p.m}^{-2}.\text{s}^{-1}$. $T=291 \text{ K}$	

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Data for Protons Radiation up to 400 keV intensity are also given by Miller & Campbell (1966). The coating binder is Dow Corning Q 90016 methyl silicone. Reflectance data are presumably taken ex situ.

7.3.2.5.4. Electrons only exposure. Coating in the table below is GSFC, 101-7 (similar to S-13 G) on Al substrate. Absorptance deduced from spectral reflectance. See pp. 1-48.56, 1-48.57.

Intensity [keV]	Cumulative Integrated Flux [e.m ⁻²]	Measured in	α _s
20		Air T = 298 K	.22
	10 ¹⁷	Vacuum T = 298 K	.22
	5 x 10 ¹⁷	1.33 x 10 ⁻⁶ Pa	.23
	10 ¹⁸		.23
	3 x 10 ¹⁸		.24
	10 ¹⁹		.26
	10 ²⁰		.29
80		Air T = 298 K	.22
	10 ¹⁷	Vacuum T = 298 K	.23
	5 x 10 ¹⁷	1.33 x 10 ⁻⁶ Pa	.24
	10 ¹⁸		.26
	3 x 10 ¹⁸		.32
	10 ¹⁹		.37
	10 ²⁰		.41

From Fogdall, Cannaday & Brown (1970).

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Data from several sources are shown in Fig 1-48.6.

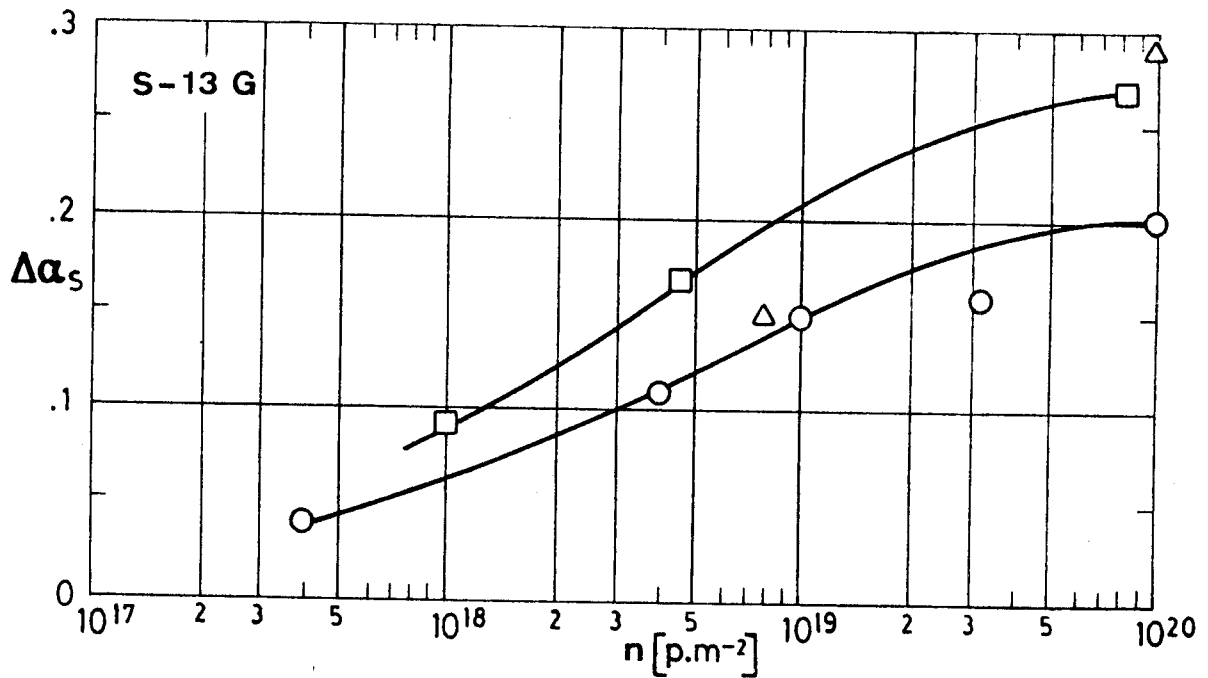


Fig 1-48.6. Change in solar absorptance, $\Delta\alpha_s$, of S-13 G coating due to Electrons Radiation vs. integrated flux, n . Data taken in situ. Compiled by Bourrieau, Paillous & Romero (1976).

Explanation

Key	Intensity [keV]	Flux [e.m ⁻² .s ⁻¹]	T [K]
○	35	10 ¹⁴ - 7 x 10 ¹⁴	291
□	50	2 x 10 ¹⁴ - 5 x 10 ¹⁵	295
△	80		281

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7.3.2.5.5. Contamination. Changes in α_s and ϵ of S-13 G coating due to rocket exhaust impingement have been given by McCargo et al. (1971). The results are hardly useful due to their very limited scope (they depend on the motor generating the exhaust products) and to the inability to reproduce the space environment on a laboratory scale. The main phenomena inducing contamination and (or) degradation are heating, chemical reactions, deposition of solid particles and liquids, and erosion.

No change in emittance was observed, but the change in solar absorptance was appreciable.

Exhausts from non-chemical thrusters also affect the optical properties of the coating.

Results are summarized in the table below.

t [h]	ϵ	α_s	α_s/ϵ
0	.880	.163	.185
.167	.872	.309	.354
.667	.877	.344	.392
3.25	.876	.338	.386

From McCargo, Spradley, Greenberg & McDonald (1971).

7.3.2.5.6. Combined exposure

The available information regarding in flight meas-

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Measurements of solar absorptance is summarized in the following.

The experiments performed both before and during OSO III flight are described in Millard (1969) and Millard & Pearson (1973). An uncertainty analysis is given in Millard (1968).

a) Laboratory tests. The coatings were bombarded with Ultra-Violet radiation, 2 and 10 keV protons, and both UV and protons.

UV irradiations were made with a Xenon lamp and a mercury arc lamp at one Sun level up to 265 h, and with mercury arc lamps at 10 Suns intensity for the remaining ESH. Mercury arc irradiation at one Sun level seems to match the flight data to about 1 000 ESH.

Data were taken in situ.

Coating	UV [ESH]	p [p.m ⁻²]	UV + p [ESH + p.m ⁻²]	$\Delta\alpha_s$ UV	$\Delta\alpha_s$ p	$\Delta\alpha_s$ UV + p
S-13	90	.43x10 ¹⁹	90(.28x10 ²⁰)	.08	.01	.06
	432	1.3x10 ¹⁹	432(1.1x10 ²⁰)	.10	.02	.09
	1 098	3x10 ²⁰	1 098(2.8x10 ²⁰)	.11	.10	.19
S-13 G	750	2x10 ¹⁹	750(2x10 ¹⁹)	.01	.05	.08

From Millard (1969).

b) Flight Experiments. OSO III was launched on March 8, 1967 in a near circular orbit (of about 550 km)

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with a 33° angle of inclination relative to the Equator. The zone of the spacecraft on which the experiment was mounted continually spun at a rate of about 37 rpm. The plane of spin contained the satellite-Sun line. Thus the sensors alternatively viewed Sun and Earth without being affected by this spin because of their relatively large thermal mass. Upper and lower temperatures for each orbit were 255 K and 210 K respectively.

Data from OSO III coatings experiment up to four years are given by Millard & Pearson (1973).

Unfortunately, in the case of S-13, data are only available up to 2 400 ESH, afterward the temperature of the calorimeter exceeded the instrumentation range. On the other hand figures for S-13 and S-13 G in the mentioned reference are the same as those in 1969 Millard's paper.

The results, see Fig 1-48.7 overleaf, do not compare well with previous tests. It seems that the degradation of S-13 G coating depends on the exact method of preparation (see, however, comments in p. 1-48.36).

Figures 1-48.8 and 1-48.9 show data from several coatings experiments as compiled from Touloukian, DeWitt & Hernicz (1972). Agreement for the Pegasus I

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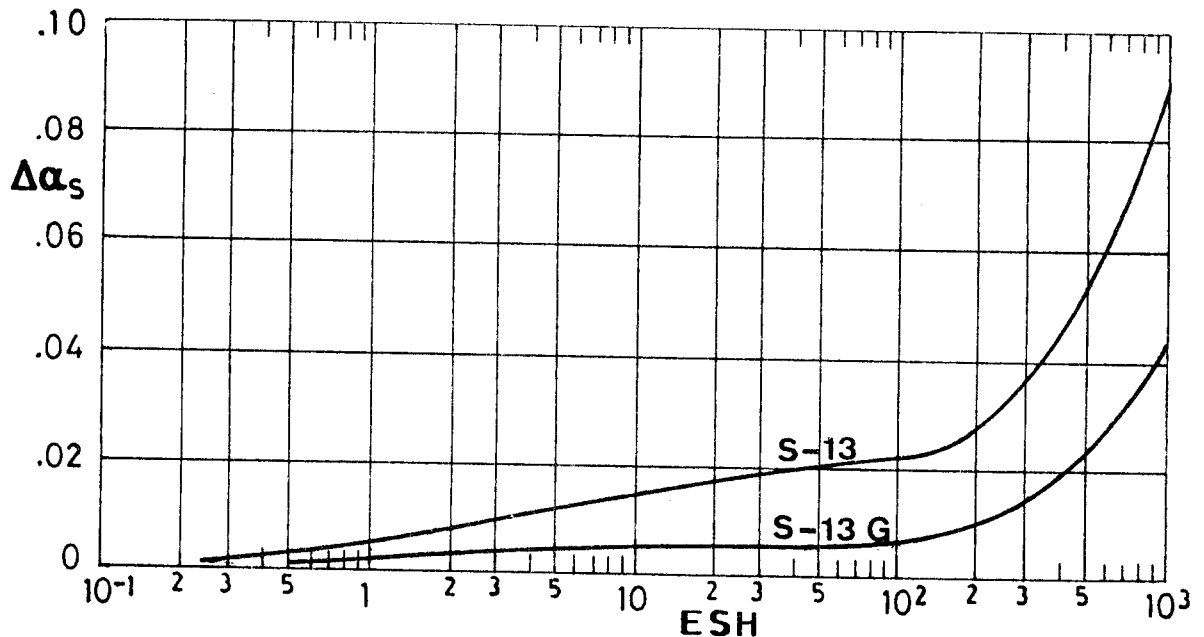


Fig 1-48.7. Changes in solar absorptance of S-13 and S-13 G coatings. OSO III experiment. From Millard (1969).

and II, OSO II and III is excellent. In flight contamination looks negligible for all four flights. Data for Mariner V and ATS-1 exhibit increased damage due to the particulate environment in deep space.

Comparison of the S-13 and S-13 G data confirms the increased protection in the later due to the silicate treated binder. This is now generally accepted, nevertheless, information on the contrary from the early seventies can be found (see f.e. Keyte (1972), p. 38). Although the reasons for the discrepancies remain unclear, they could be due to an inappropriate manipulation of the coating.

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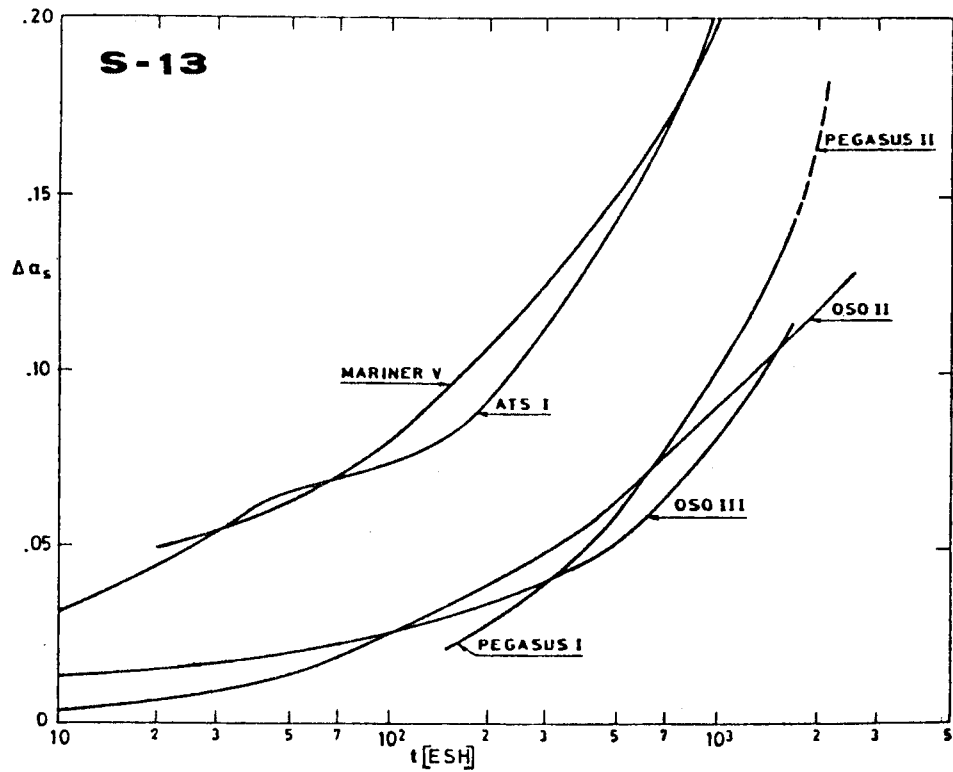


Fig 1-48.8. Change in solar absorptance, $\Delta\alpha_s$, of S-13 coatings vs. flight time in ESH as measured in orbital flight. Prepared by the compiler after Touloukian, DeWitt & HERNICZ (1972).

Explanation

Satellite	Orbit Altitude [km]	Inclination [deg]	Duration of Data Acquisition [mo]
OSO II	550-630	33	16
OSO III	540-560	33	< 1
Pegasus I	500-740	32	< 26
Pegasus II	510-750	32	< 23
ATS I	35 790	0	< 4
Mariner V	Deep Space Venus probe	-	-

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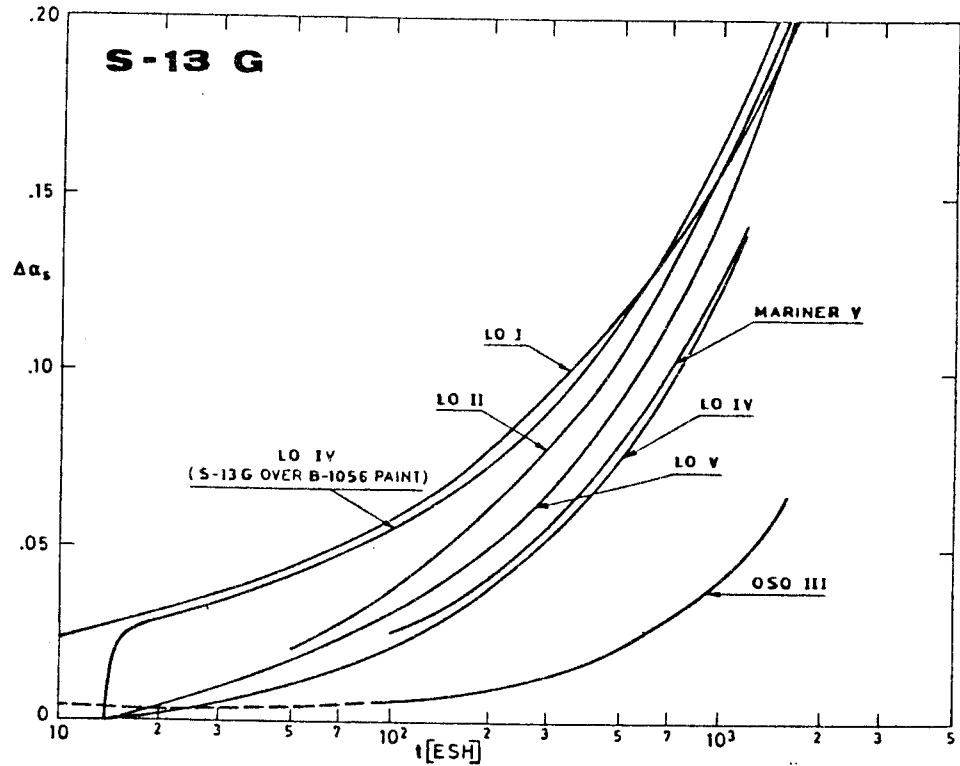


Fig 1-48.9. Change in solar absorptance, $\Delta\alpha_s$, of S-13 G coating vs. flight time in ESH as measured in orbital flight. Prepared by the compiler after Touloukian, DeWitt & Hernicz (1972).

Explanation

Satellite	Orbit Altitude [km]	Inclination [deg]	Duration of Data Acquisition [mo]
OSO III	540-560	33	< 1
Mariner V	Deep Space Venus probe	-	-
Lunar Orbiter I			
Lunar Orbiter II	-	-	-
Lunar Orbiter IV			
Lunar Orbiter V			

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More recent experimental data on S-13 G, plasma annealed and potassium silicate treated binder, are given in the adjacent table. Measurements have

Exposure	$\Delta\alpha_s$
600 ESH + 668 EWH	.044
Above plus 700 ESH	.065
Above plus O ₂ bleaching	.032

From Gilligan and Zerlaut (1971).

been performed in situ. Spectral reflectance curves and additional information are given in p. 1-48.61. Experimental data for S-13 G/LO on Al substrate are summarized in Table 1-7.6 overleaf, after DERTS.

CAUTION

See pp. 1-59 and 1-60. Now the initial value of the solar absorptance is:

$$\alpha_{s0} = .18$$

The tests simulate geosynchronous orbit exposure of the OTS equatorial faces. See S , Chap. 2.

Solar absorptance deduced from spectral reflectance (see pp. 1-48.63 to 1-48.65).

Two samples (here labelled Sample 1 and Sample 2) were tested among several others. Fig 1-48.10 shows the location of the different samples during the irradiation.

Test conditions are the same as in Table 1-13, p. 1-76. Irradiation and measurement procedures are explained in pp. 1-74 and 1-75.

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Table 1-7.6
Combined Exposure Effects on Solar Absorptance of S-13 G/IO Coating

Test Conditions	Sample 1						Sample 2					
	Measured in situ			Corrected ^a			Measured in situ			Corrected ^a		
	α_s	$\Delta\alpha_s$	$\Delta\alpha_s/\alpha_s$	α_s	$\Delta\alpha_s$	$\Delta\alpha_s/\alpha_s$	α_s	$\Delta\alpha_s$	$\Delta\alpha_s/\alpha_s$	α_s	$\Delta\alpha_s$	$\Delta\alpha_s/\alpha_s$
BEFORE IRRADIATION	.336			.180			.343			.180		
AFTER A UNDER VACUUM ^b	.456	.120	.358	.329	.149	.828	.471	.128	.373	.339	.159	.883
BEFORE B	.395	.059	.176	.253	.073	.406	.400	.057	.167	.251	.071	.394
AFTER B ^b	.517	.181	.539	.405	.225	1.250	.531	.188	.547	.414	.234	1.300
AFTER PUMP DAMAGE ^c	.384	.049	.146	.241	.061	.339	.391	.048	.139	.240	.060	.333
BEFORE C	.419	.083	.248	.283	.103	.572	.423	.080	.233	.279	.099	.550
AFTER C ^b	.537	.201	.600	.430	.250	1.388	.545	.202	.589	.413	.251	1.394
BEFORE D	.513	.177	.528	.400	.220	1.222	.519	.176	.514	.399	.219	1.217
AFTER D UNDER VACUUM ^b	.594	.258	.770	.501	.321	1.783	.599	.256	.746	.498	.318	1.767
AFTER D AND AIR EXPOSURE	.530	.194	.577	.421	.241	1.339	.541	.198	.577	.426	.246	1.367

^a The correction has been made by the compiler as follows:

1) Value before irradiation, $\alpha_{so} = .18$

$$2) \frac{\Delta\alpha_{s\text{corrected}}}{\Delta\alpha_{s\text{in situ}}} = \frac{1 - \alpha_{so}}{1 - \alpha_{so\text{in situ}}} = \frac{.82}{.66}$$

where α_{so} has been measured (in air) with an integrating sphere attached to a Beckman DK2A reflectometer. $\alpha_{so\text{in situ}}$ is the value measured, before irradiation, as indicated in p. 1-65.

^b Steps A to D correspond, respectively, to the following times in geosynchronous orbit.

- A: .18 yr = 508 ESH
- B: .94 yr = 2 443 ESH
- C: 2.11 yr = 5 604 ESH
- D: 3 yr = 7 949 ESH

^c See p. 1-75 for further details.

From Paillous (1976).

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The "Corrected" values in Table 1-7.6 were used to estimate the degradation of the coating up to 3 years in orbit. Results are represented in Fig 1-48.11. Incidents during testing, see p. 1-75, could cast some doubts on the validity of the data beyond 1 year in orbit. Nevertheless, the comparison with OTS measurements, up to three years, is excellent, as can be seen in the figure.

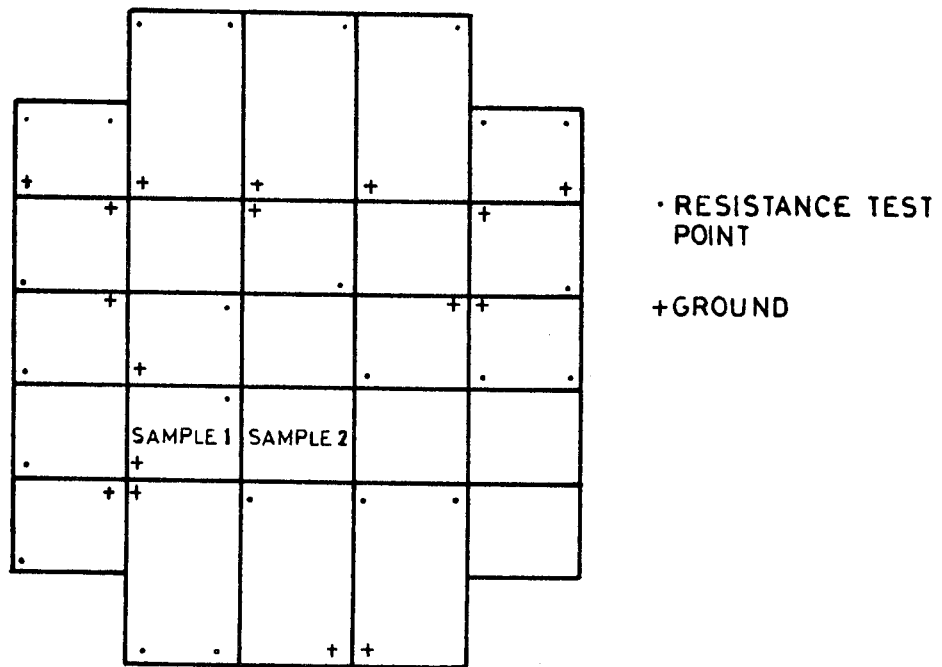


Fig 1-48.10. Position on the sample holder of the samples 1 and 2, for irradiation and measurement. From Paillous (1976).

Data in Fig 1-48.11 are recent in orbit measurements. They correspond to OTS and Navstar 6, respectively. The coating is S-13 G/LO.

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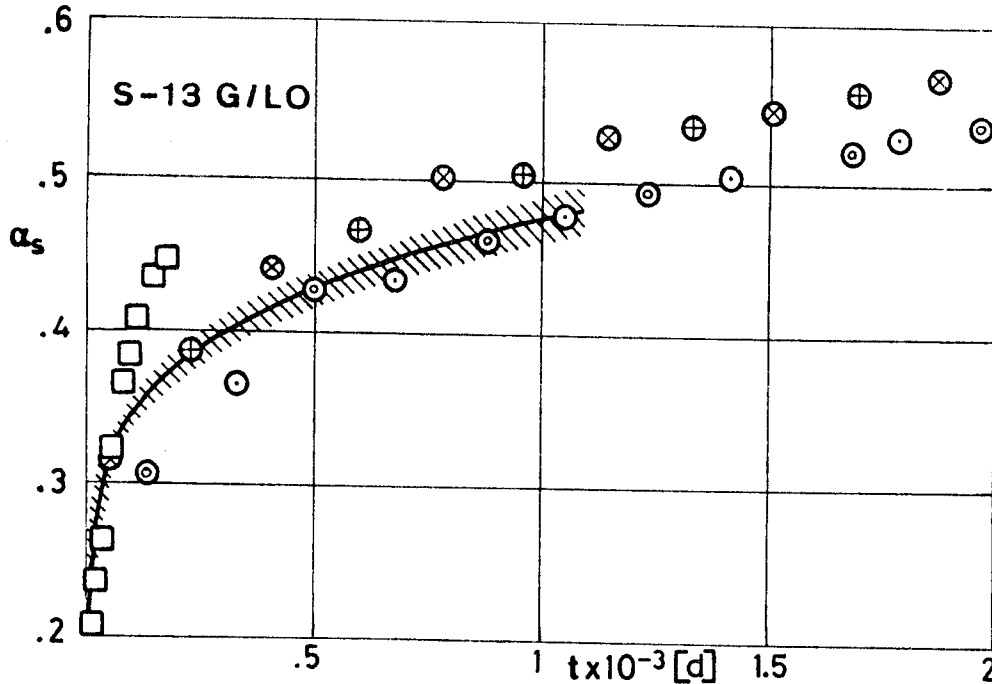


Fig 1-48.11. Solar absorptance, α_s , of S-13 G/LO coating vs. flight time, t .

\circ OTS, see p. S 2-10.

- \otimes SS
- \oplus WS
- \odot VE
- \otimes AE

From Chalmers, Konzok, Bouchez & Howle (1983).

\dashv Prediction, up to three years in orbit by Paillous (1976). See Table 1-7.6, p. 1-48.30.

\square Navstar 6

From Pence & Grant (1981).

OTS was launched in May 11, 1978 in a geostationary orbit 35 779 km - 35 072 km.
 Navstar 6 was launched in April 26, 1980. Orbit altitude 170 km - 20 288 km. Inclination 63.02° .
 The reasons for the severe degradation of the coatings tested onboard Navstar series are unclear.
 See pp. 1-123 and 1-40.2.

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7.3.2.6. Effects of the Space Environment on solar absorptance to emittance ratio. Results from several flight experiments are given in Figs 1-48.12 and 1-48.13.

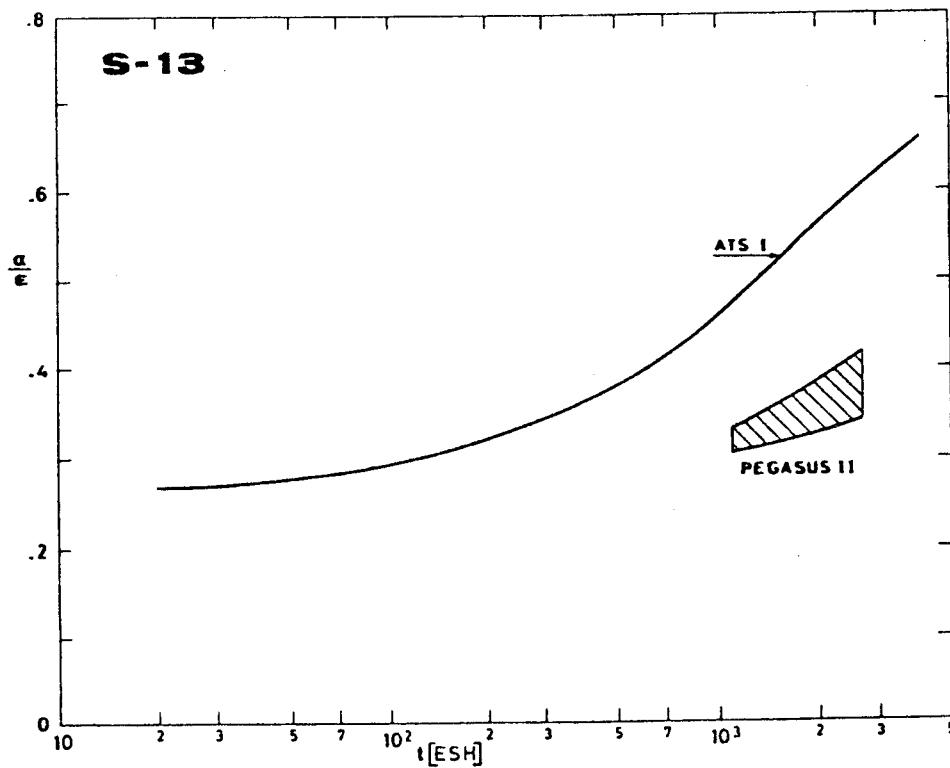


Fig 1-48.12. Variation of absorptance to emittance ratio, α/ϵ , of S-13 coating vs. flight time. Prepared by the compiler after Touloukian, DeWitt & Hernicz (1972) and Triolo (1973).

Explanation

Satellite	Orbit Altitude [km]	Inclination [deg]	Duration of Data Acquisition [mo]
Pegasus II	510-570	32	< 23
ATS I	35 790	0	< 36

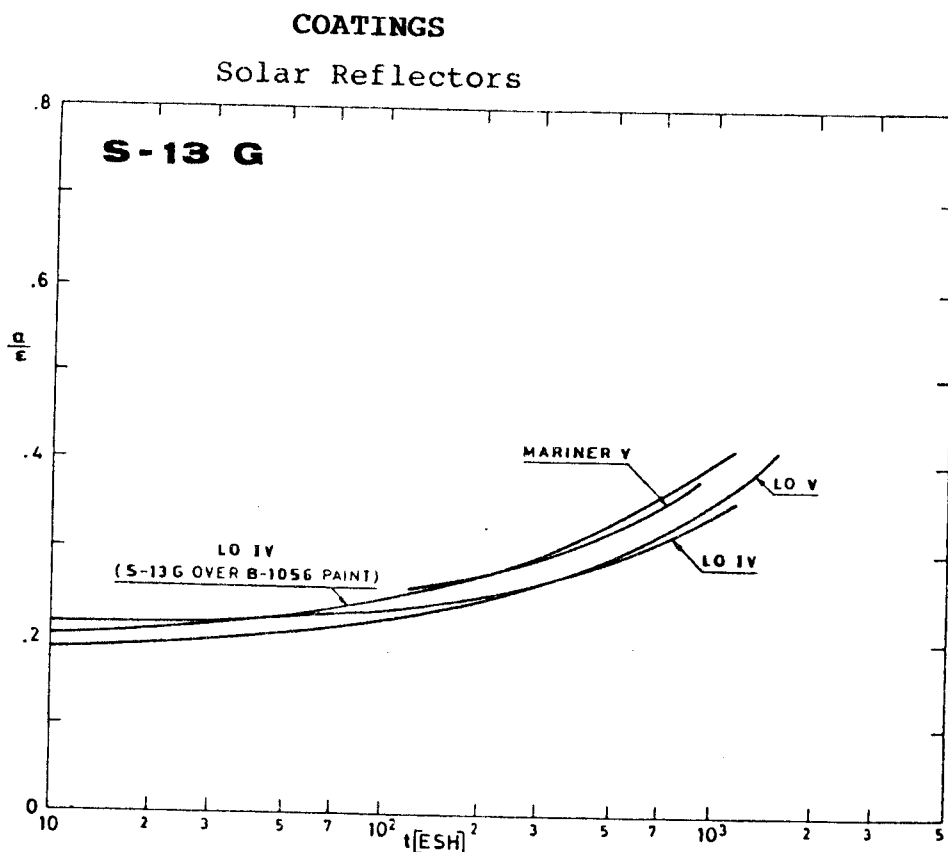


Fig 1-48.13. Variation of absorptance to emittance ratio, α/ϵ , of S-13 G coating vs. flight time. Prepared by the compiler after Touloukian, DeWitt & Hernicz (1972).

Explanation

Satellite	Orbit Altitude [km]	Inclination [deg]	Duration of Data Acquisition [mo]
Mariner V	Deep Space Venus probe		
Lunar Orbiter IV			
Lunar Orbiter V			

7.3.3. Reflectance.

7.3.3.1. Normal-hemispherical spectral reflectance. The available information regarding slightly different coating preparations is abundant. As an example Fig 1-48.14 shows the influence of pigment volume concentration (P-VC) on spectral reflectance.

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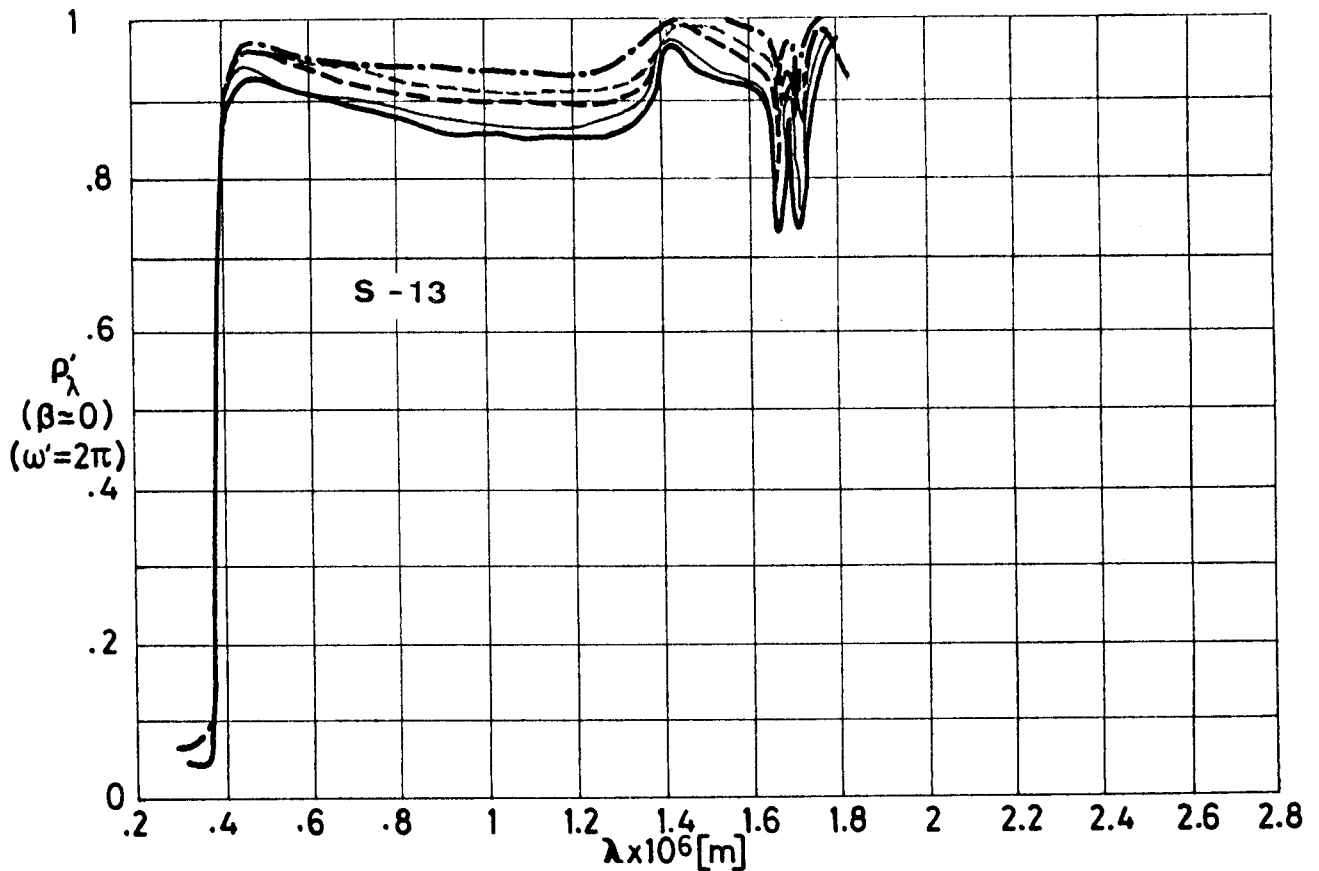


Fig 1-48.14. Normal-hemispherical spectral reflectance, ρ_{λ}' , of S-13 coating vs. wavelength, λ , for five different values of P-VC. G.E. LTV-602 binder. From Touloukian, DeWitt & Hemicz (1972).

Explanation

Key	P-VC	Comments
————	15	.17 x 10 ⁻³ m thick 6061 Al substrate. T ~ 298 K Measured relative to magnesium carbonate. P-VC is the pigment volume concentration, percent
————	20	
-----	25	
-----	35	
.....	40	

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7.3.3.2. Effects of the Space Environment on reflectance

7.3.3.2.1. Ultra-Violet Radiation. We will mention two points:

1st. Stability of these coatings to UV radiation strongly depends on their composition. The optimum composition has been obtained after a lengthy process and data exist to evaluate the sensibility of the coatings to small changes in composition.

2nd. Ex situ vs. in situ measurements. Up to 1965, the standard practice for space simulation was to irradiate the coatings with UV under vacuum, performing the measurements ex situ. Since a recovery exists after breaking vacuum, early flight tests showed an extreme degradation not foreseen at the light of the space simulation tests.

Figures 1-48.15 and 1-48.16 show the influence of pigment-binder ratio (PBR) on the stability against UV radiation. Data after irradiation have been obtained from ex situ measurements.

Figures 1-48.17 and 1-48.18, on the other hand, compare in situ with ex situ measurements.

Figure 1-48.18 indicates that S-13 exhibits a reflectance decrease of about 35% at $\lambda = 2 \times 10^{-6}$ m after approximately 800 ESH of UV radiation in vacuum and an almost instantaneous increase when the irradiated specimen is admitted to the atmosphere.

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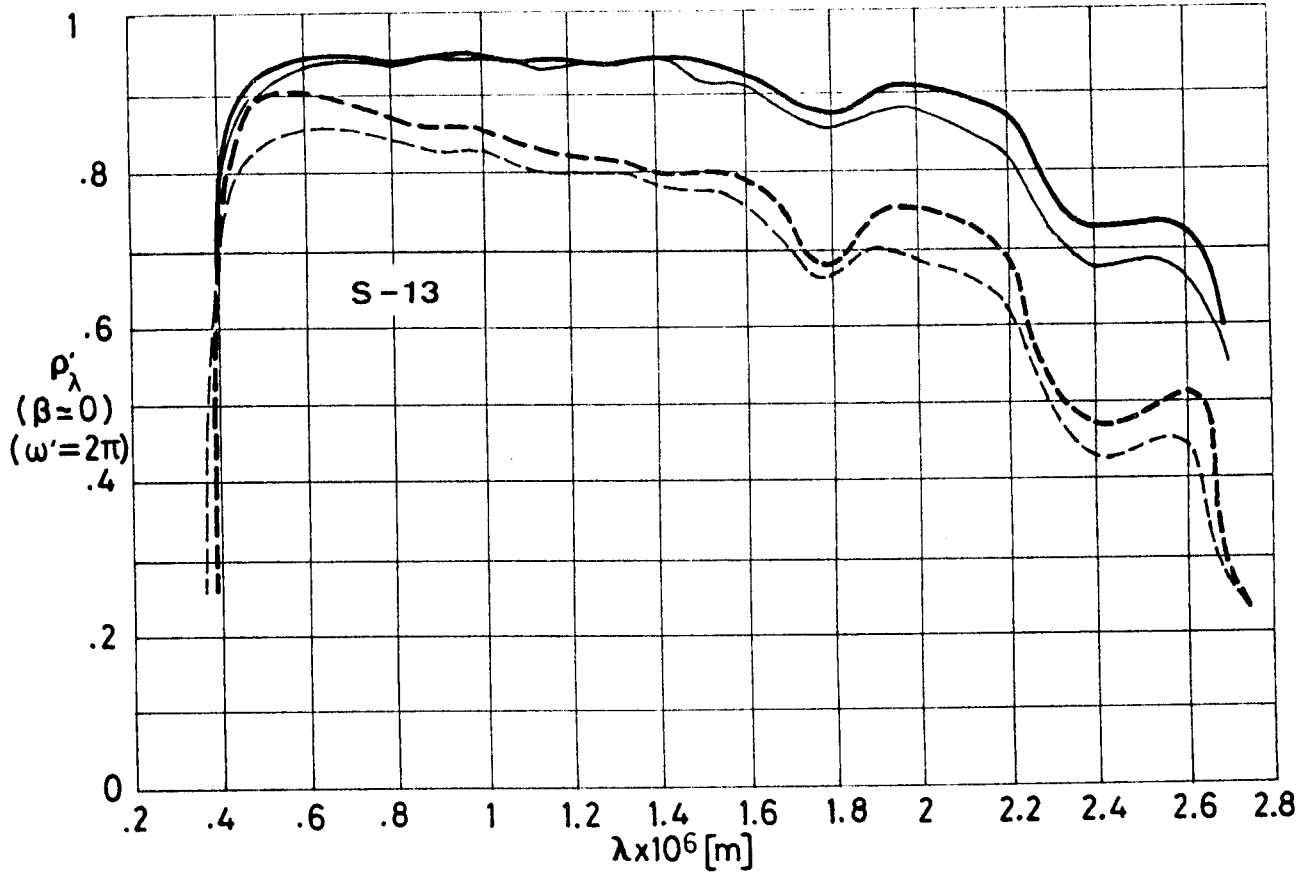


Fig 1-48.15. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 coating vs. wavelength, λ . LTV-602 silicone binder. Two different pigment-binder ratios (PBR). From Touloukian, DeWitt & Hernicz (1972).

Explanation

Key	PBR	P-VC	Exposure	Comments
—	3.73	40	In vacuum before irradiation.	Sample on Al substrate. Airbrush application T ~ 298 K Exposed in vacuum. p ~ 1.33x10 ⁻³ Pa. Measured ex-situ
---			UV. 1 200 ESH.	
---	1.40	20	In vacuum before irradiation.	Above specimen and conditions except Catalyst G.E. SRC-04 and toluene as solvent
---			UV. 1 460 ESH.	

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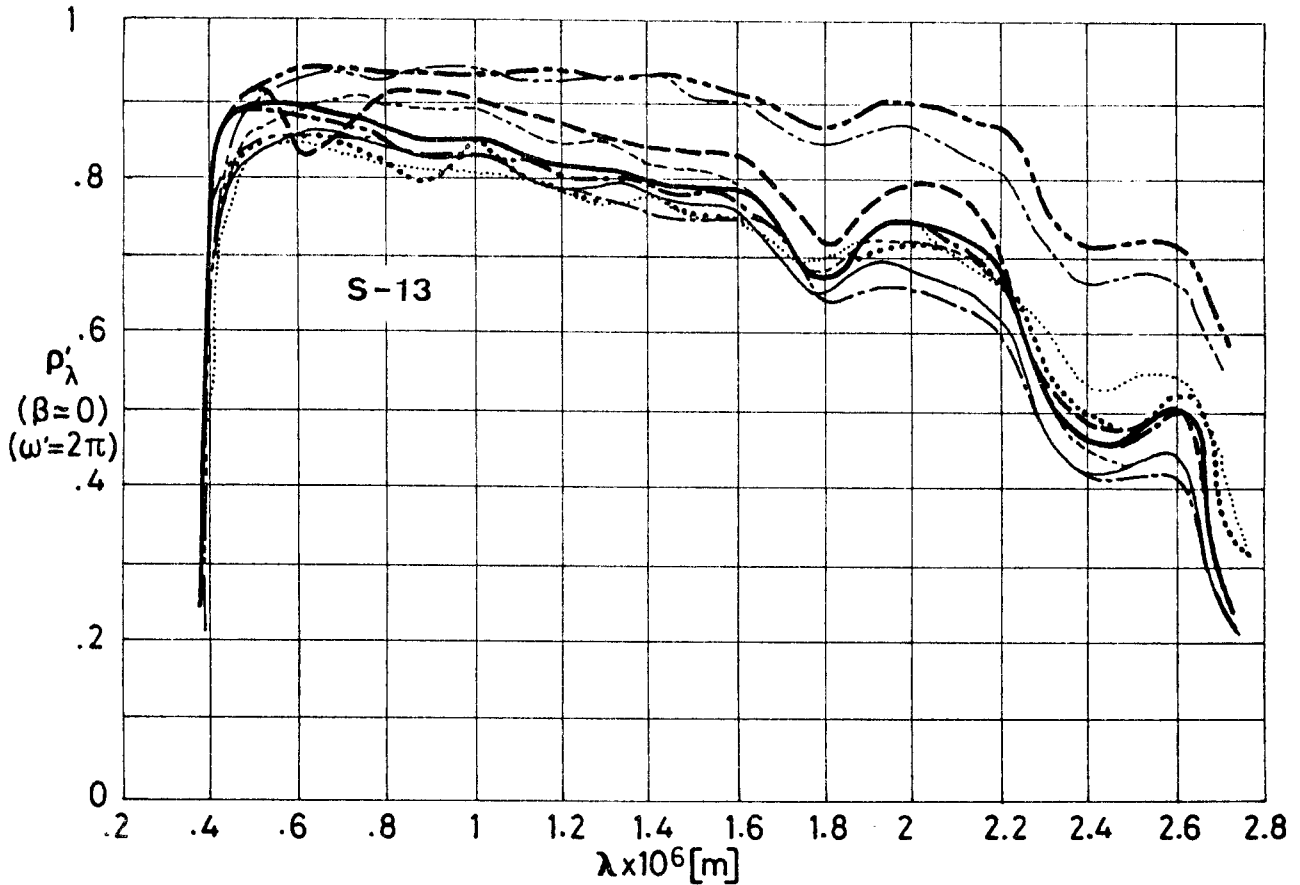


Fig 1-48.16. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 coating vs. wavelength, λ . Several binders and PBRs. From Touloukian, DeWitt & HERNICZ (1972).

Explanation

Key	Binder	Me-Si Ratio	PBR	P-VC	Exposure	Comments
—	LTV-602		1.40	20	In vacuum before irradiation. UV. 1 460 ESH.	Catalyst, G.E. SRC-04; solvent, toluene. Sample on Al substrate. Airbrush application. T ~ 298 K. Exposed in vacuum. p ~ 1.33 x 10 ⁻⁵ Pa. Measured ex situ.
---	R-2	1.46	1.70	25	In vacuum before irradiation. UV. 1 460 ESH.	
-.-.-	R-5	1.38	1.63	25	In vacuum before irradiation. UV. 1 460 ESH.	
.....	R-7	1.33	1.64	25	In vacuum before irradiation. UV. 1 600 ESH.	
----	LTV-602		3.73	40	In vacuum before irradiation. UV. 1 200 ESH.	

COATINGS
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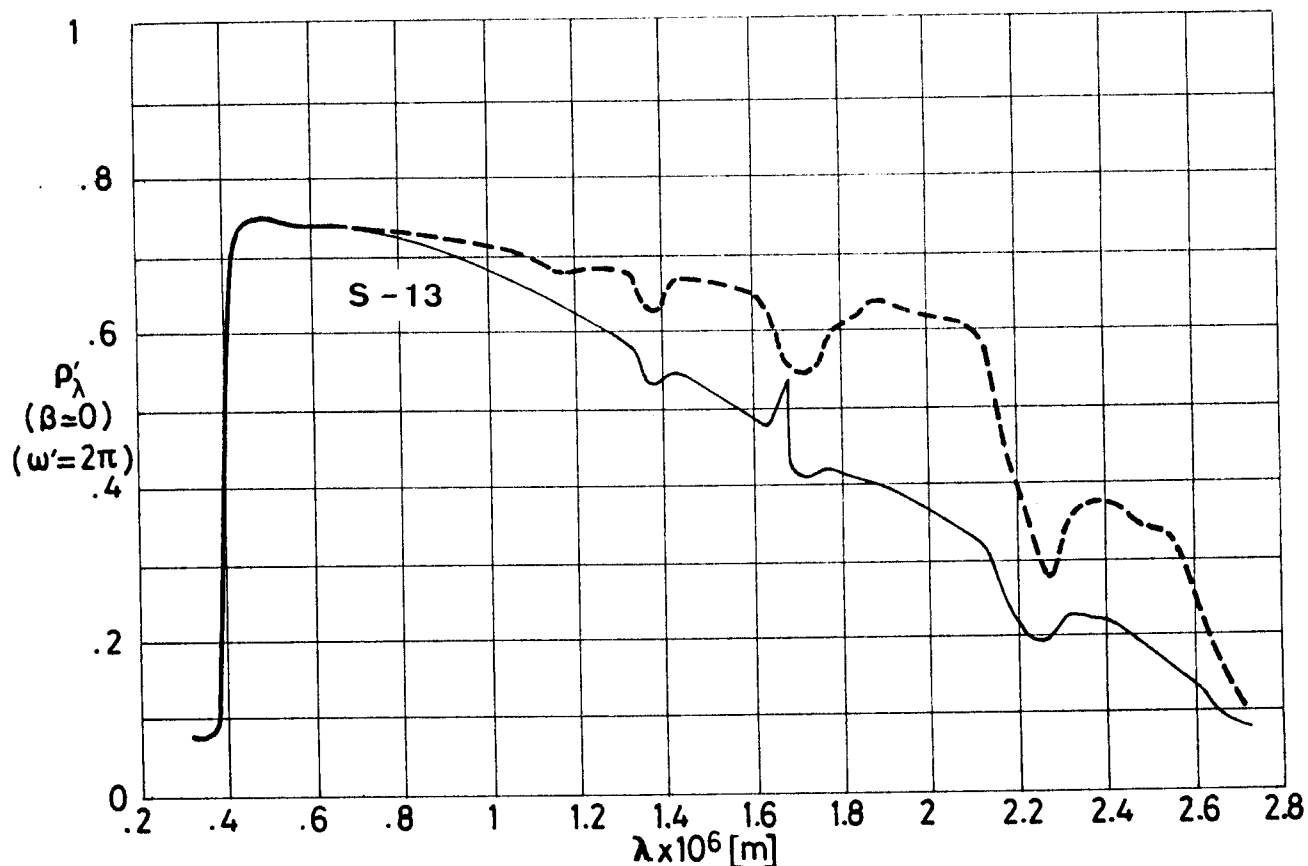


Fig 1-48.17. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 coating vs. wavelength, λ . From Touloukian, DeWitt & Hernicz (1972).

Explanation

Key	Exposure	Comments
—	In vacuum before irradiation.	T ~ 298 K Measured and exposed in situ.
—	UV. 1 200 ESH.	
- - -	Above after breaking vacuum.	Recovery is complete.

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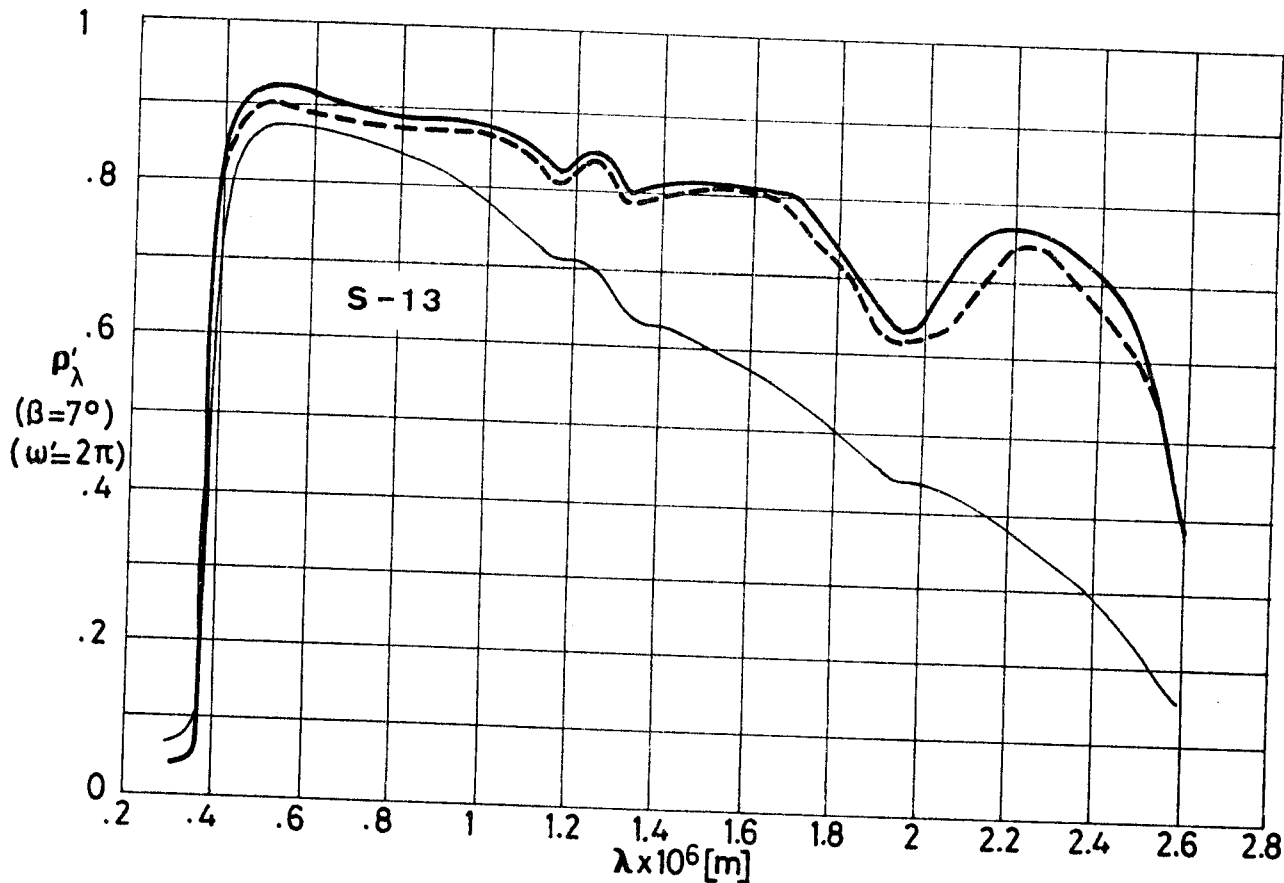


Fig 1-48.18. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 coating vs. wavelength, λ . From Zerlaut, Rogers & Noble (1969). Drawn from Touloukian, DeWitt & Hernicz (1972).

Explanation

Key	Exposure	Comments
—	In vacuum before irradiation.	T \sim 298 K. p \sim 1.33×10^{-5} Pa. Measured and exposed in-situ. UV source G.E. AH-6 lamp. IITRI test facility (In situ Reflectometer Irradiation Facility, see Zerlaut & Courtney (1967)). α_s and $\Delta\alpha_s$ in p. 1-48.19.
—	UV. 800 ESH.	
- - -	Above after breaking vacuum.	

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Figures 1-48.19 to 1-48.24 present data taken when optimizing the composition of S-13 G.

Figure 1-48.19 compares sweating (see p. 1-48.1) versus sweating and calcining. Calcination of the sweated pigment decreases the stability in the infrared. This could be due to the greater grinding required to reduce the calcined pigment which yields ZnO surfaces devoided of barriers to photodesorption reactions which produce the bleachable degradation. Figure 1-48.20 shows partial results in the process of solvent optimization. Originally toluene was used as the sole solvent. This resulted in excessive spray dust, in very poor shelf life, and in the production of "orange peel" in RTV-602 films (a pock marked appearance due to film failure to flow out to a level surface).

Films from solutions containing petroleum ether showed inferior stability. Paints prepared from sweated pigment are less sensitive to solvent composition. The optimum composition resulted to be

Toluene	40% by weight
Xilene	20% by weight
n-Butanol	15% by weight
Isopropanol	20% by weight
Butyl acetate	5% by weight

This composition provides: 2 weeks shelf life, good spray flow-out, and good cure characteristics.

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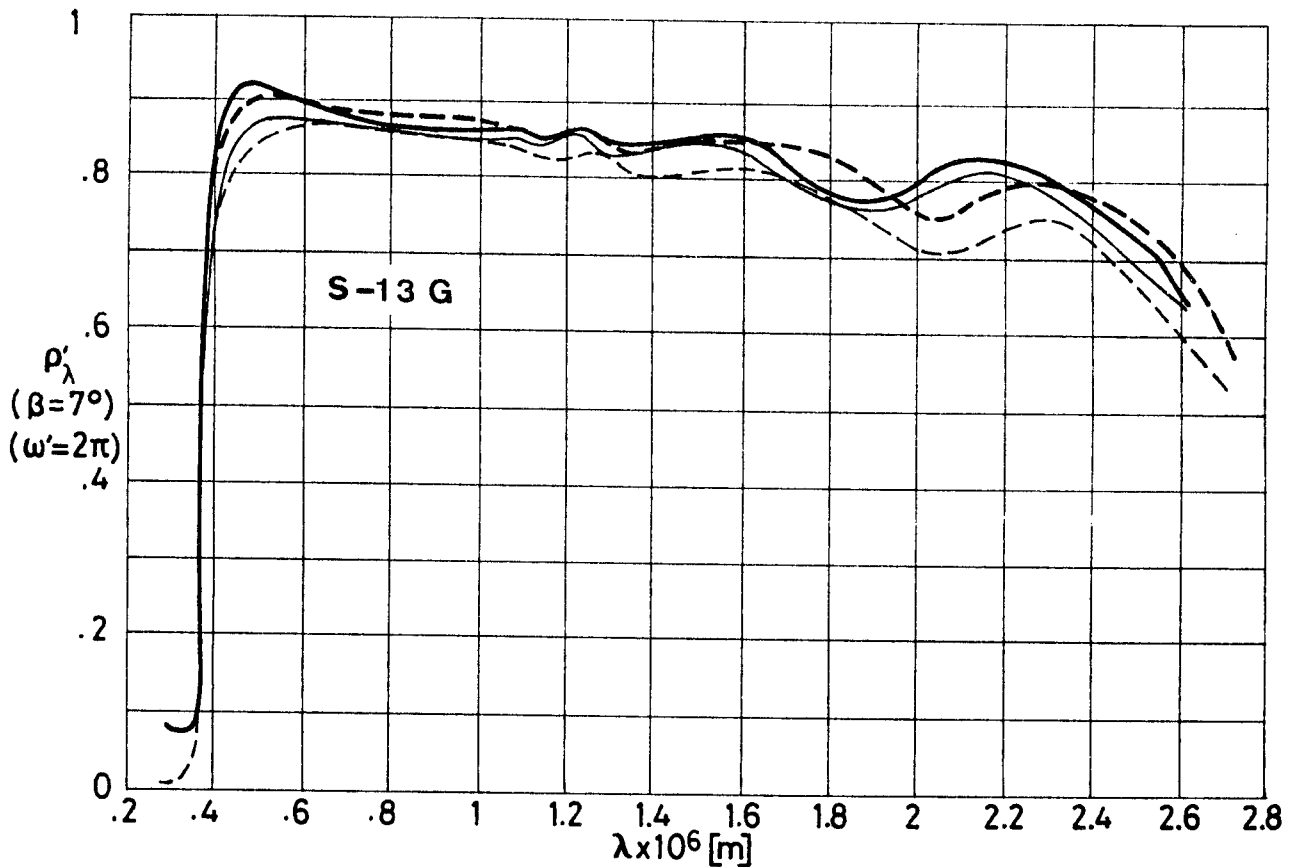


Fig 1-48.19. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 G coating vs. wavelength, λ . Two different pigment treatment processes. From Zerlaut, Rogers & Noble (1969). Drawn from Touloukian, DeWitt & HERNICZ (1972).

Explanation

Key	Pigment Treatment	Exposure	Comments
—	16 h. sweating. Solvent toluene	In vacuum before irradiation.	T ~ 298 K. p ~ 1.33 x 10 ⁻⁵ Pa. Measured and exposed in situ. UV source G.E. AH-6 lamp. IITRI test facility (In situ Reflectometer Irradiation Facility, see Zerlaut & Courtney (1967)). α_s and $\Delta\alpha_s$ in p. 1-48.19.
—		UV. 600 ESH.	
---	Sweating, calcining for 16 h at 293 K.	In vacuum before irradiation	
---		UV. 600 ESH.	

COATINGS
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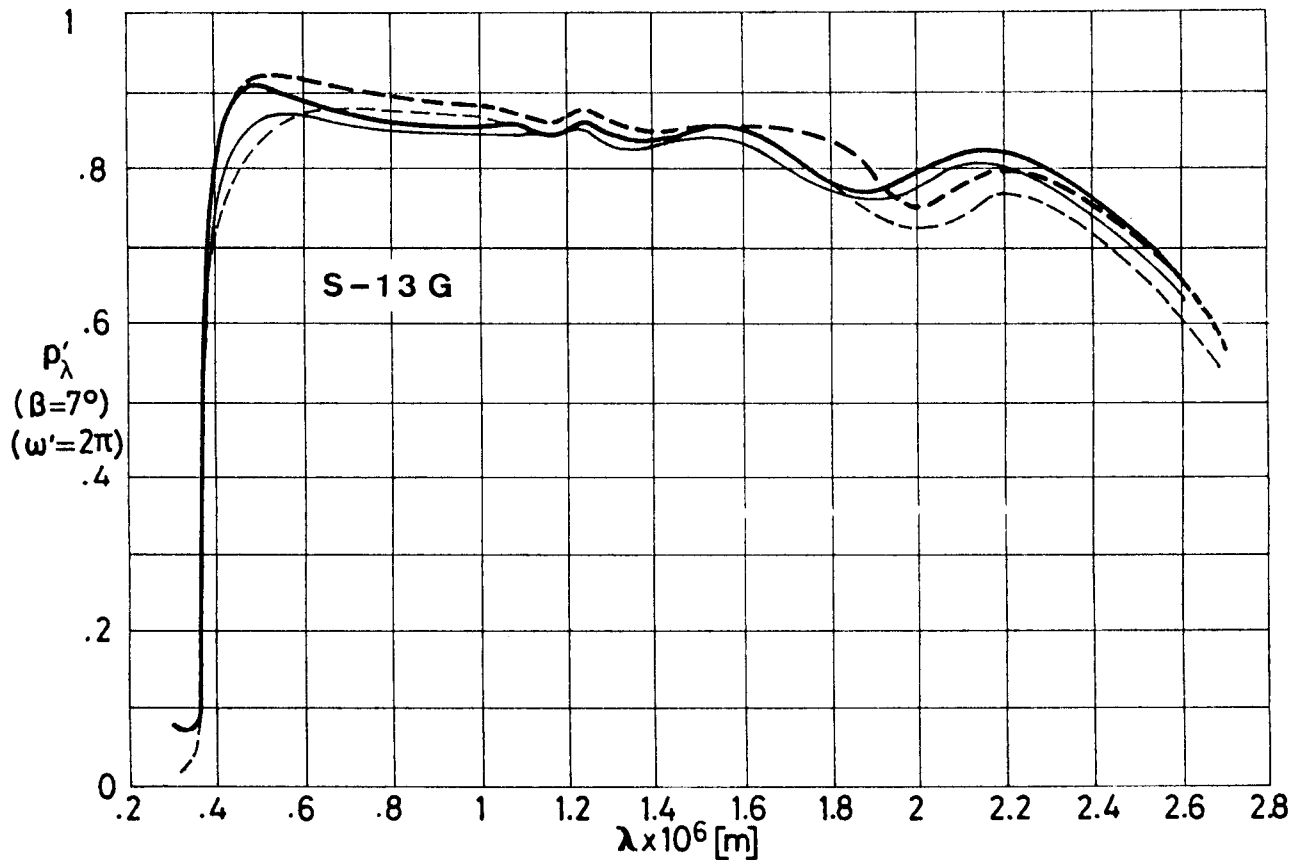


Fig 1-48.20. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 G coating vs. wavelength, λ . Sweated pigment. Two different solvent systems. From Zerlaut, Rogers & Noble (1969). Drawn from Touloukian, DeWitt & HERNICZ (1972).

Explanation

Key	Solvent	Exposure	Comments
—	Toluene	In vacuum before irradiation.	T ~ 298 K. p ~ 1.33 x 10 ⁻⁵ Pa. Measured and exposed in situ. UV source G.E. AH-6 lamp. IITRI test facility (In situ Reflectometer Irradiation Facility, see Zerlaut & Courtney (1967)). α_s and $\Delta\alpha_s$ in p. 1-48.19.
—		UV. 600 ESH.	
---	Toluene and petroleum ether	In vacuum before irradiation	
---		UV. 800 ESH.	

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Figure 1-48.21 shows results of two attempts made to neutralize the sweated pigment prior to manufacture. The specimen prepared from the sodium acid phosphate neutralized pigment exhibited the greatest UV stability that has been observed for S-13 G prepared from calcined pigment. On the other hand, stability at most wavelengths was destroyed by neutralization with formic acid.

Neutralization was required because in this case Owens-Illinois 650 resin was used. This resin is highly stable against UV irradiation and can be thermally cured at low temperatures without using catalysts. Unfortunately this causes nearly instantaneous gellation when mixed with silicate-treated zinc oxide. Gelled coatings exhibit a jelly-like condition.

Figures 1-48.22 and 1-48.23 show additional effects of different pigment treatment processes.

In Fig 1-48.22 pigment was sifted before wet grinding, a technique which is no longer used.

Reaction of ZnO with potassium silicate provides an effective barrier to photodesorption reactions on the surface of ZnO which the binder does not.

The idea behind this treatment was put forward in the Z-93 coating (see pp. 1-13 to 1-28) where the

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reactivity of ZnO with potassium silicate precluded the bleachable infrared degradation exhibited by ZnO powder and ZnO-silicone coatings.

Figure 1-48.23 deals with silicate treated pigments under different mechanical processes. The only difference between the different coatings was the manner in which the dried, treated ZnO powder was conditioned for grinding into the paint.

The data show that the stability to UV radiation in vacuum is an inverse function of the shear stress applied to the dry pigment prior to wet-grinding. A fivefold increase in damage, as measured by $\Delta\alpha_s$, was observed between the paint prepared from only sifted pigment and the hand-mulled prior to wet-grinding specimen (recall comment in p. 1-48.41 regarding Fig 1-48.19). Hand-mulling is no longer used after these studies.

Sifting out the millable pigment is a highly inefficient and costly technique, even though it permits shorter wet-grinding times and greater stability. At present only wet-grinding is used.

Figure 1-48.24 corresponds to the state of the art S-13 G coating.

From Zerlaut, Rogers & Noble (1969), Gilligan & Zerlaut (1971).

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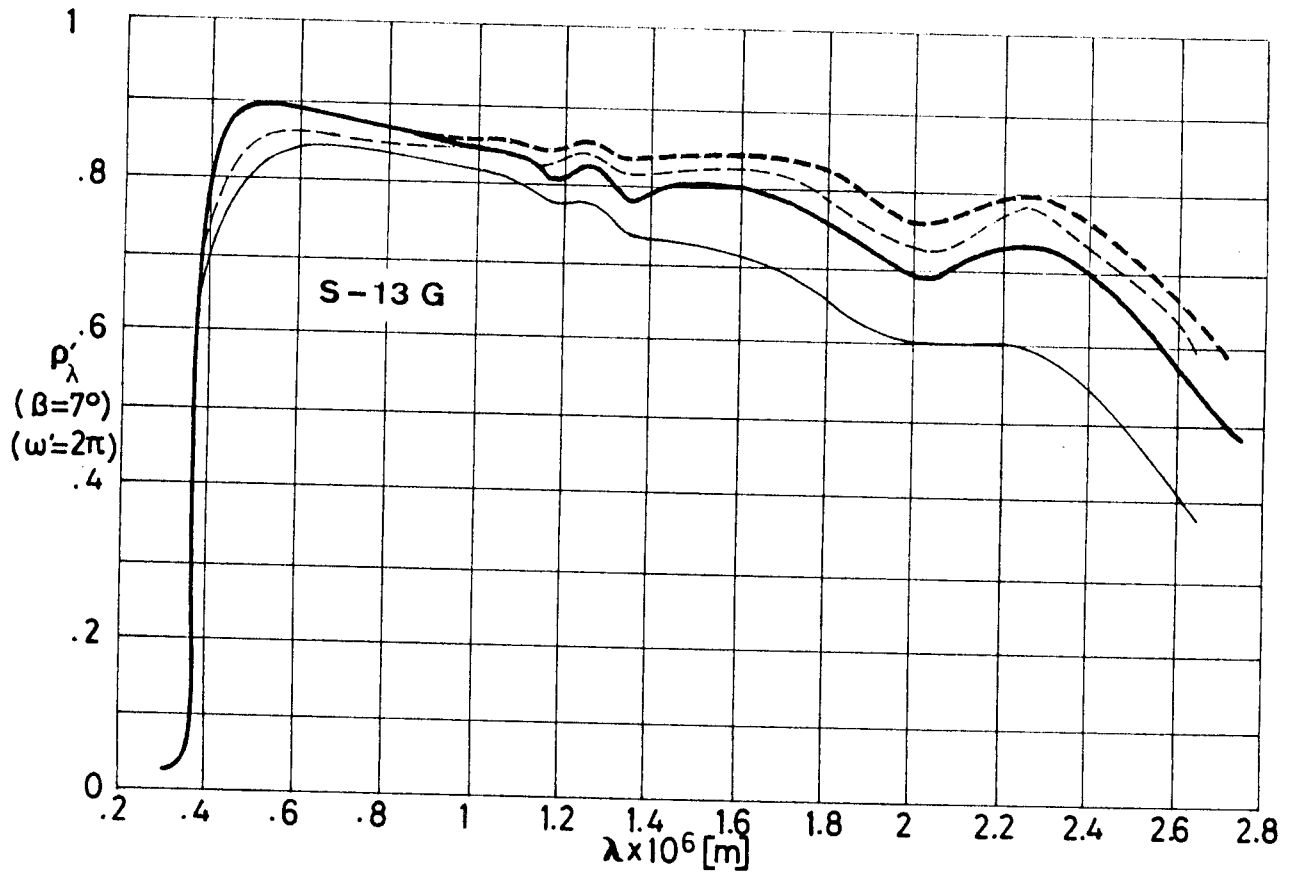


Fig 1-48.21. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 G coating vs. wavelength, λ . Two different pigment treatment processes. Owens-Illinois 650 binder. From Zerlaut, Rogers & Noble (1969). Drawn from Touloukian, DeWitt & Hernicz (1972).

Explanation

Key	Pigment Treatment	Exposure	Comments
—	Sweated, neutralized with formic acid and calcined for 16 h at 923 K.	In vacuum before irradiation.	T ~ 298 K. p ~ 1.33 x 10 ⁻⁵ Pa. Measured and exposed in situ. UV source G.E. AH-6 lamp. IITRI test facility (In situ Reflectometer Irradiation Facility, see Zerlaut & Courtney (1967)). α_s and $\Delta\alpha_s$ in p. 1-48.19.
—		UV. 600 ESH.	
- - -	Sweated, neutralized with sodium acid phosphate and calcined for 16 h at 923 K.	In vacuum before irradiation	
- - -		UV. 600 ESH.	

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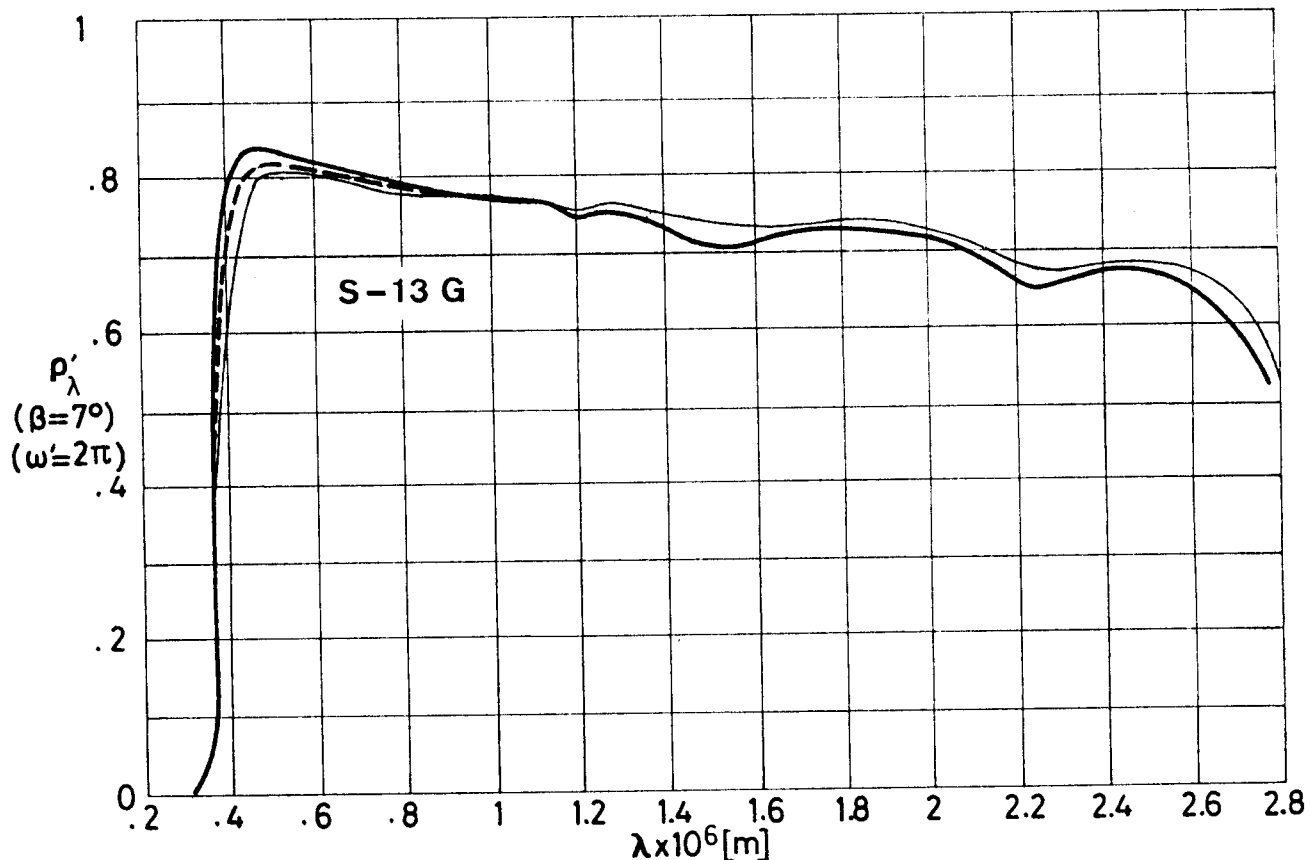


Fig 1-48.22. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 G coating vs. wavelength, λ . Pigment was sifted prior to wet grinding. Paint grind time 3 h. From Zerlaut, Rogers & Noble (1969). Drawn from Touloukian, DeWitt & HERNICZ (1972).

Explanation

Key	Exposure	Comments
—	In vacuum before irradiation.	T \approx 298 K. p \approx 1.33×10^{-5} Pa. Measured and exposed in-situ. UV source G.E. AH-6 lamp. ITRI test facility (In situ Reflectometer Irradiation Facility, see Zerlaut & Courtney (1967)). α_s and $\Delta\alpha_s$ in p. 1-48.19.
—	UV. 1 400 ESH.	
- - -	Above after breaking vacuum.	

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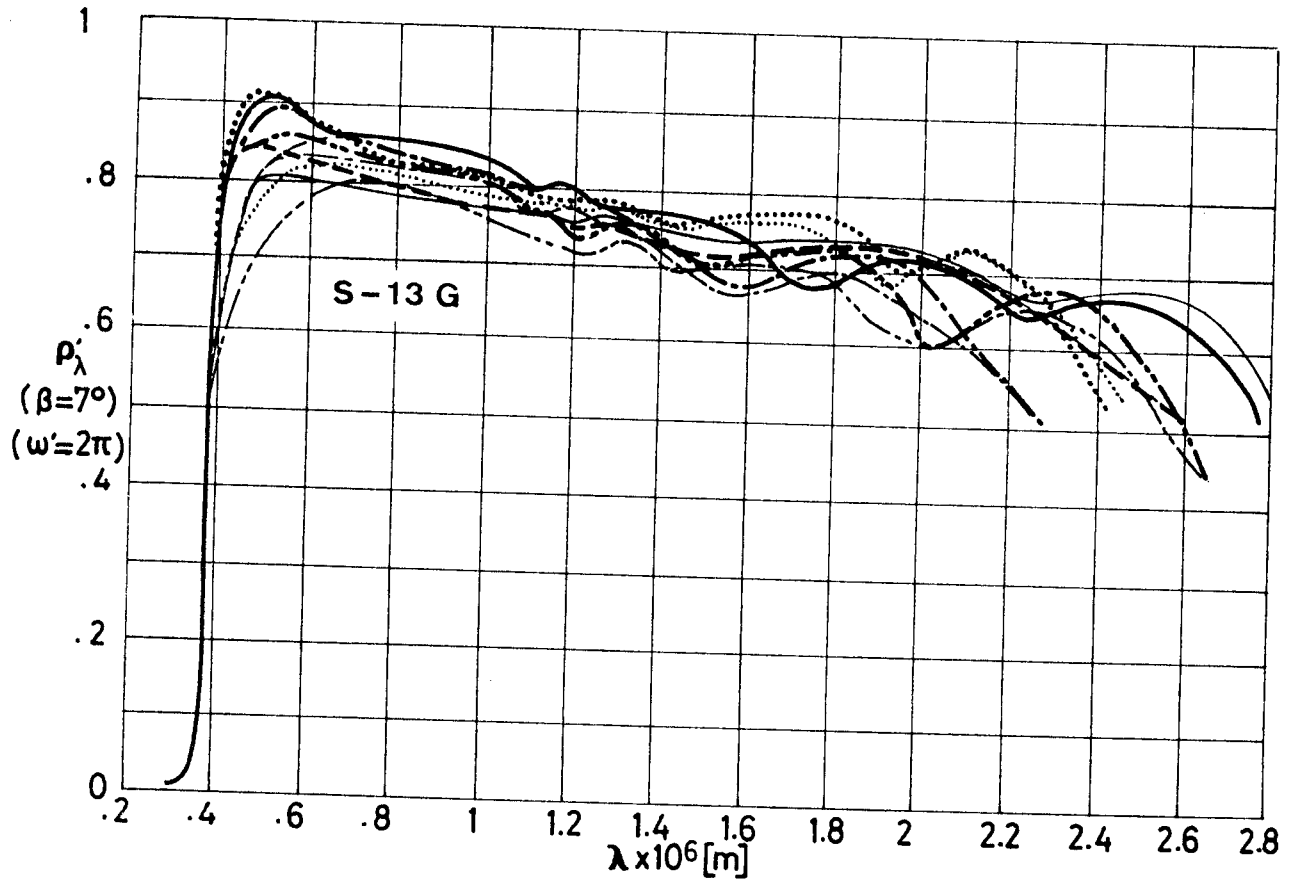


Fig 1-48.23. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 G coating vs. wavelength, λ . Silicated pigment with five mechanical perturbations. From Zerlaut, Rogers & Noble (1969). Drawn from Touloukian, DeWitt & Hernicz (1972).

Explanation

Key	Pigment Mechanical Perturbation	Exposure	Comments
————	Sifting prior to wet-grinding. Grind time 3 h.	In vacuum before irradiation. UV. 1 400 ESH.	T ~ 298 K. p ~ 1.33 x 10 ⁻⁵ Pa. Measured and exposed in situ. UV source G.E. AH-C lamp. IITRI test facility (In Situ Reflectometer Irradiation Facility, see Zerlaut & Courtney (1967)). α_s and $\Delta\alpha_s$ in p. 1-48.19.
-----	Unsifted and unground prior to wet-grinding. Grind time 4 h.	In vacuum before irradiation. UV. 1 400 ESH.	
-----	Dry-ground 30 min. Grind time 3 h.	In vacuum before irradiation. UV. 1 400 ESH.	
.....	Hand-mulling prior to wet grinding. Grind time 3 h.	In vacuum before irradiation. UV. 1 400 ESH.	
-----	Remulled from first-hand mulling. Grind time 5 h.	In vacuum before irradiation. UV. 1 400 ESH.	

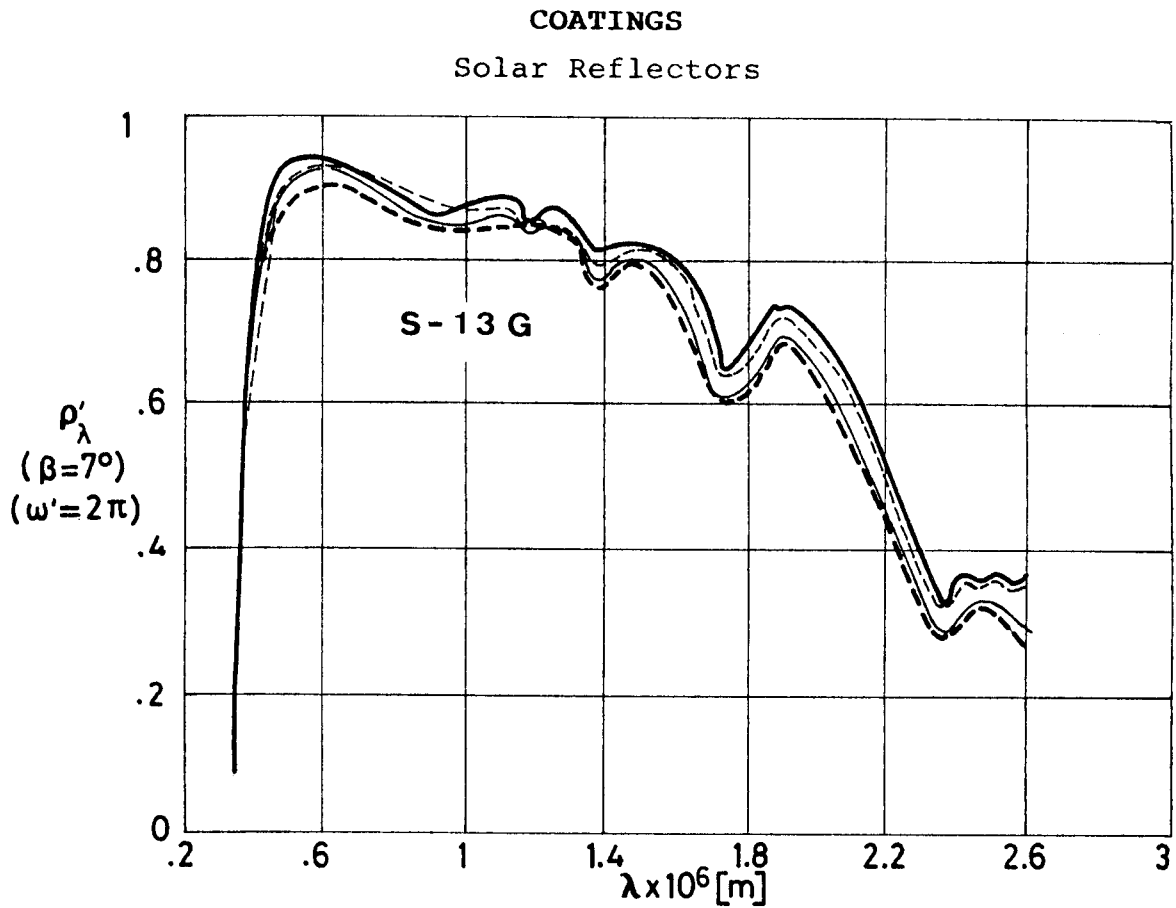


Fig 1-48.24. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 G coating vs. wavelength, λ . Plasma annealed and potassium silicate treated pigment. From Gilligan & Zerlaut (1971).

Explanation

Key	Exposure	Comments
—	In vacuum before irradiation.	T = 285 K. Measured in-situ. Initially at 8×10^{-6} Pa pressure. Irradiation performed at 1.33×10^{-5} Pa. IITRI test facility. (Combined Environment Radiation Facility) $\Delta\alpha_S$ in p. 1-48.19.
—	UV. 600 ESH. First part of exposure.	
- - -	Above plus UV. 700 ESH. Second part of exposure.	
- - -	Above plus O ₂ bleaching.	

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7.3.3.2.3. Protons only exposure. Fig 1-48.25 refers to S-13 and Fig 1-48.26 to S-13 G coating.

Unfortunately both the exposure conditions and the measuring method widely differ in either case.

In Fig 1-48.25 an Earth to Mars Mission has been simulated whereas Fig 1-48.26 seems to represent the conditions of a high altitude (200 000 km to 250 000 km) nearly circular orbit.

After exposure data in Fig 1-48.25, which were taken in the early sixties, were measured in air and those in Fig 1-48.26, from the seventies, in situ.

Figure 1-48.25 shows that changes in reflectance include a slight increase in the UV region ($\lambda < .35 \times 10^{-6}$ m) a shift in the Ultra-Violet absorption cut off, and a general increase in the infrared wavelength region.

The reflectance of a typical exposed sample was measured at time intervals of 14 h to 2 070 h after irradiation. No annealing of damage was observed between reflectance measurements at 14 h and 2 070 h after exposure.

Changes in solar absorptance of similar samples are given in p. 1-48.20.

From Gillette, Brown, Seiler & Sheldon (1966).

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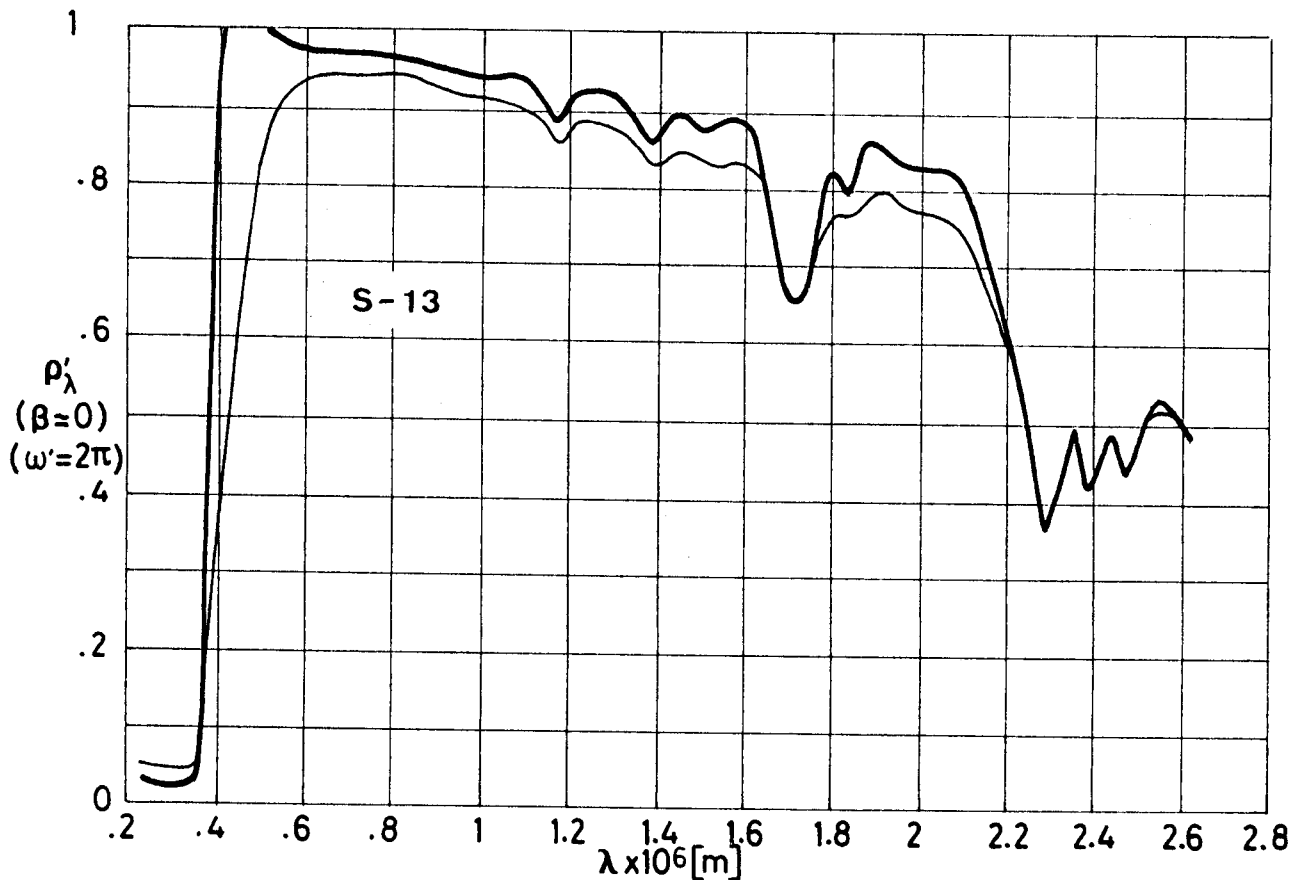


Fig 1-48.25. Protons exposure effects on normal-hemispherical spectral reflectance, ρ_{λ}^i , of S-13 coating vs. wavelength, λ . LTV-602 silicone binder. From Gillette, Brown, Seiler & Sheldon (1966). Drawn from Touloukian, DeWitt & Hernicz (1972).

Explanation

Key	Exposure	Comments
—	In air before irradiation.	Sprayed on aluminium substrate. T = 300 K. Measured in air, exposed in vacuum (1.33 x 10 ⁻⁴ Pa). Measurement relative to MgO. Boeing low-energy particle accelerator.
- - -	Protons. 8.2 keV. 6.1 x 10 ¹⁹ p.m ⁻² Integrated Flux. In air 20 h - 40 h after irradiation.	

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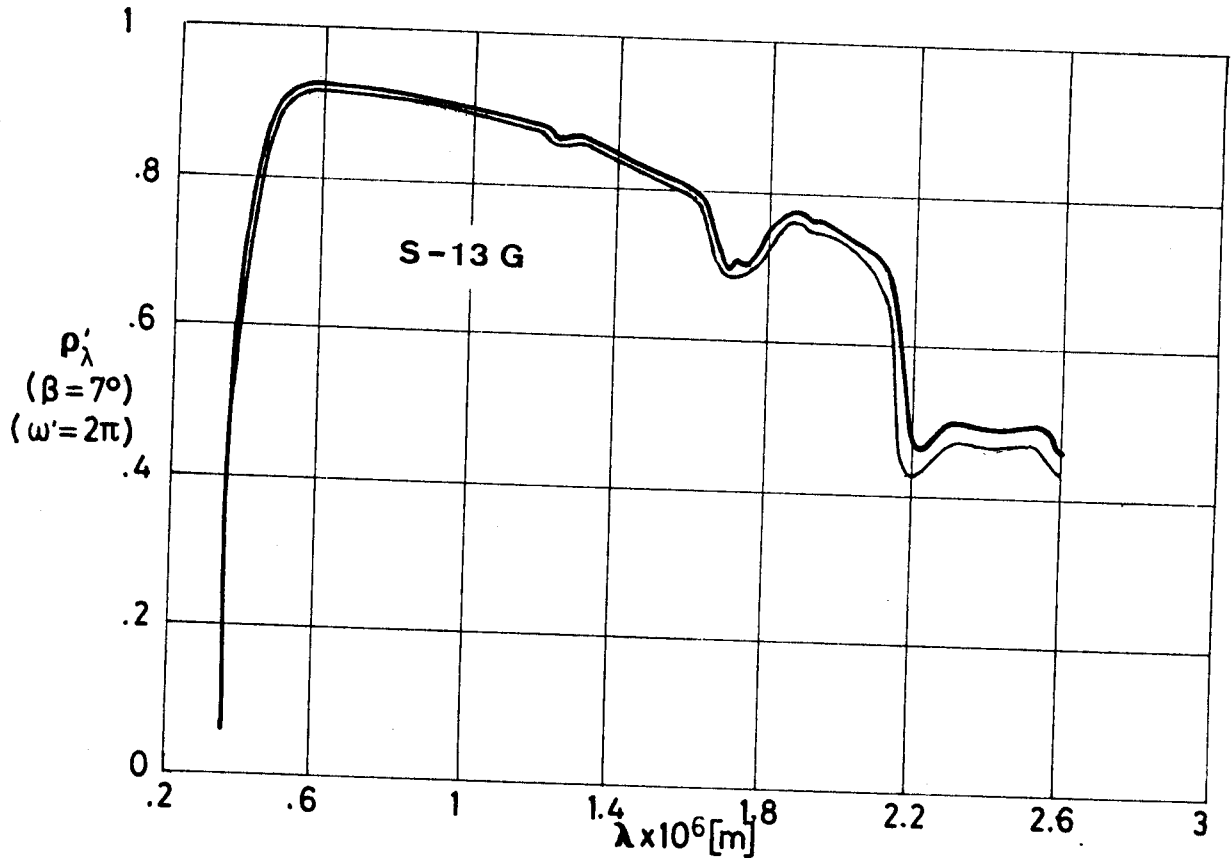


Fig 1-48.26. Protons exposure effects on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 G coating vs. wavelength, λ . Plasma annealed and potassium silicate treated pigment. From Gilligan & Zerlaut (1971).

Explanation

Key	Exposure	Comments
	In vacuum before irradiation.	T = 285 K. Measured in situ. Initially at 8×10^{-6} Pa pressure. Irradiation performed at 1.33×10^{-5} Pa. IITRI facility (In situ Reflectance Irradiation Facility - IRIF).
	Protons. 1.2 keV 4.9×10^{13} p.m ⁻² .s ⁻¹ Flux. 2.5×10^{19} p.m ⁻² Integrated Flux	

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7.3.3.2.4. Electrons only exposure. Figs 1-48.27 and 1-48.28 concern S-13 G coating, whereas Figs 1-48.29 to 1-48-32 are related to GSFC, 101-7, a similar coating developed by NASA Goddard.

Both coatings exhibit a slow improvement in reflectance with time after exposure, even when the samples remain in the dark in a 1.33×10^{-6} Pa vacuum. The mechanisms of recovery are not quite understood. They probably depend on time, temperature, chamber residual atmosphere species, sample composition, radiation particle type, flux and integrated flux. Recovery occurs after exposure whether the impinging particle is stopped in the sample or passes through to its substrate.

Recovery proceeds to a greater extent and at a faster rate after 20 keV exposure than after 80 keV exposure and is probably reduced at improved vacuum conditions.

Compared to S-13 G, series 101-7 recovers more slowly and to a smaller fraction of original degradation.

From Fogdall, Cannaday & Brown (1970).

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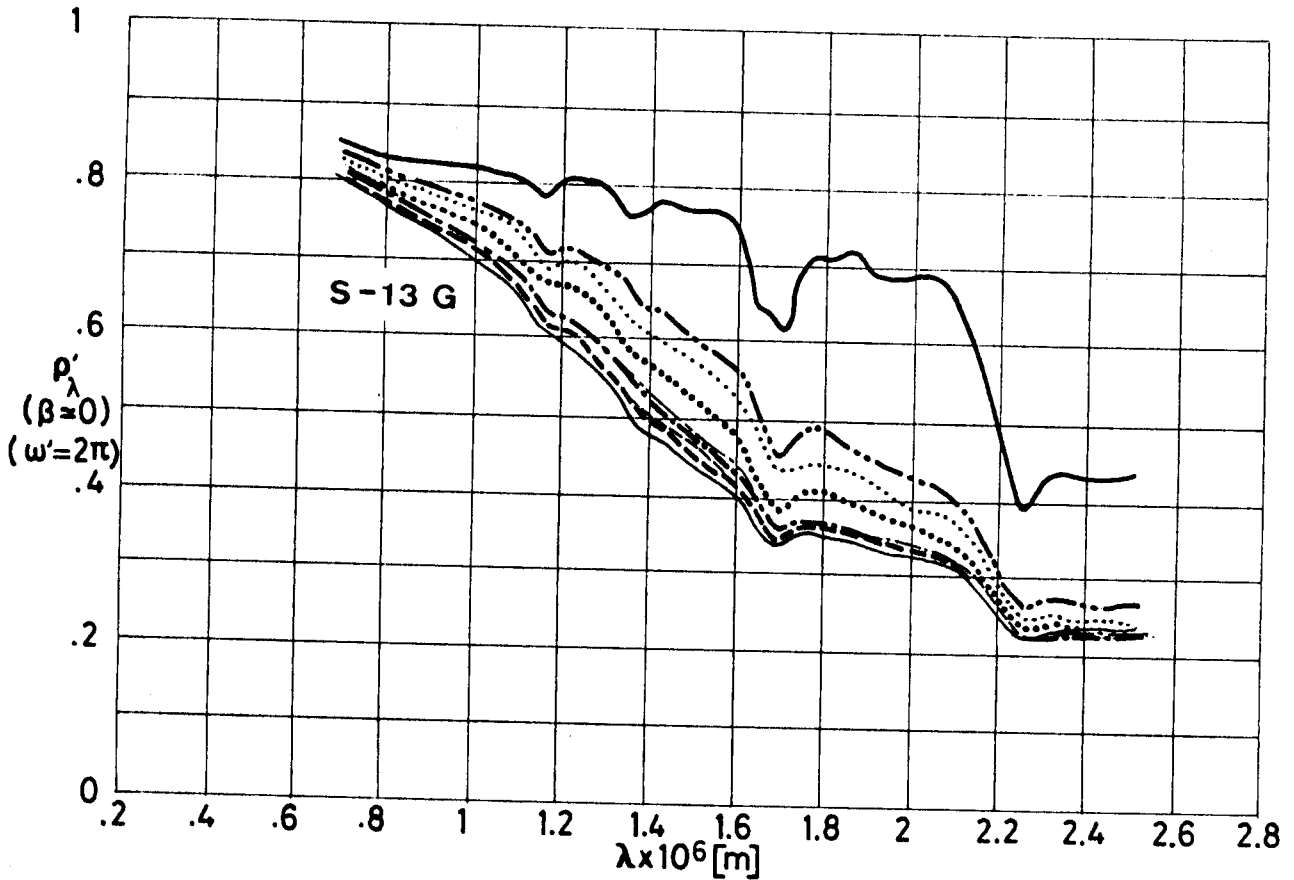


Fig 1-48.27. Electrons exposure effects on normal-hemispherical spectral reflectance, ρ'_{λ} , of S-13 G coating vs. wavelength, λ . Radiation intensity 20 keV. Recovery after exposure. From Fogdall, Cannaday & Brown (1970). Drawn from Touloukian, DeWitt & Hernicz (1972).

Explanation

Key	Intensity [keV]	Cumulative Integrated Flux [e.m ⁻²]	Time after Exposure [h]	Comments
—	In air before irradiation			Sample on Al substrate. T = 298 K.
—	20	10 ¹⁹ (10 ¹⁴ to 5x10 ¹⁵ e.m ⁻² .s ⁻¹)	.066	Sample on Al substrate. T = 281 K. 1.33 x 10 ⁻⁶ Pa vacuum maintained by ion pump. Measured in situ after exposure. Boeing test facility (Radiation Effects Laboratory) see Brown, Fogdall & Cannaday (1969).
- - -			.82	
- - - -			1.65	
- - - - -			4.12	
- - - - - .			6.92	
.....			23.07	
.....			53.68	
- - - -			122.87	

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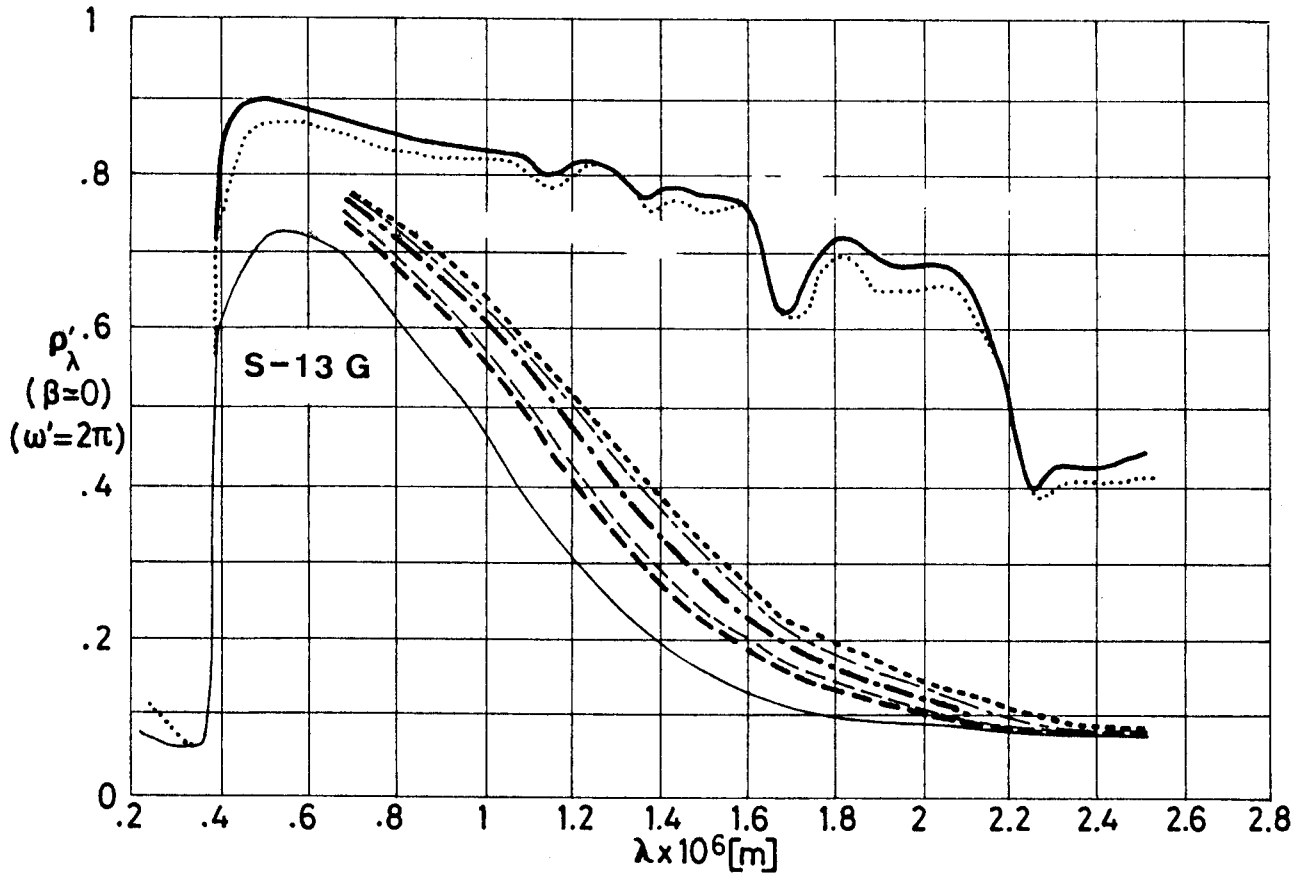


Fig 1-48.28. Electrons exposure effects on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 G coating vs. wavelength, λ . Radiation intensity 80 keV. Recovery after exposure. From Fogdall, Cannaday & Brown (1970). Drawn from Touloukian, DeWitt & Hernicz (1972).

Explanation

Key	Intensity [keV]	Cumulative Integrated Flux [e.m^{-2}]	Time after Exposure [h]	Comments
	In air before irradiation			Sample on Al substrate. T = 298 K.
—	80	10^{20} (10^{14} to 5×10^{15} $\text{e.m}^{-2} \cdot \text{s}^{-1}$)	0	Sample on Al substrate. T = 281 K.
---			48	1.33×10^{-6} Pa vacuum maintained by ion pump.
----			72	Measured in situ after exposure.
-----			96	Boeing test facility (Radiation Effects Laboratory) see Brown, Fogdall & Cannaday (1969).
.....			168	
.....			432	
.....			Measured in air after the above tests had been made. T = 298 K.	

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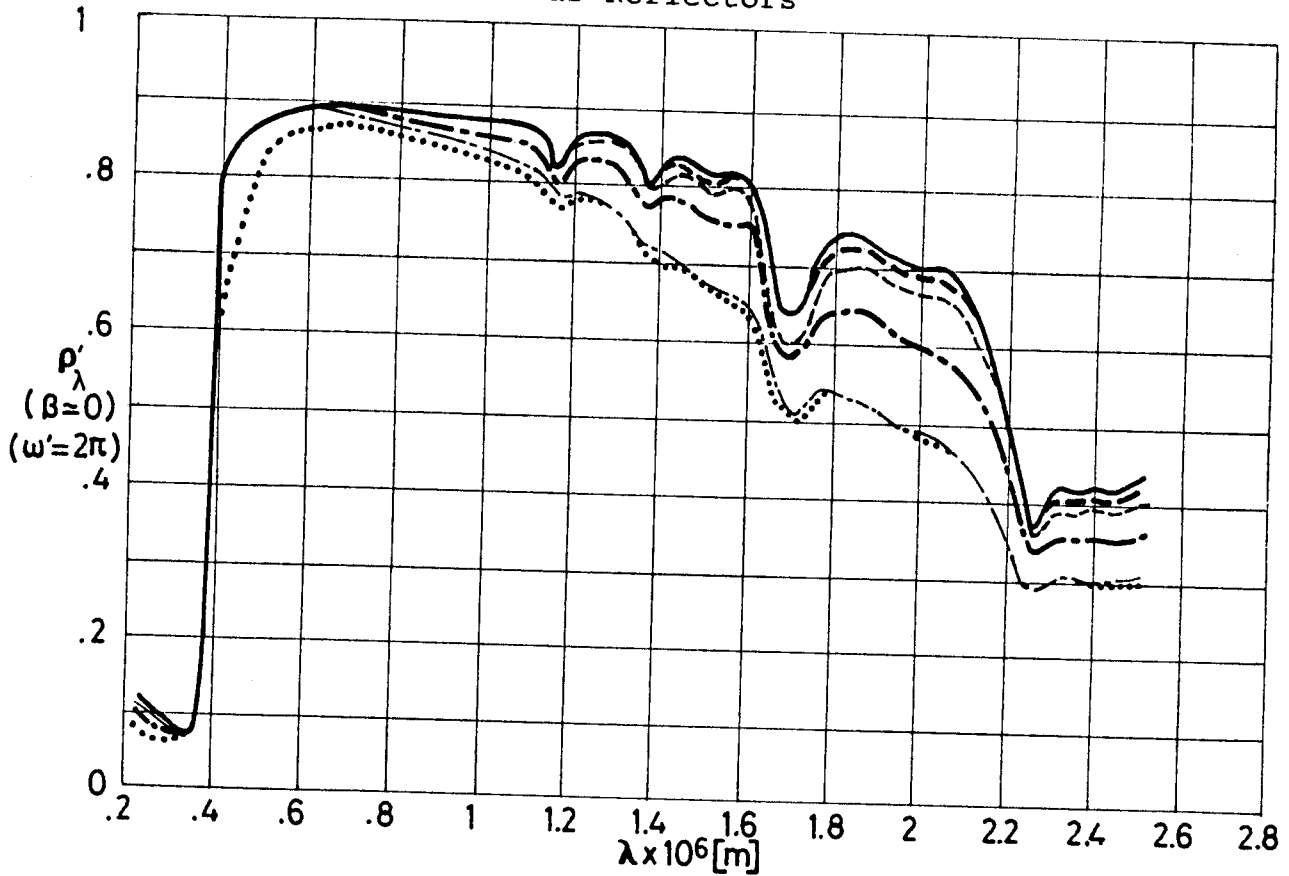


Fig 1-48.29. Electrons exposure effects on normal-hemispherical spectral reflectance, ρ_{λ} , of GSFC, 101-7 coating vs. wavelength, λ . Radiation intensity 20 keV. Different integrated fluxes. 101-7 is a coating, similar to S-13 G, developed by NASA Goddard. From Fogdall, Cannaday Brown (1970). Drawn from Touloukian, DeWitt & Hernicz (1972).

Explanation

Key	Intensity [keV]	Flux [e.m ⁻² .s ⁻²]	Cumulative Integrated Flux [e.m ⁻²]	Comments
—	In air before irradiation			Sample on Al substrate. T = 298 K.
—	20	10 ¹⁴ to 5x10 ¹⁵	10 ¹⁷	Sample on Al substrate. T = 281 K.
—			5 x 10 ¹⁷	1.33 x 10 ⁻⁶ Pa vacuum maintained by ion pump.
- - - -			10 ¹⁸	Measured in situ after exposure.
- - - -			3 x 10 ¹⁸	Boeing test facility (Radiation Effects Laboratory) see Brown, Fogdall & Cannaday (1969).
.....			10 ¹⁹	
.....			10 ²⁰	α_s in p. 1-48.21.

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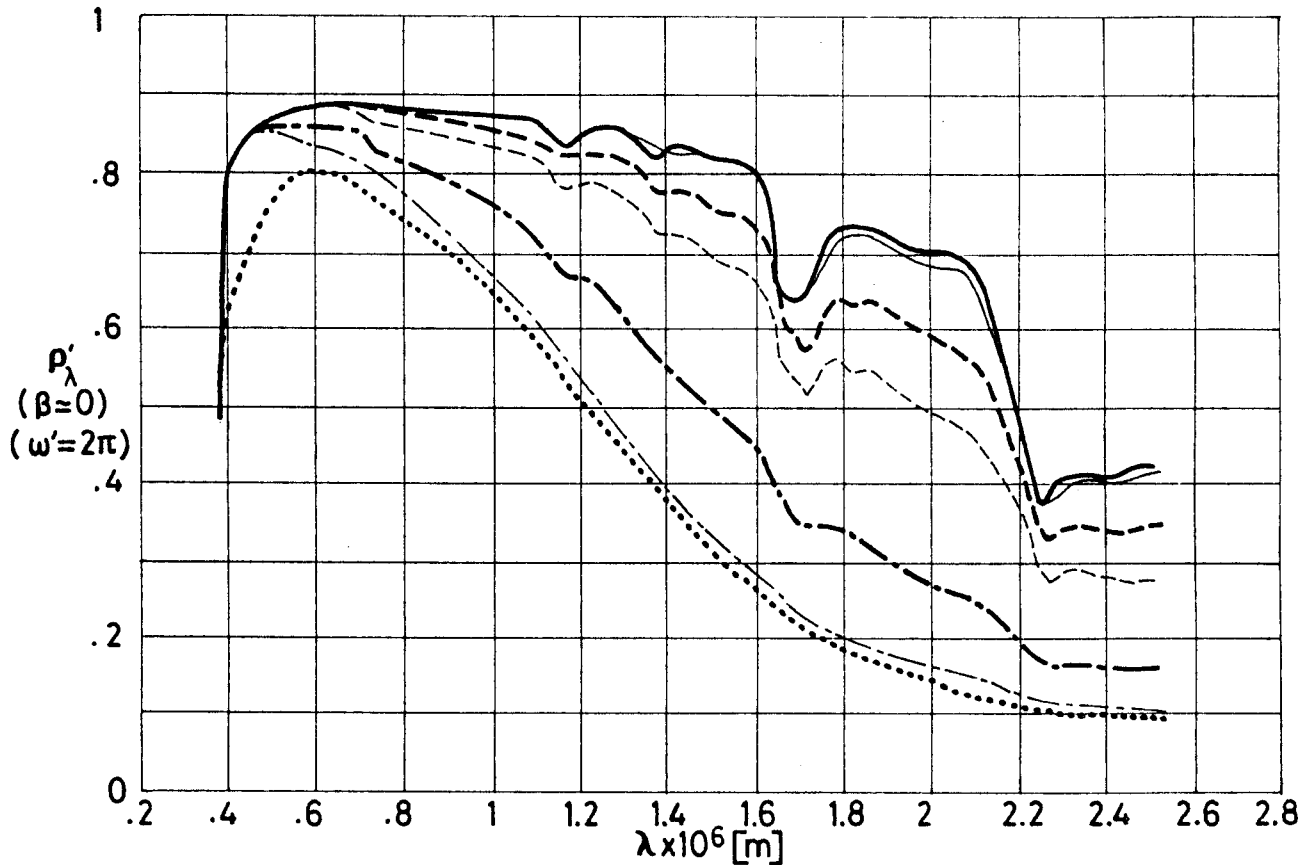


Fig 1-48.30. Electrons exposure effects on normal-hemispherical spectral reflectance, ρ_{λ}' , of GSFC, 101-7 coating vs. wavelength, λ . Radiation intensity 80 keV. Different integrated fluxes. 101-7 is a coating, similar to S-13 G, developed by NASA Goddard. From Fogdall, Cannaday & Brown (1970). Drawn from Touloukian, DeWitt & Hernicz (1972).

Explanation

Key	Intensity [keV]	Flux [e.m ⁻² .s ⁻²]	Cumulative Integrated Flux [e.m ⁻²]	Comments
—	In air before irradiation			Sample on Al substrate. T = 298 K.
—	80	10 ¹⁴ to 5x10 ¹⁵	10 ¹⁷	Sample on Al substrate. T = 281 K. 1.33 x 10 ⁻⁶ Pa vacuum maintained by ion pump. Measured in situ after exposure. Boeing test facility (Radiation Effects Laboratory) see Brown, Fogdall & Cannaday (1969). α_s in p. 1-48.21.
—			5 x 10 ¹⁷	
—			10 ¹⁸	
—			3 x 10 ¹⁸	
—			10 ¹⁹	
.....			10 ²⁰	

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Solar Reflectors

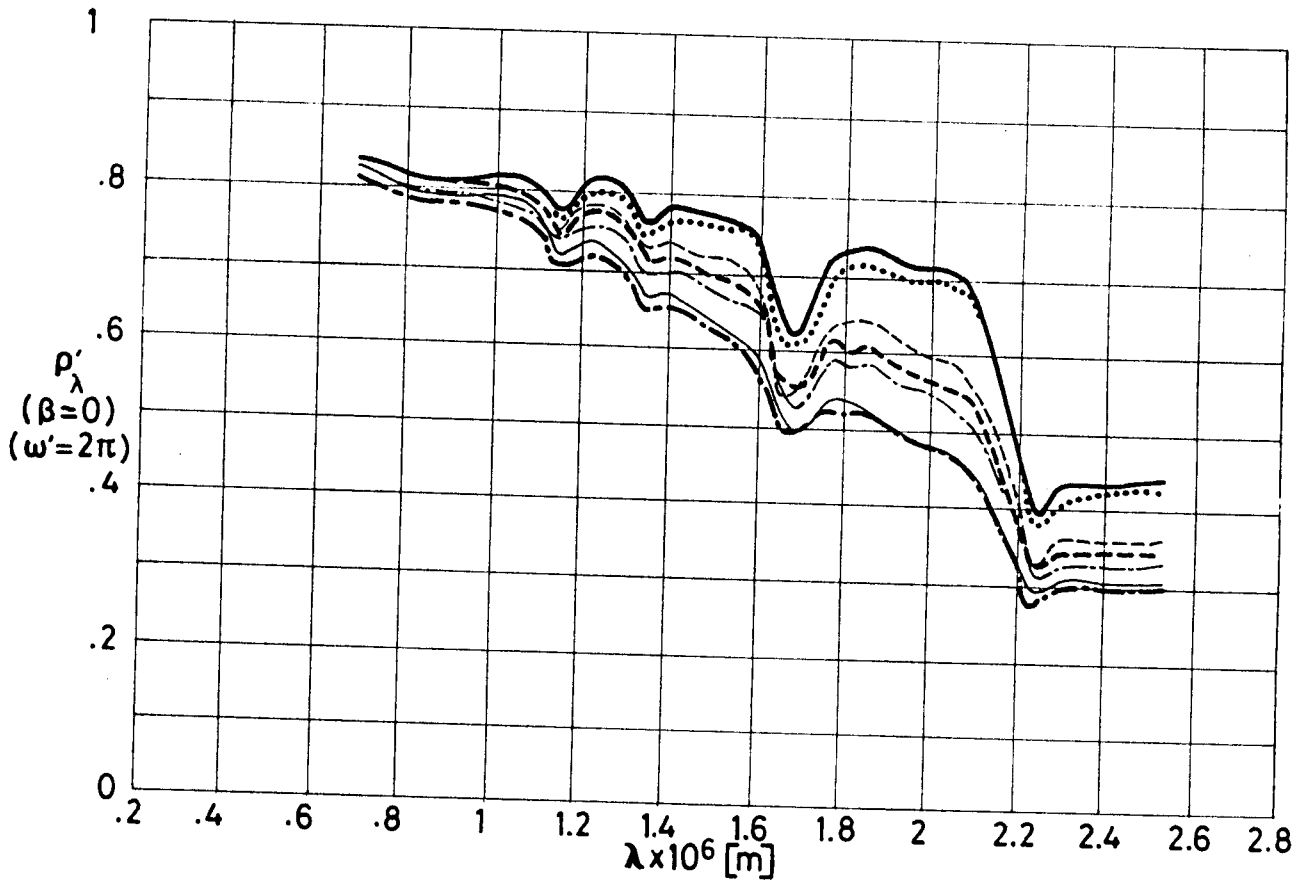


Fig 1-48.31. Electrons exposure effects on normal-hemispherical spectral reflectance, ρ_{λ} , of GSFC, 101-7 coating vs. wavelength, λ . Radiation intensity 20 keV. Recovery after exposure. 101-7 is a coating, similar to S-13 G, developed by NASA Goddard. From Fogdall, Cannaday & Brown (1970). Drawn from Touloukian, DeWitt & HERNICZ (1972).

Explanation

Key	Intensity [keV]	Cumulative Integrated Flux [e.m ⁻²]	Time after Exposure [h]	Comments
—	In air before irradiation			Sample on Al substrate. T = 298 K.
—	20	10 ¹⁹	3.87	Sample on Al substrate. T = 281 K. 1.33 x 10 ⁻⁶ Pa vacuum maintained by ion pump. Measured in situ after exposure. Boeing test facility (Radiation Effects Laboratory) see Brown, Fogdall & Cannaday (1969). 120 h after dry air back fill. T = 298 K.
---			54.	
----			123.	
-.-.-		10 ²⁰	1.08	
----			50.	
.....			168.	

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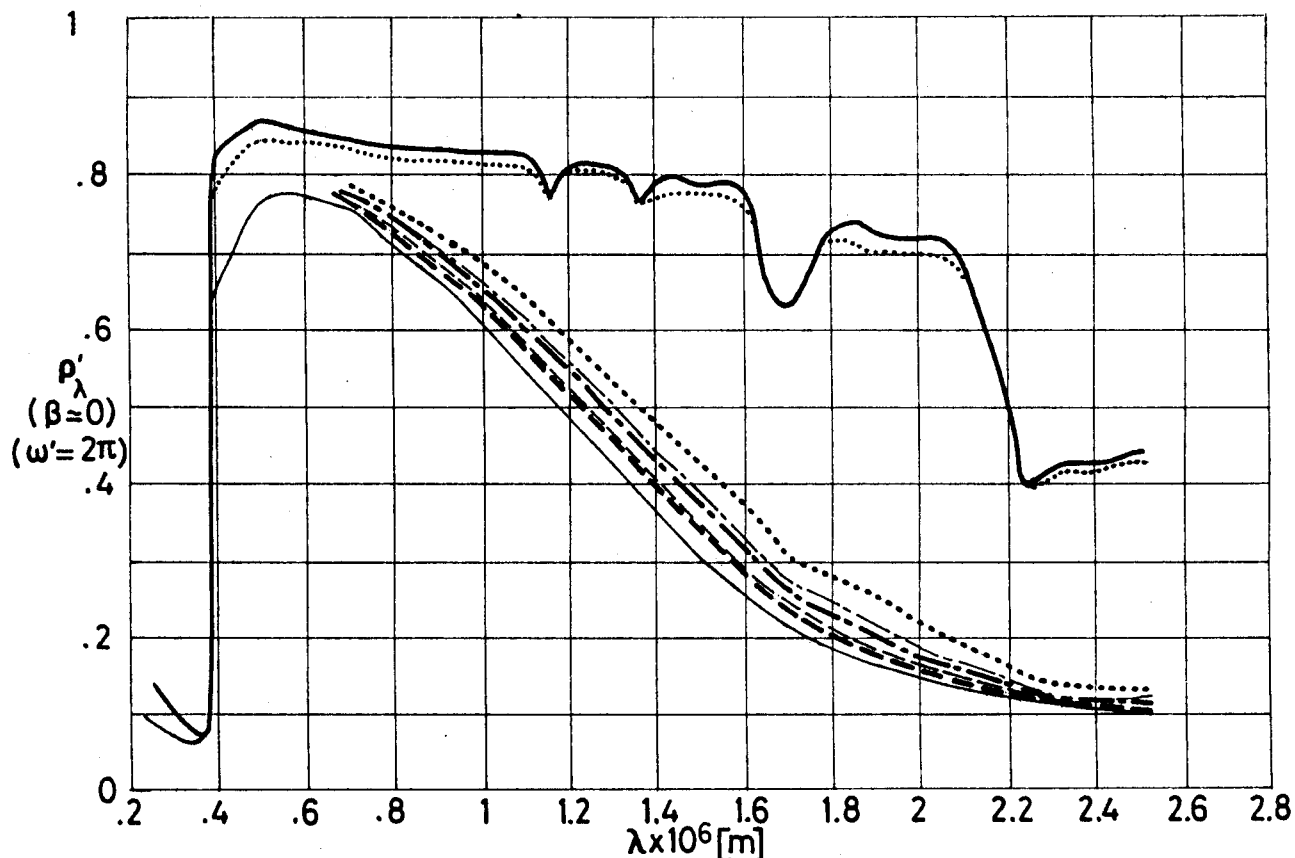


Fig 1-48.32. Electrons exposure effects on normal-hemispherical spectral reflectance, ρ_{λ}' , of GSFC, 101-7 coating vs. wavelength, λ . Radiation intensity 80 keV. Recovery after exposure. 101-7 is a coating, similar to S-13 G, developed by NASA Goddard. From Fogdall, Cannaday Brown (1970). Drawn from Touloukian, DeWitt & Hernicz (1972).

Explanation

Key	Intensity [keV]	Cumulative Integrated Flux [e.m ⁻²]	Time after Exposure [h]	Comments
—	In air before irradiation			Sample on Al substrate. T = 298 K.
—	80	10 ²⁰ (10 ¹⁴ to 5x10 ¹⁵ e.m ⁻² .s ⁻¹)	0	Sample on Al substrate. T = 281 K.
- - -			48	1.33 x 10 ⁻⁶ Pa vacuum maintained by ion pump.
- · - · -			72	Measured in situ after exposure.
- - - - -			96	Boeing test facility (Radiation Effects Laboratory) see Brown, Fogdall & Cannaday (1969).
· · · · ·			168	
· · · · ·			432	
	Measured in air after the above tests had been made. T = 298 K.			

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7.3.3.2.6. Combined exposure. Two different set of data are presented here.

Fig 1-48.33 shows the effect of Ultra-Violet and Protons exposure on S-13 G coating.

The damage in the visible spectrum ($\lambda = .4 \times 10^{-6}$ m to $.7 \times 10^{-6}$ m) is fairly slight and bleacheable. The exposure produces displacement of atoms, ionization and excitations. After exposure most of the atoms return to the previous or similar equilibrium positions and a recovery process follows, in which X ray and Ultra-Violet radiations are emitted. When long wavelength radiation is not present the damage is not bleached.

Charged particle damage produces effects which Ultra-Violet produces, as well as others which result from massive interactions. In combined exposures radiative bleaching will produce "synergism" and invalidate any reciprocity which might have existed in single environment testing.

$\Delta\alpha_s$ is given in p. 1-48.29.

From Gilligan & Zerlaut (1971).

The other set of data, Figs 1-48.34 to 1-48.36, are for S-13 G/LO on Al substrate and are intended to represent up to three years exposure in geosynchro-

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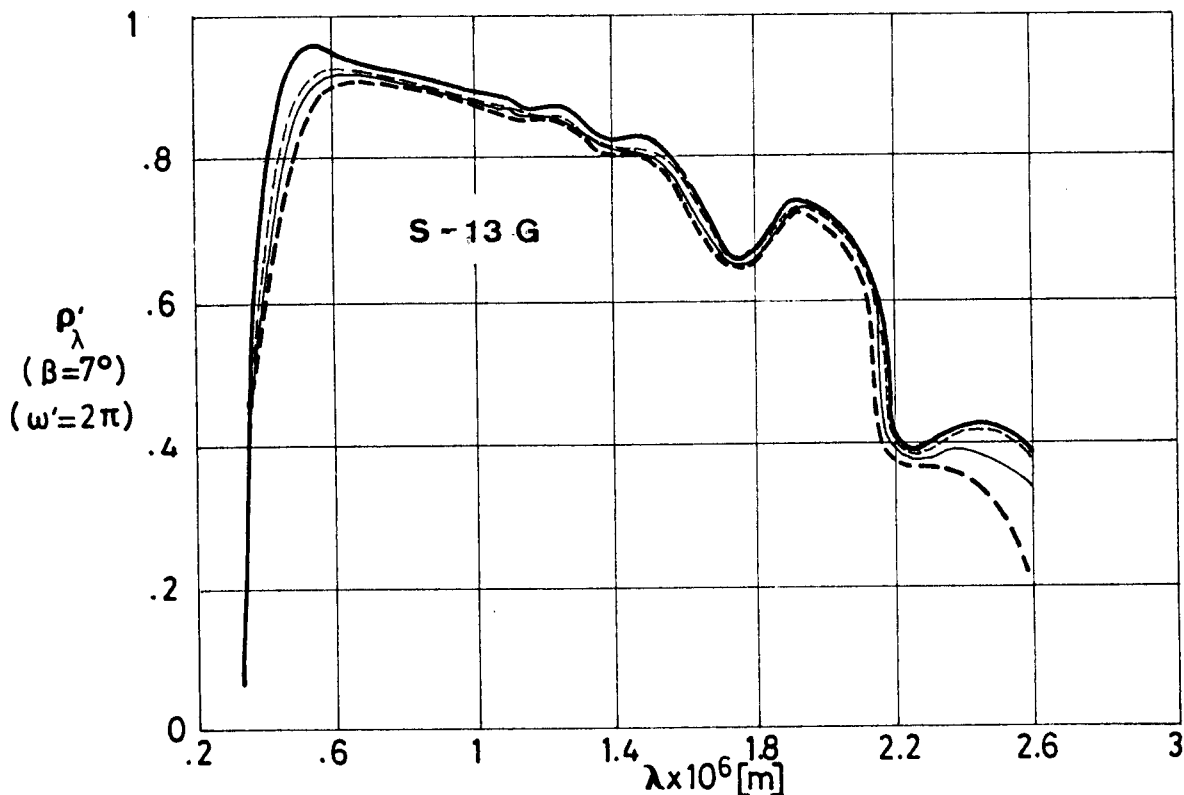


Fig 1-48.33. Effect of Combined Exposure on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 G coating vs. wavelength, λ . Plasma annealed and potassium silicate treated pigment. From Gilligan & Zerlaut (1971).

Explanation

Key	Exposure	Comments
—	In vacuum before irradiation.	T = 285 K. Measured in situ. Initially at 8×10^{-6} Pa pressure. Irradiation performed at 1.33×10^{-5} Pa. IITRI facility (In situ Reflectance Irradiation Facility - IRIF). $\Delta\alpha_S$ in p. 1-48.29.
—	UV. 600 ESH. Protons. 668 EWH . $1.05 \times 10^{13} \text{ p.m}^{-2} \cdot \text{s}^{-1}$ Flux. $\sim 6 \times 10^{18} \text{ p.m}^{-2}$ Integrated Flux. First part of exposure.	
---	Above plus UV. 700 ESH. Second part of exposure.	
----	Above plus O_2 bleaching.	

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nous orbit of the Orbital Test Satellite (OTS) equatorial faces. Solar absorptance data have been presented and evaluated in pp. 1-48.29 to 1.48-32. Figure 1-48.34 indicates that in the visible range ($\lambda = .4 \times 10^{-6}$ m to $.7 \times 10^{-6}$ m) the reflectance decreases regularly with the exposure time; whereas the decrease in the infrared ($\lambda > .8 \times 10^{-6}$ m) rapidly reaches a saturation.

Figure 1-48.35 shows the influence of air exposure after irradiation. To this aim the upper and lower reflectance curves in Fig 1-48.34 have been compared with that resulting from air exposure.

Figure 1-48.36 indicates that bleaching appears after pump damage but an increased reflectance also results when an irradiation with Ultra-Violet and particles is followed by an irradiation with particles only. Again the infrared part of the spectrum ($\lambda > .8 \times 10^{-6}$ m) is the most affected, as can be seen by comparing the curves corresponding to data taken after step C and before step D.

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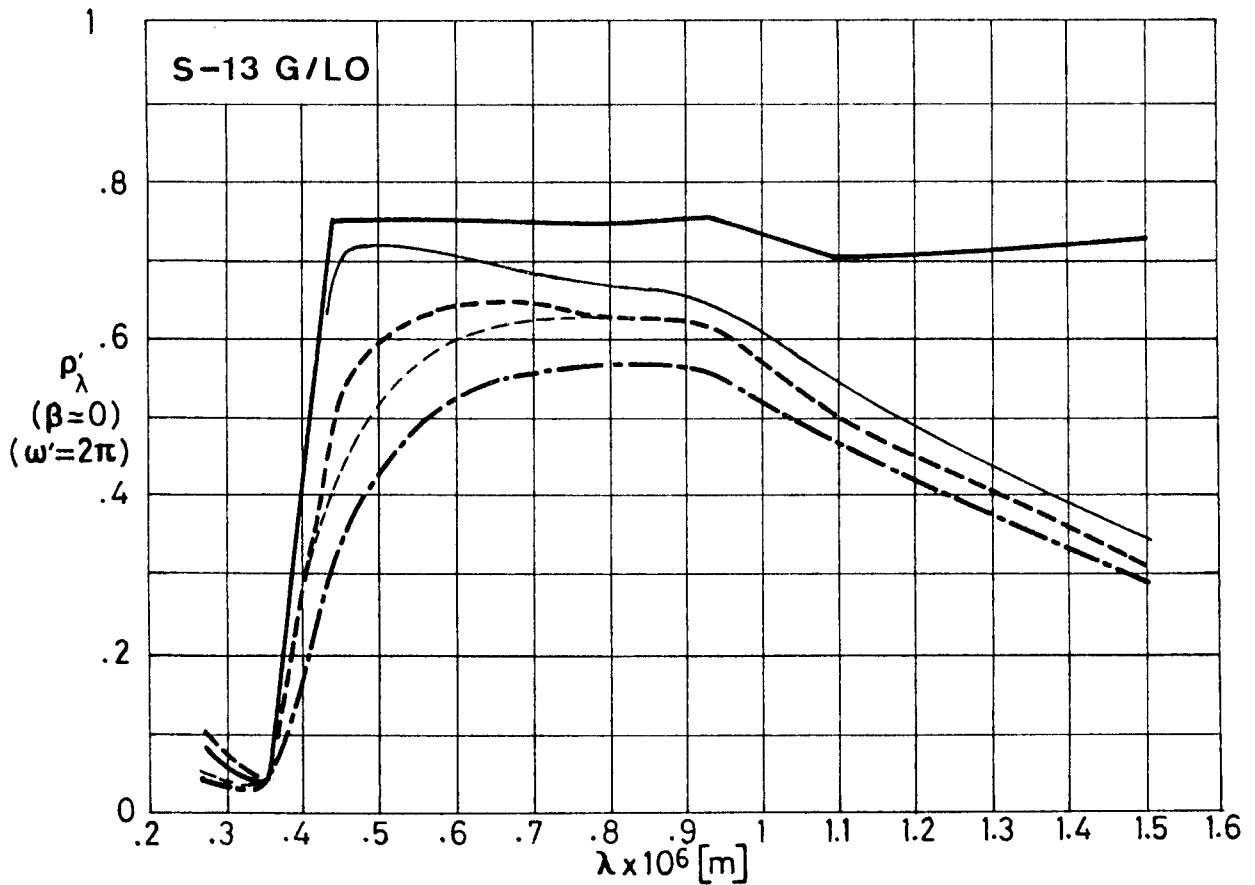


Fig 1-48.34. Effect of Combined Exposure, simulating up to three years in geosynchronous orbit, on normal-hemispherical spectral reflectance, ρ_{λ}' , of S-13 G/LO coating vs. wavelength, λ . From Paillous (1976).

Explanation

Key	Description	Comments
————	After 125 h below 1.3×10^{-4} Pa pressure. T = 363 K.	Test conditions: See Table 1-13, p. 1-76.
-----	After step A (.18 years in orbit). T = 363 K.	
-----	After Step B (.94 years in orbit). T = 363 K.	
-----	After Step C (2.11 years in orbit) T = 363 K.	After unintentional O ₂ bleaching.
-----	After Step D (3 years in orbit) T = 363 K.	

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Solar Reflectors

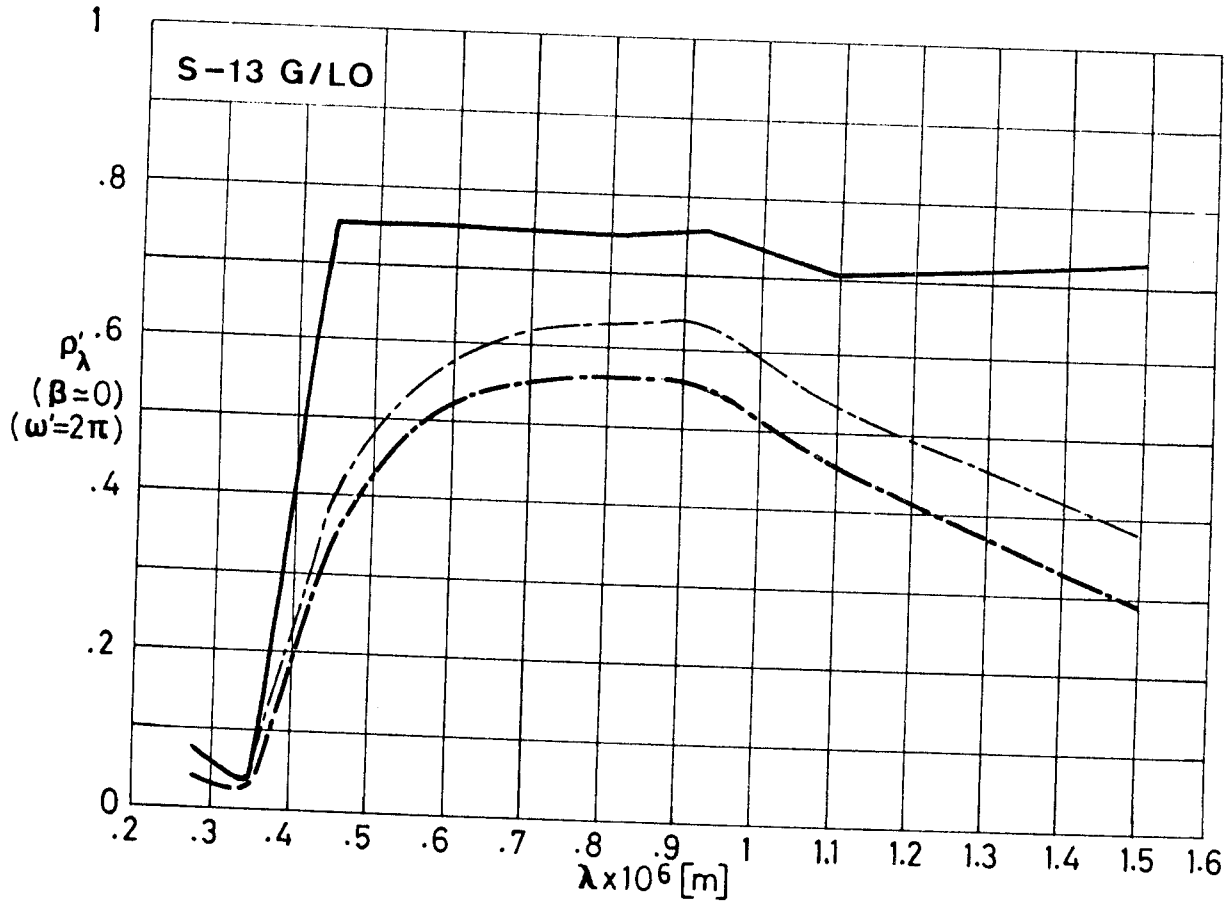


Fig 1-48.35. Effect of O₂ bleaching, after Combined Exposure, on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 G/LO coating vs. wavelength, λ . Curves — and -.- are those shown in Fig 1-48.34. From Paillous (1976).

Explanation

Key	Description	Comments
—	After 125 h below 1.3×10^{-4} Pa pressure. T = 363 K.	Test conditions: See Table 1-13, p. 1-76. After unintentional O ₂ bleaching.
-.-	After Step D (3 years in orbit) T = 363 K.	
-.-.-	After Step D and Air exposure. T = 293 K.	

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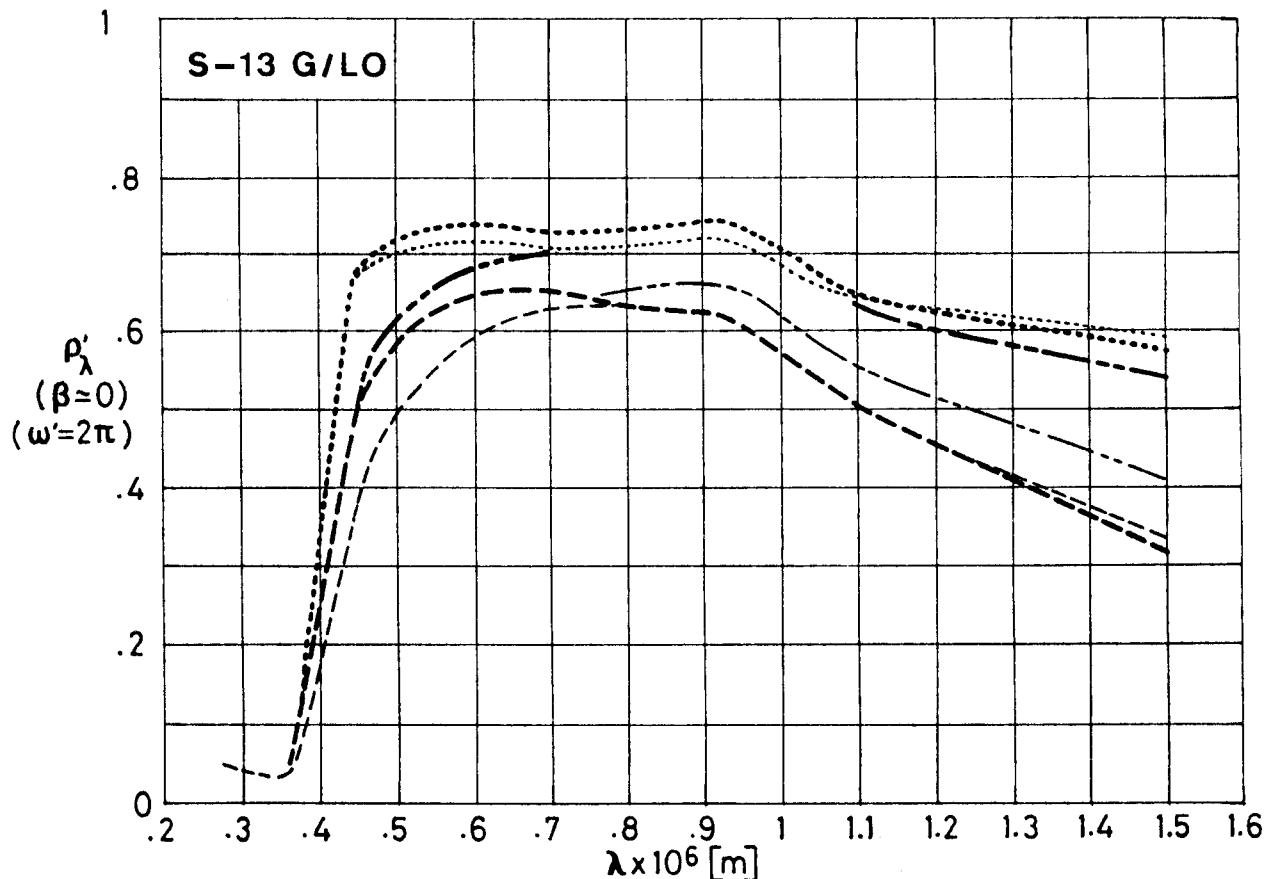


Fig 1-48.36. Effect of Combined Exposure, simulating up to three years in geosynchronous orbit, on normal-hemispherical spectral reflectance, ρ'_λ , of S-13 G/LO coating vs. wavelength, λ . Curves ---- and - - - - are those shown in Fig 1-48.34. From Paillous (1976).

Explanation

Key	Description	Comments
.....	Before step B. T = 363 K.	Test conditions: See Table 1-13, p. 1-76.
- - - -	After step B (.94 years in orbit). T = 363 K.	
.....	After pump damage. T = 363 K.	After unintentional O ₂ bleaching.
- - - -	Before step C. T = 363 K.	
- - - -	After Step C (2.11 years in orbit). T = 363 K.	
- - - -	Before step D. T = 363 K.	

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7.4. Electrical resistance.

These coatings are non conductive.

A slight conductivity has been observed in S-13 G/LO by Paillous (1976) under two experimental conditions:

1) For the sample in air. Conductivity vanished to zero after exposure in vacuum. This was attributed to sample moisture.

2) When the sample was UV irradiated. Now the effect was attributed to photo-emission on the electrodes attached to the sample.

8. ENVIRONMENTAL BEHAVIOR

8.1. Prelaunch. These paragraphs concern S-13 G and S-13 G/LO coatings. Early information on S-13 can be found in Breuch (1967).

Two NASA Specifications cover the properties, qualification test and preparation of S-13 G and S-13 G/LO coatings. These are NASA Specification 10M01835, entitled "Paint, S-13 G, Temperature Control, Specification For" and 10M01836, entitled "Paint, S-13 G, Temperature Control, Application of, Specification For". Although these specifications are for S-13 G, they apply to S-13 G/LO since the only difference between them is that S-13 G/LO uses a stripped binder (see p. 1-48.2).

These coatings are easy to apply, flexible, cleanable and repairable. The surface is soft, rubbery and should be

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protected from sand, dust, salt, smog and human sebum with appropriate plastic coverings. No ill effects were evident when exposed to UV and vacuum after 14 months in storage under Mylar, H-polymer, Lexan, Teflon A or Tedlar films.

8.2. Postlaunch. These coatings have an accepted low α_s ($\alpha_s \leq .22$) high emittance ($\epsilon \sim .90$) and a low outgassing (the LO version).

8.2.1. Ascent. These coatings are thermal shock resistant when cured as indicated in § 5.5, p. 1-48.5, provided that the primer is not too thick.

8.2.2. Orbital. UV and vacuum degradation are fair (UV degradation is due to damage in the binder).

These coatings have been often used on short flights at low altitudes.

From Cull, Stevenson, Mell & Harada (1984).

9. THERMAL CYCLING

The maximum and minimum temperatures at which these coatings have been tested with no cracking or spalling evident to the unaided eye or at 100x magnification were

T min = 83 K

T max = 395 K Chamber pressure below $.7 \times 10^{-3}$ Pa.

(Cunnington, Grammer & Smith (1969)).

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10. SOURCE

IIT Research Institute. 10 West 35 Street, Chicago,
Illinois 60616.

11. COST

Quotations in the early eighties were of the order of 350 US \$/pint (FOB, Chicago) for 1-7 pints and 300 US \$/pint for 8 or more pints of S-13 G. (1 US pint = $473.2 \times 10^{-6} \text{ m}^3$).

Quotations for S-13 G/LO were 30 % higher.

12. PAST SPATIAL USE

Spacecraft or Programme	Launching Date	Used or Tested	References
OSO-II	Feb. 3, 1965	Tested	McCargo, Spradley, Greenberg & McDonald (1971)
Pegasus I	Feb. 16, 1965	Tested	Touloukian, DeWitt & Hernicz (1972)
Pegasus II	May 25, 1965	Tested	McCargo, Spradley, Greenberg & McDonald (1971)
Pegasus III	July 30, 1965	Tested	
Lunar Orbiter I	Aug. 10, 1966	Tested	Touloukian, DeWitt & Hernicz (1972)
Lunar Orbiter II	Nov. 6, 1966	Tested	
ATS-I	Dec. 7, 1966	Tested	Reichard & Triolo (1967) Triolo (1973) Triolo, Heaney & Hass (1978)
OSO-III	March 8, 1967	Tested	Millard (1969)

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Spacecraft or Programme	Launching Date	Used or Tested	References
ATS-II	Apr. 5, 1967	Tested	McCargo, Spradley, Greenberg & McDonald (1971)
Lunar Orbiter IV	May 4, 1967		Touloukian, DeWitt & Hernicz (1972)
Mariner V	June 14, 1967	Tested	
Lunar Orbiter V	Aug. 1, 1967	Tested	McCargo, Spradley, Greenberg & McDonald (1971)
Prospero	Oct. 28, 1971	Tested	Keyte (1975)
OTS	May 11, 1978	Used on the antenna dishes. See p. S 2-10.	Chalmers, Konzok, Bouchez & Howle (1983)
NAVSTAR 6	Apr. 26, 1980	Tested	Pence & Grant (1981)
LANDSAT D	July 16, 1982	Used on an- tennae. See p. S 3-3.	Bachofer (1979)
LDEF	Apr. 6, 1984	Tested	Clark (1981)

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1.2.4. ZINC OXIDE-METHYLSILICONE1. COMPOSITION

Pigment: New Jersey Zinc Co., SP500 zinc oxide.

Binder: RTV 121 silicone elastomer.

From Guillaumon & Guillin (1979, 1981).

RHODORSIL RTV 121 is a bicomponent liquid silicone elastomer.

This liquid, once mixed with catalyst 10028 and vulcanized at room temperature, yields a transparent material which is used as a potting and encapsulating compound.

From RHONE-POULENC (1978).

2. FORMULATION

Not given by the producer.

3. USUAL DESIGNATION

PSG 120. ASTRAL.

PSG 120 FD CNES has the same composition as above, but with the RTV 121 binder purified by CNES (Toulouse).

From Guillaumon & Guillin (1979, 1981).

4. SUBSTRATE

Practically any metallic substrate. Fiber-glass also quoted.

See Preparation of surfaces for painting.

5. METHOD OF APPLICATION

5.1. Preparation of paint for application. PSG 120 is delivered as a system consisting of:

Base PSG 120: 1 kg ,

Hardener CT 122: .2 kg ,

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Thinner S 105: 10^{-3} m^3 ,

to mix when using it.

Shelf life, in the temperature range 288 K - 298 K, between 10 h and 12 h.

Storage time of the unmixed components, held in closed containers, in the above temperature range, is 6 months.

From ASTRAL (1976)a.

5.2. Preparation of surfaces for painting. Excellent adhesion is obtained on metallic substrates such as: ferrous metals, steels and light alloys, as well as on fiber-glass composites, by use of P 128 primer which can be applied either by hand-rubbing or by spray painting.

Adhesion to electrolytic gold is excellent provided that the substrate is primed either with P 123 or with P 131, using P 128 as post-primer.

5.2.1. Use of P 123 primer. The surface should be cleaned from any trace of oxide or die lubricant and degreased with a rag soaked with toluene, trichloroethylene, acetone or ether.

The primer consists of three components which should be mixed as follows:

Base	P 123:	4 parts by volume,
Hardener	CX 124:	1 part by volume,
Thinner	S 125:	2 parts by volume.

The mixing should be filtered through a nylon net, mesh

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size 5×10^{-5} m.

Shelf life in the temperature range 288 K - 298 K is 8 h.

The primer can be spray-applied. Use Kremlin model Junior or comparable gun, at about 2×10^5 Pa air pressure. Also recommended, Blinks model Wren B or comparable at 2.4×10^5 Pa air pressure. In the last case, an additional thinning of 1 part by volume of S 125 should be used.

A single crosswise layer should be applied in an environment at 288 K to 298 K temperature.

Polymerization times at 293 K are:

Dust off : 30 min,

Dry to be handled : 4 h,

Final polymerization: 8 d.

The primer should be allowed to air-dry for 8 h at 293 K before application of the finishing coat.

Use paint remover D 165 for cleaning.

From ASTRAL (1976)b.

5.2.2. Use of P 128 primer. Ferrous metals, steels, light alloys and fiber-glass composites should be cleaned as above.

In the case of electrolytic gold, the surface should be degreased before application of a thin layer of primer P 123 or P 131, using P 128 as post-primer after at least 8 h drying at 293 K.

Primer P 128 is delivered ready for use. It can be applied as a thin and uniform single crosswise layer, either by hand rubbing or by spray painting. Application temperature

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in the range 288 K - 298 K.

Polymerization times at 293 K are:

Dust off : 15 min,

Dry to be handled : 30 min,

Final polymerization: 3 h.

The primer should be allowed to air-dry for 30 min at 293 K before application of the finishing coat.

From ASTRAL (1976)c.

5.3. Application of paint. By spray gun.

Yield (five layers): 1 kg.m^{-2} .

From ASTRAL (1976)a.

5.4. Coating thickness. Measured on A-U4G T4 aluminium alloy substrate, primed with P 128. $t_c = .9 \times 10^{-4} \text{ m}$ to $1.1 \times 10^{-4} \text{ m}$.

From ASTRAL (1976)a.

5.5. Curing process. On the above substrate and primer, the polymerization times at 293 K are:

Dust off : 3 h,

Dry to be handled : 24 h,

Final polymerization: 5 d.

Once cured, the coating appears as a glossless white surface.

From ASTRAL (1976)a.

CAUTIONS

Flammability. Primers P 123, P 128 and P 131, and coating PSG 120 must be handled far from any flame and in properly

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ventilated rooms.

Flash points of coating components, per NI M 07-019, are:

PSG 120: 278 K,

CT 122: 278 K,

S 105: 290 K.

Toxicity. Avoid breathing vapors during application.

Avoid frequent and lasting contacts on the skin, particularly while handling hardeners CT 122 and CX 124.

From ASTRAL (1976)a.

6. SOLVENTS RESISTANCE

A list of solvents of silicone elastomers is given in p. 1-4. RHODORSIL HUILE 47 V 50 can be used for decreasing the viscosity of RTV 121.

From RHONE-POULENC (1978).

7. PHYSICAL PROPERTIES

7.1. Density. On A-U4G T4 aluminium alloy, primed with P 128, the surface density is: $.26 \text{ kg.m}^{-2}$ to $.30 \text{ kg.m}^{-2}$.

These values, together with the above quoted coating thicknesses yield a density close to 2800 kg.m^{-3} .

The densities of the wet components are:

Base PSG 120: 1380 kg.m^{-3} ,

Hardener CT 122: 860 kg.m^{-3} ,

Thinner S 105: 910 kg.m^{-3} .

From ASTRAL (1976)a.

7.2. Outgassing. See Table 1-8 overleaf. Outgassing characteristics given in that Table have been measured per Specifica-

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tion ESA PSS-09/QRM-02T. According to this specification, the sample is heated at 398 K, below 1.3×10^{-4} Pa pressure, during 24 h. The condensing plate is held at 298 K.

Table 1-8

Outgassing Characteristics of PSG 120 Coating

Coating	% TML ^a	% CVCM ^b	Cure Time [h]	Cure Temp. [K]	References
PSG 120 FD (binder purified by CNES). On aluminium substrate. Primer P 128.	.70	.03	120	298	Guillaumon & Guillin (1979, 1981).
	.79	.05	120	298	
	.80	.03	120	298	
	.43	.03	120 c 24	298 333	
	.49	.03	120 c 24	298 333	
	.24	.02	120 c 24	298 373	
	.24	.03	120 c 24	298 373	
PSG 120 FD (binder purified by CNES). Primer P 128.	.63 % RML: .61 ^d	.04			ESTEC (1980).
PSG 120 FD (binder purified by CNES). Primer P 128.	.65 % RML: .62 ^d	.03		298	ESTEC (1981).

^a TML: Total Mass Loss.

^b CVCM: Collected Volatile Condensable Materials.

^c Each one of these cures was used in the order given.

^d RML: Remainder Mass Loss.

7.3. Thermal radiation properties.

7.3.1. Emittance.

7.3.1.1. Hemispherical total emittance.

$$\epsilon = .87 \pm .02$$

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From ASTRAL (1976)a.

The following value refers to PSG 120 FD.

$$\epsilon = .88 \quad .$$

From Guillaumon & Guillin (1979, 1981).

7.3.1.3. Effects of the Space Environment on hemispherical total emittance.

7.3.1.3.1. Ultra-Violet Radiation.

$$\Delta\epsilon < .01$$

Chamber pressure below 1.3×10^{-3} Pa.

Sample temperature: 353 K.

Exposure time: 120 ESH.

From ASTRAL (1976)a.

7.3.2. Absorptance.

7.3.2.1. Solar absorptance.

$$\alpha_s = .17 \pm .02$$

From ASTRAL (1976)a, Guillaumon & Guillin (1979, 1981).

7.3.2.5. Effects of the Space Environment on absorptance.

7.3.2.5.1. Ultra-Violet Radiation. Figs 1-16 to 1-18, from CNES.

Data measured in vacuum (below 1.3×10^{-5} Pa), several sample temperatures, with an integrating sphere attached to a Beckman DK2A reflectometer, $\beta = 0^\circ$.

Aluminium used as standard.

Irradiated in vacuum.

Degrading source: OSRAM type XBO 900 W, Arc Xenon lamp, quartz Suprasil envelope. Around 1 Sun level.

From Simon (1973).

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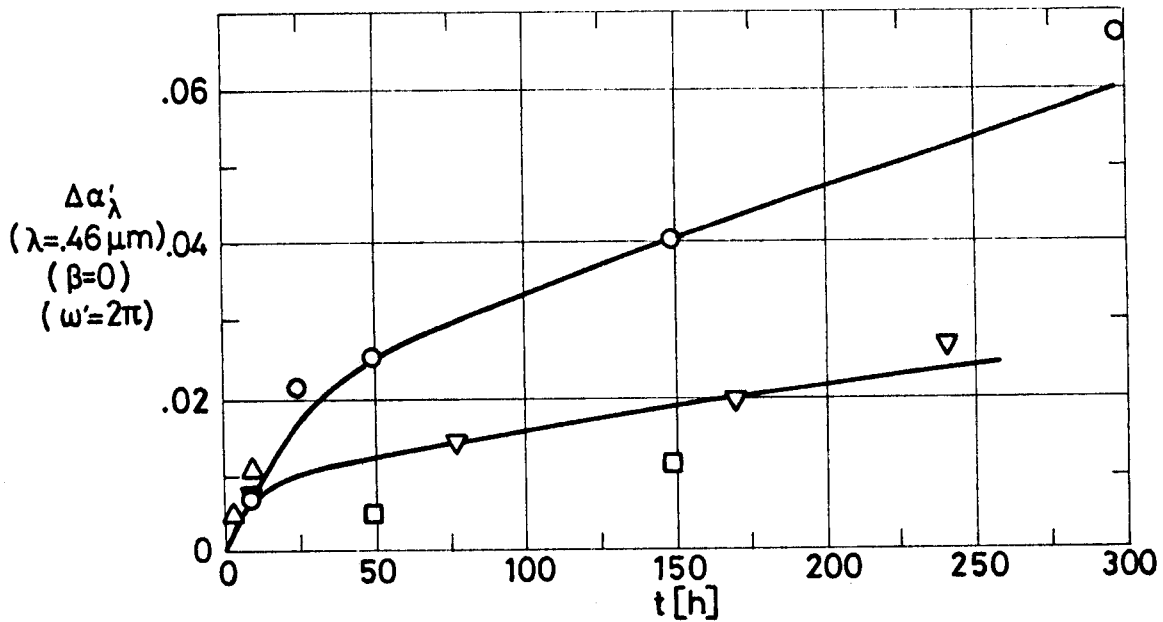


Fig 1-16. Change in normal-hemispherical spectral absorptance, $\Delta\alpha'_\lambda$, of PSG 120 coating, due to Ultra-Violet Radiation, vs. exposure time, t . Wavelength, $\lambda = .46 \times 10^{-6}$ m. From Simon (1974).

Explanation

Key	T [K]	$\lambda \times 10^6$ [m]	Comments
\circ	393	.46 (Fig 1-16).	
\square	353	2.5 (Fig 1-17).	
\triangle	283		
∇	283		After 9 h of UV radiation plus 25 h in nitrogen (bleaching).

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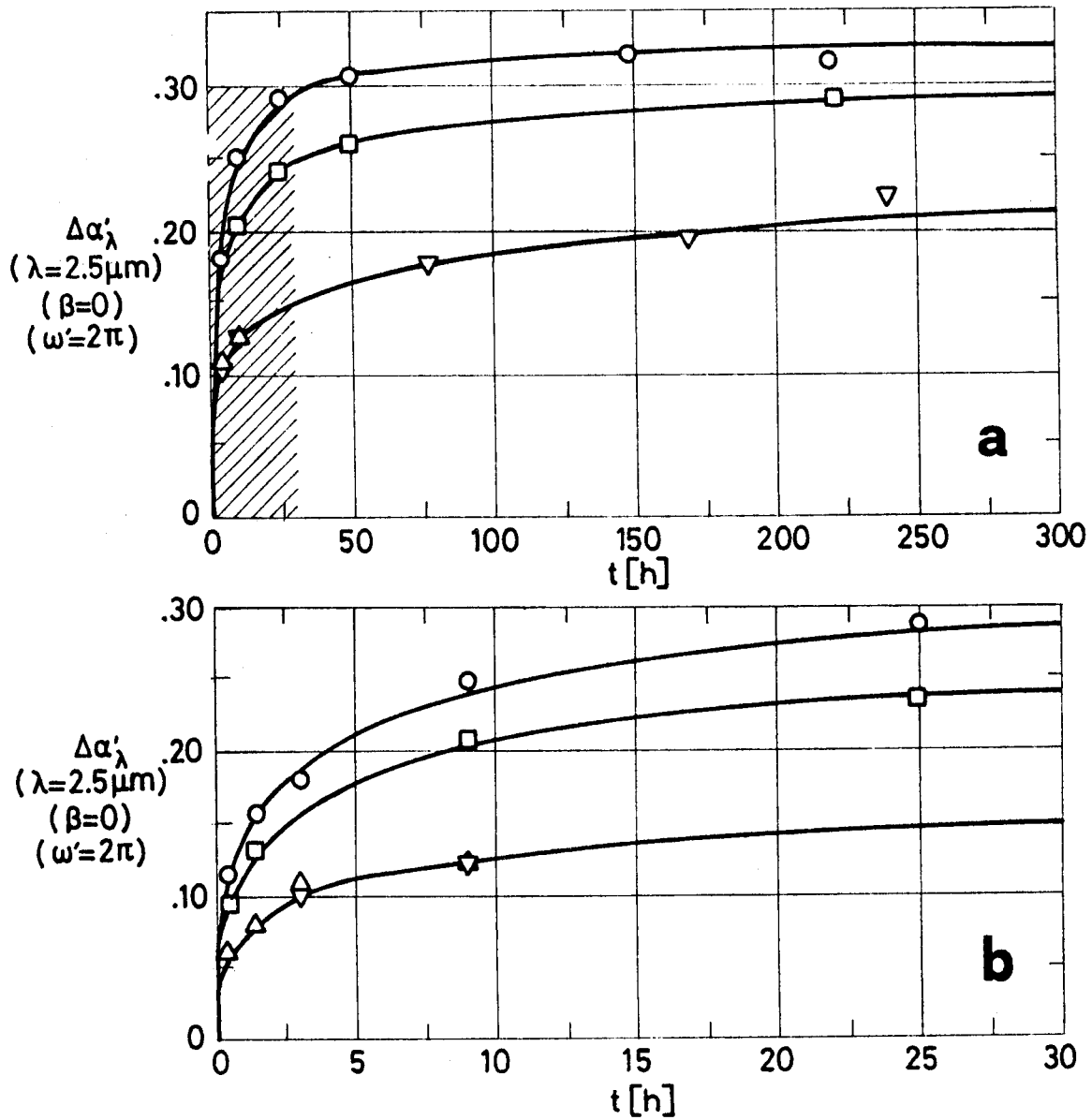


Fig 1-17. Change in normal-hemispherical spectral absorptance, $\Delta\alpha'_\lambda$, of PSG 120 coating, due to Ultra-Violet Radiation, vs. exposure time, t . Wavelength, $\lambda = 2.5 \times 10^{-6}$ m. Shaded zone in a is enlarged in b. See Explanation in the caption of Fig 1-16. From Simon (1974).

Data concerning the effect of ultra-violet radiation on solar absorptance are given in Fig 1-18. α_s deduced from spectral reflectance measured as above.

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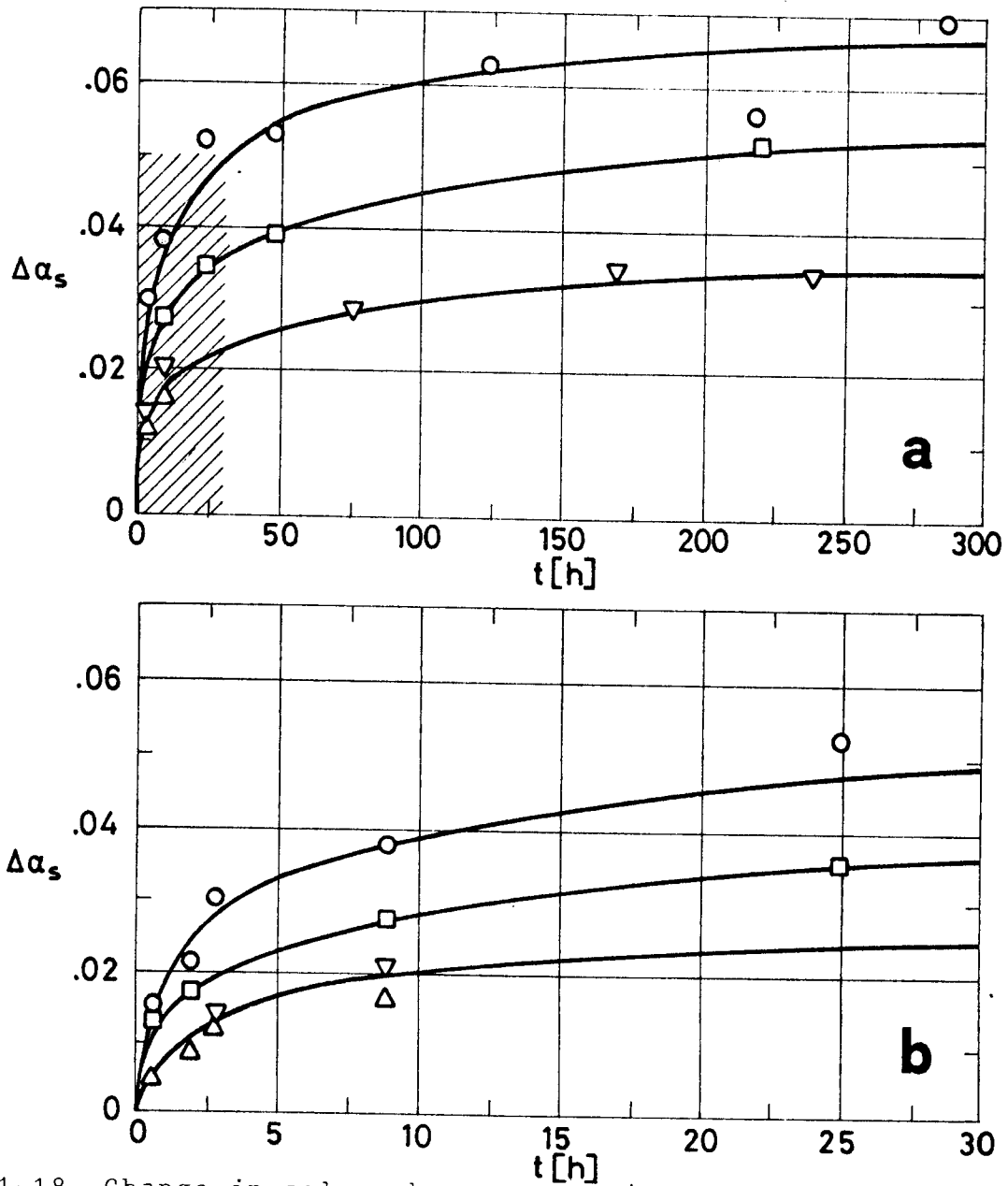


Fig 1-18. Change in solar absorptance, $\Delta\alpha_s$, of PSG 120 coating, due to UV Radiation, vs. exposure time, t . Shaded zone in a is enlarged in b. From Simon (1974).

Explanation

Key	T [K]	Comments
○	393	
□	353	
△	283	
▽	283	After 9 h of UV radiation plus 25 h in nitrogen (bleaching).

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7.3.2.5.3. Protons only exposure. Table 1-9 has been prepared after results reported by DERTS (Toulouse).

Solar absorptance is deduced from the spectral reflectance data given in p. 1-65 and ff.

CAUTION

Solar absorptance values of white paints deduced from spectral reflectance data by DERTS group, are larger, by a factor close to 2, than other widely accepted values.

The following table has been prepared by the compiler. Values of α_s before irradiation.

Solar Absorptance, α_s , of Four White Paints

Coating	S 13 IITRI	PSG 120 ASTRAL	Z 93 IITRI	PSZ 184 ASTRAL
DERTS	.37±.03	.38±.02	.33±.02	.36±.03
Other	.19±.04	.17±.02	.15±.02	.14±.02

Sources of data

S 13 DERTS, 6 values from Paillous (1976).

Other, 42 values from Touloukian, DeWitt & Hernicz (1972).

PSG 120 DERTS, 9 values from Paillous (1976) and Paillous, Amat, Marco & Panabiere (1977).

Other, p. 1-55.

Z 93 DERTS, 6 values as for S 13.

Other, p. 1-16 (soiled specimen has been excluded).

PSZ 184 DERTS, 9 values as for PSG 120.

Other, p. 1-86.

Spectral reflectance is measured in situ by DERTS group using a movable integrating sphere one of whose apertures faces successively each one of the samples in the sample holder, and the standard coating. See for further details p. 1-65.

A distance of the order of 3×10^{-3} m (not the same for all samples) exists

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between the sample and the sphere during reflectance measurements. This results in a loss of reflected light for diffusely reflecting coatings which affects ALL THE DATA regarding protons, electrons and combined exposure effect on reflectance (and absorptance) of PSG 120 coating. Integrated values of solar absorptance from DERTS in Table 1-11 have been corrected, according to Paillous (1976), as follows:

1) The initial value for PSG 120 has been assumed to be,

$$\alpha_{s0} = .20 ,$$

measured (in air) by ESTEC and by CNES using an integrating sphere attached to a Beckman DK2A reflectometer.

2) $\Delta\alpha_{s \text{ corrected}}$ has been related to $\Delta\alpha_{s \text{ in situ}}$ as follows,

$$\frac{\Delta\alpha_{s \text{ corrected}}}{\Delta\alpha_{s \text{ in situ}}} = \frac{\Delta\rho_{s \text{ corrected}}}{\Delta\rho_{s \text{ in situ}}} = \frac{.80}{1 - \alpha_{s0 \text{ in situ}}}$$

α_s variations in the different subranges of the spectrum (ultra-violet, visible, infrared) are given by Paillous, Amat, Marco & Panabiere (1977) regarding protons and electrons, and by Paillous (1976) regarding combined exposure. These data have not been compiled here.

Table 1-9
Protons Radiation Effects on Solar Absorptance of PSG 120 Coating

Intensity [keV] →	45			75			150		
	α_s	$\Delta\alpha_s$	$\Delta\alpha_s/\alpha_s$	α_s	$\Delta\alpha_s$	$\Delta\alpha_s/\alpha_s$	α_s	$\Delta\alpha_s$	$\Delta\alpha_s/\alpha_s$
↓ Integrated Flux [$p.m^{-2}$]									
Before (in air)	.293			.353			.348		
Before (in vacuum)	.326			.384			.383		
10^{17}	.325	-.001	-.004	.397	.013	.033	.385	.002	.005
10^{18}	.333	.007	.020	.401	.017	.043	.397	.014	.036
10^{19}	.383	.057	.148	.459	.075	.164	.495	.112	.226
2.1×10^{19} for 45 keV 2.8×10^{19} otherwise	.456	.130	.285	.528	.144	.273	.582	.199	.342
After (in air)	.390			.438			.458		

From Paillous, Amat, Marco & Panabiere (1977).

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7.3.2.5.4. Electrons only exposure. Table 1-10 after results from DERTS.

Solar absorptance is deduced from the spectral reflectance data given in p. 1-68 and ff.

Table 1-10

Electrons Radiation Effects on Solar Absorptance of PSG 120 Coating

Intensity [keV] →	40			80			210		
↓ Integrated Flux [e.m ⁻²]	α_S	$\Delta\alpha_S$	$\Delta\alpha_S/\alpha_S$	α_S	$\Delta\alpha_S$	$\Delta\alpha_S/\alpha_S$	α_S	$\Delta\alpha_S$	$\Delta\alpha_S/\alpha_S$
Before (in air)	.333			.335					
Before (in vacuum)	.341			.366			.346		
2×10^{14}	.354	.013	.035	.392	.026	.066	.412	.066	.160
5×10^{14}	.356	.015	.043	.403	.037	.091	.411	.065	.158
10^{15}	.365	.024	.067	.416	.049	.119	.426	.080	.189
2×10^{15}	.375	.034	.091						
After (in air)	.334			.363			.355		

From Paillous, Amat, Marco & Panabiere (1977).

7.3.2.5.6. Combined exposure. Table 1-11 after DERTS.

Solar absorptance from spectral reflectance data.

The tests simulate geosynchronous orbit exposure of the Orbital Test Satellite (OTS) equatorial faces.

"Corrected" values in Table 1-11 were used to estimate coating degradation up to 3 years in orbit, Fig 1-19.

Also shown data from Guillaumon & Guillin (1981), CNES.

Incidents during testing, see p. 1-75, cast doubts on

the validity of the data beyond 1 year in orbit.

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Table 1-11
Combined Exposure Effects on Solar Absorptance of PSG 120 Coating

Test Conditions	Sample 1						Sample 2					
	Measured in situ			Corrected ^a			Measured in situ			Corrected ^a		
	α_s	$\Delta\alpha_s$	$\Delta\alpha_s/\alpha_s$	α_s	$\Delta\alpha_s$	$\Delta\alpha_s/\alpha_s$	α_s	$\Delta\alpha_s$	$\Delta\alpha_s/\alpha_s$	α_s	$\Delta\alpha_s$	$\Delta\alpha_s/\alpha_s$
BEFORE IRRADIATION	.358			.200			.367			.200		
AFTER A UNDER VACUUM ^b	.422	.063	.177	.279	.079	.395	.440	.073	.199	.291	.091	.455
BEFORE B	.388	.029	.082	.236	.036	.180	.402	.035	.096	.244	.044	.220
AFTER B ^b	.410	.051	.144	.264	.064	.320	.451	.084	.230	.305	.105	.525
AFTER PUMP DAMAGE ^c	.378	.020	.055	.225	.025	.125	.390	.023	.062	.229	.029	.145
BEFORE C	.425	.067	.188	.284	.084	.420	.440	.073	.200	.291	.091	.455
AFTER C ^b	.485	.127	.354	.359	.159	.795	.502	.135	.369	.369	.169	.845
BEFORE D	.474	.116	.323	.345	.145	.725	.487	.120	.327	.350	.150	.750
AFTER D UNDER VACUUM ^b	.505	.147	.410	.384	.184	.920	.516	.149	.405	.386	.186	.930
AFTER D AND AIR EXPOSURE	.430	.072	.201	.290	.090	.450	.557	.190	.518	.438	.238	1.19

^a The correction has been made by the compiler as follows:

1) Value before irradiation, $\alpha_{s0} = .20$.

$$2) \frac{\Delta\alpha_{s \text{ corrected}}}{\Delta\alpha_{s \text{ in situ}}} = \frac{1 - \alpha_{s0}}{1 - \alpha_{s0 \text{ in situ}}} = \frac{.80}{.64}$$

where α_{s0} has been measured (in air) with an integrating sphere attached to a Beckman DK2A reflectometer. $\alpha_{s0 \text{ in situ}}$ is the value measured before irradiation as indicated in p. 1-65.

^b Steps A to D correspond, respectively, to the following times in geosynchronous orbit.

- A: .18 yr = 508 ESH.
- B: .94 yr = 2 443 ESH.
- C: 2.11 yr = 5 604 ESH.
- D: 3 yr = 7 949 ESH.

^c See p. 1-75 for further details.

From Paillous (1976).

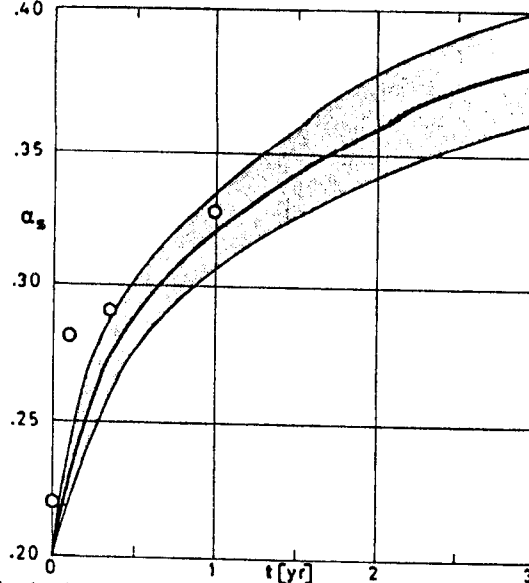


Fig 1-19. Estimated change in solar absorptance, α_s , of PSG 120 vs. time, t . From Paillous (1976).

○ From Guillaumon & Guillin (1981).

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7.3.3. Reflectance. Data related with bidirectional total reflectance are given in Fig 1-20.

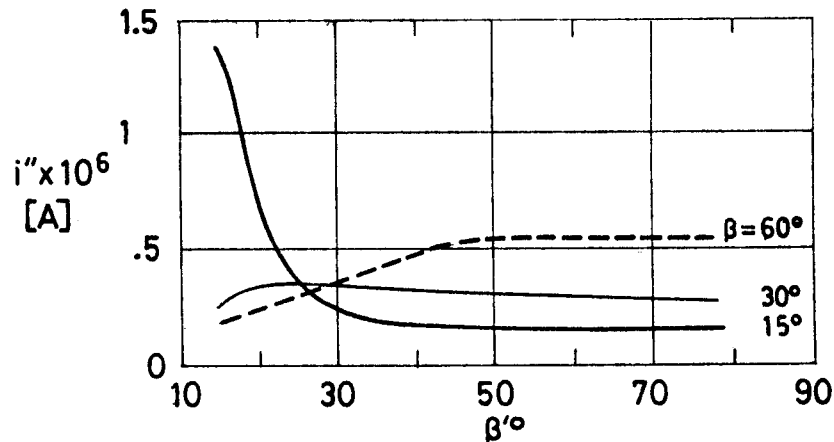


Fig 1-20. Bidirectional total radiation intensity of reflected flux, i'' , vs. cone angle, β' , for several values of the cone angle of the incident flux, β . PSG 120 coating. Incident and reflected fluxes are coplanar. i'' is measured by the response of a photocell attached to a photogoniometer. From ASTRAL (1976)a.

7.3.3.1. Normal-hemispherical spectral reflectance. Fig 1-21 from CNES.

Chamber pressure below 1.3×10^{-5} Pa.

Sample temperature: 348 K.

Spectral reflectance measured in situ with an integrating sphere, operating in the direct mode, attached to a Beckman DK2A reflectometer.

Aluminium used as standard. Sample and standard are alternatively illuminated.

See Simon (1973) for further details on the measurement procedure.

7.3.3.2. Effects of the Space Environment on reflectance.

7.3.3.2.1. Ultra-Violet Radiation. Fig 1-21.

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Sample conditions and spectral reflectance measurements as above.

Sample irradiated in vacuum.

Degrading source: OSRAM type XBO 900 W, Arc Xenon lamp, quartz Suprasil envelope.

Radiation flux density at the sample level: ~ 1 Sun.

Exposure time: 212 ESH.

See Fig 1-16 and ff. where similar data from CNES are presented.

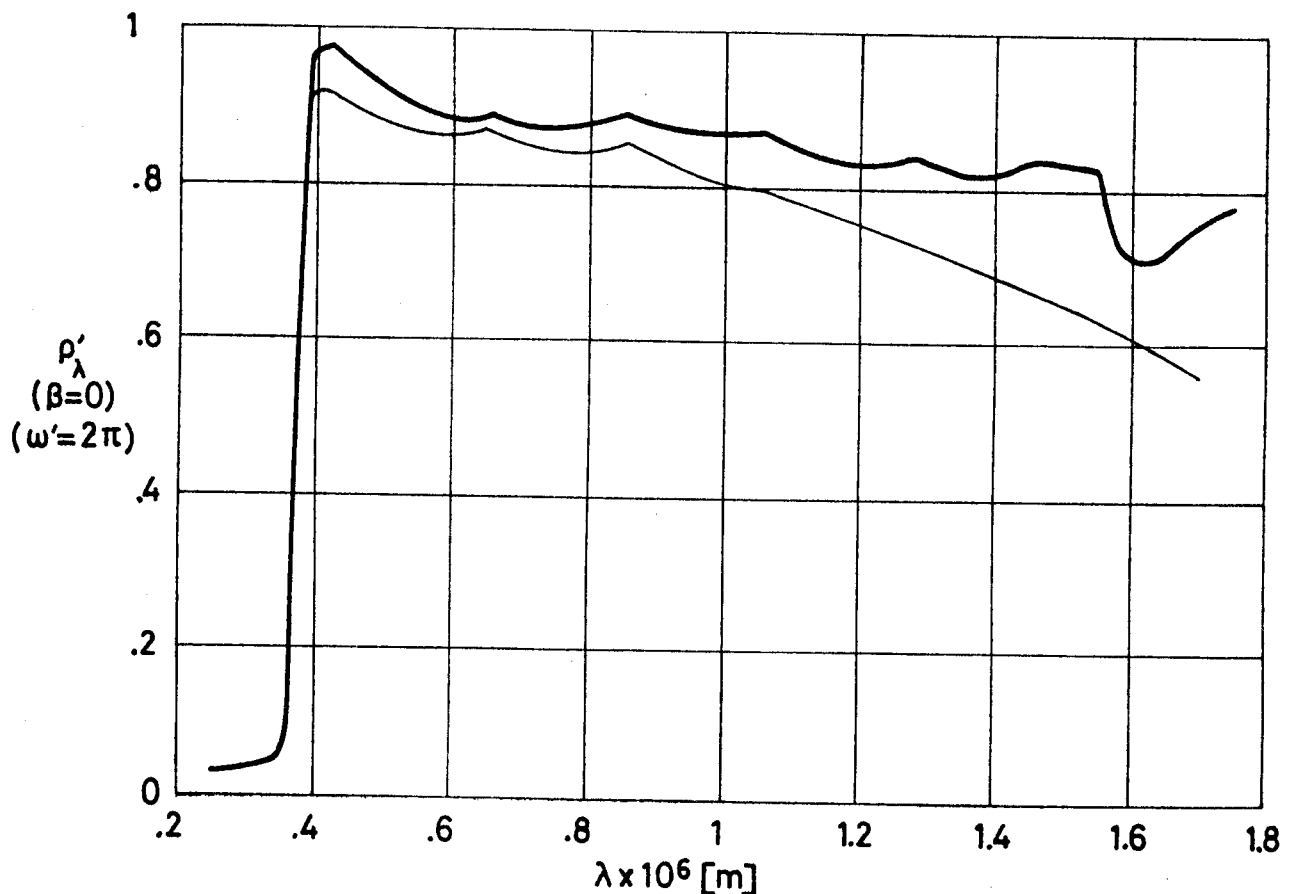


Fig 1-21. Effect of Ultra-Violet Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of PSG 120 coating vs. wavelength, λ .

— Before irradiation. $p < 1.3 \times 10^{-5}$ Pa. $T = 348$ K.

- - - After irradiation. $p < 1.3 \times 10^{-5}$ Pa. $T = 348$ K.

1 Sun level. $t = 212$ ESH. From Simon (1973).

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7.3.3.2.3. Protons only exposure. Fig 1-22 and ff., from DERTS.

Sample on aluminium substrate.

A SAMES proton accelerator has been used. The proton beam impinges normally on the sample.

Tests were performed in four successive steps. Data, which were taken before 3 h from the end of each step, are for cumulative damage.

Chamber pressure in the range 6.7×10^{-5} Pa to 10^{-4} Pa.

Sample temperature: $303 \text{ K} \pm .5 \text{ K}$.

Spectral reflectance measured in situ with an integrating sphere, operating in the direct mode, and appropriate detectors (depending on the λ range) viewing an area of the sphere inner wall.

A Zeiss monochromator can be displaced, together with the sphere, to successively illuminate the sample (2×10^{-2} m square) and a vacuum deposited aluminium standard (not exposed to the damaging irradiation).

Readings for the sample and for the standard provide the directional-hemispherical reflectance factor, given in the following figures as directional-hemispherical spectral reflectance.

The experimental set-up is basically that described by Paillous (1975), except for minor improvements in the optical detector system.

Neither the incidence angle, β , nor a schematic of the sphere are given in the source.

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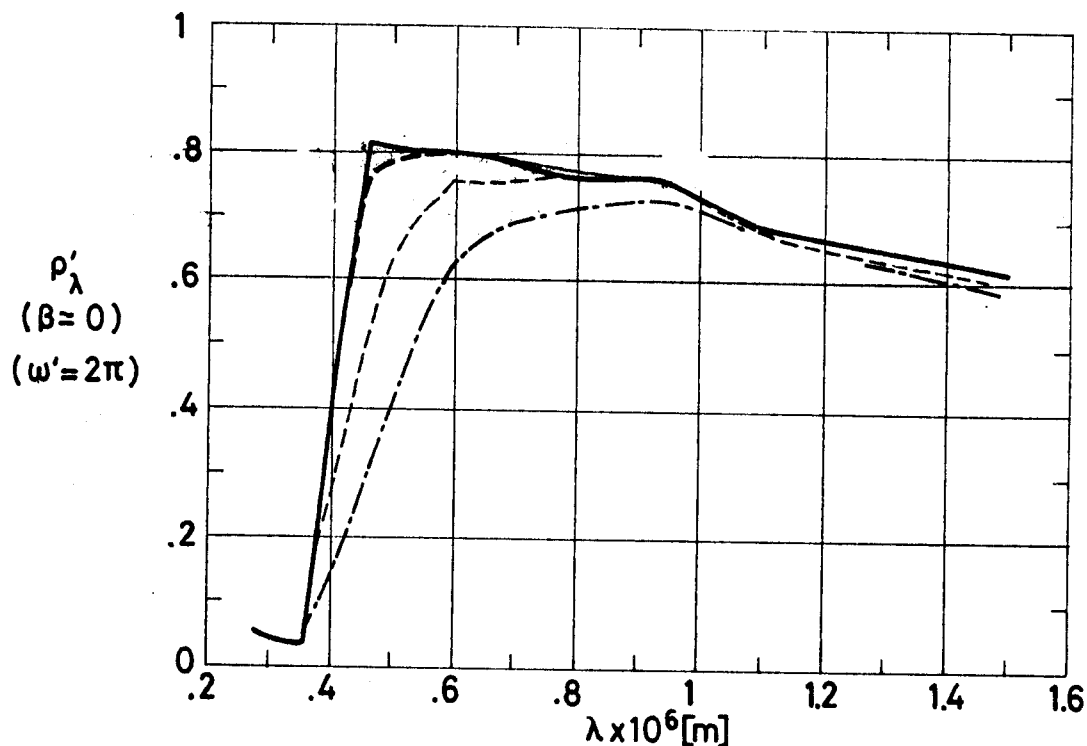


Fig 1-22. Effect of Protons Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of PSG 120 coating vs. wavelength, λ . Radiation intensity ≈ 45 keV. See Explanation in the caption of Fig 1-24. From Paillous, Amat, Marco & Panabiere (1977).

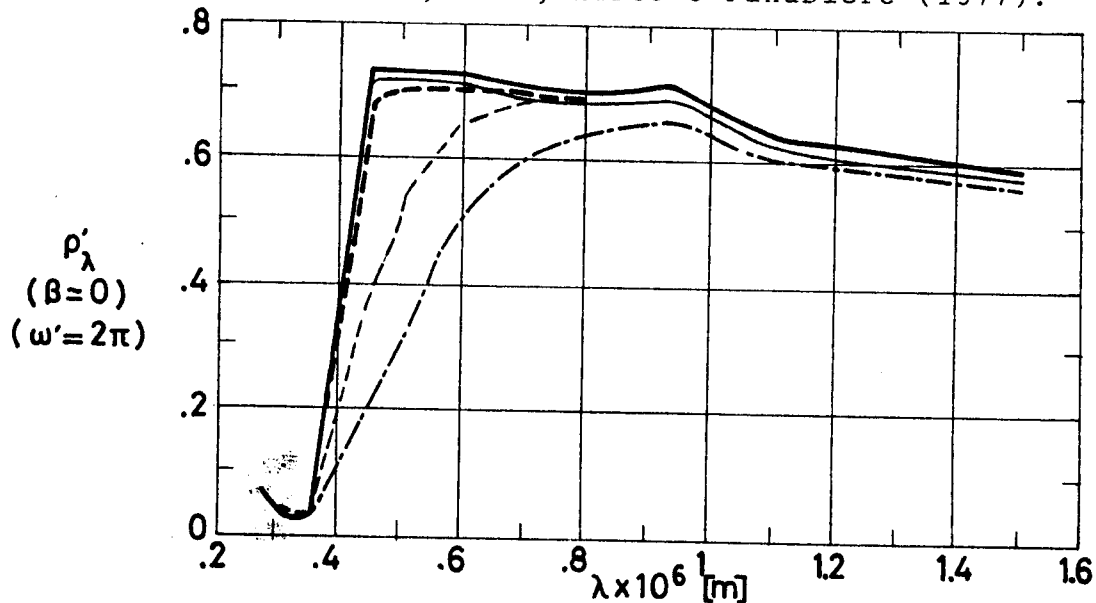


Fig 1-23. Effect of Protons Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of PSG 120 coating vs. wavelength, λ . Radiation intensity ≈ 75 keV. See Explanation in the caption of Fig 1-24. From Paillous, Amat, Marco & Panabiere (1977).

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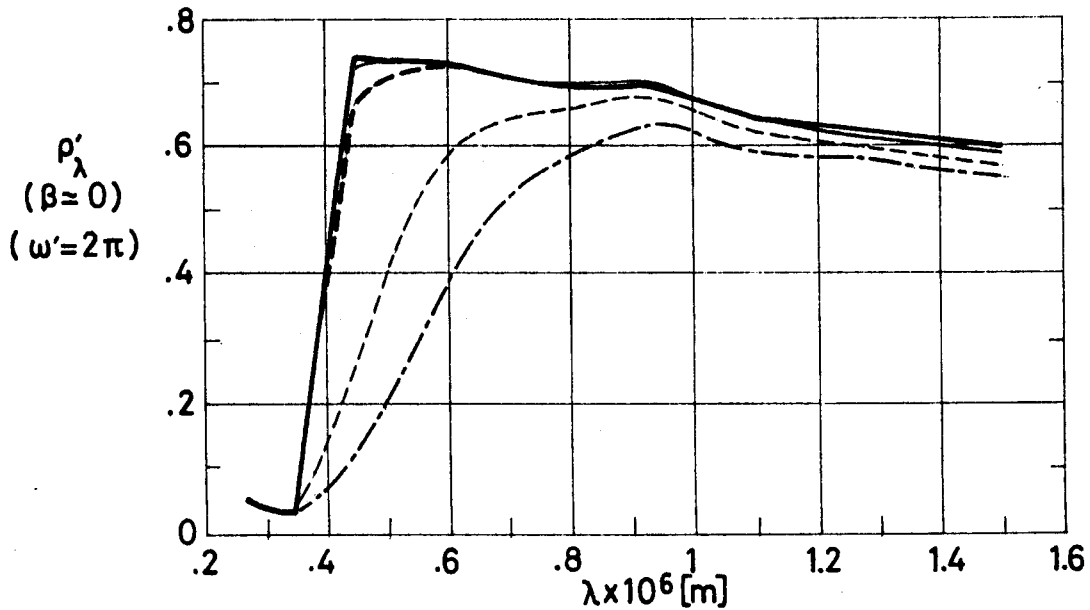


Fig 1-24. Effect of Protons Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of PSG 120 coating vs. wavelength, λ . Radiation intensity ≈ 150 keV. From Paillous, Amat, Marco & Panabiere (1977).

Explanation

Key	Intensity [keV]	Flux [$\text{p.m}^{-2}.\text{s}^{-1}$]	Integrated Flux [p.m^{-2}]	Cumulative Integrated Flux [p.m^{-2}]	Comments
————	45 keV in Fig 1-22.				Sample on aluminium substrate. $p = 1.3 \times 10^{-4}$ Pa. $T = 303 \text{ K} \pm .5 \text{ K}$. Incidence of the protons beam: 0° .
————	75 keV in Fig 1-23.	1.3×10^{14}	10^{17}	10^{17}	
-----	150 keV in Fig 1-24.	2.5×10^{14}	9×10^{17}	10^{18}	
-----		2.5×10^{14} (Fig 1-22). 6.2×10^{14} (Figs 1-23 & 1-24).	9×10^{18}	10^{19}	
-----		6.2×10^{14}	1.1×10^{19} (Fig 1-22). 1.8×10^{19} (Figs 1-23 & 1-24).	2.1×10^{19} (Fig 1-22). 2.8×10^{19} (Figs 1-23 & 1-24).	

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7.3.3.2.4. Electrons only exposure. Fig 1-25 and ff., from DERTS.
Sample on aluminium substrate.

A SAMES electron accelerator has been used. The electron beam impinges on the sample at 45° , but this has been taken into account for estimating the mean flux and the deviation from the mean. This is kept within $\pm 35\%$ for the 25 samples being irradiated all at once. The achievable electrons energy at the samples is of the order of 200 keV.

See Paillous (1975) for further details.

The tests were performed in four successive steps, and readings were taken at the end of each step. Sample conditions and reflectance measurements as in p. 1-65.

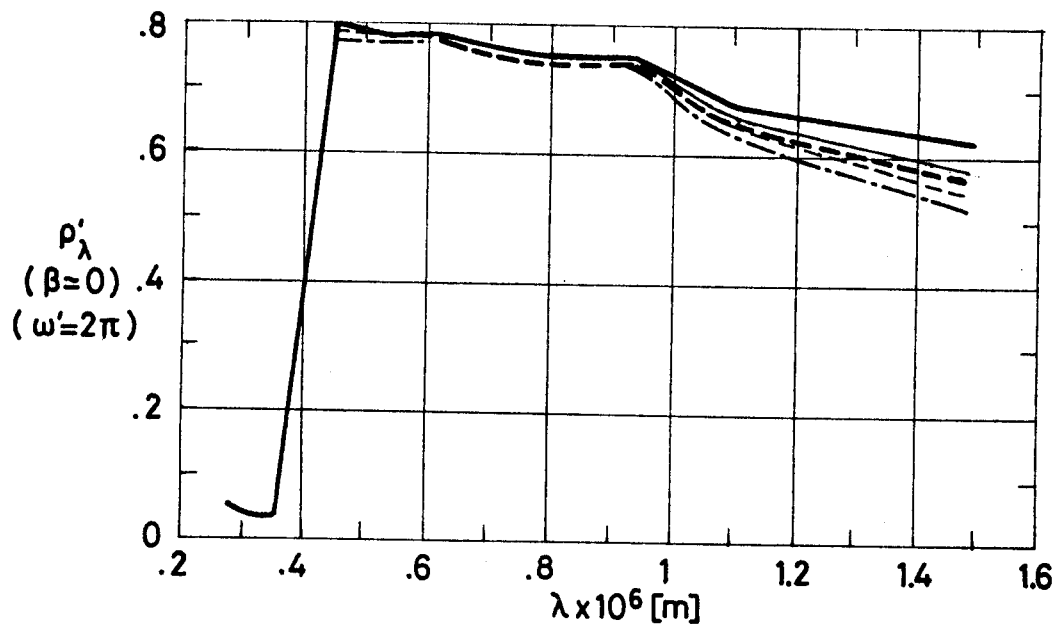


Fig 1-25. Effect of Electrons Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of PSG 120 coating vs. wavelength, λ . Radiation intensity ≈ 40 keV. See Explanation in the caption of Fig 1-26.

From Paillous, Amat, Marco & Panabiere (1977).

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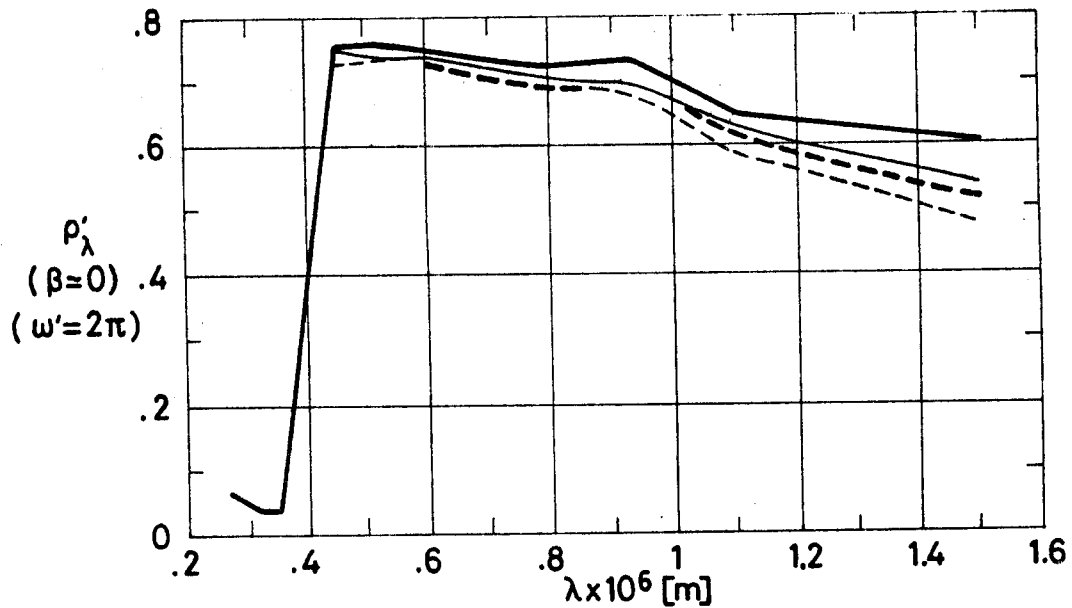


Fig 1-26. Effect of Electrons Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of PSG 120 coating vs. wavelength, λ . Radiation intensity ≈ 80 keV. From Paillous, Amat, Marco & Panabiere (1977).

Explanation

Key	Intensity [keV]	Flux [e.m ⁻² .s ⁻¹]	Integrated Flux [e.m ⁻²]	Cumulative Integrated Flux [e.m ⁻²]	Comments
—	40 keV in Fig 1-25. 80 keV in Fig 1-26.	2.7×10 ¹⁴ (Fig 1-25).	2×10 ¹⁸	2×10 ¹⁸	Sample on aluminium substrate. p = 1.3×10 ⁻⁴ Pa. T = 303 K ± .5 K. Incidence of the electron beam: 45°.
—		2.9×10 ¹⁴ (Fig 1-26).			
---		4×10 ¹⁴ (Fig 1-25). 2.8×10 ¹⁴ (Fig 1-26).	3×10 ¹⁸	5×10 ¹⁸	
---		4×10 ¹⁴ (Fig 1-25). 5.3×10 ¹⁴ (Fig 1-26).	5×10 ¹⁸	10 ¹⁹	
---		5.4×10 ¹⁴ (Fig 1-25).	10 ¹⁹ (Fig 1-25).	2×10 ¹⁹ (Fig 1-25).	

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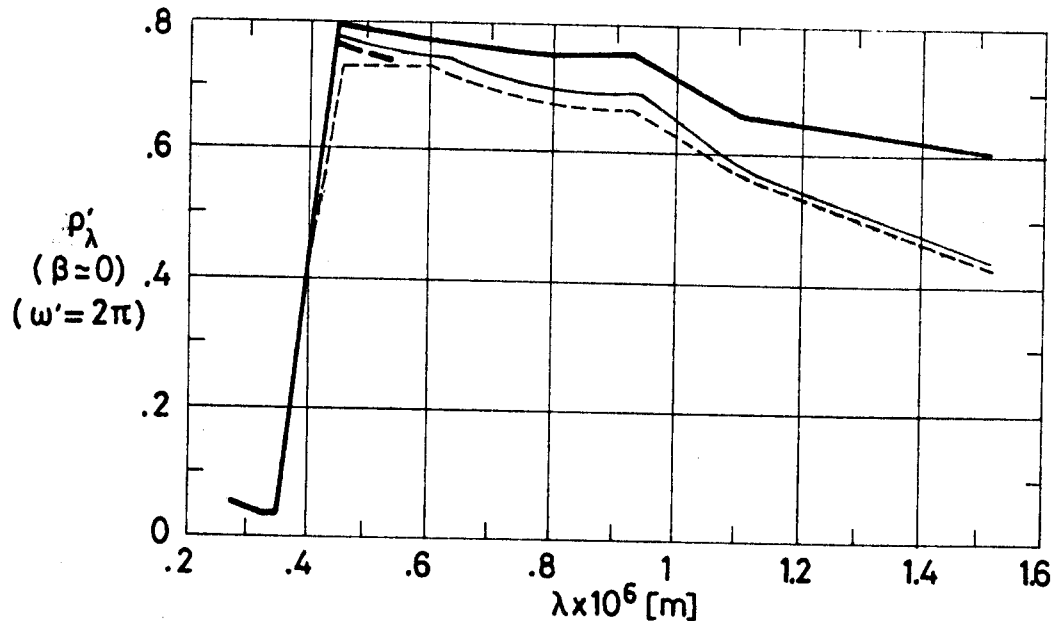


Fig 1-27. Effect of Electrons Radiation on normal-hemispherical spectral reflectance, ρ'_λ , of PSG 120 coating vs. wavelength, λ . Radiation intensity ≈ 210 keV. From Paillous, Amat, Marco & Panabiere (1977).

Explanation

Key	Intensity [keV]	Flux [e.m ⁻² .s ⁻¹]	Integrated Flux [e.m ⁻²]	Cumulative Integrated Flux [e.m ⁻²]	Comments
—	210				Sample on aluminium substrate. p = 1.3×10 ⁻⁴ Pa. T = 303 K ± .5 K. Incidence of the electrons beam: 45°.
—		3.0×10 ¹⁴	2×10 ¹⁸	2×10 ¹⁸	
- - -		3.1×10 ¹⁴	3×10 ¹⁸	5×10 ¹⁸	
- - -		6.3×10 ¹⁴	5×10 ¹⁸	10 ¹⁹	

An analytical model of the solar absorptance degradation because of the irradiation of protons and electrons, with application to white paints, has been set forth by Bourrieau (1978), Bourrieau & Paillous (1979).

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The model ascribes the changes in solar absorptance to the creation within the coating of defect centers, the concentration of which depends only on the local absorbed dose.

The defect density produces an absorption band which results in the optical degradation of the coating. The intensity of that absorption band is assumed to depend only on the defect density.

The absorption bands become apparent when the spectral reflectance curves before and after irradiation are compared to each other.

The distribution of absorbed dose in the coating can be calculated by use of available computational techniques (Bourrieau (1978)). In practice a mean dose, \bar{D} , is assumed to be uniformly distributed throughout a disturbed layer, the thickness of which, X_d , is called the penetration range.

The analytical model shows that:

1) When the disturbed layer is much thicker than the layer of photon absorption and scattering (optical range, X_u), the change in spectral reflectance does not depend on X_d . This occurs for high energy particles or very large irradiation doses.

2) On the other hand, when $X_d \ll X_u$ the changes in spectral reflectance are proportional to the penetration range, X_d .

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In the case of PSG 120 coating two absorption bands are present, probably at $\lambda = .41 \times 10^{-6}$ m and $\lambda = 2.1 \times 10^{-6}$ m. None of them was clearly detected, since measurements of spectral reflectance were made at discrete values of λ , and the nearest values were, respectively, $\lambda = .45 \times 10^{-6}$ m and $\lambda = 2.5 \times 10^{-6}$ m.

The experimental results for $\lambda = 2.05 \times 10^{-6}$ m have been used to test the applicability of the analytical model to PSG 120 coating degradation.

The relevant irradiation parameters are summarized in Table 1-12.

Table 1-12
Application of the Degradation Model to PSG 120 Coating

Type of Particle	Protons			Electrons		
	45	75	150	40	80	210
Intensity [keV]						
Flux [particles.m ⁻² .s ⁻¹]	1.3×10 ¹⁴ to 6.2×10 ¹⁴			2.7×10 ¹⁴ to 5.4×10 ¹⁴	2.9×10 ¹⁴ to 5.3×10 ¹⁴	3.0×10 ¹⁴ to 6.3×10 ¹⁴
Cumulative Integrated Flux [particles.m ⁻²]	10 ¹⁷ to 2.8×10 ¹⁹			2×10 ¹⁸ to 2×10 ¹⁹	2×10 ¹⁸ to 10 ¹⁹	
Penetration Range, X _d [kg.m ⁻²]	2.4×10 ⁻³	3.4×10 ⁻³	5.6×10 ⁻³	2.5×10 ⁻²	9.0×10 ⁻²	5.0×10 ⁻¹
Mean Dose, \bar{D} GY/particle ^a	3.0×10 ⁻⁸	3.6×10 ⁻⁸	4.3×10 ⁻⁸	1.7×10 ⁻⁹	10 ⁻⁹	5.8×10 ⁻¹⁰
Related Figure	1-22	1-23	1-24	1-25	1-26	1-27

^a 1 GY (Gray) = 1 J.kg⁻¹.

From Bourrieau (1978).