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LDEF'S CONTRIBUTION TO THE SELECTION OF THERMAL CONTROL COATINGS FOR THE SPACE STATION

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ABSTRACT

The design of the Space Station presented new challenges in the selection and qualification of thermal control materials that would survive in low Earth orbit for a duration of up to 30 years. Prior to LDEF, flight data were obtained from Orbiting Solar Observatory (OSO) satellites, a number of Orbiter flights, and limited ground tests. The excellent data obtained from the OSO satellites were based on calorimetry and temperature measurements which were transmitted to Earth; these satellites were not recovered. For some of these flight experiments it was difficult to distinguish between changes due to contamination, atomic oxygen (AO), ultraviolet radiation (UV), particle radiation and the synergistic effects between them. The data from Shuttle flights were primarily focused on developing a better understanding of atomic oxygen (AO) effects. Although UV and AO were present, the relatively short duration of the Orbiter flights, about one week, was viewed as too short to show the effects from UV or possible synergistic interactions with AO and contamination. At the beginning of the program in 1989 there was no established design data base for AO resistant thermal control coatings for the Space Station. Then came the Long Duration Exposure Facility (LDEF). It provided the first long life data for materials exposed and recovered from space with a characterized environment. Post flight analysis proved data on the effects of contamination on optical properties in the ram (velocity) and wake directions and the erosion of Teflon and multilayer insulation (MLI) covers. The results from LDEF confirmed and, in some cases, modified the approach used for the Space Station, as well as helped to focus our development activities. These development activities resulted in a number of new technical solutions which are applicable to many spacecraft surfaces and missions. LDEF also showed the detrimental effects that could occur from silicone contamination, an issue that has not been completely resolved. An investigation was initiated in 1993 on the effects of silicone contamination and was continuing at the time this paper was prepared.

INTRODUCTION

The importance of identifying and qualifying long life thermal control coatings was established early in the evolution of the Space Station (SS) design. Satellite manufacturers have long been faced with the requirement to provide thermal control and have done so through a combination of thermal control coatings, multilayer insulation (MLI) blankets, louvers, heat pipes, and heaters. For many satellites the thermal control coatings were primarily used for radiator applications with the rest of the spacecraft enveloped in MLI blankets along with various other thermal control devices. For the size and limited life of most satellites, these design approaches were and are completely satisfactory.

However, early in the Space Station Program (SSP), it was decided that the structure would be exposed directly to the low Earth orbit (LEO) environment with a specified design life of 30 years. This decision was made because the MLI blankets and heaters would add additional weight and be power-intensive for long-life use, and because the blankets would impede astronaut access to hardware located on the structure. Figure 1(J30593S) shows a photograph of a typical satellite which is contrasted to the open and exposed truss structure of one of the SS segments.

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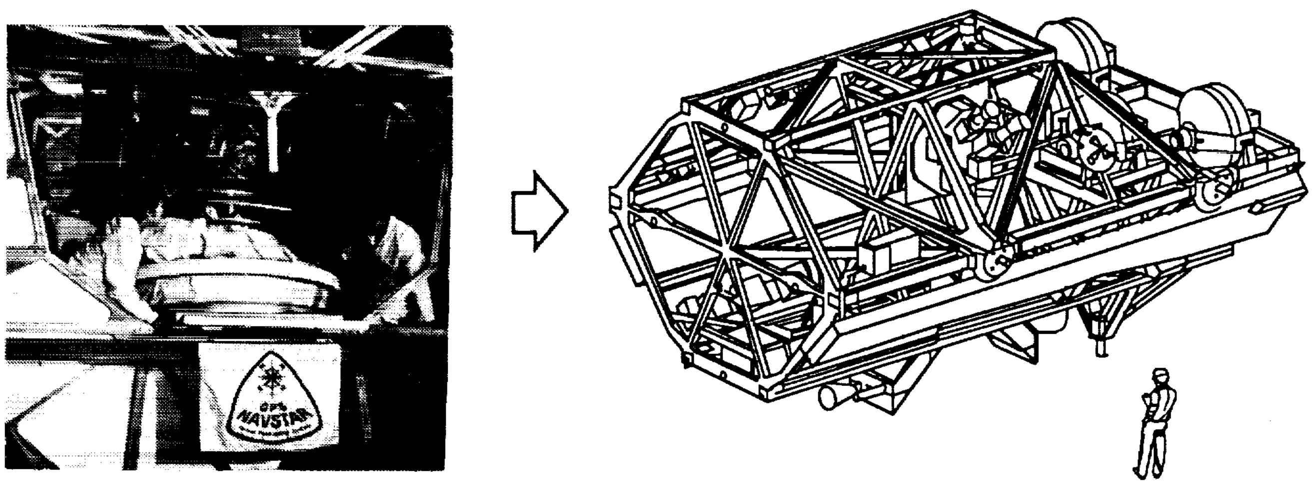

MLI Blankets and Heaters Exposed Anodized Structures

Figure 1. The open exposed truss stucture contrasted to a typical satellite design where the structure is covered by MLI

For the SS, there are three general areas where temperature restrictions exist. The SS has a variety of different fluids that are required to be kept within both low and high temperature bounds. These bounds are different for each fluid. The SS reboost fuel needed to be protected from freezing, which, for the hydrazine monopropellant fuel originally planned for the SSF, occurred at around 35°F. The fuel also had an upper storage temperature limit to ensure proper performance at the time it reached the thrusters. There were requirements for the astronauts' glove touch temperature to prevent frost bite or burning from contacting a surface that was too cold or too hot. Initially, the touch temperature was used as a requirement but was later modified to account for the mass of the structure being contacted. To ensure proper functioning of the electronic hardware there are also minimum non-operating temperatures as well as maximum temperatures that should not be exceeded, usually occurring during system operation. Finally, temperature variations that would lead to unacceptable distortions of the structure had to be prevented. In selecting passive thermal control coatings, MDA had to consider each of these factors as relevant to the particular design as well as the natural and induced environmental exposure.

SPACE STATION
THERMAL CONTROL DESIGN PRIOR TO LDEF RETURN

The exposed coatings on the segments have to survive a variety of different natural and induced environments. These include atomic oxygen (AO); ultraviolet radiation (UV); thermal cycling stresses during the approximate 90 minute day-night cycle; plasma coupling from the ionized residual atmosphere present at the SS altitude (typically around 180 to 240 nautical miles); the electron, proton, and heavy nuclei radiation, and the environments induced by man, including debris impacts and contamination deposition. For the initial design of the SS, which had an orbit inclination of approximately 28.5°, analysis showed that the 30 year particle radiation was a maximum of 10^6 rads silicone. This radiation dosage was sufficiently low that it would not affect any of the structural materials or thermal control coatings with the possible exception of fluorocarbon materials. No further consideration or analysis relative to particle radiation effects was made for the coatings and structural materials. Because the structure was solar-exposed, any coating had to survive the 175,000 thermal cycles experienced in 30 years in addition to the AO and UV. A typical thermal cycle is shown in Figure 2.(J30591S) Be cautioned that this is only an example, as the temperatures for any particular structure will depend on the coating, conduction paths, materials, mass, orientation, and shading from other structures. In addition to the natural environments, the effects of impacts from man-made debris on coating spallation and damage and the effects of the natural environment on any contamination on the coatings also had to be taken into consideration.

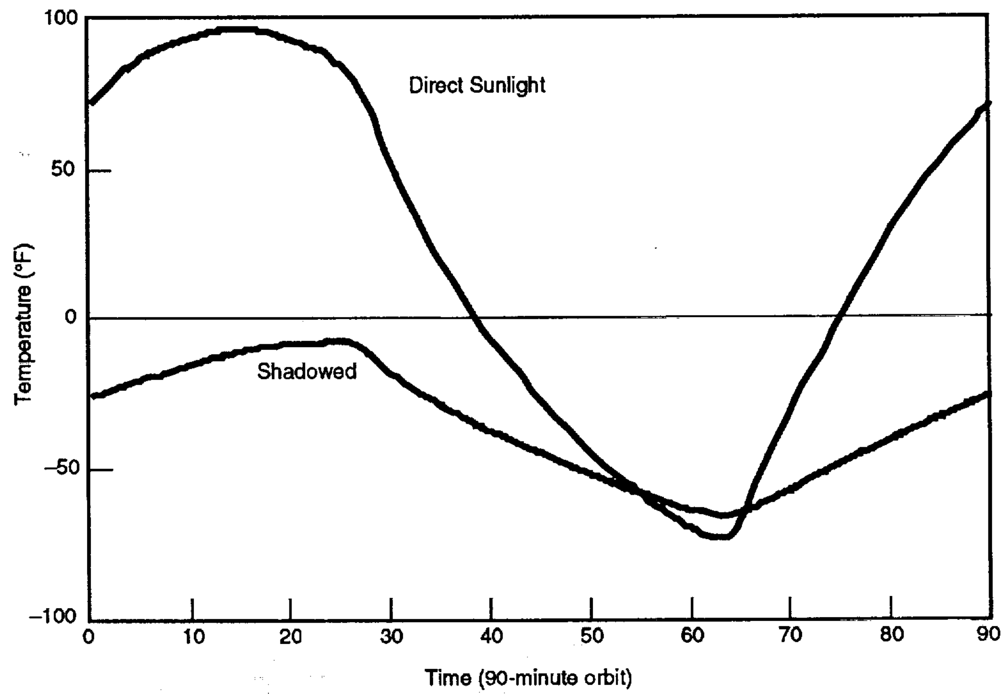

Figure 2. Typical thermal cycle experienced by a 2219 aluminum alloy truss element without shadowing from other structural elements

As for all hardware programs with defined schedules, a review was made of the available data and decisions were made based on those data augmented by additional ground and flight tests as schedules and funding constraints permitted. The SSP was started prior to retrieval and analysis of LDEF; the available data base at that time was limited. The flight data consisted of a number of Space Transportation System (STS) flights which were helping to develop an understanding of the AO effects on materials (References 1-3). In the mid 1980s there were no ground-based facilities operational that provided a good representation of LEO, although many groups were working on the development of such facilities. Plasma Ashers were primarily being used for AO screening purposes, but there was controversy among the specialists in the field as to whether they should be used since ashers do not accurately simulate several of the parameters of the LEO AO environment.

The other group of flight data had been obtained from controlled material experiments on satellites where telemetry was used to relay changes in temperature of the various samples back to Earth. Great care was exercised in these experiments to prevent contamination from masking changes induced by the natural environment, primarily UV, AO, and at higher altitudes, particle radiation. Although the UV is the same at various orbits, particle radiation and AO are different for higher orbits. The data available from OSO orbits was of limited value for assessing the individual effects of UV, AO and particle radiation (References 4-6). Ground testing for UV had been primarily conducted in the longer wavelength, near UV region, with only a few studies using the shorter, more energetic wavelengths in the far/vacuum UV region.

The prevailing viewpoint was that most of the designs up to that point were not close to the temperature limits and did not require more rigor in the analysis or testing. This may well have been true for the satellite applications, but was not true for the SS where numerous design applications arose that were close to allowed temperature limits. There was almost a complete absence of data of synergistic effects between AO and UV, particularly in the presence of contamination. The lack of these data created high uncertainties in end-of-life properties that were selected for design. A summary of the knowledge base at the time design activities for the SS were initiated in the late 1980s is shown in Table 1.

Table 1. Summary of design and test information available at the beginning of the Space Station Program in the mid-1980's

Item	Status
AO	• Erosion model based on one week Orbiter flights extrapolated to 30 years • Metals and oxides didn't erode and all appeared to be acceptable except osmium and silver, which oxidized
UV	• Some satellite data • Ground tests data, primarily near UV • Most effects seemed to occur in first 1000 sun hours of exposure
AO + UV	•None except limited satellite data
Contamination + AO + UV	•No data
Plasma coupling	• No test data • Coating resistivity data used as an indicator • Data obtained in air with only a few materials tested in vacuum
Debris hits	Essentially no data on thermal control coatings
Optical properties	•Beginning of life—data available or easily obtainable for most coatings •End-of life—estimates based on limited data

The early configurations of the SS had composite truss tubes which required AO protection. The AO protection was provided by an aluminum cover. Chromic acid anodize had been selected to provide the desired optical properties. This selection was based on the ground test results in preparation for LDEF (Reference 7) which showed very little change in absorptance when exposed to UV. The literature data for UV effects on sulfuric acid anodized coatings was primarily for coatings with low absorptances. These coatings showed significant increases in absorptance after testing ranging from 0.1 to 0.2 (References 5, 6, and 8).

The composite tube baseline design prevailed to 1990, at which time a major restructuring of the configuration was made. An aluminum truss structure was selected for the baseline design which replaced the composite truss tubes. The use of ceramic coatings was rejected as being impractical for the large aluminum bulkheads and truss elements. The issue then was what type of coating should be selected for the 2219-T851 truss materials. Anodic coatings were selected for study.

There were many other material areas in 1990 that had not been addressed, such as MIL covers. LDEF had been recovered during the time of the restructuring activity. From this point forward, LDEF influenced everything that was done for selecting environmentally exposed materials on McDonnell Douglas Aerospace (MDA) SS hardware.

INTEGRATION OF LDEF RESULTS

MDA contacted several of the principal investigators with trays on LDEF to obtain preliminary information that was being developed. A summary of this early information is shown in Table 2.

Table 2. Initial results obtained from LDEF

Material	Environmental Effects	Suitable for SS
Silicone Thermal Control Coatings	Contaminated LDEF; coatings darkened on wake side	No
Teflon	Erodes slowly, but faster than STS results	Yes, some orientations
MLI Kapton Cover	Completely eroded away	No
Other Organics	Erode unacceptably	No
Chromic Acid Anodize	Stable	Yes
Z-93	Stable	Yes

These results supported the judgments made based on the ground and flight data reviewed previously with one notable exception. Originally, silicone had been allowed, but based on the LDEF results, it was considered advisable to prohibit its use as a thermal control coating. Teflon also eroded faster than had been derived from the STS results, but this erosion rate could easily be taken into account by increasing the Teflon thickness. The 5-3/4 years that LDEF was in space thus provided the best information for extrapolating the expected condition after 30 years in space. The LDEF results confirmed our view that the outer surfaces of the SS should be either a metal, a metal oxide or other ceramic, or, for selected applications, fluorinated polymers such as Teflon. Based on these preliminary LDEF results, a set of ground rules were created and imposed on the effort being managed by MDA. These requirements and guidelines are listed in Table 3

Table 3. Ground rules and guidelines established for WP-2 hardware

Item	Ground Rules and Guidelines
Thermal Control Coatings	• Exposed surfaces—use a metal, a metal oxide or other ceramic, or in special cases, Teflon • Do not use any organics except Teflon • No silicone materials on exposed surfaces
	• MDA will develop an AO resistant outer cover
Lubricants	• Shield from AO and UV environments
Analysis	• Use LDEF results to calculate AO erosion including various angles of incidence to the velocity direction
Contamination	• Minimize use of all silicones • Include effects to determine end-of-life optical properties

There were no significant program reactions when these ground rules were established, except for lubricants. The responsible design engineers were not initially receptive to the additional weight associated with shielding all lubricated surfaces but eventually accepted this position.

MDA DEVELOPMENT ACTIVITIES AND RESULTS FOR ENVIRONMENTALLY EXPOSED MATERIALS

MDA's thermal design engineers requested that we provide nominal beginning-of-life (BOL) properties with guaranteed tolerance limits. After due consideration, we selected a 95% confidence level, i.e., plus and minus two standard deviations. This meant that the reproducibility of each of the processes selected had to be established. In addition, the thermal designers required that an estimate be provided of the end-of-life (EOL) optical properties, both nominal values and tolerances. The latter required evaluation of both natural environmental effects as well as contamination effects. Again, LDEF was a very important source of data to help make these assessments.

Anodizing

Although little data were available from LDEF for sulfuric acid anodize and none for 2219 aluminum, the use of anodic coatings in general was judged as the right approach. No optical property data existed for either chromic or sulfuric acid anodized coatings when this effort was initiated for this alloy. The initial focus of our activities was to develop controlled optical properties for the 2219-T851 aluminum truss structure. Although it was not a common aerospace practice to chromic acid anodize this alloy, studies were conducted on both chromic and sulfuric acid anodizing. The major differences in optical properties resulting from these two processes is illustrated in Figure 3. The optical properties of chromic acid anodizing (CAA) can be varied over a wider range than sulfuric acid anodized (SAA) surfaces, but CAA requires greater process control to ensure repeatability to obtain the desired optical properties. During this time period there was a great deal of discussion of the plasma coupling effects because of the voltage potential between the SS and the surrounding plasma. This potential difference was 140 volts. Limited ground test results indicated that the break down voltage of CAA was less than 140 volts while that of SAA was significantly higher than 140 volts. Based on these results and the processing studies conducted, SAA was selected as the baseline. Arbitrarily, the limit that the absorptance could increase at the EOL was set at 0.2 which was to account for environmental and contamination effects. Under laboratory conditions, short wave length UV (VUV) exposure of uncontaminated sulfuric acid anodized samples resulted in no change in absorptance although a small increase occurred after AO exposure. This was in contrast to the nonstructural, low absorptance aluminum alloys that had been tested previously which showed substantial increases in absorptance when exposed to VUV.

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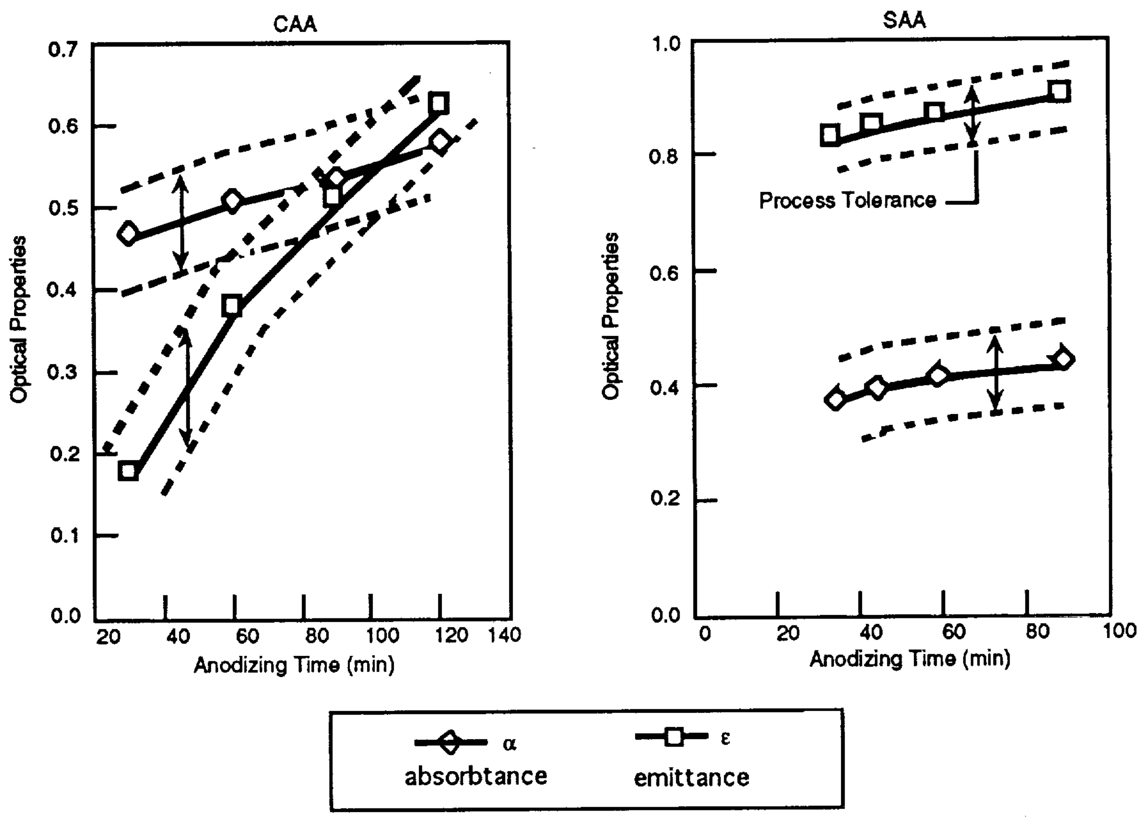

Figure 3. Difference in optical properties of CAA and SAA as a function of anodizing time

Silicone contaminated SAA 2219-T851 samples were exposed to VUV under laboratory conditions. The samples exhibited no changes in optical properties after exposure. The results were contrary to expectations since the CAA contaminated samples on LDEF had shown an increase in absorptance. After test of the SAA contaminated samples, surface analyses were conducted which verified the presence of silicone, but the amount of silicone present was not determiend. The exposure tests were repeated and the same results were obtained. The thickness of the inital contamination layer was slightly less than 4000Å and only one type of silicone oil was used as a model material (Reference 9). Subsequently it was learned that some silicones will evaporate when placed in a vacuum for several hours. Since in MDA's tests, the silicone was first deposited followed by UV exposure, it is conceivable that the silicone evaporated prior to being fixed to the surface in the VUV exposure test. The tests are scheduled to be repeated with UV radiation of the sample surfaces during contamination deposition. The results of this test are expected to better model the exposures that can be expected in space.

MDA's thermal designers also requested that stable (optical properties not altered by the environments) coatings be provided that also had an absorptance/emittance ratio of approximately one. A black coating was judged most likely to provide the required properties. The LDEF results also contributed to MDA focusing on anodizing processes with and without inorganic black dyes. The process finally selected was a one-step anodizing process know as the "Duranodic process," a special type of SAA process. The trade studies and evaluations conducted that led to this selection are reported in Reference 10. BOL tolerances were tighter than for standard SAA. Contamination deposition and UV exposures showed that the absorptance of this coating was not changed just as had been found for the standard SAA.

The results from the anodizing studies showed that commercial sulfuric acid anodizing processes including the Duranodic™ process provided consistent, reproducible results. Specialized processing controls were not required. In addition, silicone contaminated samples showed no change in absorptance after VUV exposure, but as already mentioned there are reservations as to the validity of the results and additional testing is being conducted. The results obtained to date are shown in Table 4.

Table 4. Environmental exposure of clean and silicone contaminated 2219 and 7075 aluminum

Alloy	Coating and Condition	Exposure	Results
2219-T851	SAA, Clean	Near UV	No change
		VUV	No change
		AO	$\Delta\alpha = -0.03$
	SAA, Contaminated ≤ 4000Å	VUV	No change
7075-T7351	SAA, clean	AO	No change
		VUV	$\Delta\alpha = +0.04$
7075-T6 clad	Black SAA, clean	VUV	No change
	Black SAA, Contaminated 375Å - 4000Å	VUV and AO	No change

Z-93

The original baseline for the large radiators was 5-mil thick embossed silver-Teflon. With the higher Teflon erosion rates experienced on LDEF, it would have been necessary to increase the Teflon thickness from 5 to 10 mils. This led to a trade study comparing 10 mil silver-Teflon with Z-93. Because of the 1200 pound weight savings, and the excellent performance of Z-93 on LDEF, Z-93 was selected as the new baseline for the active thermal control radiators as well as for many smaller, passive radiators.

For weight economies, MDA designers selected 2219 for the approximately 70 passive radiators rather than 6061 aluminum, the latter being the substrate most commonly used for Z-93. Since 2219 has poorer corrosion resistance, an evaluation was made of whether Z-93 could be applied to anodized aluminum, a process which had not been seriously studied previously. The results were highly successful and the baseline was changed from applying Z-93 to bare 2219 to applying Z-93 to anodized 2219 aluminum. The application of Z-93 to anodized aluminum is now generally accepted. A patent was awarded to Henry W. Babel and Huong G. Le for this concept, Patent No. 5,296,285, entitled "High Emittance, Low Absorptance Coatings."

The margins associated with thermal activities required a high confidence in the optical properties used. Measurements of the absorptance of Z-93 by various instruments led to the understanding that significantly different results are obtained depending on the instrument. A comparison of three instruments is shown in Table 5.

Table 5. Comparison of Z-93 absorptance measurements with three different instruments on the same sample

Measurement Device	Absorptance Value
Gier-Dunkle MS-251	0.101
Spectrophotometer, Perkin-Elmer Lambda 9	0.134
Surface Optics Spectrophotometer and Infrared Reflectometer	0.169

The results using an infrared reflectometer that measures reflectance from 1.6 to 25.0 microns showed that there is a large drop in reflection between 2500 and 3000 nanometers and the reflection remains low above 3000 nanometers. Spectrophotometers used to measure solar absorptance have a cutoff at or below 2500 nm. The true thermal behavior of Z-93 is best approximated by the value 0.169 instead of 0.12 or 0.134. The value 0.169 was used in conjunction with tolerances in our thermal design analysis. The differences described above had not been reported previously in the open literature. Most other coatings tested did not exhibit such differences because their reflectance did not change as dramatically as Z-93 in this region, in which there is still a significant portion of solar energy present.

MLI Cover

Post flight analysis of LDEF has provided MDA and the technical community in general with an understanding of the effects of long space exposure on MLI. The results showed that the blankets performed well after multiple small debris hits. Also the blankets continued to function even after the cover had been eroded away. Double aluminized layers were not eroded away, although significant undercutting at debris hits was evident. The conclusion that could be drawn was that MLI would be satisfactory for the Space Station Program and that the blankets could be made more durable if an AO resistant cover was developed.

The cover not only had to be AO resistant, but in addition, the thermal designers wanted a light-block (zero transmission of solar radiation) and optical properties similar to that of Beta™ cloth, i.e., high emittance and low absorptance. After conducting various screening tests, PTFE Teflon-impregnated Beta cloth was selected with vapor deposited aluminum on the back side. The tight weave used in fabricating the Beta cloth helps protect the underlying Teflon from AO erosion. The Beta cloth is to be woven without the use of a silicon or other sizing material that darkens under UV exposure. The trade studies conducted are reported in Reference 11.

To make the entire blanket AO resistant, designs were developed to protect the hook-and-pile (Velcro™ type) attachment favored by the astronauts, and MDA learned to machine sew with glass, but had to hand sew with quartz threads in exposed areas. All these features are shown in the blanket schematic shown in Figure 4.

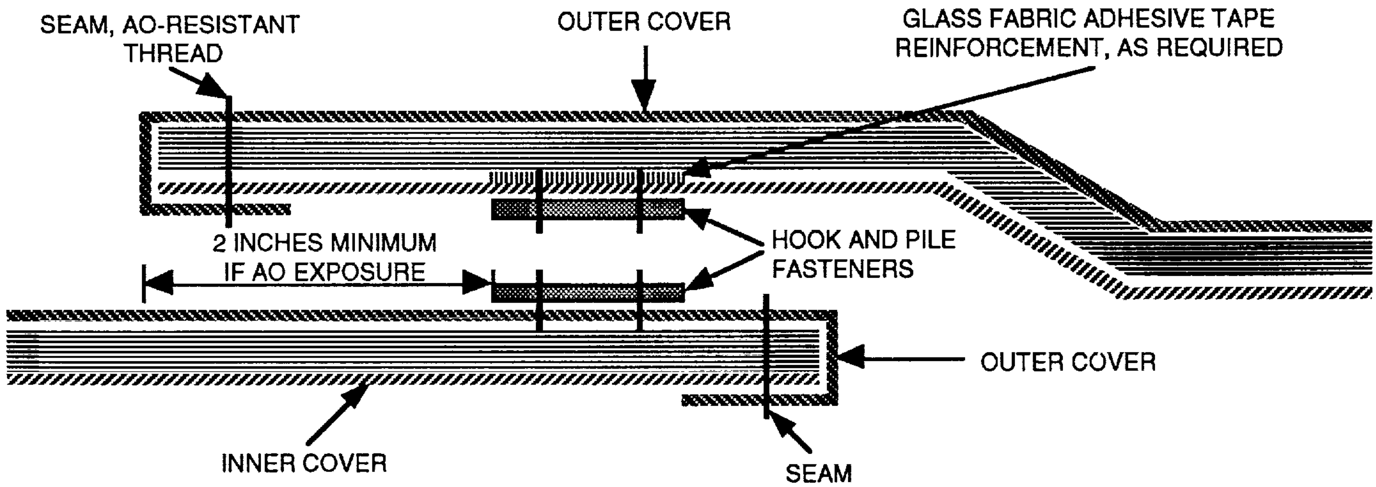

Figure 4. MLI blanket design to protect AO susceptible materials

BENEFITS THE SSP DERIVED FROM LDEF RESULTS

The results from LDEF provided a great service to the SSP. Significant economies were realized because trade studies could be limited and focused. With today's high level of technology, there are often many alternatives to consider when developing a design solution. This focus also resulted in MDA re-examining a number of commonly held perceptions and discovering that test data were lacking to support these perceptions. In a number of cases it was later shown by test that approaches previously not extensively evaluated were viable. These efforts have directly contributed to advancing the state-of-the-art of thermal control coatings for long life spacecraft. Those discussed in this paper are summarized below.

1. Z-93

   a. MDA showed that the bond integrity of Z-93 to anodized aluminum was excellent. Z-93 had not been applied in production applications to anodized aluminum.

   b. MDA showed that different measuring instruments used on Z-93 result in different values of absorptance. The absorptance value to be used for design is higher than that used for previous designs with Z-93.

2. Sulfuric acid anodize

   a. MDA showed that reproducible optical properties within acceptable tolerance ranges are obtainable with commercial processes. Conventional and black coatings were qualified for Space Station use.

   b. MDA's ground tests results to date have shown that the absorptance of structural alloys did not increase after contamination with one model silicone material, but there are reservations whether the test procedures could have produced erroneous results. Additional testing is scheduled to better model the exposures that can be expected in space.

3. MDA developed and qualified AO resistant MLI covers with light blocks and developed MLI designs using AO resistant threads and AO protected attachment techniques.

4. MDA is continuing to develop a data base on the response of thermal control coatings to UV exposure after receiving deposits of various amounts and different kinds of contaminants.

It was found that many of the ideas above and others inspired by LDEF were sufficiently novel that patent applications have been made. One has been issued and five others are still pending.

CONCLUSIONS

At the time this paper was prepared, the Space Station configuration was being restructured to include the Russian hardware. The work described here will have SS applications independent of the final configuration selected. This technology represents basic building blocks that can be used for the SS and many other future spacecraft.

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