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Contamination Effects on the Geostationary Operational Environmental Satellite Instrument Thermal Control System

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The instrument thermal control system of the Geostationary Operational Environmental Satellite may have been affected by specific contamination problems that arose because of the unique conditions and requirements of the spacecraft mission. This paper addresses some specific contamination effects from the coatings used in the instrument cavities. Contamination control actions that were implemented during ground processing to ensure limited impact on the on-orbit temperature control are described. The selection of thermal coatings is an integral part of the overall spacecraft design. Molecular contamination accretion on thermal coatings may alter the design properties of the surface coatings. In an effort to quantify the molecular contamination effects from material outgassing, an assessment was conducted to address the concerns inside the instrument cavities. The study results prompted an extensive prelaunch vacuum bakeout effort and an on-orbit solar radiation avoidance exercise. In addition, the thermal performance of the instrument radiant coolers could have been detrimentally affected by scattered solar radiation from particulate contamination. To mitigate the impact of the particulate contamination the radiant cooler surfaces were cleaned to an established criteria prior to launch.

Nomenclature

A = illuminated area of cooler panel
E = energy scattered
F_{1p}, F_{2p} = view factors
S = solar constant
α = solar absorptance

Subscripts
$1p$ = first reflection
$2p$ = second reflection

Introduction

THE mission of the Geostationary Operational Environmental Satellite (GOES) I-M series spacecraft is to provide a key element in the National Weather Service operations.[1,2] The ability to obtain improved atmospheric and oceanic observations enables the National Oceanic and Atmospheric Administration to gain a better understanding of the meteorological phenomena of the Western Hemisphere. These advanced data are especially useful for aiding in the ability to protect life and property through early storm warning. The primary instruments on the spacecraft are the Imager and Sounder. The GOES spacecraft configuration for the on-orbit deployed position is shown in Fig. 1. The spacecraft is in a geosynchronous orbit with the instruments, operating continuously facing the Earth. This spacecraft orientation exposes the instrument cavities to many hours of sunlight each day. The sunlight intrusion into the optical cavity increases outgassing. The increased outgassing allows for molecular deposition to increase on surfaces and potentially change thermal parameters.

Both the Imager and Sounder instruments are geometrically similar to each other. Each instrument cavity consists of a flat scan mirror and a Cassegrain-type telescope with a 31.1-cm-diam primary mirror and a 5.3-cm-diam secondary mirror. The Imager and Sounder instruments' main components are shown in Figs. 2 and 3, respectively. The Imager collects radiometric data in 5 distinct wavelength regions, and the Sounder collects data in 19 distinct wavelength regions. Both instruments contain visible and infrared channels. Thermal control of the main body of the GOES spacecraft is essentially independent of the instruments. On-orbit thermal performance of the instruments is maintained through louver cooling, electrical heating, and solar radiation. Two main areas of the thermal control system (TCS) for the instrument are 1) sensor module components and structure sidewalls and 2) the detector radiant cooler assembly. Each radiant cooler consists of approximately 180 optical solar reflectors (OSRs) and 8 vapor deposited aluminum (VDA) panels adjacent to the cooler patch and radiator. Figure 3 shows an expanded view of the Sounder instrument. The Sounder has a filter wheel cooler; whereas the Imager does not.

During the spacecraft fabrication process, contaminants may accumulate on hardware surfaces. Particulate or molecular films may increase scatter or adsorb energy at various wavelengths. This could result in a loss of optical throughput or signal-to-noise detector requirements or the decrease in the ability of a radiant cooler to dissipate heat from the cooler patch. The first part of this paper addresses the effects from molecular contamination, and the second part examines the particulate effects on thermal performance.

Molecular Contamination Effect on TCS

One of the significant contamination effects on the TCS is that outgassing products from spacecraft materials degrade system performance by changing thermal properties. Problems caused by changing thermal properties can occur when volatile condensable materials from spacecraft surface components and bulk material become redistributed onto critical thermal surfaces. This outgassing is most significant at the beginning of the mission and decays with time. Once the contaminants deposit on the critical thermal surfaces, undesirable changes in either emittance or solar absorptance may occur. For example,

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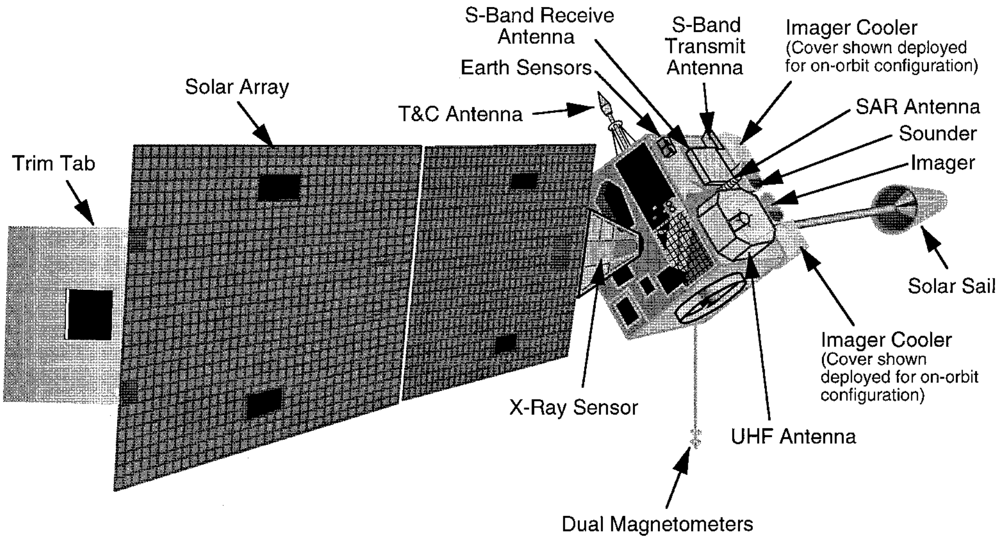

Fig. 1 GOES spacecraft on-orbit configuration.

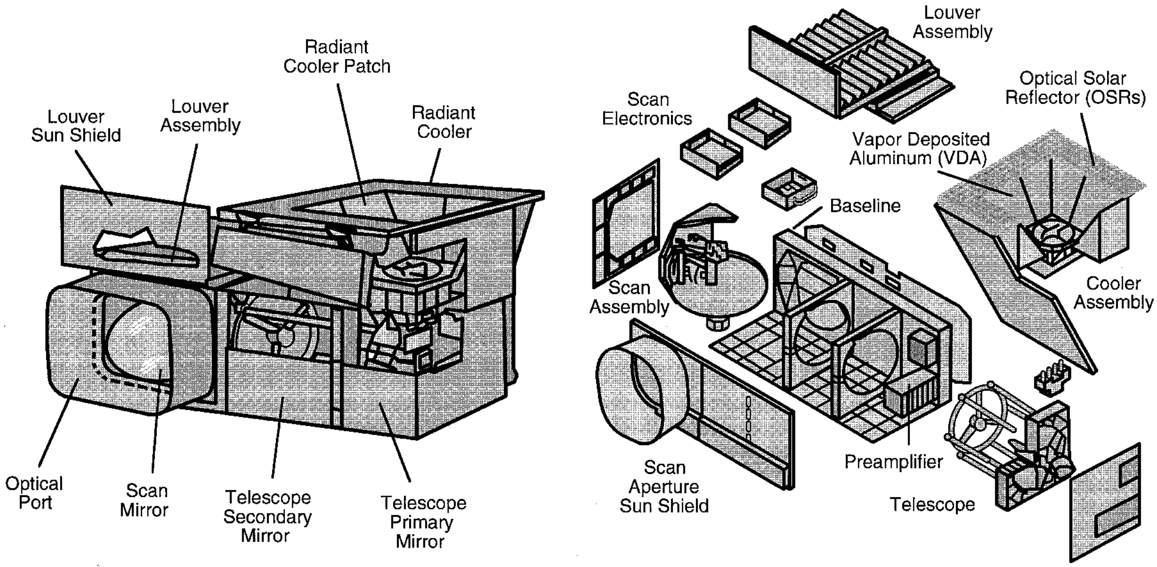

Fig. 2 GOES Imager instrument and expanded view.

quartz mirrors and aluminized or silvered Teflon® films show degradation in solar absorptance caused by contaminant deposition.[3] These changes would degrade further if synergistic uv and charged particles cause the contaminants to form a polymerized film.[4,5]

To address the high-temperature/paint outgassing concern of the cavity, a contamination assessment was conducted at the NASA Goddard Space Flight Center (GSFC). A series of activities for this assessment included the thermal coating outgassing tests, the analytical modeling, and the thermal performance predictions. A derived requirement recommendation from the assessment initiated an on-orbit solar radiation avoidance plan.

The assessment applied to three sets of instruments, which include the serial number SN/02 (pathfinder instruments), SN/03 (on 1994 launched GOES-I spacecraft), and SN/04 (on 1995 launched GOES-J spacecraft). Because of the different development and integration stages of the various spacecraft instruments, the paint configurations on various sets of instruments are not analogous.

Thermal Coating Outgassing Tests

Several types of paints were used in the instruments, depending on the desired thermal and optical requirements. Combinations of white Aeroglaze A276 and black Chemglaze Z306, NSB 69–82, and MSA 94B paints were applied in the cavities of the Imager and Sounder instruments. A detailed paint configuration for parts on the SN/02, SN/03, and SN/04 instruments is shown in Table 1. A thorough understanding of the type, condition, and location of the paints was necessary for determining the effects of outgassing on the thermal performance. Aeroglaze A276 and Chemglaze Z306 are commercially available polyurethane-based paints. Both NSB 69–82 (silicone-based) and MSA 94B (silicate-based) are black paints developed by NASA/GSFC. Because of schedule, material, and vacuum chamber availability, most of the Z306 paints on SN/02 were not subjected to high-temperature bakeout under vacuum conditions. Vacuum bakeout (i.e., $\leq 1 \times 10^{-5}$ torr) is an effective means for reducing outgassing products from materials. However, some parts were only high-temperature-processed using a conventional air-recirculating oven. These parts are identified as air in Table 1. Relatively small areas with higher predicted temperature were coated with NSB 69–82 to reduce outgassing concerns. For SN/03 instruments, most of the Z306 paints were vacuum baked at elevated temperatures. A276 was applied only on the back lower half of the scan mirrors. However, for the SN/04 instruments, most of the surfaces were replaced with MSA 94B, because it is an

Table 1 Paint configurations on SN/02, SN/03, and SN/04 instruments

Part description	SN/02	SN/03	SN/04
Calibration target	Z306, unbaked	Z306, 75°C/72 h, air	Z306, 65°C/72 h, vacuum
Scan mirror (back)	Z306, unbaked	Z306, unbaked/A276	MSA 94B, unbaked
Secondary mirror assembly	Z306, unbaked	Z306, 60°C/5 h, air	MSA 94B, unbaked
Limit frame	Z306, 125°C/48 h, air	Z306, 125°C/48 h, air	MSA 94B, unbaked
Primary cell	Z306, 125°C/48 h, air	Z306, 125°C/48 h, air	MSA 94B, unbaked
Structural bulkhead	Z306, 125°C/48 h, air	Z306, 125°C/48 h, air	MSA 94B, unbaked
Scan support plate	Z306, 125°C/48 h, air	Z306, 125°C/48 h, air	MSA 94B, unbaked
Electronic housings	Z306, 125°C/48 h, air	Z306, 125°C/48 h, air	MSA 94B, unbaked
Primary baffle	Z306, 125°C/48 h, air	Z306, 125°C/48 h, vacuum	MSA 94B, unbaked
INR[a] sunshields	Z306, 125°C/48 h, air	Z306, 125°C/48 h, vacuum	MSA 94B, unbaked
Limit frame sunshield	NSB 69-82, 250°C/48 h, vacuum	NSB 69-82, 250°C/48 h, vacuum	MSA 94B, unbaked
Baseplate sunshield	NSB 69-82, 250°C/48 h, vacuum	NSB 69-82, 250°C/48 h, vacuum	MSA 94B, unbaked
Calibration target sunshield	NSB 69-82, 250°C/48 h, vacuum	NSB 69-82, 250°C/48 h, vacuum	MSA 94B, unbaked
Optical port sunshield	NSB 69-82, 180°C/48 h, vacuum	NSB 69-82, 180°C/48 h, vacuum	MSA 94B, unbaked
Spider sunshield	MSA 94B, 210°C	MSA 94B, 210°C	MSA 94B, 210°C
Yoke ear sunshields	Z306, 125°C/48 h, air	MSA 94B, unbaked	MSA 94B, unbaked
Metering tube sunshields	Z306, 125°C/48 h, air	Z306, 125°C/48 h, air	MSA 94B, unbaked

[a]Image navigation and registration.

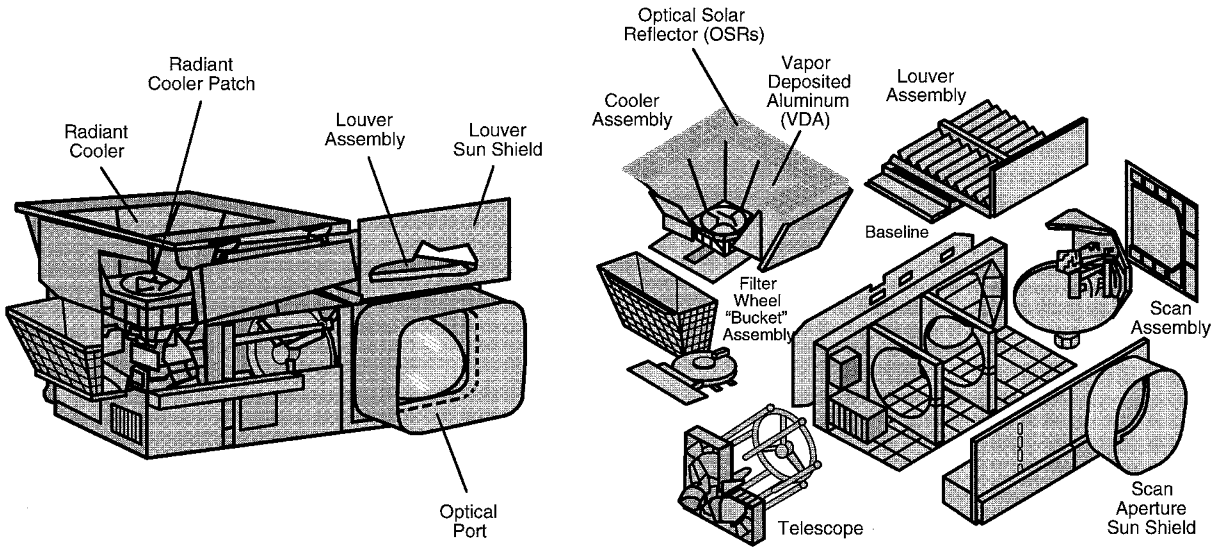

Fig. 3 GOES Sounder instrument and expanded view.

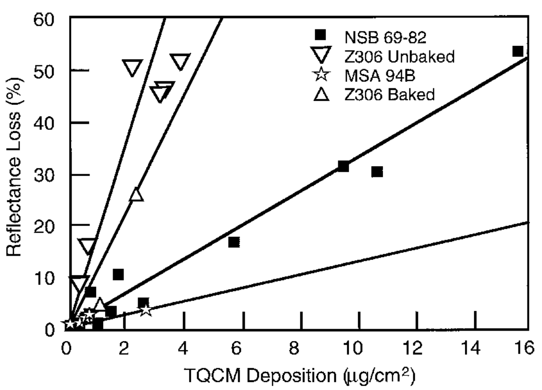

Fig. 4 TQCM deposition and witness mirror reflectance loss.

inorganic paint that exhibits negligible outgassing at elevated temperatures. Normal application of MSA 94B requires that it be applied directly on surfaces and cured for 14 days under ambient conditions. Because the spider sunshield reaches extremely high temperatures during the orbital cycle, the MSA 94B was required to be baked in an air-recirculating oven at 210°C. This high-temperature bakeout was performed as an added precaution to reduce any residual outgassing caused by the extreme temperature exposure of the spider sunshield.

In an effort to quantify the degree of outgassing and the effects of reflectance changes from outgassing, 32 paint samples were tested individually for a duration of 48 h each. Each test sample was spray-painted on a 6 × 4 in. aluminum plate and placed in a 2 × 2 ft top-loading, diffusion-pumped vacuum chamber. A Celesco/Berkeley MK9 temperature-controlled quartz crystal microbalance (TQCM) was used to detect the deposition of mass. A temperature-controlled witness mirror was used for reflectance loss measurement. After the test, the reflectance of the witness mirror was immediately measured as a function of wavelength. A metallic cylindrical cold finger was also applied to collect the contaminant for further chemical analysis. Figure 4 shows TQCM depositions vs witness mirror reflectance loss for all paints tested. Results demonstrated a clear correlation between the TQCM deposition and the mirror reflectance loss for each group of paint samples. Unbaked Z306 had the highest reflectance loss. As expected because of the low outgassing silicate, MSA 94B had the lowest outgassing as well as the lowest reflectance loss. Details of the setup and results of this outgassing test are described in Ref. 6.

Analytical Modeling

A complete Contamination Analysis Program (CAP) model for the GOES was developed by NASA/GSFC to analytically quantify molecular depositions on scan mirror surfaces. CAP is a generalized dynamic computer program capable of analyzing comprehensive molecular transport mechanisms in the free molecular flow environment. For the GOES model, the phenomena investigated included transient behavior of temporarily residing contaminant material, transient behavior of permanently deposited photopolymerized contaminants, and end-of-life (EOL) molecular deposition on mirrors.

The GOES model considered material emission and re-emission from the outgassing tests previously described. Transient solar data sets and uv effects on deposited contaminants were also incorporated in the analyses. The analyses predicted depositions on the various contamination-sensitive surfaces of the GOES Imager during its mission lifetime. For the deposition on each surface, individual contributions from each type of paint were also established.

According to the modeling results, permanent molecular deposition on the scan mirror was caused by solar uv fixing. Without the uv effect, the majority of the outgassed molecules eventually escaped through the large instrument aperture. In general, higher depositions were observed near the bottom of the scan mirror because of its proximity to the instrument calibration target. The distribution ranged from 47 to 125 Å for SN/02, 23 to 60 Å for SN/03, and 5 to 12 Å for SN/04. At the center of the scan mirror the contamination thickness prediction was 95 Å for SN/02, 45 Å for SN/03, and 10 Å for SN/04. Higher deposition on SN/02 was mainly contributed by the outgassing of unbaked Z306, especially from the calibration target.

Thermal Performance Predictions

The correlation with test and flight data for the scan mirror reflectance loss and solar absorptance change was based upon predicted contaminant thickness. The predicted reflectance loss at the center of the mirror was 16.2% for SN/02, 4.2% for SN/03, and 0.2% for SN/04. The solar absorptance caused by contamination was increased by 0.06 for SN/02, 0.03 for SN/03, and 0.01 for SN/04. Based on the average beginning-of-life (BOL) solar absorptance ($\alpha_{av,BOL}$) of 0.12, the average EOL solar absorptance ($\alpha_{av,EOL}$) had increased to 0.18 for SN/02, 0.15 for SN/03, and 0.13 for SN/04. Table 2 summarizes the results and impacts on the scan mirror caused by the outgassing contamination accretion. The results showed an overall performance improvement for the SN/03 and the SN/04 over the SN/02.

On-Orbit Solar Radiation Avoidance

Based on the analysis, the molecular depositions could be reduced by half, and the performance degradation could be improved from 15 to 7% for SN/03. It is obvious that the degree of performance degradation by uv photopolymerization is proportional to the length of sun exposure. To minimize the probability of uv effect, direct sun irradiation on the scan mirror was avoided after GOES was inserted into its orbit. This direct sun avoidance, known as the decontamination exercise, consisted of commanding the scan mirrors into a calibration mode (i.e., facing opposite to the sun) prior to solar incidence, and maintaining this position until temperature limits were reached. The scenarios are based upon SN/03 scan mirrors, BOL thermophysical properties, and a 10 N of equinox launch orbit. The intent of the on-orbit solar radiation avoidance exercise was to minimize the duration of sun exposure on the cold scan mirror surface in the early mission phase. When the first rays struck the scan mirror, the temperatures were 49.4°C for the Imager and 38.0°C for the Sounder. The exercise lasted 216 and 80 min for the Imager and Sounder, respectively. Then the scan mirrors were commanded back to the nadir position when the scan mirror/preamp temperatures reached 56.0°C/44.5°C for the Imager and 54.0°C/46.0°C for the Sounder. These temperatures were several degrees lower than the mission-allowable temperatures of 60.0°C/47.0°C. The daily activity of commanding the rotation of the scan mirrors was performed for 2 weeks on GOES-I in 1994 and GOES-J in 1995. The rotation of the scan mirrors was not originally baselined before these predicted analytical results. This exercise prevented the direct sun impingement on the scan mirror surface in the early outgassing stage of the spacecraft, thus reducing the possibility of contaminants polymerizing on the mirrors.

Table 2 Depositions and impacts on the scan mirror

Scan mirror	SN/02	SN/03	SN/04
Deposition, Å	95	45	10
Reflectance loss, %	16.2	4.2	0.2
Solar absorptance change, $\Delta\alpha$	0.06	0.03	0.02

Particulate Contamination Effect on TCS

Historically, spacecraft that are designated as communication satellites generally are processed without stringent particulate cleanliness controls, because they lack optical instruments. However, for the GOES I-M series spacecraft, two optical instruments required stringent cleanliness to preserve thermal performance. These controls were employed during manufacture, assembly, integration, test, and launch-site processing. In addition, temperature changes could affect the channel registration and focus stability of the instruments. The following text briefly describes the GOES instrument concerns for the thermal performance impacts as related to contamination control.

The main contamination effects on the TCS were the accretion of particles on the detector radiant coolers for both of the instruments and the filter wheel cooler for the Sounder instrument. The problem was the effect particles had on the specular properties of the radiant cooler and the resultant heat load input to the cooler patch. The particles caused specular surfaces to become Lambertian. This resulted in light rays becoming focused on sensitive areas of the radiant cooler and impacting thermal performance. Therefore, it was imperative that any contamination impact on the TCS be accounted for in the overall thermal performance design.

Since particulate contamination was determined to have the greatest potential impact on the cooler performance, the objective was to determine the degradation effects in terms of energy scattered from the VDA panels to the radiant cooler patch. An analysis was performed to determine the effect of energy scattered to the radiant cooler patch as a function of the obscuration ratio (OR). In the analysis, the view factors from the VDA surfaces to patch were generated using a Thermal Radiation Analysis System model. These data were used in conjunction with the Lambertian energy-scattering equation to determine the scattered energy and the patch temperature increase.

$$E = A \cdot S \cdot \left(\mathrm{OR} \cdot \sum F_{1p} + \mathrm{OR}^2 \cdot \sum F_{2p} \right) \qquad (1)$$

Note that in Eq. (1) only the first and second reflection terms are considered significant. Using this equation yields the re-

Table 3 Energy scattered as a function of obscuration ratio

Obscuration, %	SCL	Energy scattered (W) Panel angle, deg 25°	32°
0.05	341	0.002	0.002
0.15	430	0.007	0.005
0.20	456	0.010	0.007
0.30	496	0.014	0.010
0.40	524	0.019	0.014
0.50	550	0.024	0.017

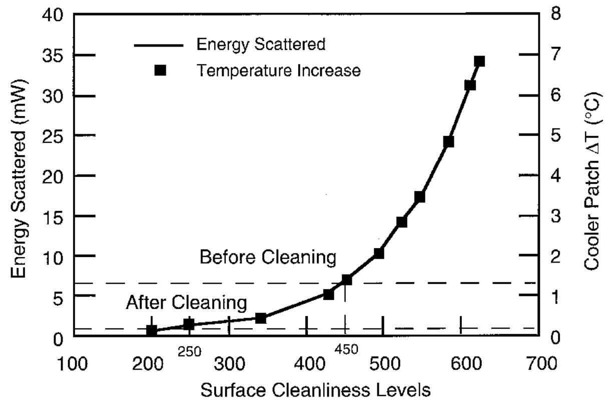

Fig. 5 SCL effects on energy scattered and cooler patch temperature change.

sults reported in Table 3. The two tilt angles that represent the instrument radiant cooler VDA panels are 25 and 32 deg. Table 3 also shows the relationship between obscuration ratio and energy scattered from two different VDA surfaces. Obscuration provides the area coverage that a particle has on a surface. The MIL-STD 1246 surface cleanliness level (SCL) values provided in Table 3 are based upon Ref. 7. Contamination control practices use the SCL method for quantifying the degree of cleanliness of a precision-cleaned surface. SCLs are usually obtained using microscopy methods from tapelifts of the actual surfaces or from an equivalent method, such as photographs.

The thermal budget requirement delineated that ground processing and launch contamination effects should only allow a temperature degradation of $\leq 2°C$. According to an established requirement for thermal heat load to the patch, a 10-mW budget was incorporated (Fig. 5). Figure 5 shows the relationship between SCL, energy-scattered, and the cooler patch temperature change. Prior to launch, the SCL of the cooler surfaces was measured as level 450. From Table 3, the corresponding particulate requirement to remain within 10 mW was 0.20% obscuration for the 25-deg VDA cooler panel. Without cleaning, this level of particulate contamination would have degraded cooler performance by 1.3°C.

Based upon performance, a quantifiable particulate cleanliness level of 450 per MIL-STD 1246 was established for the instrument radiant coolers. Since VDA is inherently soft and easily scratched when physically contacted, an effective, noncontact cleaning method and SCL verification needed to be developed and applied. The most effective cleaning method was CO_2 snow cleaning. This method proved to be adequate in removing particles from both the OSRs and VDA surfaces. Obscuration and SCLs were quantified using photographs to count particles of known size from established area dimensions. A SCL of approximately 250 was achieved after CO_2 cleaning. The cleaning reduced the cooler patch temperature degradation from 1.3 to 0.2°C. This improvement increased the margin for contamination allowance during launch and on-orbit activities.

The filter wheel (FW) cooler shown in Fig. 3 had VDA on the interior surfaces. Although the temperature constraints for the FW were significantly less restrictive than the radiant coolers, the CO_2 snow cleaning method was performed on the interior surfaces. Similar results were achieved on the FW cooler for SCLs.

Conclusion

Spacecraft thermal performance could have been adversely affected by solar absorptance changes caused by predicted molecular deposition on thermal control surfaces. Unbaked Z306 paint was identified as the major outgassing source. In the interest of enhanced thermal and optical performance, low outgassing MSA 94B paint materials were recommended in the instrument cavity for the SN/04 and follow-on instruments. The calibration target paint change was excluded on SN/04 because of the development stage of the target. Instead, the calibration target was vacuum baked at NASA/GSFC, and the Z306 on the back of the scan mirror was replaced with A276 to improve and minimize impacts to the thermal performance.

Modeling results suggested that permanent molecular deposition on the scan mirror was caused by solar uv fixing. Operational restrictions (on-orbit solar radiation avoidance) were imposed to avoid scan mirror uv exposure at the early stages of on-orbit mission operation. Rotating the scan mirrors to avoid sun impingement during the high initial outgassing orbital periods reduced polymerization effects.

Because of the small temperature margin of the GOES radiant cooler, predicted particulate contamination on the VDA surfaces represented a potential problem. Surface cleanliness requirements were developed for the instrument radiant coolers based upon a thermal heat load requirement to the patch. Quantitative results were obtained through CO_2 cleaning and verified by photographs. The requirements and verification methods formed the basis for ensuring that the thermal performance would not be compromised during ground processing activities.

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