# Studies on thermal-control paints for use as diffuse targets in the calibration of flight sensors

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## ABSTRACT

In recent years data have been collected on conductive thermal-control paints, such as PCBZ and NS43G, in order to evaluate their stability to the space environment. In addition to being considered for spacecraft thermal control, the paints have been considered as an alternate material for use within on-orbit calibration systems. For example, several NASA/Earth Observing System (EOS) and European Space Agency (ESA) instruments to be flown later this decade will require near-lambertian, bright, and spatially uniform surfaces to reflect sunlight into their camera fields-of-view. This will provide both an absolute calibration, by knowing the magnitude of the reflected light, and flat-field pixel-to-pixel comparisons within an instrument. Data are summarized here, as collected by the Cassini, Multi-angle Imaging SpectroRadiometer (MISR), and the Medium Resolution Imaging Spectrometer (MERIS) projects. Properties evaluated include absorptance, reflectance factor, electrical conductivity, thermal cycling, resistance, and environmental exposure stability. Finally, the suitability of **thermal paints** for calibration applications are compared to Spectralon, as the latter material is baseline for many next-generation remote sensing systems.

## 1. INTRODUCTION

Many instrument teams have spent some effort searching for a flight-qualified, stable, reflective material to support calibrations of remote-sensing systems in-orbit, To date there has been little flight-experience with any material other than roughened aluminum. This material, however, has a specular-like component to its reflectance and is less than 50% reflective in the visible. A comprehensive materials search was conducted several years ago[1] to identify a surface with improved properties over roughened aluminum, A thermal-control spacecraft paint called YB-7 1 (also known as ZOT) was identified as being non-ideal, but the best compromise between optical performance and stability in orbit. As a result of this study the Sea-viewing Wide-Field-of-view Sensor (SeaWifs), a NASA ocean-viewing sensor to be launched early in 1994, has constructed a diffuse calibration target using this thermal paint. Since that time, however, many more studies have been conducted. Spectralon, made from pure polytetrafluoroethylene (PTFE), has been baselined for use on instruments such as MISR, and tested in the Space Shuttle environment during three flights of the Shuttle Solar Backscatter Ultraviolet (SSBUV)[2]. As some stability issues still remain with this material, it is appropriate to collect data on other candidate materials, such as thermal control paints. As PCBZ and NS43G have the added advantage of being electrically conductive, these thermal control paints arc the preferred candidates for this study. This paper, therefore, reports on testing of PCBZ and NS43G, as disclosed by three flight projects. A brief summary of these projects is given first.

### 1.1 Cassini

The NASA/ Jet Propulsion Laboratory Cassini project is a major interplanetary exploration effort to study Saturn, its moons and atmosphere. The Cassini spacecraft is scheduled for launch in 1997 on a **Titan IV rocket with a** solid rocket motor upgrade and Centaur upper stage. Upon arrival at Saturn, a four year mission will be conducted, with fifty orbits and many satellite encounters, Detailed studies of Saturn's atmosphere, rings and magnetosphere will be conducted. The Huygens atmospheric entry probe provided by ESA will be used to study Titan, Saturn's principal moon,

The principal area of application for white conductive thermal control coatings on the Cassini spacecraft is the four meter diameter High Gain Antenna (HGA). An effective thermal control coating is of critical importance because temperature extremes will be encountered as the spacecraft will approach within 0.61 astronomical units (AU) of the sun during Venus flybys, and will be as far

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as 10 AU from the Sun while orbiting Saturn. Electrical conductivity of the HGA thermal control coating is necessary to prevent electrical discharge damage to the onboard electronic equipment and to avoid electromagnetic interference with onboard field and particle detectors. Because of the long duration of the Cassini mission, environmental resistance, as will as electrical conductivity and good optical properties are important. Further details on the Cassini testing of conductive thermal control paints can be found in Hsich, et al.[3].

The requirements on Cassini's thermal control paints are:

- Electrical conductivity. The paint must not develop larger than a 10 V static-charge potential, when exposed to 10 KeV protons at 0.5 nA $cm^{-2}$ current density.
- Absorptance. The paint must have an absorptance of less than 0,20 and emittance of 0.90 or greater to be effective thermally.
- UV exposure/ proton bombardment. The paint must be stable to 19,000 hours of total exposure during the Cassini mission.
- Thermal excursions. The paint must withstand ± 180° C temperature extremes without cracking, flaking, or loss of adhesion to the substrate,
- Outgassing. It is required that the total mass loss (TML) not exceed 1.0% and vacuum condensable material (VCM) not exceed 0.170.
- Specularity. The paint must be less than 1% specular to minimize heating of adjacent hardware,

### 1.2 The MISR Instrument

The Multi-angle Imaging SpectroRadiometer (MISR) is currently under development and build at the Jet Propulsion Laboratory (JPL). One of its principal objectives is to monitor global and regional trends in aerosols, and to assist in the atmospheric correction of surface images from other remote sensing instruments. Over cloud fields, MISR measurements will be used to investigate how spatial and seasonal variations of different cloud types affect the planetary solar radiation budget. Retrieved surface hemispherical albedos will yield improved measures of vegetation canopy photosynthesis and transpiration rates.

MISR will be launched as part of the Earth Observing System (EOS) payload in 1998. It will use nine separate charge coupled device (CCD)-based pushbroom cameras to observe the Earth at the nine viewing geometries shown in Table 1. The angles form a fore/aft set of observations with cosines of 1.0,0.9,0.7,0.5, and 0.33. Wavelength coverage is in the visible and near infrared, from 420 to 880 nm. The calibration program includes pre-flight and in-flight use of detector-based radiometric standards, an on-board calibrator (OBC) which illuminates the entire camera geometric and stray-light fields-of-view, and plans to acquire surface and atmospheric data during an "overflight calibration". The OBC will provide accurate absolute and relative (pixel-to-pixel, band-to-band, and angle-to-angle) radiometric calibrations. This is needed due to the challenging calibration requirements, such as the need to measure incoming spectral radiance to within 3% in absolute units of energy. Key to the OBC system is a pair of deployable diffuse panels which reflect sunlight into five cameras simultaneously, Thus, the aftward-looking and nadir cameras are calibrated with one view of one panel, and the forward-looking and nadir cameras are calibrated during view of a second diffuse panel. During

**Table 1. MISR Instrument Parameters**

| Parameter | Value |
|---|---|
| View angles at Earth's surface | O.O° (nadir)<br>26.1°,45.6°,60.0°,70.5° (fore and aft) |
| Spectral bands (bandwidths) | 443 (30), 555 (15), 670 (15), 865 (25) nm |
| Radiometric uncertainty (1$\sigma$) for 100% equivalent reflectance uniform target | 3% absolute<br>1% relative camera-to-camera |
| Swath width | 360 km |
| Crosstrack pixel size | 275 m off-nadir/ 250 m nadir |

the initial design phases of MISR it was recognized that no flight-qualified material met the optical and stability requirements needed for this diffuse panel. For this reason MISR began studies on Spectralon, a polytetrafluoroethylene (PTFE) material used as an optical reference standard in ground applications, and thermal control paints. Details of the flight qualification studies on Spectralon have been reported on earlier[4,5]. The requirements on MISR's diffuse panel are:

- Lambertian-like diffuse reflector. This requirement allows near equal amounts of energy to fall simultaneously on all five cameras under test. Also, with a near constant reflectance distribution with angle, there is less error in computing reflected energy into a given detector field-of-view.
- High hemispheric reflectance (>80%). Calibration accuracy is improved if the signal input during calibration is matched to the dynamic range of the sensor. It is noted that some of the MISR in-orbit calibrations will be conducted with a solar illumination angle of 50°, thus there is a reduction in reflected light of 60% (cosine of the illumination angle) over that of a target reflecting near-nadir illumination. (Energy from a 100% reflecting diffuse target illuminated by an overhead Sun would fill MISR's CCD pixels to 80% of fullwell).
- Spatial uniformity to <0.5%. This allows energy to be measured by MISR's panel-monitoring photodiodes to be used as a measure of the energy reflected into the cameras, since the cameras and photodiodes view different areas of the diffuse panels.
- Stability to better than 5% during the five-year mission. If panel degradation occurs slowly with time, then there is improved reflectance knowledge over a panel which changes abruptly with time, or by extremes in value.

As compared to the Cassini requirements, MISR is less sensitive to static-charge build-up. It is desirable that less than 120 V static charge be accumulated during passage through an auroral storm. In addition, UV exposure is only on the order of 20-100 hours, as the panels are stowed when not in use. The thermal environment will not exceed temperatures of –75° C to +90° C.

### 1.3 MERIS

The Medium Resolution Imaging Spectrometer (MERIS)[6] is a passive optical instrument which is dedicated to ocean evolution monitoring. Secondary goals of MERIS include investigations of cloud and aerosol parameters and land surface processes. Currently under development and build at Aerospatiale in Cannes, France, MERIS will fly on the European polar-orbiting ENVISAT platform, scheduled for launch mid-1998.

The MERIS instrument consists of six independent optical modules with overlapping fields. Each module views a 14° section of the total instrument field-of-view (FOV). The scene is imaged onto the entrance slit of a programmable imaging spectrometer with high spectral resolution and medium spatial resolution. The instrument will operate in a pushbroom mode with a large total FOV (±41° across track), covering a swath of about 1450 km, The spatial resolution at the subsatellite point is 1 km over the open ocean, and 250 m over coastal zones and land surfaces. The solar radiation backscattered through the system will be simultaneously imaged in the spectral range of 400-1050 nm through a spectral dispersing system with a diffraction grating. The spectral bandwidth is an average of 10 nm in the visible part of the spectrum.

The in-flight calibration strategy uses two separate optical calibration systems - deployable diffuser panels and a solar illuminated integrating sphere. The diffuse panels illuminate the first and six camera modules (for redundancy) to provide an absolute spectral calibration (radiometric accuracy better than 2% albedo). Relative spatial and wavelength (spectral position of any pixel must be known to within 1 nm accuracy) calibrations are to be accomplished by viewing a spatially uniform scene. This is provided by the output port of the integrating sphere both with and without a rare earth filter positioned at the input port (the sun illumination port) of the sphere for the wavelength calibration. High registration between camera modules and between spectral bands is also required,

To achieve the optical and stability requirements needed for the diffuse panels and the integrating sphere, MERIS has built on materials studies of Spectralon and thermal paints initiated by JPL/MISR. The requirements of MERIS's diffuse panel and integrating sphere are similar to those presented previously for MISR.

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### 2.4 Paint preparation

PCBZ, produced by M.A.P. of France is a two part coating system, The topcoat consists of zinc orthostannate pigment in a silicone binder and provides high emittance and low absorptance. The basecoat consists of metallic flakes in a silicone binder and is responsible for the electrical conductivity. To prepare PCBZ on aluminum, the aluminum substrates were scoured with a Scotchbrite pad dipped in a paste mixture of Alconox detergent powder, Institutional Grade Ajax scouring cleanser, and water. The substrates were rinsed first with tap water, then deionized water. Next they were dried with dry nitrogen, and wiped with 1,1,1 trichloroethane and rinsed with acetone. A base coat was applied, followed one hour later with a top coat of the PCBZ.

NS43G was developed at NASA/ Goddard Space Flight Center. It consists of a fixed zinc oxide pigment doped with one percent by weight aluminum oxide and a potassium silicate binder. It is prepared in a similar way to the PCBZ samples, with the omission of the trichloroethane cleaning step.

### 2.5 Test results

The results of the JPL conducted electrostatic charging tests are given in Table 2. During testing the samples were mounted on an aluminum plate and placed in a vacuum chamber. The chamber was pumped to less than 2x $10^{-3}$ Pa, then bombarded with electrons at 10 KeV at a current density of 0.5 nA cm$^{-2}$. It is found that the first two paints, chosen on the bases of their conductivity by the Cassini project, have superior charge performance as compared to SpectraIon. Data are also included here onYB-71. The results on YB-71 were acquired with the sample at 100K, simulating in-orbit data in which water-vapor does not contribute to the conductivity of the sample under test. As stated earlier, however, the charge build-up requirement is instrument and platform dependent. None of these materials would be deselected for usage on MISR, for example, on the basis of these results. It is believed that only if MISR passes through an auroral storm during calibration when the panels are deployed that these charge levels could occur. Quick] y, however, the spacecraft would pass through the storm, and the panels would be neutralized by the background environment before panel stow.

**Table 2. Electrostatic Charging Results**

| Material | Charge build-up, volts |
|---|---|
| NS43G | -4 |
| PCBZ | -20 |
| YB-71 (ZOT) | -1500 |
| Carbon-doped Spectralon (77% reflectance) | -2000 |
| Pure Spectralon | -6228 |

The data compiled on absorptance, UV exposure and proton bombardment environmental testing, thermal cycling, outgassing, and specularity are given in Table 3. Adhesion was measured using ASTM D3359 x-cut tape test and evaluated on a scale of OA (poor) to 5A (excellent); both materials had satisfactory adhesion. UV and VUV, electron, and proton testing were conducted at Lockheed, Sunnyvale, Ca. Ultraviolet testing was done using a 4200 xenon lamp at one Sun intensity; vacuum ultraviolet exposure was provided with a deuterium lamp of 1 to 2 Sun intensity at Lyman Alpha (1216Å). After 1357 hours of exposure the PCBZ had a 16% change in absorptance, with no observable change in NS43G. Radiation particle fluxes ranged from $10^{13}$ to $10^{14}$ particles cm$^{-2}$ SW-l; neither material showed significant degradation as a result of this test, Thermal cycling was conducted with use of a vacuum chamber to provide heating or cooling, followed by the adhesion test. No change in adhesion for either material was noted after this thermal cycling. Outgassing of the PCBZ was measured after treatment at 120” C for 16 hours and $10^{-3}$ torr. This is similar to the procedure which will be used to clean the spacecraft. The NS43G samples demonstrated a lower VCM value.

**Table 3. PCBZ and NS43G Flight Qualification Test Results**

| Test | PCBZ | NS43G |
|---|---|---|
| **Absorptance** | **0.19** | **0.29** |
| UV exposure testing (change in absorptance) | +0.03 | None |
| Proton bombardment (change in absorptance) | +0.05 to +0.06 | None |
| Adhesion | 4A | 3A to 4A |
| Thermal cycling (change in adhesion) | None | None |
| **Outgassing** | 0.25% TML; 0.11% VCM | 1,0% TML; 0.05% VCM |
| **Specularity** (40° angle of illumination; 6° view cone) | **0.007** | **0.005** |
| **Specularity** (80° angle of illumination; 6° view cone) | 0.336 | **0,014** |

Specularity was the final test. This parameter is computed as the integration of the hi-direction reflectance distribution function (BRDF) within a specified view cone about the specular direction, and ratioed to the total hemispheric-integrated reflectance. These latter data were acquired at Surface Optics Inc., San Diego, as were the BRDF data which follow. At 40° illumination there is no significant difference in this parameter. However, at larger illumination angles NS43G appears to be the better diffuse reflector.

Figure la and lb show BRDF data for PCBZ and NS43G, respectively. Data were collected for an illumination angle of 40° and at a wavelength of 488 nm. Three curves show the forward scatter ("0) and back scatter principle plane data ("A"), as well as a 90° azimuth Sean ("B"). At this illumination angle these data indicate that PCBZ is more reflective and perhaps even more diffuse than NS43G, irrespective of the specularity measure given in Table 3. Although NS43G has slightly more energy directed into the 50° direction, this did not increase it's specularity value over that of PCBZ. This is because this parameter only compares energy in the specular direction, 40° angle for this test configuration. Not shown are the data at an illumination angle of 80°. Here PCBZ has a BRDF of 100 in the specular direction, while NS43G has a value close to 4.

One final comparison of reflectance is shown in Figures 2a and 2b. These data were collected at JPL by a materials screening BRDF test set-up. From top to bottom are the detector output while viewing SpectraIon, PCBZ, and NS43G. The angle of illumination was 45°, and data are shown at both 440 and 875 nm. Clearly SpectraIon is brighter than the other materials, but not necessarily more diffuse at this illumination angle. It is interesting to note that the specularity of PCBZ and NS43G seems to be wavelength dependent.

As a result of these studies NS43G may be preferred over PCBZ by the Cassini team, As MISR will use illumination angles no greater than 55°, and as PCBZ was brighter, this material was selected for further MISR/ MERIS testing. Cost prohibited further studies on both paints.

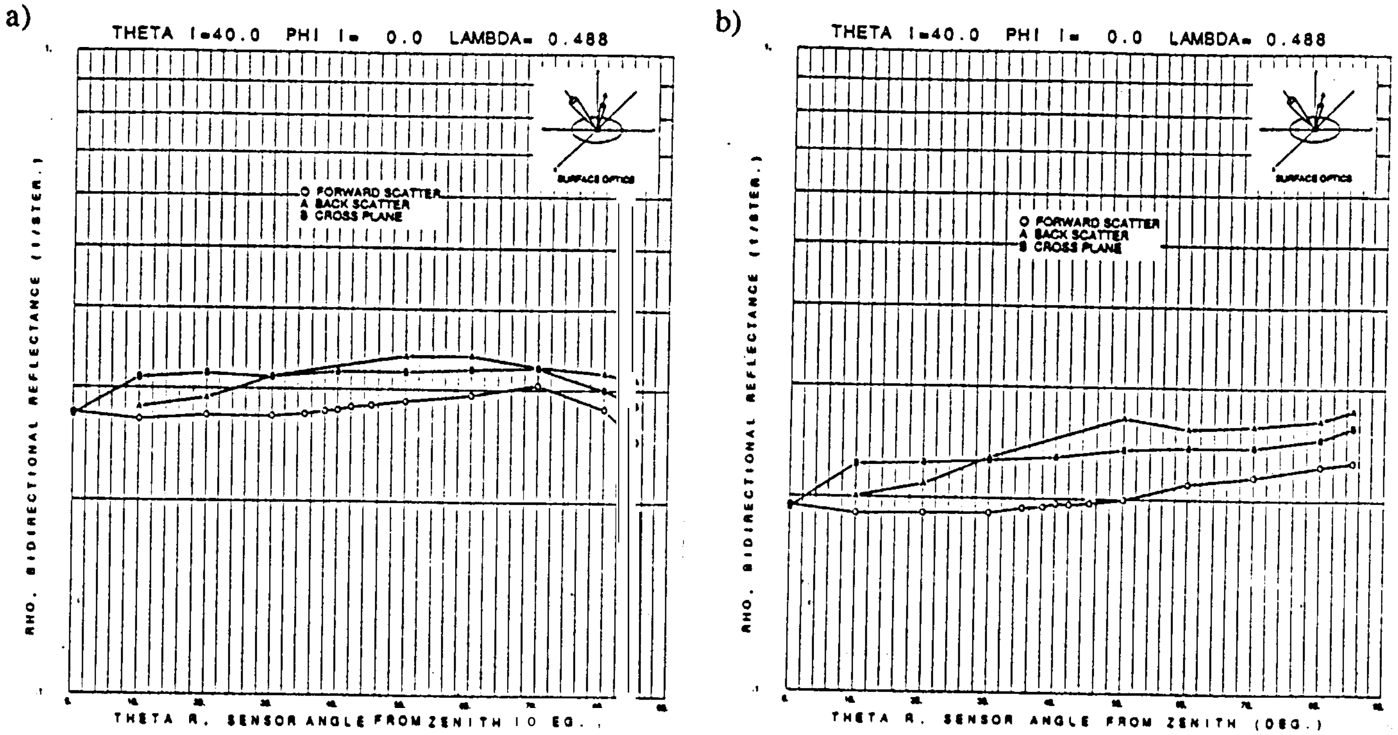

Figure 1. **BRDF data on a) PCBZ and b) NS43G.** Data were collected at an illumination angle of 40° and wavelength of 488 nm. Data are from Surface Optics, Inc., San Diego.

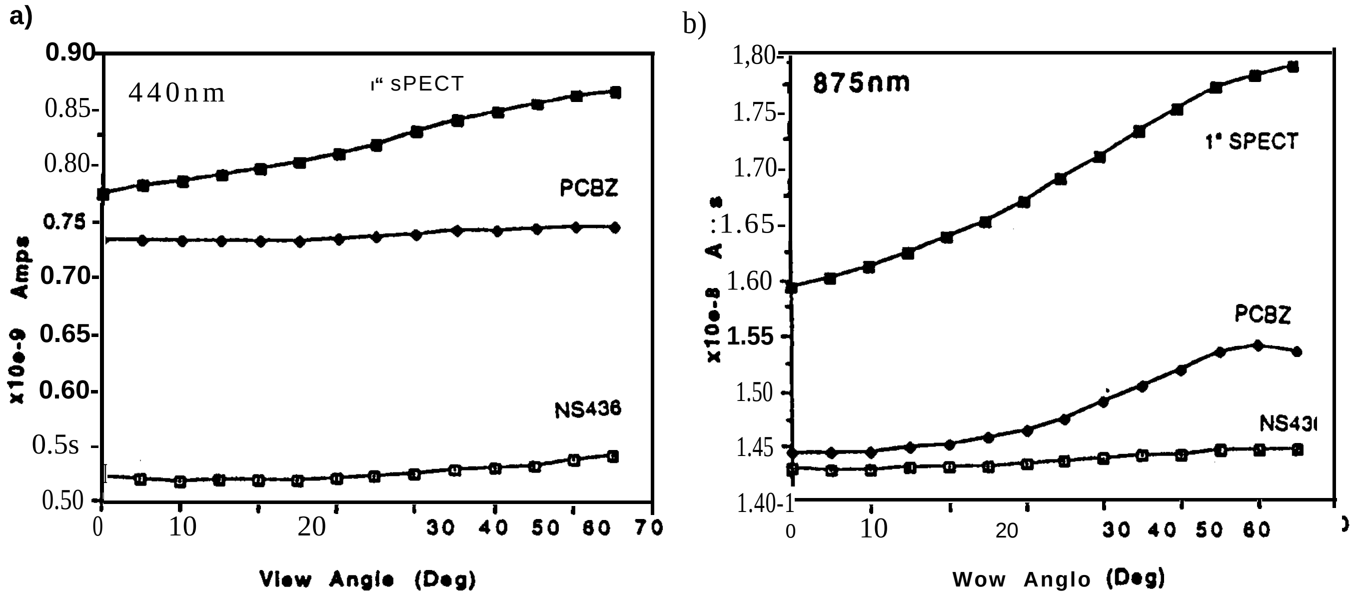

Figure 2. BRDF data on for **Spectralon, PCBZ,** and NS43G. Data were collected at an illumination angle of 45° and at wavelengths of a) 488 nm and b) 875 nm. Data collected at JPL.

## 3. MISR/ MERIS studies

### 3.1 Lockheed test plan

UV/ VUV exposure and proton bombardment testing was done using the same test facilities (Lockheed, Sunnyvale, Ca.) utilized during Cassini testing. Here, however, UV testing only went to 500 equivalent solar hours (ESH), as these data are sufficient to bracket exposures anticipated for the MISR and MERIS calibration systems. In addition atomic oxygen bombardment, and testing of uncontaminated ("clean") versus contaminated samples was conducted. The contaminated samples were exposed to silicone, phthalate, and an organic machining oil. These contaminants are representative of those which could be present during test and integration, if due care is not taken. In the case of Spectralon, an "uncleaned" sample was also UV irradiated. Here "cleaned" Spectralon refers to the process of vacuum baking 24 hours at 90° C and $10^{-6}$ torr; "uncleaned" Spectralon refers to a product which has not been conditioned with vacuum heating prior to the environmental tests. This vacuum heating procedure is known to remove much of the hydrocarbon contaminates which are in the PTFE powder prior to panel manufacture. It has been demonstrated that this contaminant is responsible for UV degradation of Spectralon[5] Atomic oxygen testing was done at a fluence of $5.3 \times 10^{20}$ oxygen ions cm$^{-2}$, and proton current density was at 1012 protons cm$^{-2}$ at 40 KeV in energy.

### 3.2 Test results

Figures 3a through 3d summarize the degradation in hemispheric reflectance for cleaned, uncleaned, and contaminated Spectralon, and contaminated PCBZ. The legend summarizes the cumulative testing that the samples were subject to prior to reflectance measurement. Although not all the test data are shown here, it was observed that neither the contaminated Spectralon, nor the contaminated PCBZ samples degraded significantly more than their cleaned counterparts. (Chemical tests after contamination confirmed that Spectralon, and to a lesser extent PCBZ, was a poor absorber of the contaminants.) Thus neither material type seemed to be sensitive to these particular contaminants. In comparing Figures 3a and 3b, however, it is noted that hydrocarbon contamination is problematic for Spectralon. That is, the Spectralon samples which were vacuum baked improved in stability by a factor of two. (Even better stability might be achieved if the samples are vacuum baked for an even longer period of time. Thus further Spectralon testing is in progress.) Data collected to date suggest that Spectralon is most sensitive to the hydrocarbons present in the raw PTFE starting material. In Figures 3c and 3d proton bombardment results are presented, The pre-exposure to proton curves are marked with black triangles (post 110 ESH UV data), and the post-proton exposure data are marked with white triangles. No significant differences in these curves are noted, thus both the Spectralon and PCBZ samples are insensitive to proton exposure, as simulated by their total mission dose. There was a vacuum break in the experiment prior to the 516 ESH measurement. It was observed that the materials bleached when exposed to air, but returned again to a degraded state in vacuum. This confirms our need to do these environmental tests in a vacuum environment, simulating space conditions.

To better quantify these results, Table 4 gives the degradations observed at two wavelengths of interest to MISR and MERIS. Percentages are computed by comparing hemispheric reflectance as measured after a specified level of UV exposure, to the pre-exposure measurements, In the case of the proton data, however, a comparison is made with the 110 ESH UV result, that is those measurements made just prior to proton bombardment. In summary we see that degradation of the PCBZ samples is of the order of magnitude of that observed on cleaned Spectralon.

## 4. CONCLUSIONS

From the data presented above it is shown that PCBZ is no better, or worse, than Spectralon in terms of stability to UV or proton mission levels. Although not as reflective, the paints can at times be more diffuse than the Spectralon samples studied in parallel. The biggest advantage to the use of thermal control paints may be the weight savings. The two Spectralon panels weigh together about 1.5 pounds for the current MISR design, To their disadvantage, the paints maybe more susceptible to micrometeorite damage and atomic oxygen exposure. It has been noted during the course of testing that PCBZ, for example, has cracked slightly under the heating effects created during UV and atomic oxygen testing. This feature would need to be investigated more extensively if these materials were to be considered further. Also unknown is the spatial uniformity of the paint reflectance, and consistency of these optical properties with manufacture (from one lot to the next).

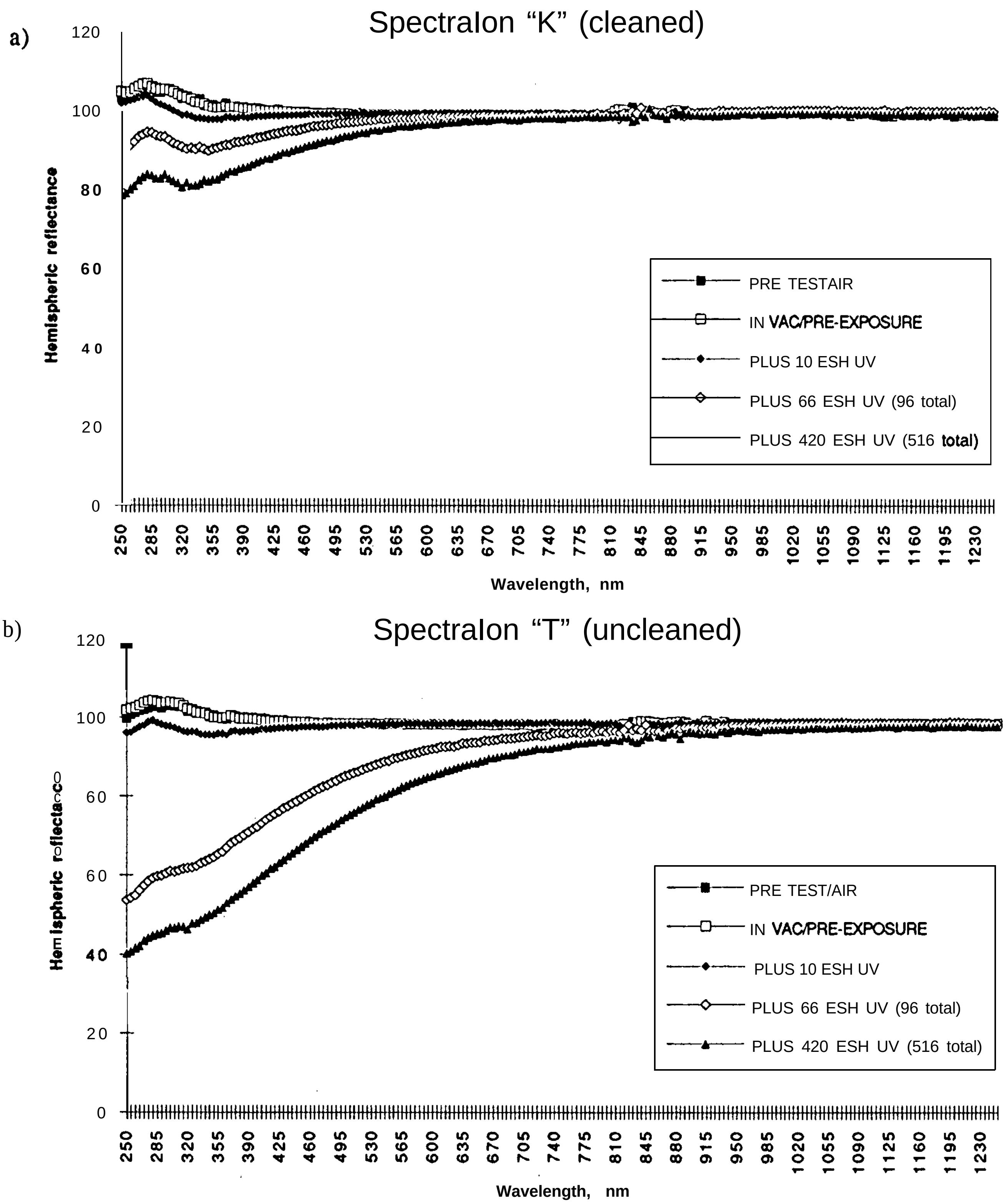

Figure 3. Hemispheric reflectance data for a) cleaned Spectralon and b) uncleaned Spectralon. Data were collected at Lockheed, Sunnyvale, Ca.

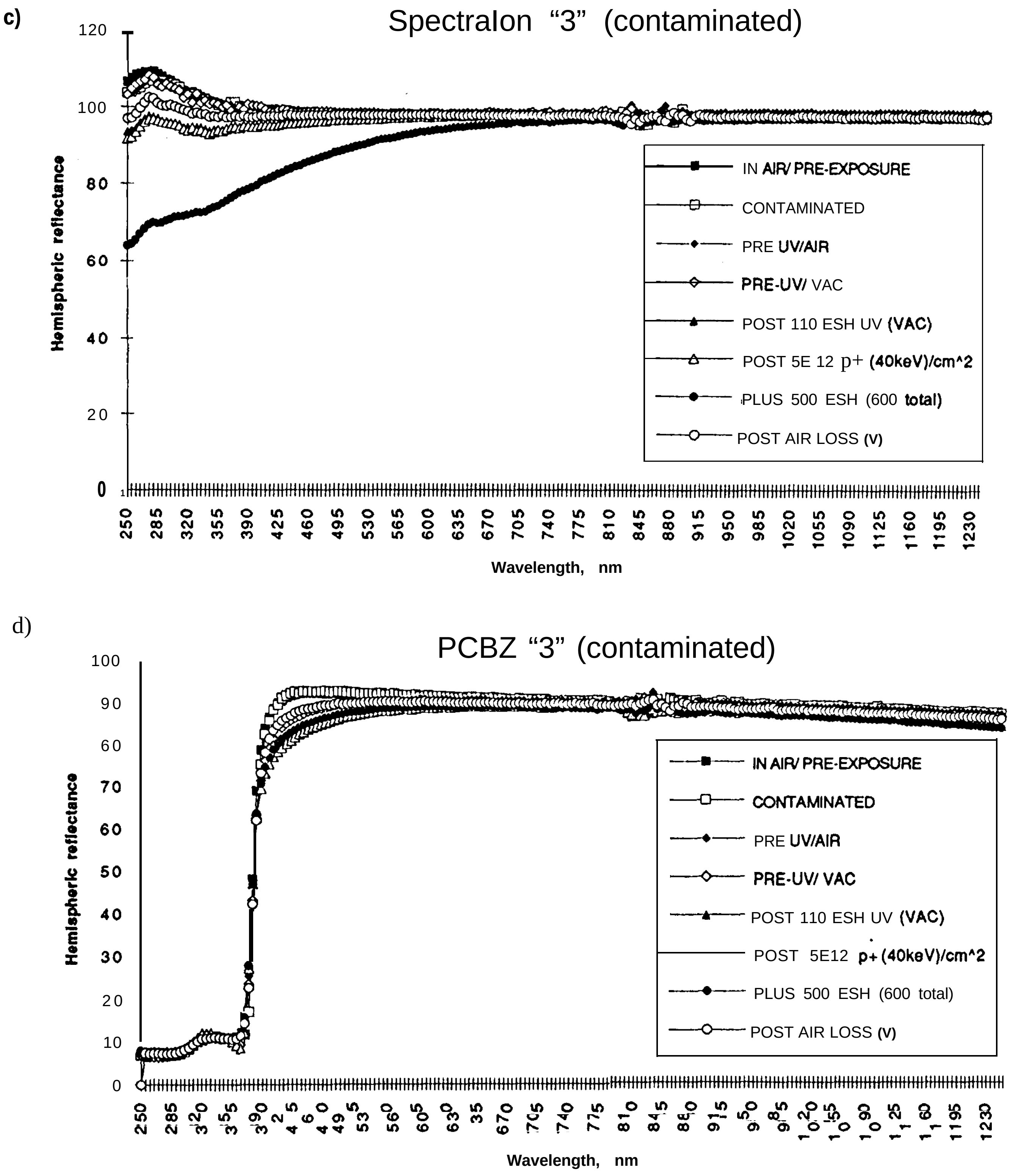

Figure 3, cont. Hemispheric reflectance data for c) contaminated Spectralon, and d) contaminated PCBZ.

**Table 4. Percent change in hemispheric reflectance made following specified test, as compared to pre-exposure conditions**

| | Change in hemispheric reflectance, % | |
|---|---|---|
| **Test completed** | **450 nm** | **650nm** |
| **Spectralon "K" (cleaned):** | | |
| 10 ESHUV | 1 | 0 |
| 96 ESH UV | 5 | 1 |
| 516 ESH UV | 10 | 2 |
| **Spectralon "T"** (uncleaned): | | |
| 10 ESH UV | 1 | 0 |
| 96 ESH UV | 20 | 5 |
| 516 ESH UV | 32 | 10 |
| Spectralon **"3"** (contaminated): | | |
| 110 ESH UV | 3 | 1 |
| Proton bombardment | 0 | 0 |
| 600 ESH UV, including vacuum break | 14 | 3 |
| **PCBZ "3" (contaminated):** | | |
| 11 OESHUV | 7 | 2 |
| Proton bombardment | 2 | 0 |
| 600 ESH UV, including vacuum break | 7 | 1 |

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