ARTICLE NO. 78-1621R

Ultraviolet Irradiation Effects on Candidate Spacelab Thermal Control Coatings

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The advent of Spacelab has made it necessary to review those materials that are acceptable for passive thermal control. This paper describes the ultraviolet vacuum simulation tests performed on several candidate Spacelab thermal control coatings. The in-situ degradation curves of solar absorptance as well as in-air degradation values of normal emittance and solar absorptance are presented. Also included is a description of the ESTEC combined irradiation chamber. This facility is equipped for simultaneous particle (electron and proton) and ultraviolet irradiation. An integrating sphere inside the chamber enables in-situ measurements of the spectral and total solar absorptance of a test specimen. The test results of several candidate materials, including a white paint and a silica fabric, are discussed.

Introduction

IN the past, the selection of thermal control coatings for conventional satellites has always been based on two considerations: 1) the materials should be stable during long-term exposures to space environment; and 2) the materials should not be exposed to excessive ground handling. The short duration of Spacelab missions and the rigors of ground handling are obviously in contrast with these requirements. Furthermore, the purpose of Spacelab to serve as a reusable manned laboratory introduces the possibility of refurbishment of exposed surfaces after re-entry.

Various coatings, e.g. IITRI's S13GLO white paint, which are well established for satellites with long exposure times, are not suitable because their low mechanical resistance does not meet the typical ground handling requirements of Spacelab.

The main source of damage in orbit will be solar ultraviolet irradiation, the effects of the expected particle environment being negligible. The number of missions before refurbishment is required depends, among other things, on the degradation rate of the thermo-optical properties as a function of exposure time to ultraviolet irradition. An evaluation has been made of mechanically durable materials with an ultraviolet stability sufficient to withstand the short-term exposures of Spacelab.

Test Program

Test A

Samples of six different materials (see Table 1) were submitted to a minimum of 600 equivalent sun hours (ESH) exposure to 250-400 nm ultraviolet irradiation at an intensity of 1 solar constant (SC). Tests were conducted in a secondary vacuum of 10^{-7} Torr (or better) at an ambient temperature of 25°C. In-situ measurements were made of total absorptance and spectral absorptance at 350, 400, 500, 600, 1000, and 1500 nm. In-air measurements were made of solar absorptance and normal emittance before and after irradition.

Test B

Test conditions were similar to test A, however the exposure was reduced to 300 ESH and the intensity raised to 2 SC. Again, the materials tested are listed in Table 1. The prime objective was definition of the ultraviolet stability of different configurations of Chemglaze A276 white paint. This paint is the prime candidate for coating all surfaces inside and outside the pallet structure. The same measurements were made as in test A, plus in-situ spectral measurements at 450 and 550 nm.

Measured Material Properties

Solar Absorptance

This value was measured in air directly before and after each test with a Beckman DK 2A spectrophotometer in combination with an Edwards-type integrating sphere.

Normal Emittance

This value was measured in air directly before and after the test with a Gier and Dunkle DB 100 reflectometer.

In-situ Total Reflectance

This value was measured in vacuum with a compensated thermopile (Hilger and Schwarz FT 17) and an integrating sphere as described later at regular time intervals during the test.

In-situ Spectral Reflectance

This value was measured in vacuum with a photomultiplier, type RTC XP 1118, at 350, 400, 450, 500, 550, and 600 nm wavelengths, and with a photodiode infrared detector, type RTC OAP 12, at 1000 and 1500 nm, again in combination with the integrating sphere and at regular intervals.

Description of Test Facility

The tests were performed in a combined irradiation chamber equipped for simultaneous particle and ultraviolet irradiation. Figure 1 shows the main elements of this facility, viz.: proton source, electron source, ultraviolet irradiation source, vacuum chamber, and in-situ measuring system.

In view of the specific Spacelab requirements, the particle generators were decoupled from the main chamber.

Vacuum Chamber

The main section of the chamber is a stainless steel cylinder with a diameter of 740 mm and a height of 450 mm. The vacuum is maintained by a two-stage primary pump and a 650 cycle/s turbomolecular pump in combination with a liquid nitrogen shroud. The main purpose of this shroud is to trap contaminants. A vacuum of better than 10^{-7} Torr is achieved.

Presented as Paper 78-1621 at the AIAA/IES/ASTM 10th Space Simulation Conference, Bethesda, Md., Oct. 16-18, 1978; submitted Dec. 4, 1978; revision received Feb. 19, 1980.

Index categories: Thermal Control; Thermal Surface Properties.

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Table 1 Test materials

No.	Test	Trade name	Manufacturer	Chemical nature	Preparation method
1	A	S13GLO	IITRI	White silicone paint	On Al substrate
2	A	A276	Chemglaze	White polyurethane paint	On Al substrate with toluene thinner
3	A	Armalon	Dupont	PTFE impregnated with TiO_2 pigment	On Al substrate with Scotch 467 tape
4	A	Luigi Cloth	Sheldahl	Teflon-coated fibre-glass with gold-deposited backside	On Al substrate with Scotch 467 tape
5	A	Beta Cloth/Tedlar	Dupont	Impregnated Textile/PVF	On Al substrate with Scotch 467 tape
6	A	Textiquartz 610	Stevens-Genin	Silica fiber	Vacuum-deposited aluminum on backside, on Al substrate with DC 93500
7	B	A276 "72"	Chemglaze	White polyurethane paint	On Al substrate with proprietary Chemglaze thinner
8	B	A276 "73"	Chemglaze	White polyurethane paint	On Al substrate with chromic acid anodization and Alocrom 1200
9	B	A276 "74"	Chemglaze	White polyurethane paint	On Al substrate with chromic acid anodization and Ciba Geigy BSL 119 primer
10	B	A276	Chemglaze	White polyurethane paint	Sample no. 2 refurbished
11	B	F152-R802	ICI	White acrylic paint	On Al substrate
12	B	7D-1586	Astral	White polyurethane paint	On Al substrate
13	B	PSG 120 FD	Astral	White silicone paint	On Al substrate
14	B	Beta Cloth/ Goldized Kapton	Dupont	Impregnated textile/PPMI	On Al substrate

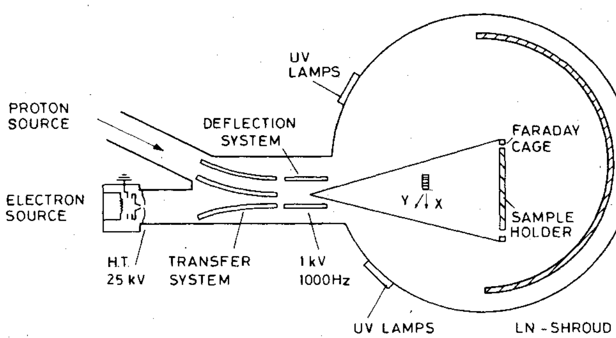

Fig. 1 Particle and ultraviolet irradiation chamber.

The sample holder is situated inside the chamber and consists of a hollow disk of 230 mm diameter. Two pipelines circulate the temperature-regulating fluid through the disk. The temperature of the sample holder can be regulated from -20 to $+130°C$ with an accuracy of $\pm 1°C$. The capacity of the sample holder during a test is 21 samples.

In-situ Measuring System

An integrating sphere is provided with three detectors and a light-guiding system. It can be placed in front of the sample holder and is attached to a mechanical system which permits movements in three axes. These movements in the X, Y, and Z directions are controlled by a relay panel on which the sphere's position is indicated in coordinates relative to the sample holder.

Ultraviolet irradiation affects the thermo-optical properties of materials and solar absorptance in particular. The integrating sphere enables in-situ measurement of both total and spectral absorptance of a test material by determination of the reflectance ratio between test sample and reference sample, the latter being protected against incident irradiation. Movement in the Z direction positions the aperture of the sphere in front of the reference sample in a $+Z$ direction and in front of the test sample in a $-Z$ direction (the reference sample is an integral part of the sphere which is positioned in front of the aperture by means of a mechanical system).

For the total measurements the reflected light is integrated by the sphere and detected with a Hilger and Schwarz FT 17 thermopile. The incident beam is supplied by a 75 W xenon lamp which is filtered to produce an approximate solar simulation, and transmitted into the sphere by an optical fiber guide.

For the spectral measurements, a 200 W xenon lamp and a monochromator are added to the aforementioned equipment. The reflected light is detected by a photomultiplier or an infrared photodiode.

Ultraviolet Irradiation Source

Type of Lamp Used

Simulation of the solar spectrum between 250 and 400 nm is provided by four Osram Uvistra HVI 400 W lamps. These are filled with argon as a starting gas, mercury and iron-iodine for desired spectral irradiance, and tin iodine for increased lamp life. In operational conditions, all of the additives are evaporated, i.e., the discharge occurs in an unsaturated atmosphere. These recently developed lamps should not be confused with the high-pressure mercury and mercury xenon lamps formerly employed.

Figure 2 shows a comparison between the spectral distributions of a high-pressure Mercury lamp and an early design of the HVI lamp (manufacturer's data).

The Osram Uvistra lamp has been developed primarily for industrial use and for this reason the quartz envelope is doped with a titanium-oxide additive which cuts off the ultraviolet at ~ 280 nm. The lamps were supplied without any TiO_2 in the quartz so that ultraviolet transmission down to 200 nm was guaranteed.

Figure 3 shows the relative spectral distribution of the lamp without TiO_2 at different lifetimes in comparison with the solar spectrum according to Thekaekara. 20% of the total energy is in the wavelength band of 250-400 nm.

Although the start-of-life spectral distribution of the HVI lamp does not simulate the solar spectrum as closely as a

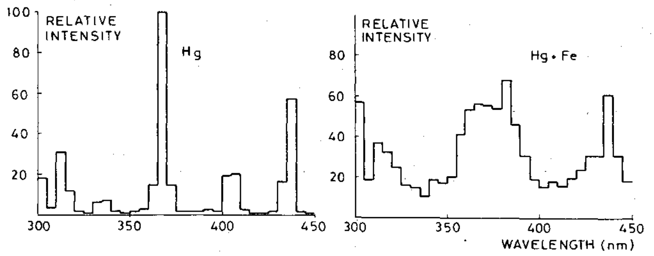

Fig. 2 Relative spectral distribution of high-pressure mercury lamps with metal halogene additives.

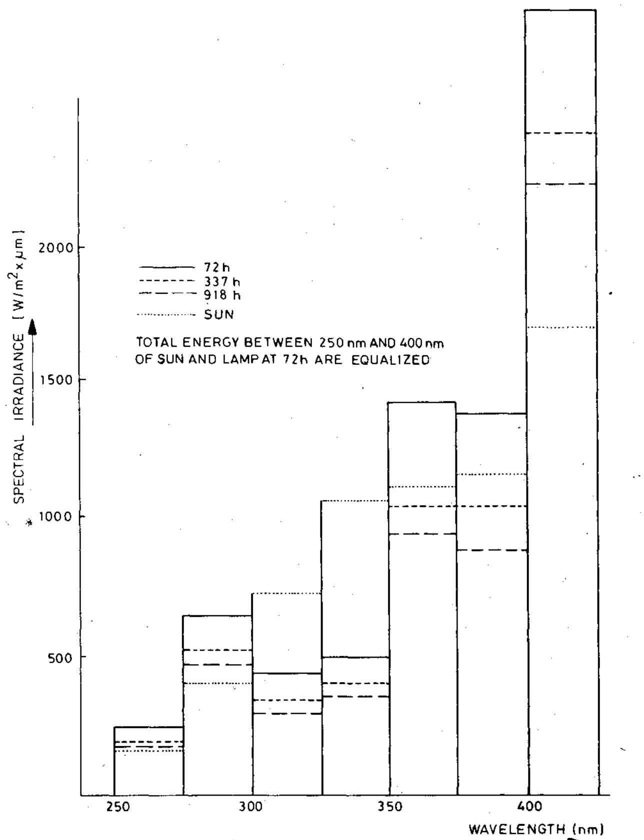

Fig. 3 Spectral distribution of Osram HVI 400 W lamp as a function of time.

xenon lamp, it shows a more favorable performance over time. A xenon lamp exhibits considerable losses, particularly in the ultraviolet range, with time, whereas the HVI lamp shows a more gradual decrease.

Positioning of the Lamps

Two lamp holders, each fitted with two HVI 400 W lamps, are provided with a reflecting mirror of electropolished aluminum and placed outside the chamber in front of two portholes with suprasil windows of 100 mm diameter and 8 mm thickness.

In-situ Monitoring of Ultraviolet Intensity

The intensity of the ultraviolet irradiation is measured with an AEG high-efficiency solar cell, type A2. The cell is fixed on the sample holder and its temperature measured with a copper/constantan thermocouple. The cell is connected to a 1 Ω precision resistance and during testing the output is continuously recorded. The solar cell is calibrated comparatively with a thermopile in front of the HVI lamp in mV per solar constant of ultraviolet energy in the wavelength band of 250-400 nm with a correction for spectral distribution by the HVI 400 W lamp.

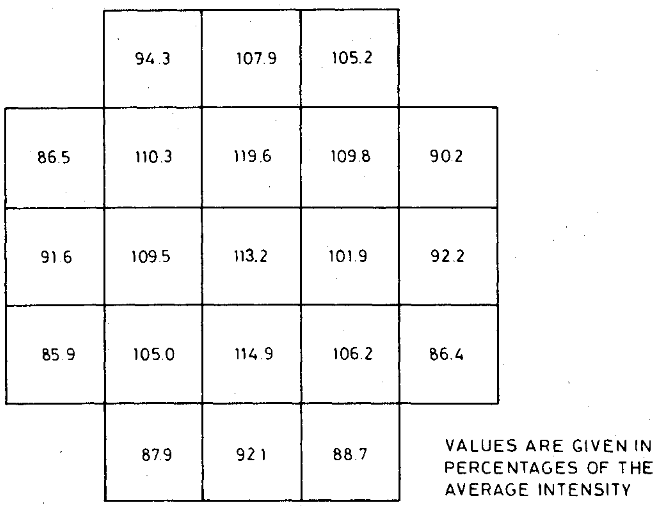

Fig. 4 Relative intensity across the sample holder.

The chamber is further provided with a thermopile mounted at the same level as the samples and, in front of the thermopile, a filter wheel consisting of several ultraviolet interference filters. Thus, the relative change in irradiation intensity in the various wavelength bands can be monitored at regular intervals.

Additionally, two photoconductive cells are placed at either side of the sample holder. During the test, the outputs of these cells are registered at regular intervals and correlated with the output of the solar cell.

Irradiation Parameters

For test A, the initial intensity was 1 solar constant (SC) of ultraviolet irradiation (wavelength band 250-400 nm) and for test B, 2 SC, both values being related to the position of the solar cell. The actual dose applied to the various samples was corrected according to the intensity distribution over the irradiated area. Figure 4 shows the homogeneity during test B.

Test Sequence

The following sequence of steps was used to perform a typical test.

1) Obtain preirradiation in-air thermo-optical properties (ϵ_N, α_S spectral reflectance curve).

2) Evacuate the chamber and allow conditioning of the samples for 48 hours.

3) Obtain in-situ reflectance data.

4) Irradiate the samples to the desired exposure level.

5) Obtain in-situ reflectance data at the various exposure levels.

6) Backfill the chamber to 1 atm.

7) Obtain in-air thermo-optical properties.

8) Monitor thermo-optical properties in air during regular intervals for determination of recovery effects.

During the test, the irradiation was stopped at regular intervals. The integrating sphere and its detectors were permitted to cool down to their approximate equilibrium temperatures. For this purpose, the sphere, reference sample and photomultiplier were provided with copper/constantan thermocouples for temperature monitoring.

Subsequently, the spectral and total measurements were made on each sample. A record of the output of the solar cell has been kept for use in the calculation of the number of equivalent sun hours (ESH) of ultraviolet irradiation received by each sample at the time of the spectral and total measurements.

Calculation of In-situ Solar Absorptance

The actual in-situ value that was measured represents the reflectance ratio between test material and reference sample

$(\rho_x/\rho_{\mathrm{ref}})$. The following equation is presented:

$$R_{x,t} = (\rho_{x,t}/\rho_{\mathrm{ref}} \times) R_{\mathrm{ref}} \tag{1}$$

where $R_{x,t}$ is the true solar reflectance of the test material at irradiation time t; $\rho_{x,t}$ is the reflectance of the test material measured with the in-situ integrating sphere at irradiation time t; ρ_{ref} is the reflectance of reference sample measured with the in-situ integrating sphere; and R_{ref} is the true solar reflectance of reference sample. The reference sample is considered to remain unchanged during irradiation.

The true solar absorptance R_x of the test material in vacuum at 0 hours irradiation is considered to be equal to R_s the value measured by the Beckman DK 2A in air.

Based on the in-situ total measurements performed in vacuum at 0 hours irradiation, it is thus possible to determine R_{ref}:

$$R_s = (\rho_{x,0}/\rho_{\mathrm{ref}}) R_{\mathrm{ref}} \qquad R_{\mathrm{ref}} = R_s(\rho_{\mathrm{ref}}/\rho_{x,0}) \tag{2}$$

The true solar reflectance value of the test sample after t_I hours of irradiation is

$$R_{x,t_I} = (\rho_{x,t_I}/\rho_{\mathrm{ref}}) R_{\mathrm{ref}} \tag{3}$$

Substitution of Eq. (3) into Eq. (2) results in

$$R_{x,t_I} = (\rho_{x,t_I}/\rho_{\mathrm{ref}})(\rho_{\mathrm{ref}}/\rho_{x,0}) R_s \tag{4}$$

Degradation of the true reflectance of the test material with irradiation time is

$$\Delta R_x = R_{x,t_I} - R_{x,0} \tag{5}$$

$$\Delta R_x = R_s[(\rho_{x,t_I}/\rho_{\mathrm{ref}})(\rho_{\mathrm{ref}}/\rho_{x,0}) - 1] \tag{6}$$

The degradation of the solar absorptance is

$$\Delta\alpha_s = -\Delta R_x \tag{7}$$

A similar method of calculation is used for determination of the in-situ spectral reflectance at the various predetermined wavelengths. During test B, the spectral reflectance values were used for calculation of the solar reflectance according to the following equation:

$$R_s = \sum_{\lambda=i}^{\lambda=j} R(\lambda)E(\lambda)\Delta\lambda \Big/ \sum_{\lambda=i}^{\lambda=j} E(\lambda)\Delta\lambda \tag{8}$$

where $E(\lambda)$ is the solar irradiance according to Thekaekara. Following the relation

$$\Delta\alpha_s = -\Delta R_s \tag{9}$$

an approximate value for the degradation of solar absorptance can be determined from the spectral data and compared with the value obtained from the total measurement with the thermopile.

Table 2 In-situ degradation values from test A

Material	Initial value α_S	ϵ_N	$\Delta\alpha_S$ after 600 ESH
S13 GLO	0.189	0.902	0.07
Chemglaze A276	0.271	0.856	0.14
Luigi Cloth	0.331	0.889	0.02
Textiquartz	0.216	0.836	0.03
Beta Cloth/Tedlar	0.270	0.890	0.03
Armalon	0.325	0.886	0.04

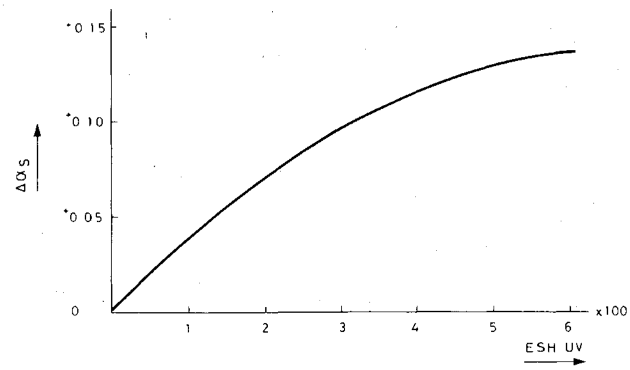

Fig. 5 Solar absorptance as a function of exposure time—Chemglaze A276.

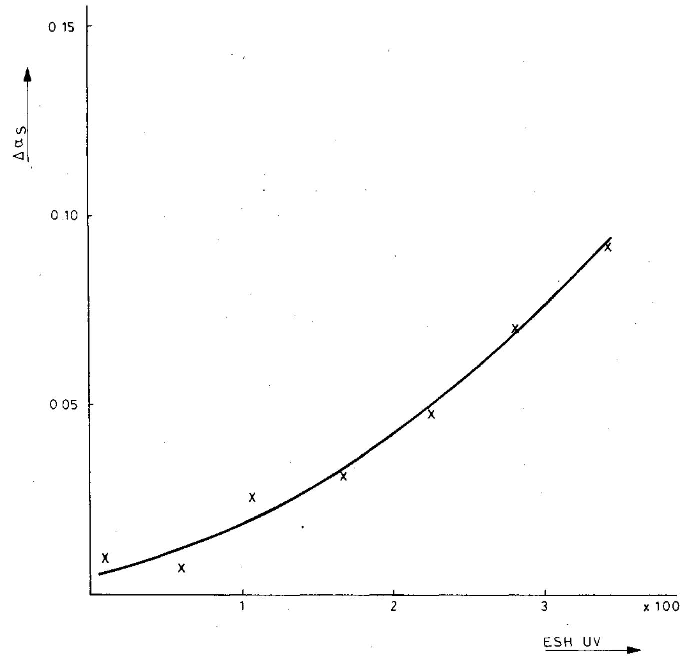

Fig. 6 Solar absorptance as a function of exposure time—Chemglaze A276 "72".

Results

Test A

The presentation of results is limited to only the in-situ degradation values of solar absorptance after 600 ESH (see Table 2).

Figure 5 shows a typical in-situ degradation curve of the solar absorptance as established for Chemglaze A276 white paint.

Test B

The results obtained from this test are listed in Table 3. Figures 6-9 show the in-situ degradation curves of solar absorptance as measured with the thermopile. They are the most probable according to correlation with the measuring points. The in-situ value of degradation of solar absorptance after 300 ESH was derived from these curves.

Measurement Accuracy

Solar absorptance, α_S	Reproducibility ± 0.005
	Max. absolute error ± 0.02
Normal emittance, ϵ_N	Reproducibility ± 0.005
	Max. absolute error ± 0.02
Solar absorptance variation, $\Delta\alpha_S$	Reproducibility ± 0.01

Table 3 Results from test B

Material	Total dose (ESH)	Initial value α_s	Initial value ϵ_N	$\Delta\alpha_s$ (in-situ) after 300 ESH Measured[a]	$\Delta\alpha_s$ (in-situ) after 300 ESH Calculated[b]	$\Delta\alpha_s$ (after 1 h in air)
S13 GLO	368	0.180	0.908	0.04	0.06	0.04
Chemglaze A276 "72"	339	0.268	0.874	0.08	0.09	0.10
Chemglaze A276 "73"	338	0.334	0.836	0.06	0.08	0.09
Chemglaze A276 "74"	313	0.310	0.864	0.09	0.10	0.08
Chemglaze "Refurbish"	277	0.237	0.881	0.12	0.13	0.09
Astral 7D1586	348	0.256	0.888	0.17	0.19	0.16
ICI F152-R802	337	0.286	0.867	0.13	0.16	0.14
PS G 120FD	282	0.176	0.876	0.03	0.06	0.01
Beta Cloth/Goldized Kapton	284	0.248	0.886	0.07	0.08	0.08

[a] Determined from the total measurement with the in-situ thermopile.
[b] Calculated on the basis of the spectral measurements.

Table 4 Solar absorptance variation $\Delta\alpha_S$ after re-exposure to air

Material	1 h in air	24 h in air	72 hr in air
S13 GLO	0.038	0.023	0.022
Chemglaze A276 '72'	0.098	0.097	0.093
Chemglaze A276 '73'	0.092	0.090	0.087
Chemglaze A276 '74'	0.081	0.077	0.075
Chemglaze A276 ('refurbish')	0.087	0.086	0.085
Astral 7D 1586	0.159	0.138	0.135
ICI F152-R802	0.135	0.127	0.120
PSG 120FD	0.011	0.010	0.012
Beta Cloth/ Goldized Kapton	0.079	0.078	0.076

Table 5 Recovery of solar absorptance after three weeks

S13 GLO	0.004
Chemglaze A276	0.012
Luigi Cloth	0.004
Beta Cloth/Tedlar	0.004
Armalon	0
Textiquartz	0

Table 6 Reflectance losses for S13GLO

Wavelength, nm	$(R_i - R_e)/R_i$, %[a]
1500	12
1000	4
600	5
550	6
500	8.5
450	12
400	17.5
350	12

[a] R_i is the initial in-situ reflectance value; R_E is the final in-situ reflectance value.

Table 7 Reflectance losses for A276

Wavelength, nm	$(R_i - R_e)/R_i$, %[a]
1500	2
1000	0.5
600	16
500	26
400	33
350	19

[a] R_i is the initial in-situ reflectance value; R_E is the final in-situ reflectance value.

Recovery after Re-exposure to Air

The solar absorptance measurements were performed 1, 24, and 72 hours after re-exposure to air of the samples of test B. The results are presented in Table 4. A routine check made three weeks after re-exposure to air of the test A samples gave the results shown in Table 5.

Discussion of Results

The results described in the following paragraphs are discussed on the basis of each individual material.

IITRI S13GLO

In accordance with results obtained by other sources,[1] the S13GLO white paint showed a low degradation. Reflectance losses tended to be largest near the ultraviolet edge and in the infrared region, as is shown in Table 6. This paint was mainly used during the tests as a reference material whose basic degradation level with ultraviolet irradiation was well known.

Chemglaze A276 White Paint

This paint is an aliphatic isocyanate polyurethane. The standard application is one washcoat plus one top coat, using toluene as a thinner with nominal curing of seven days at room temperature. The total thickness of the paint layer was ~50 μ.

During test A, a standard configuration of A276, as described, showed considerable degradation in the visible spectrum (see Table 7).

After test A, the sample was refurbished and included in test B. Refurbishment consisted of removal of the discoloration by abrasion and recoating. The refurbished sample had a total thickness of ~70 μ.

The refurbished sample showed a degradation curve characteristic with a tendency to saturation similar to the one of the original sample, but with a slightly higher degradation rate. This higher rate may be surprising, but can be explained by the penetration depth of the ultraviolet light which was of the same order of magnitude as the thickness of both samples. In the case of the refurbished sample, an additional 20 μ were degraded by irradiation which, in the case of the original sample, were absorbed by the underlying substrate.

The thickness of the paint layer also affected the initial solar absorptance value, which was lower for the refurbished

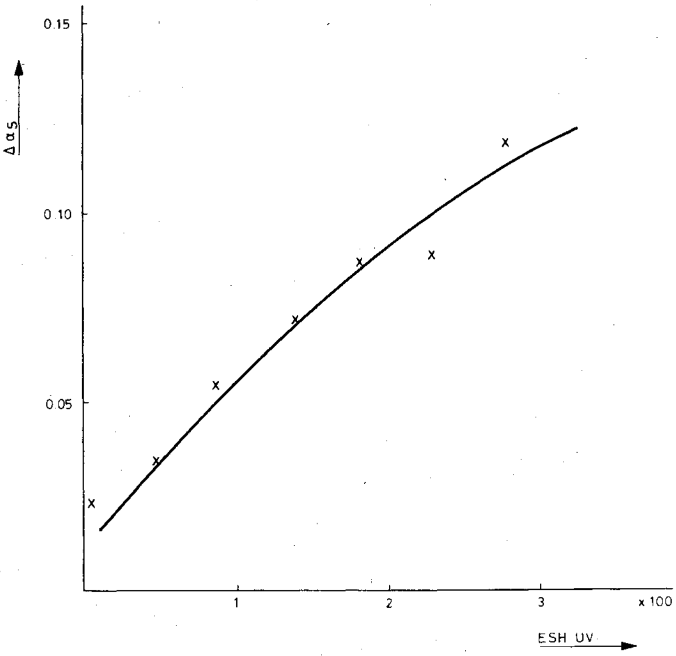

Fig. 7 Solar absorptance as a function of exposure time—"refurbished" Chemglaze A276.

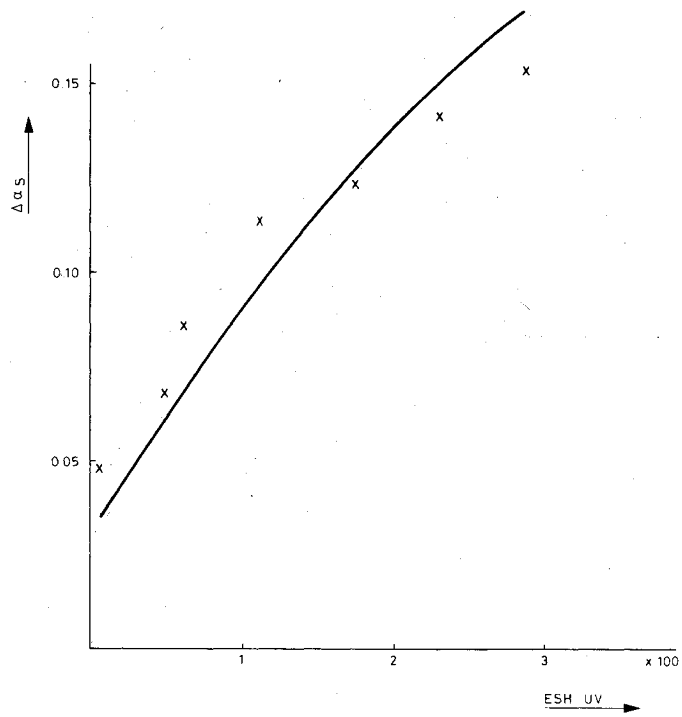

Fig. 8 Solar absorptance as a function of exposure time—Astral 7D1586.

sample. A comparison between the solar absorptance values after 300 ESH irradition of both the original and the refurbished sample produced almost identical results—0.37 vs 0.36.

The samples used for test B were treated with a proprietary Chemglaze thinner instead of toluene to reduce the offgassing of the paint.

For sample A276 "72" which had the same composition and substrate material as the test A sample, except for the thinner, it appeared that the variation in solar absorptance was less. The degradation curve did not, however, show the typical saturation characteristic of the "toluene" sample; this level is probably reached after longer exposure to ultraviolet

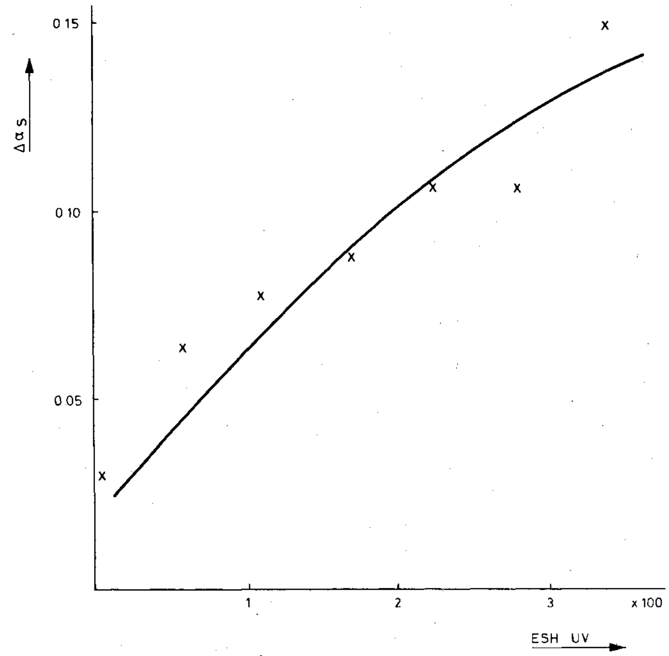

Fig. 9 Solar absorptance as a function of exposure time—ICI F152-R802.

light and this would indicate that the long-term (e.g. 600 ESH) degradation values of both sample types should be almost identical.

On the actual Spacelab pallet, the underlying aluminum will be anodized with chromic acid. For the application of the Chemglaze A276, it will be necessary to reactivate the anodization. Therefore, two samples were included in test B: sample "73", reactivation with Alocrom 1200, and sample "74", priming with Ciba Geigy BSL 119.

Visual inspection of sample "73" showed that the applied paint layer was very thin, and from this it may be concluded that the initially high solar absorptance value was mainly due to the underlying substrate. The thin paint layer also explains the low degradation values, because most of the irradiation was absorbed in the underlying substrate.

Sample "74" showed a degradation which was similar to that of sample "72", but the initial solar absorptance value was considerably higher.

ICI F152-R802 White Paint

This paint is an acrylic finish and especially prepared for aircraft (it has been used for the Concorde Project). Degradation of solar absorptance was quite high and apparent over all monitored wavelength ranges. Reflectance losses varied from 15% at 1500 nm to 55% at 400 nm.

Astral 7D 1586

This paint is a polyurethane and has been used on the Airbus Project. The degradation of solar absorptance was again very high and apparent over all monitored wavelength ranges. Reflectance losses varied between 18% at 1500 nm and 51% at 450 nm.

Astral PSG 120 FD

This paint is a silicone-based coating and the European equivalent of IITRI's S13GLO. It has a very low degradation rate and although its reflectance losses varied between 2 and 3% in the visual range, they increased toward the infrared—15% at 1500 nm.

Thermal Blanket Materials

Generally, the tested materials showed a low degradation rate. The following two phenomena were noted, however.

Textiquartz

This material, being a silica fabric, was expected to be stable under ultraviolet irradiation. The small degree of degradation which did occur was thought to originate from the underlying DC 93500 adhesive, but the discoloration could not be removed by mild chemical solvents. Indications are that, in fact, the impurities in the silica degraded.

Beta Cloth

This material proved to be relatively stable in combination with Tedlar. However, with an underlying layer of guilded Kapton, the degradation increased considerably due to the latter's reflectance ratio being higher than that of Tedlar and thus causing additional exposure of the Beta Cloth.

Conclusions

On the basis of the various test results, it has been established that such paints as S13GLO and PSG 120FD, which have been especially developed for space application, have an ultraviolet stability which is superior to that of conventional aircraft finishes. The choice of Chemglaze A276 as prime candidate for the Spacelab pallet is a reasonable tradeoff between ultraviolet stability and mechanical resistance. Its degradation rate will depend on the actual paint and substrate composition of the pallet and refurbishment will be possible without a considerable loss in ultraviolet stability. The number of missions before refurbishment is required will be determined by the results of ultraviolet irradiation testing at 80°C conducted in late 1978.[2]

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