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Lessons Learned From the Long Duration Exposure Facility

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The Long Duration Exposure Facility (LDEF) was launched by the space shuttle in April 1984 and recovered in January 1990. There were 57 experiments containing over 10,000 specimens to test the effects of the space environment on materials, components, and systems. Originally planned for one year, the exposure actually lasted almost six years. While many LDEF investigations are continuing, results to date have given valuable information on long-term performance in orbit. Results from the LDEF investigators and the Special Investigation Groups are briefly summarized along with potential benefits from LDEF for future missions.

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PREFACE

The contributions of the LDEF investigators in the Mechanics and Materials Technology Center are gratefully acknowledged, especially S. Gyetvay, C. S. Hemminger, M. Meshishnek, and G. L. Steckel.

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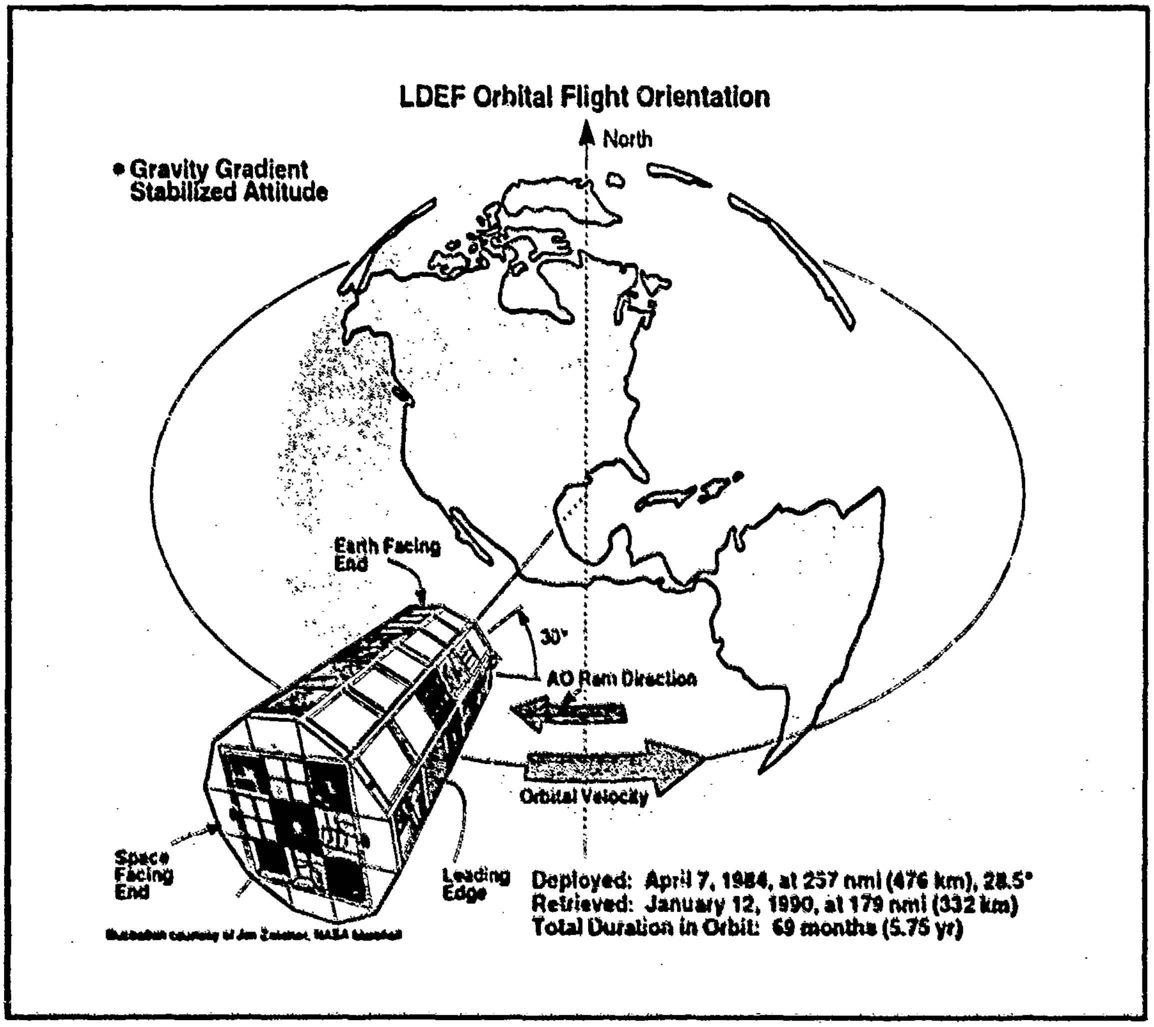
1. THE LONG DURATION EXPOSURE FACILITY

The Long Duration Exposure Facility (LDEF) was launched on April 7, 1984, into an orbit at 257 nmi, 28.5°, and retrieved on January 12, 1990, at 179 nmi. The 69-month duration in orbit resulted in far longer exposures of material surfaces than other hardware returned from orbit, such as the short duration shuttle experiments or hardware from the Solar Max Repair Mission. LDEF was a gravity gradient stabilized vehicle, controlled by a viscous damper that performed as expected to maintain one surface of LDEF always into the velocity vector, within 1° in stability. The vehicle was approximately 9.14 m (30 ft) long and 4.27 m (14 ft) in diameter with 86 experiment trays. These trays were oriented around the vehicle in 12 rows of 127-cm (50-in.)-long and 86-cm (34-in.)-wide trays with additional trays on the earth and space ends. One row of samples was always on the leading edge, facing into the velocity vector as shown in Figure 1.



Deployed: April 7, 1984, at 257 nmi (476 km), 28.5°
Retrieved: January 12, 1990, at 179 nmi (332 km)
Total Duration in Orbit: 69 months (5.75 yr)

Figure 1. Long Duration Exposure Facility Flight Orientation.

During the mission, the leading-edge materials were exposed to ~9 x 10^{21} oxygen atoms/cm^2, a level where erosion of over 10 mils would be expected for many polymers. The trailing edge exposure was only about 10^4 oxygen atoms/cm^2 so effects of the ultraviolet and other environmental exposures were not significantly altered by the atomic oxygen exposure. Trailing-edge samples are, therefore, more representative of higher altitude spacecraft exposures. The solar exposure ranged from about 5,000 to 14,500 equivalent sun hours, depending on location on LDEF, with 34,200 thermal cycles. The radiation environment was ~2.5 x 10^5 rads of electron and 1.6 x 10^3 rads of proton radiation (Ref. 1).

There were 57 experiments on LDEF with over 200 Principal Investigators and well over 10,000 test samples. In addition, NASA formed four Special Investigation Groups: Materials, Systems, Ionizing Radiation, and Meteoroid & Debris. The results of these investigations to date have been presented at LDEF Symposia, and proceedings are becoming available. An overview of some of the results that are significant to spacecraft materials performance and testing is presented herein.

2. THERMAL CONTROL MATERIALS

The LDEF observations on thermal control materials are particularly significant since these materials represent a large fraction of the external surface of any spacecraft. While atomic oxygen effects on the leading edge are only significant for low earth orbits (LEOs), the trailing-edge samples show the effects of ultraviolet radiation. The thermal-control properties (alpha/epsilon) of organic binder paints, commonly used for their ease of application, have been observed to degrade by as much as a factor of 3 on the trailing edge, but are essentially unchanged on the leading edge. The polyurethane paint, A276, was present on LDEF hardware completely around the vehicle so the effects of orientation on performance of the paint could be clearly measured as shown in Figure 2 (Ref. 2). The trailing edge clearly shows the degradation of the paint by the solar ultraviolet (UV) while the degraded material on the leading edge has been removed by the atomic oxygen erosion to maintain properties close to the initial values.

The Thermal Control Surfaces Experiment provided on-orbit data on thermal properties of 25 materials during the first 18 months of the mission (Ref. 3). The inorganic binder paints, such as Z93 (zinc oxide in a potassium silicate binder) and YB-71 (zinc orthotitanate in a potassium silicate binder), were shown to be stable in the LEO environment. Some thermal-control materials degraded more, others less, than predicted. The 5-mil silver FEP Teflon blankets were visibly

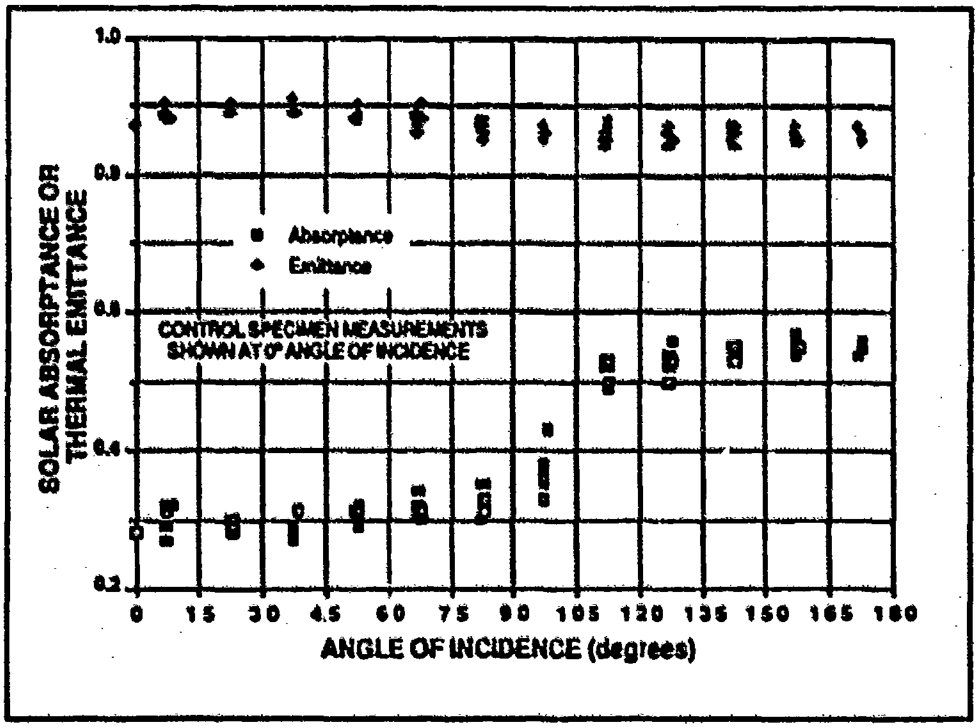


Figure 2. Optical Properties From A276 White Thermal Control Discs (Ref. 2).

altered during the LDEF mission, but did not degrade significantly in thermal properties except in those areas that were contaminated. However, caution should be used in other applications depending on the thermal blanket thickness and the planned orbit. LDEF has permitted the first orbital measurement of the erosion of the Teflon layer on these blankets by atomic oxygen; previous attempts could not measure the thickness decrease of the Teflon. The ~1 mil of erosion observed is apparently due to synergistic effects of the UV and atomic oxygen environment (Ref. 4). For the trailing-edge blankets, the UV exposure caused polymer chain scission at the surface and resulted in decreases of percent elongation to failure and ultimate tensile strength (Ref. 5). Another effect observed on LDEF silver FEP Teflon blankets was the severe degradation associated with cracked silver-inconel layers. Improper application, which produced cracking of the metallization, allowed migration of the Y966 adhesive through the metallization and subsequent darkening by solar UV.

3. POLYMERS/COMPOSITES

Good agreement with earlier measurements of atomic oxygen reaction efficiency is being reported in the preliminary results for many polymeric spacecraft materials. The amount of erosion experienced on LDEF was over 10 mils for Kapton, known to be a reactive polymer to atomic oxygen. Previous data from the Effects of Oxygen Interaction with Materials (EOIM) missions and other experiments had given reactivity values of 3.0 x 10^{-24} cm^3/oxygen atom, corresponding to a prediction of 10.6 mils of erosion for the LDEF fluence. The higher erosion observed for Teflon surfaces, as mentioned previously, indicates that the erosion of Teflon surfaces can have reactivities as high as 0.36 x 10^{-24} cm^3/oxygen atom in the presence of the UV radiation associated with LDEF (Ref. 6). More recent data on atomic oxygen effects is becoming available with the August 1992 flight of EOIM-III on STS-46.

There was a wide variety of composite samples on LDEF, well over 500 samples of various composition. The atomic oxygen erosion of organic matrix composite surfaces has proven to be interesting from the point of view of the unexpected surface morphologies (Ref. 7). The mechanical properties seem to be modified only by thickness loss associated with the atomic oxygen exposure on the leading edge. However, the response of the composites monitored on orbit has provided valuable data on the performance of composites in the space environment. On-orbit temperature and strain data, shown in Figures 3 and 4, have clearly shown the

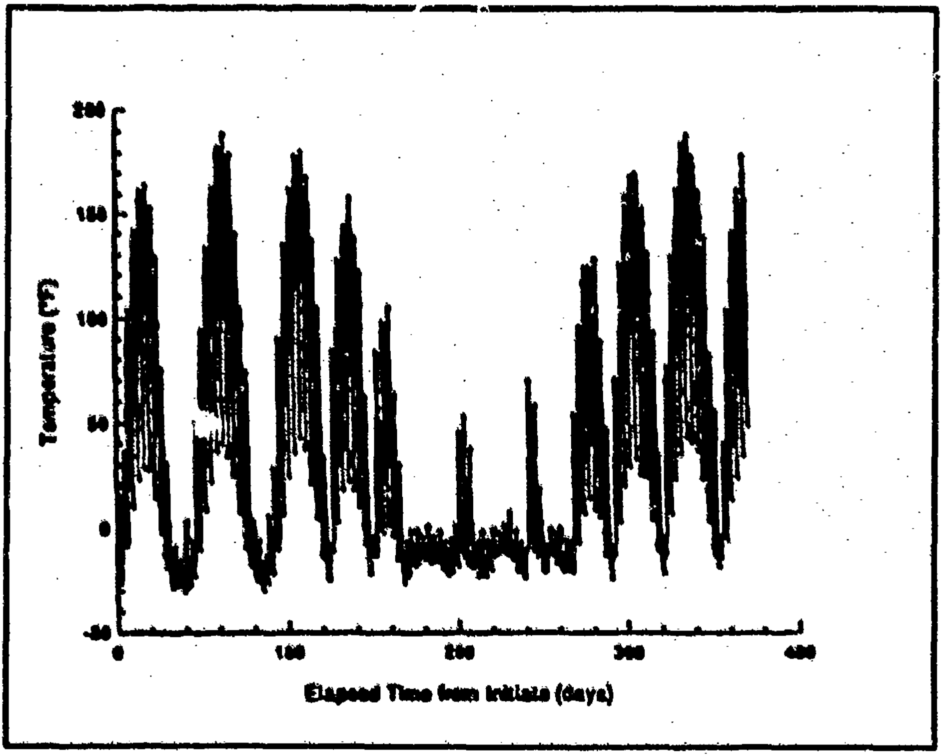


Figure 3. On-Orbit Thermal/Time Response of T-300/934 at 16-Hr Intervals (Ref. 8).

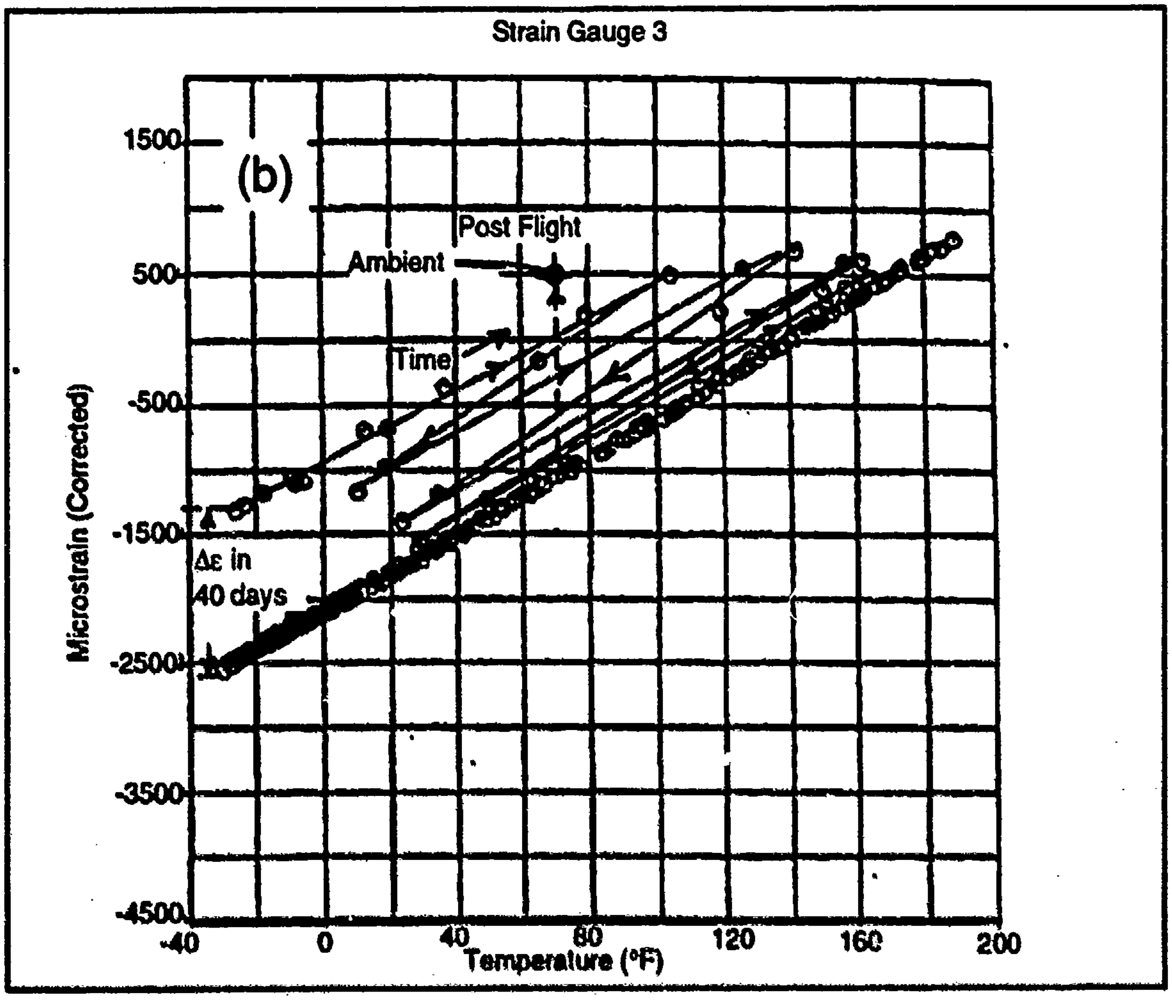


Figure 4. On-Orbit Strain/Temperature Response at 16-Hr Intervals (Ref. 8).

dimensional change associated with moisture dryout and the coefficient of thermal expansion (Ref. 8). The moisture dry-out and the associated dimensional changes for epoxy matrices are well known and were shown to require about 100 days for 4-ply T300/5208 epoxy samples.

The ultimate coefficients of thermal expansion (CTEs) observed were consistent with ground measurements and did not show any degradation on orbit. Also, interesting effects were observed associated with thermal cycling of these materials in the space environment. Thermal gradients introduced during the short solar exposure in a 90-min orbit were shown to produce the transient responses shown in Figure 5. This apparently negative CTE is consistent with bending or a deflection. This is observed in epoxy composites such as GY70/X30 but not in metal matrix composites such as P55/6061 (Ref. 9). There are few if any indications of microcracking due to thermal cycling in these composites.

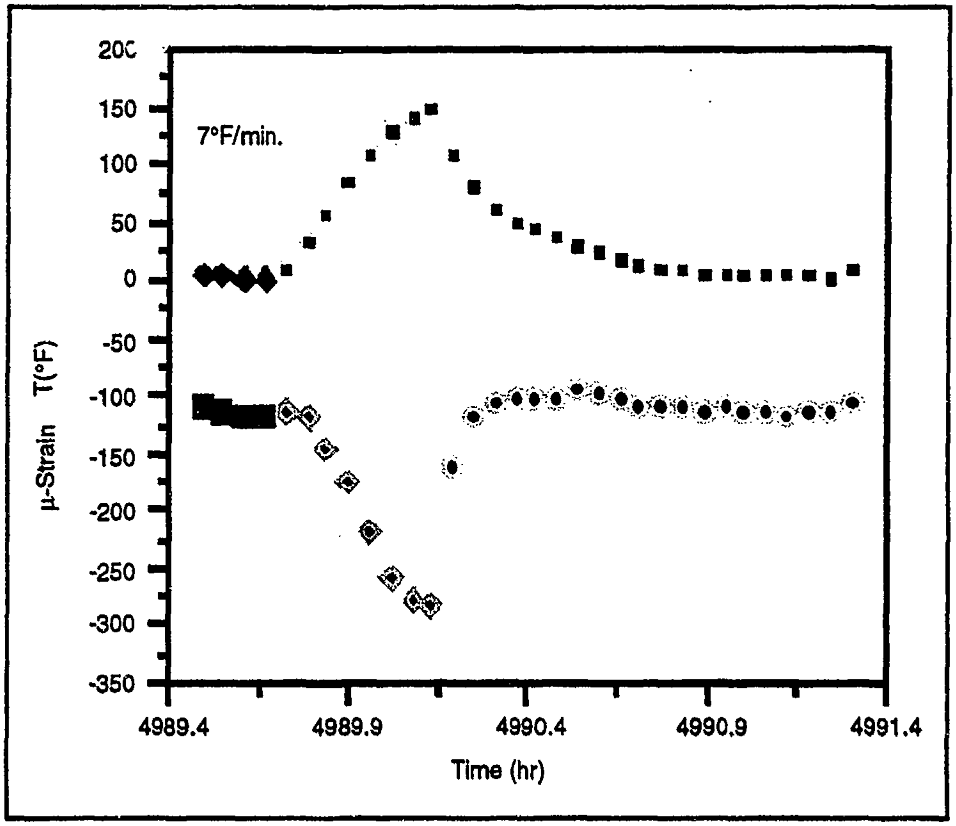


Figure 5. Flight Data from GY70/X30 (0/45/90/135)2S - Trailing Edge (Ref. 9).

4. OPTICAL MATERIALS

Optical materials demonstrated a variety of effects as a result of their exposure on LDEF. Contamination was primarily responsible for degradation in many instances, and, in some cases, removal of the contamination resulted in restoration of the original properties. However, meteoroid and debris impacts were responsible for irreversible damage to many optical materials, fiber optics, and solar cells. While contamination dominated the observations in many optical systems, interesting effects have been reported, such as shifts in the spectral transmission of filters, changes in the fluorescence spectra of paints, and synergistic effects on thin-film coatings due to the low Earth orbit environment of atomic oxygen, meteoroid and debris impacts, and UV radiation (Refs. 10,11).

5. METEOROID AND DEBRIS IMPACTS

LDEF provided large areas for the study of the impacts of man-made orbital debris and natural meteoroids on spacecraft surfaces. Prior to the LDEF recovery, the impacts on the trailing surfaces of LDEF were expected to be almost entirely meteoroid. However, analyses of the residues have shown that over 30% of the impacts were from debris. This implies that there is a high population of debris particles in highly elliptical orbits, most likely associated with geosynchronous transfer orbits. Also, there is a strong time variation of the flux striking LDEF, as measured by active impact detectors on six axes. The spatial density of impact craters is much greater on the leading edge compared to the trailing edge, with ratios of 10 to 20 depending on the size range. The materials' responses to particle impact ranged from complete penetration of up to 40 mils of aluminum to damage affected zones in paints and thermal blankets that extend to several diameters of the impact crater. The analyses of the over 34,000 impacts of 50 μm and greater on LDEF surfaces, with the largest 0.57 cm in diameter, is giving us a much better basis to improve the models of the meteoroid and debris populations in near-Earth orbit.

6. CONTAMINATION

The contamination observed on LDEF has ranged from highly visible deposits that were a characteristic deep brown to areas that were essentially contamination-free. There are areas on LDEF that were exposed to outgassing from components or materials, which has resulted in heavy deposition that increases the solar absorption and would severely degrade optical components (Ref. 12). The areas with the heaviest deposits are consistent with the photoenhanced deposition known to occur when contaminants arrive at surfaces exposed to the solar UV radiation. In addition, those surfaces on the leading edge were often covered with contaminants that resulted from the atomic oxygen reactions that formed stable, tenacious deposits. Of particular interest are the comparisons of identical samples that were on the leading and trailing edges of LDEF. The Secondary Ion Mass Spectrometry depth profiles on the surfaces of quartz crystal microbalance crystals clearly show the presence of silicon on the surfaces of both the leading edge and trailing edge, but the amount of residual silicon is higher on the leading edge (Ref. 13). Similar results were observed by X-ray photoelectron spectroscopy, which analyzes ~50-100Å surface layers (Ref. 14). These results show that while silicon is higher on the leading edge, the carbon is higher on the trailing edge. The loss of carbon compounds on the leading edge is undoubtedly the result of the atomic oxygen reactions that occurred on the leading edge while higher silicon levels are related to the higher return flux of silicone contaminants on surfaces facing into the velocity vector. Notice that in these and many other analyses, the substrate materials are still observed, which indicates that in these areas on LDEF, the thickness would correspond to ~100Å. This amount of contamination causes minimal degradation in thermal properties of thermal control surfaces like second-surface mirrors and appears to be the approximate level of molecular contamination associated with experimental trays such as the M0003 experiment on the leading and trailing edge of LDEF. However, this contamination can affect optical properties such as transmission of optical components and optical scatter. Particulate contamination and the residues or damage from meteoroid and debris impacts can result in significant additional contamination effects on performance of spacecraft materials.

7. SUMMARY

The data obtained in LDEF analyses to date have confirmed that most of the models used to predict the effects of the space environment on materials are satisfactory. There have been a number of significant observations of spacecraft material stability that are of importance to thermal control, contamination, and the synergistic effects of the ultraviolet radiation and atomic oxygen environment. While the observations of high levels of contamination are partly due to the lack of consistent contamination control by the experimenters, the fixation and tenacity of contamination deposits on the trailing edge in the presence of UV radiation and on the leading edge in the presence of UV and atomic oxygen underline the importance of contamination control in all spacecraft programs. The impacts and penetrations of the orbital micrometeoroids and debris collisions may have significant implications on the performance of spacecraft systems. Data bases now available to the technical community include the M0003 Data Base (Aerospace), LDEF Materials Data Base (MAPTIS/Materials SIG), LDEF Optics Data Base (Boeing/Systems SIG), and the Meteoroid and Debris Data Base (NASA-JSC). Work is continuing on documentation of the environmental effects of the samples returned from LDEF and updating models of the orbital environment.

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