Effects of a Simulated Synchronous Altitude Environment on Contaminated Optical Solar Reflectors

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Measurements have been made of the effects of a simulated synchronous altitude radiation environment on the solar absorptance of optical solar reflectors (OSR) contaminated with solid-propellant volatile condensible material (VCM). Samples were simultaneously irradiated with 30 keV protons, 40 keV electrons, and one equivalent sun ultraviolet (uv) radiation (200-400 nm) for a total of 245 h in a 1×10^{-7} Torr vacuum. A flux of 5×10^9 particles/cm$^2 \cdot$s of both electrons and protons produced a total fluence of 5×10^{15} particles/cm^2 of each type of particle by the end of the 245 h test period. In a separate test, OSR samples contaminated with identical propellant VCM deposits were exposed to a uv-only environment for 245 h. The results from the two tests showed a larger increase in solar absorptance with combined radiation (protons, electrons, and uv) than with uv radiation alone.

Introduction

CHANGES in the optical properties of spacecraft thermal control surfaces and solar cells are caused by the deposition of molecular contaminants outgassed from organic spacecraft materials. These optical effects include increased absorptance of reflective thermal control surfaces, which can lead to system overheating, and decreased transmittance of solar cell cover glass, which can decrease power output. The effects are compounded by the polymerizing action of ionizing radiation in the orbital environment.[1] Significant fluxes of solar ultraviolet (uv) and high-energy protons and electrons trapped in the Van Allen belt exist in orbits up to and above geosynchronous altitude.

Laboratory simulation of the combined radiation environment (simultaneous uv, protons, and electrons) is considerably more complex and expensive than the more commonly used uv radiation simulation. For this reason, it would be advantageous to be able to simulate radiation damage with uv exposure alone.

The purpose of the present investigation was to compare the effects of combined radiation with the effects of uv-only radiation on the solar absorptance of contaminated second surface thermal control mirrors.

Optical solar reflectors (OSR) were contaminated with volatile condensible material (VCM) outgassed from inertial upper stage (IUS) solid propellant. The OSRs were exposed to a simulated space radiation environment consisting of simultaneous fluxes of protons, electrons, and uv radiation in a vacuum. Other OSRs with similar VCM deposits were exposed to a uv-only environment for an equivalent length of time.

Test Description

Deposits of solid-propellant outgassing were collected on optical solar reflectors (OSR). The deposits were photographed through a microscope and the deposit thickness determined at two or three test locations on each OSR. The OSRs were then mounted in the radiation effects vacuum chamber, where in situ hemispherical spectral reflectance measurements were made at each test location before and after exposure to radiation.

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Contaminant Deposition

Outgassed deposits were collected in a standard VCM test facility using the ASTM E 595-77 standard test procedure. The sample material was live solid propellant of the type used in the IUS solid rocket motors (type HTPB, designator UTP 19,360B). Solid and chopped samples of the propellant were heated to 125°C in a 10^{-5} Torr vacuum for 24 h. Outgassing from the propellant was collected on 1 in. square fused-silica OSRs held at 25°C. Measurements of percentage of total mass loss (TML) and percentage VCM were made by weighing the propellant samples and the OSRs on a laboratory microbalance (in air) before and after vacuum treatment.

Total mass deposited on each OSR was 100-1400 μg. Each deposit exhibited some white crystalline growth in addition to liquid droplet condensation. An infrared transmittance spectrum identified the white crystalline material as 2,2' methylene-bis (4-ethyl-6-t-butyl phenol), a common antioxidant in solid propellants. Figure 1 shows a typical deposit. Due to the geometry of the effusion cell in the VCM facility, there was a large variation in thickness of deposits on each OSR. The deposits consisted of thick crystal growth in the center and droplets of decreasing size and number density toward the edges.

Determination of Deposit Thickness

The variation in deposit thickness on each OSR made it unreasonable to estimate the average thickness by simply dividing the mass of the entire deposit by the area. To obtain a good correlation between the deposit thickness and the optical effect, it was necessary to estimate the local mean deposit thickness within the 4 mm square area of the spectrophotometer beam. Figure 1 shows the approximate size of the beam at three test locations on one OSR.

Measurement of deposit thickness involved different techniques for the crystalline and droplet deposits. The thickness of the opaque crystalline areas was measured by calibrating the focus knob on an optical microscope and then focusing on the maximum height in the field of view. The mean thickness of the droplet deposits was calculated by counting droplets in a photomicrograph, estimating their total volume, and dividing by the area covered.

Photomicrographs were taken through a differential interference microscope at two or three test locations on each OSR. Figure 2 shows a typical droplet deposit magnified 600 times. The slope of the side of the droplet and the droplet height were determined from the difference in interference colors produced on opposite sides of the droplet. The number of droplets within several 1 cm square areas on each photograph

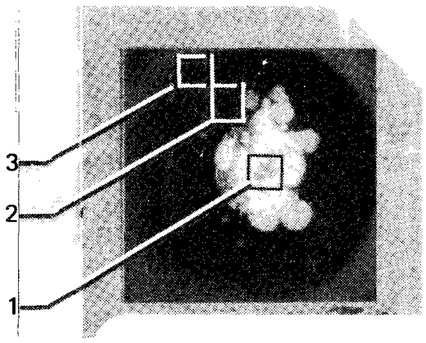

Fig. 1 Solid-propellant VCM deposit on optical solar reflector showing relative size of reflectance beam and location of reflectance measurements.

was tabulated by droplet diameter. The volume of a droplet was calculated assuming a spherical cap droplet shape. A mean deposit thickness was determined by dividing the total droplet volume by the area of the droplet counts. In cases where the reflectance beam illuminated both droplets and crystals, the mean thickness estimate was weighted by the percentage of area covered by each.

There were some difficulties with the interference technique. For very small diameter (1 μm) droplets, it was difficult to obtain sharply focused, well-defined droplets with good interference colors. It was also difficult to determine whether there were smaller droplets or a clean substrate between the smallest measurable droplets.

When all thickness measurements were made, the OSRs were transferred to the radiation effects chamber.

Radiation Testing

A combined radiation effects test chamber was used to irradiate and measure changes in the reflectance of the contaminated OSRs. A schematic diagram of the facility is shown in Fig. 3. The chamber featured all-metal seals, cryosorption and ion pumps, and liquid nitrogen shrouds that gave a working vacuum of 10^{-7}-10^{-8} Torr. Simultaneous fluxes of protons, electrons, and uv radiation converged on the sample array which was mounted on a rotatable, water-cooled manipulator. After a period of exposure, the radiation sources were shuttered and the sample array rotated 180 deg to face an integrating sphere (coated with magnesium oxide) moved in from the right side of the chamber. The spectrophotometer beam entered from the left side of the chamber and was reflected onto the sample.

The uv source was a xenon arc lamp with a fused-silica water jacket that was transparent to wavelengths of 200-1300 nm. The particle beam intensities were measured with a Faraday cup. The uv intensity was measured with a temperature-compensated radiometer in air. Particle and uv intensities were stable within $\pm 10\%$ over all test locations.

The eight contaminated OSRs were separated into two batches of four each. The first four were subjected to a combined radiation environment, the second four to a uv-only environment. A clean OSR was tested with each set of four contaminated OSRs to monitor possible cross contamination and substrate degradation due to radiation exposure.

Four contaminated OSRs and one clean OSR were attached with beryllium copper alloy clips to a flat aluminum plate that was bolted to the water-cooled manipulator. The samples were maintained at $10 \pm 2°C$ throughout the testing. Measurements of hemispherical spectral reflectance were made at the same two or three test locations at which the photomicrographs were taken and also at one spot on the clean OSR. Absolute reflectance measurements were made for wavelengths of 250-2500 nm, using a Beckman DK2A spectrophotometer with an integrating sphere.

Reflectance measurements were made at the following times: in air before irradiation; in vacuum before irradiation; after 22, 87, and 245 h total of irradiation; and after 50 h of postirradiation recovery in dry air.

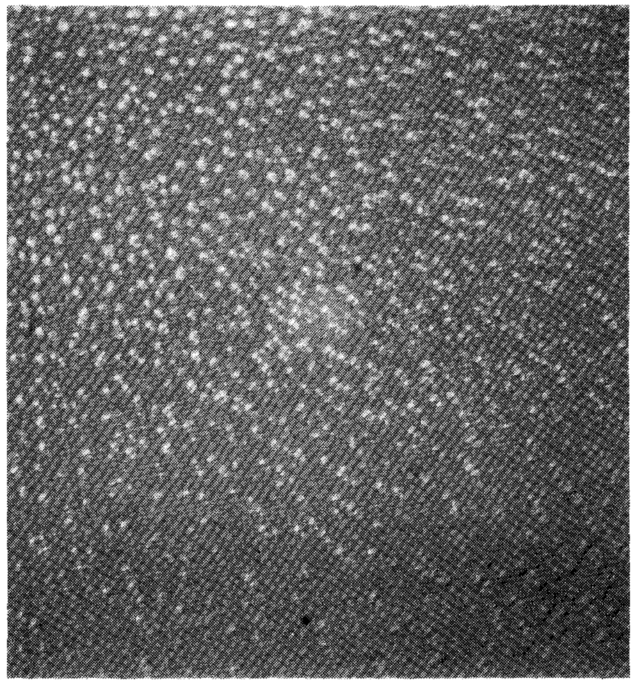

Fig. 2 Droplet region of a solid-propellant VCM deposit on an optical solar reflector, magnified 600× (1400 Å mean thickness).

The combined radiation simulation consisted of 40 keV electrons and 30 keV protons at a flux of 5×10^9 particles/cm^2-sec each and a one-sun level of uv. Total fluence of each type of particle, by the end of 245 h of testing, was estimated at 5×10^{15} particles/cm^2. The radiation environment of the second test used the same one-sun level of uv, but had no charged particles.

Test Results

Exposure to the combined radiation environment had a dramatic effect on the color of the contaminant deposits. The bright white crystalline material turned a golden brown and droplets surrounding the crystal were also visibly darkened. The change in color of the deposits exposed to only uv radiation was much less striking. Figure 4 shows pre- and postirradiation photos of two deposits, one exposed to combined radiation and one to uv only. Examination of the following results will focus primarily on the areas of the OSRs covered by droplets, since this is the most common form of molecular deposit.

Tables 1 and 2 summarize the data for the combined and uv-only radiation tests. For each OSR, the tables include a description of the propellant samples used in the VCM test, the mass of VCM collected, the form and thickness of deposit at each of two or three test locations, and the solar absorptance of the deposit at each test location as a function of the radiation exposure time. The stable absorptance values of the clean OSR in each test show that cross contamination and OSR degradation were not a significant problem.

Figure 5 is a sample of the data from the combined radiation test showing the change in solar absorptance of a contaminated mirror as a function of radiation exposure time. The solar absorptance of a clean OSR is shown for reference. The effect on solar absorptance of deposition alone (zero hour value) was generally small for the droplet deposits. The increase in absorptance due to radiation exposure was comparatively large. This illustrates the importance of including the degrading effects of the radiation environment in contamination effects testing.

Figure 6 is a comparison of the combined radiation test data with the uv-only test data. The solar absorptance after 245 h is

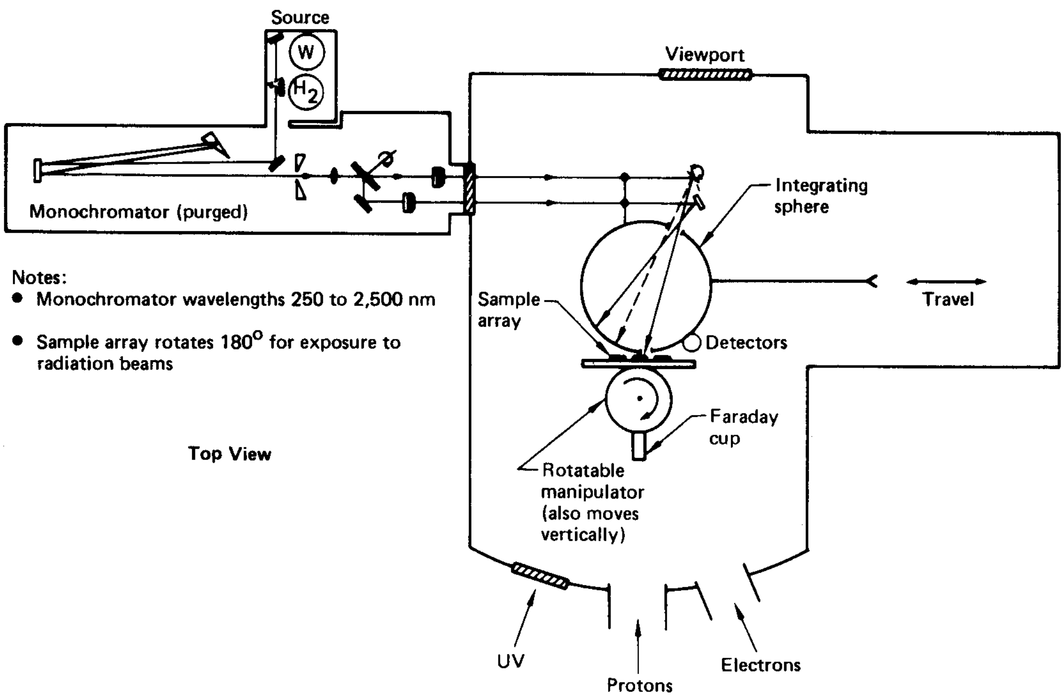

Fig. 3 Combined radiation effects test facility with samples in reflectance and dosimetry measurement position.

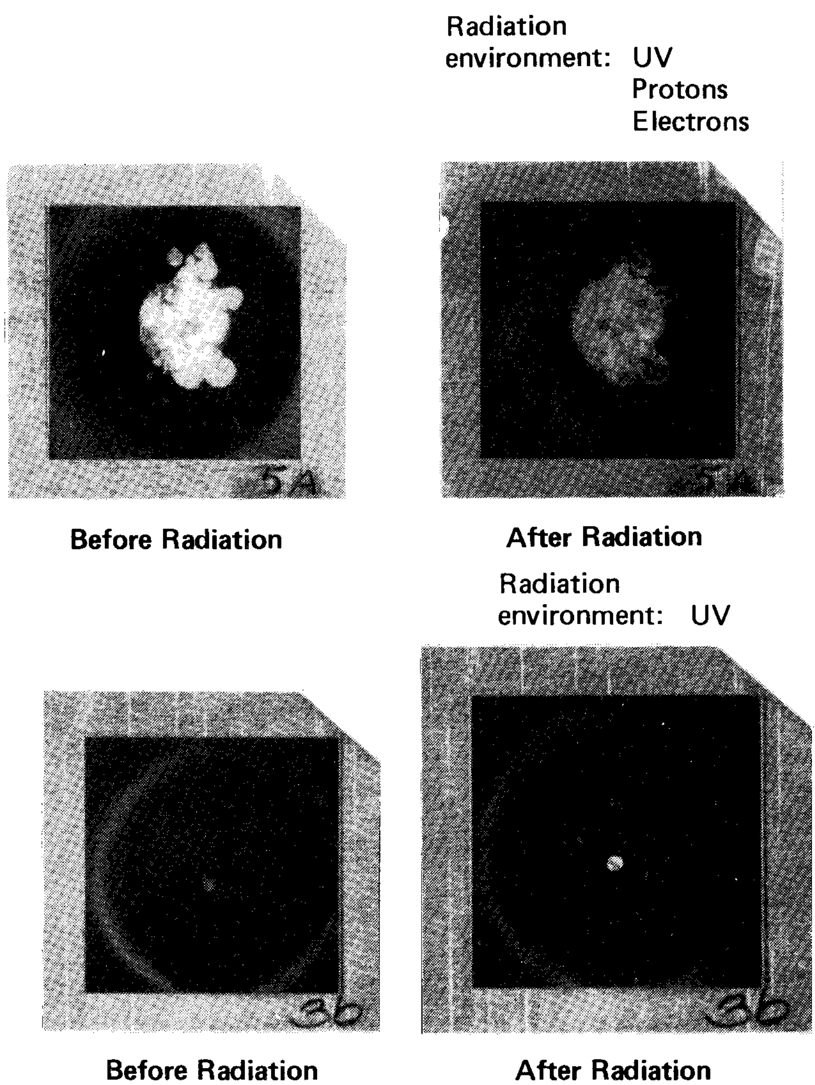

Fig. 4 Solid-propellant VCM deposits on OSRs before and after exposure to 245 h of a vacuum radiation environment.

Table 1 Propellant outgassing and combined radiation effects test.

Sample description	Deposition: Mass (μg)	Deposition: Form	Deposition: Thickness (Å)	Optical solar reflector solar absorptance, Radiation exposure time, hr: 0^a	0	22	86	245	245^b
Blank	0	—	—	0.076	0.076	0.075	0.078	0.083	
Single block 4.55g (3a)	130	Mixed	22,000	0.095	0.103	0.151	0.220	0.293	
		Droplet	700	0.081	0.086	0.143	0.216	0.291	
		Droplet	6	0.096	0.095	0.088	0.095	0.105	
Single block 4.65g (4B)	162	Crystalline	100,000	0.090	0.097	0.140	0.204	0.273	0.243
		Droplet	1,400	0.077	0.082	0.148	0.214	0.282	0.257
		Droplet	100	0.113	0.153	0.148	0.163	0.186	0.167
4 blocks 5.18g total (5a)	607	Crystalline	110,000	0.203	0.237	0.248	0.304	0.361	
		Droplet	100	0.078	0.085	0.140	0.201	0.263	
		Droplet	20	0.090	0.093	0.123	0.157	0.196	
Ground 4.90g (7a)	1371	Crystalline	860,000	0.277	0.292	0.381	0.466	0.522	0.504
		Droplet	1,100	0.084	0.091	0.105	0.128	0.156	0.142

Test conditions
- Deposition: 125°C sample on 25°C collector for 24 hours in 10^{-5} torr vacuum.
- Simulated space environment: 10^{-7} torr, 1-sun UV 40 keV electrons, and 30 keV protons at 5×10^9 $cm^{-2}s^{-1}$.

a) Reflectance measurement in air before vacuum pump-down and irradiation. All other reflectance measurements made under 10^{-7} torr vacuum, unless noted otherwise.
b) Reflectance measurement after 54 hours recovery in one atmosphere of dry air.

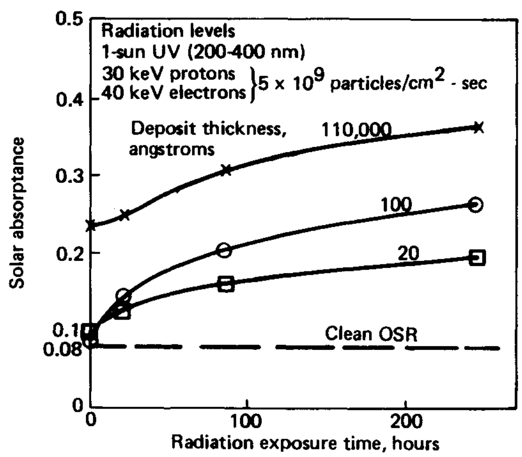

Fig. 5 Solar absorptance vs radiation exposure time, sample 5a.

plotted vs the mean deposit thickness for the droplet deposit areas. The data show a fair correlation between the deposit thickness and the optical effect. The data also show a clear difference between the effects of a combined radiation environment (uv, protons, and electrons) and a uv-only environment. The degrading effect of combined radiation was more than twice that of uv alone.

Discussion

This investigation has shown that uv and charged particles have a significant degrading effect on one type of contaminant deposit. The use of this type of data in predicting the absolute change in the absorptance of a given thickness of a deposit on a spacecraft surface depends upon the quality of the environmental simulation. The quality of the simulation is limited by the cost and complexity of the test facility.

The present test chamber can produce a flux of only a single energy of each type of particle during a test run, whereas the charged particles encountered in a given orbit in space will cover a broad spectrum of fluxes and energies. To be conservative, the chosen energy levels must be those that will do the most damage to the contaminant layer. For maximum ionization effect on the contaminant layer, the protons and electrons should dump as much of their energy as possible in the layer. This optimum condition will exist when the particles penetrate the layer, but stop just at the interface between contaminant and substrate. Range-energy calculation[2] for protons and electrons moving through various organic materials can be used to estimate the particle energies necessary to penetrate a given distance through a polymeric contaminant before stopping. See Table 3.

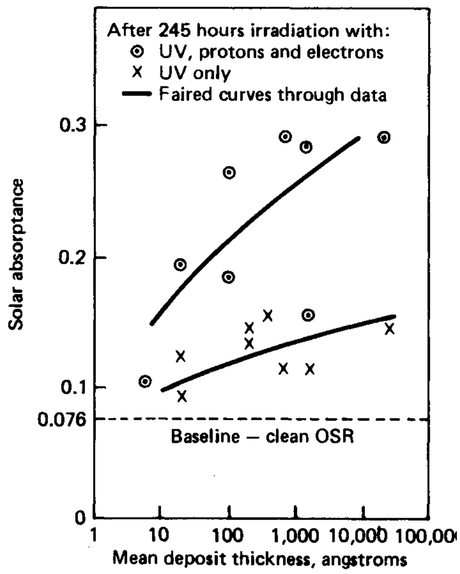

Fig. 6 Effect of simulated orbital environment on solar absorptance of second surface mirrors with solid-propellant VCM deposits.

Table 2 Propellant outgassing and uv radiation effects test.

Sample description	Deposition Mass (μg)	Deposition Form	Deposition Thickness (Å)	Optical solar reflector solar absorptance, Radiation exposure time, hr: 0^a	0	22.5	87	245	245^b
Blank	0	--	--	0.073	0.072	0.073	0.073	0.076	--
Single block 4.63g (3b)	108	Mixed	25,000	0.076	0.086	0.111	0.131	0.150	0.147
		Droplet	400	0.090	0.098	0.119	0.135	0.154	0.153
		Droplet	200	0.083	0.091	0.105	0.118	0.131	0.131
Single block 4.37g (4a)	456	Crystalline	110,000	0.145	0.185	0.248	0.308	0.367	0.375
		Droplet	200	0.086	0.087	0.107	0.125	0.145	0.144
		Droplet	20	0.097	0.101	0.111	0.117	0.125	0.125
4 blocks 5.16g total (5b)	497	Crystalline	60,000	0.261	0.209	0.277	0.351	0.398	0.421
		Droplet	600	0.088	0.087	0.095	0.102	0.114	0.113
Chopped 4.91g (7b)	316	Crystalline	710,000	0.132	0.140	0.183	0.255	0.265	0.294
		Droplet	1,400	0.097	0.094	0.100	0.108	0.117	0.119
		Droplet	20	0.085	0.083	0.088	0.091	0.095	0.095

Test conditions
- Deposition: 125°C sample on 25°C collector for 24 hours in 10^{-5} torr vacuum.
- Simulated space environment: 10^{-7} torr, 1-sun UV.

a) Reflectance measurement in air before vacuum pump-down and irradiation. All other reflectance measurements made under 10^{-7} torr vacuum, unless noted otherwise.
b) Reflectance measurement in one atmosphere of dry air.

Table 3 Range vs energy for charged particles penetrating a contaminant layer of unit density

Penetration Distance (Å)	Proton Energy (KeV)	Electron Energy (KeV)
10	4	0.01
100	14	0.1
1,000	52	0.4
10,000	188	2.
100,000	680	12.

The particle energies used in the present study were 40 keV electrons and 30 keV protons. Given these energies, electrons and protons would penetrate to depths of approximately 500,000 and 380 Å, respectively. Thus, the electrons may have been doing much less than maximum damage as they pierced the thin contaminant deposits and buried themselves in the OSR substrate. The thicker deposits would receive proportionally more energy and thus more damage from the 40 keV electrons than would the thinner deposits. The proton energy level was reasonable for the average thickness of deposits in these tests.

One problem in setting the optimum particle energy levels is that the deposits are in the form of droplets, not uniform layers. If the droplets cover only 20% of the surface, the mean thickness of a given droplet may be 5-10 times that of the mean thickness of the layer. So, the optimum particle energy for testing ultimately depends upon several deposit characteristics such as area coverage, droplet shape, and droplet size distribution.

An improvement to the present radiation simulation would be the inclusion of a vacuum uv source. Wavelengths below 200 nm are suspected of causing more damage to organic contaminants than the longer wavelength uv.[3,4] A complete radiation simulation should include a vacuum uv source.

Parametric testing should be done to investigate the effect of various particle energies and vacuum uv on absorptance of realistic contaminants. The resulting worst-case simulation of radiation should then be compared with flight data. The damage observed in the simulated environment may occur more quickly than the damage to the orbiting samples because of the use of the most effective particle energies in the chamber simulation. The ultimate increase in absorptance should be comparable for flight and ground samples with deposits of similar thickness.

Conclusions

1) The effects of contamination on the optical properties of spacecraft surfaces are significantly affected by exposure to the radiation environment of the orbit.

2) A complete study of the effects of space radiation on contaminated optical solar reflectors should include proton and electron bombardment in addition to ultraviolet radiation.

3) Parametric investigations should be done to improve the radiation simulation by determining appropriate particle energies and the necessity of a vacuum ultraviolet source.

4) Ultimately, a comparison with flight data is required to verify both the analytical and test portions of the radiation simulation.

References

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