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# Effects of 69 Months in Low Earth Orbit on Kapton Antenna Structures

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**The overall objective of the long-duration exposure facility (LDEF) experiment A0133, effects of the space environment on a space-based radar phased-array antenna, was to evaluate components considered for an antenna concept. Of primary interest was degradation of the polyimide film Kapton (DuPont trademark), the material considered for use in the antenna planes. The most striking result was the overall good condition of the Kapton antenna planes and tensile panels, despite nearly six years of exposure to the space environment. This was largely attributable to the orientation (parallel and flush on the space end) and the stability of LDEF in orbit. However, weathering of exposed Kapton surfaces was not insignificant. Results on elongation and mechanical properties of the plain and the fiberglass-reinforced Kapton are presented. The second objective was to investigate the interaction between high-voltage electrodes and typical spacecraft contaminants in simulation of discharge triggering across differentially charged dielectric surfaces (spacecraft charging conditions). Electronic data acquisition and memory systems appeared to operate correctly, but very few discharges were recorded. Induced radioactivity, contamination, impacts, and orientation features of atomic oxygen erosion were observed.**

## Introduction

LARGE space structures of low areal density are being developed for applications such as phased-array antennae for space-based radar (SBR) and the Earth observation system (EOS). The practical implementation of these structures depends largely on identifying low-cost, low-density, high-strength-to-weight materials that are not degraded by the geosynchronous Earth orbit (GEO) or the low Earth orbit (LEO) environments. Polymeric materials satisfy many of these requirements; however, the long-term stability of these materials exposed to the space environment is a major concern. This is because chemical bonds within polymers are susceptible to some degree of degradation from either ultraviolet or charged-particle (particularly high-energy electron) components of the space environment. Atomic oxygen erosion is a concern in the EOS application environment, but it becomes less of an issue at the higher altitudes flown by SBR.

The primary objective of experiment A0133 was to determine the nature and the extent of degradation that materials chosen for the antenna concept suffered during prolonged exposure to the LEO space environment. Kapton films for space blanket and substrate applications have been studied since the late 1960s.[1,2] The principal material studied in this report is DuPont's Kapton H polyimide, poly[N, N′-(p, p′-oxidiphenylene) pyromellitimide], which was selected in 1978 as a baseline material to be used for load-bearing, dimensionally critical structure in the phased-array antenna plane. The effects of atomic oxygen in LEO became widely known in the 1980s,[3,4] leading to concern about the viability of this experiment. The tray housing this experiment was located at the space end of the long-duration exposure facility (LDEF) satellite (bay H, row 7). A photograph of the experiment tray, taken prior to its integration intothe LDEF satellite in 1983, is shown in Fig. 1. Roughly one-half of the area was occupied by tension assemblies containing panels of Kapton and glass/Kapton maintained at one of four stress levels. It was of interest to determine the mechanical integrity, dimensional stability, and extent of physical property degradation these panels suffered from long-duration exposure to the space environment. The remainder of the tray contained a portion of the SBR antenna plane and active electronic components. The electronic components included a high-voltage power supply, timing control circuitry, and a memory system. This part of the experiment was designed to investigate discharge triggering across high-voltage electrodes and to determine the effects of the subsequent high-voltage discharge events on the Kapton of the antenna plane.

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## Materials and Methods

### Materials

Kapton H polyimide sheets were obtained from DuPont. A 75-$\mu$m-thick material was used to construct a polyimide/glass scrim/polyimide reinforced structure. The glass scrim was bonded to the polyimide films using a thermoplastic polyester adhesive (Sheldahl T100). Since the proposed antennae are large, e.g., 20×60 m, and the Kapton is provided in 1-m-wide rolls, the antenna plane must be fabricated with splices. Accordingly, each panel contained a central splice region approximately 2 cm long. Sheets of plain Kapton (127 $\mu$m thick) and glass/Kapton (196 $\mu$m thick) were cut into panels with widths of either 2.54 or 1.27 cm and lengths of about 50 cm. Eight 2.54-cm-wide panels and 16 1.27-cm-wide panels, affixed to a tension module that maintained constant stress levels, were exposed directly to the space environment. A like number of "shadowed" panels were on board. For clarity these space-exposed and shadowed panels will be referred to as flight space panels and flight control panels, respectively. The flight control panels experienced limited thermal excursions, were exposed to a minimum of solar and charged particle radiation, and were protected from direct atomic oxygen and micrometeoroid and debris impact. Four stress levels, 0.31, 1.03, 2.07, and 3.10 MPa (45, 150, 300, and 450 psi), were selected, based on anticipated average sustained and peak local stresses for Kapton. The maximum stress was selected to accelerate the extent of creep. The Kapton and glass/Kapton sheets from which these panels were cut were stored under ambient conditions and used for ground control specimens.

### Tensile Specimens

Selected panels of plain and reinforced Kapton, with representatives from each stress level, were removed from the flight tension assembly. A cutting fixture and a single-edge razor were used to cut uniform 0.50-cm-wide strips from the panels. The edges cut in this

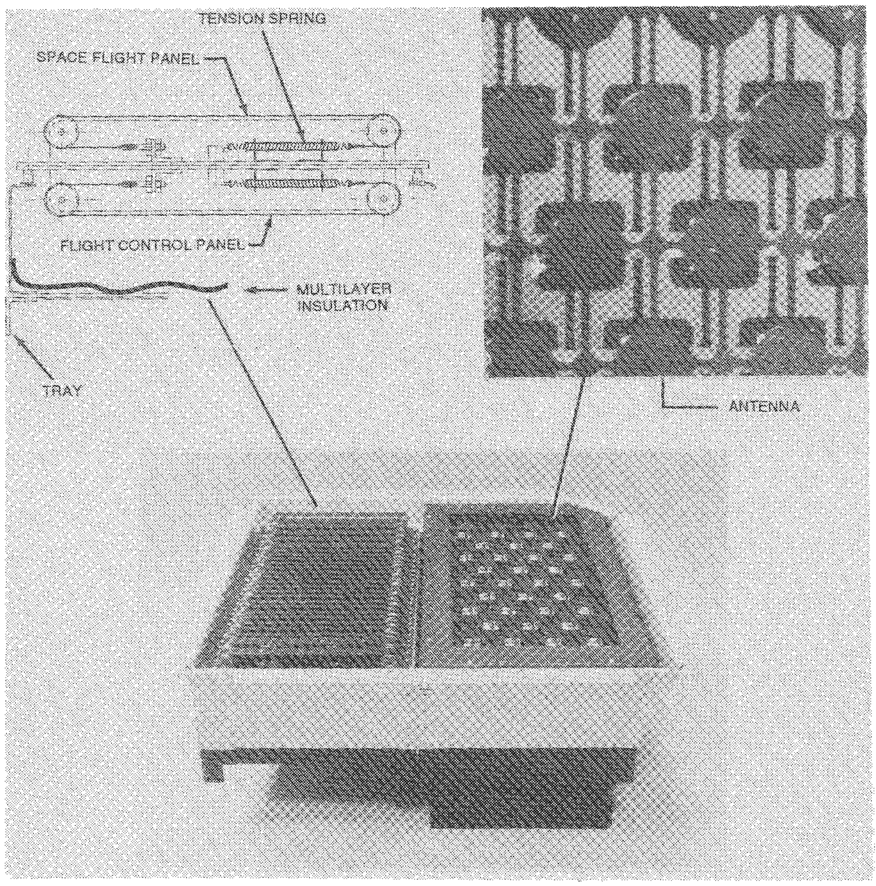


**Fig. 1 Space-based radar phased-array antenna experiment.**

manner were smooth and free of defects. The leading and the trailing edges were trimmed from the 1.27-cm-wide panels, and none of the strips cut from these panels contained an original edge. Strips that contained the original leading or trailing edge were cut from the 2.54-cm-wide flight space panels and designated LE and TE for leading edge and trailing edge, respectively. The remaining material from each 2.54-cm-wide panel was sufficient for an additional six strips, all of which had freshly cut edges. Thus, each 1.27-cm-wide panel provided four specimens for mechanical testing, and each 2.54 cm-wide panel provided 10 specimens.

### High-Voltage Discharges

Electrodes were formed from knife-edge cuts in copper dipole elements bonded to the glass/Kapton sheet that constitutes the outer antenna plane. Discharge events at the four electrodes (two each at 1.5 and 3.0 kV) were counted during 20-min blocks of time and then transferred sequentially to a nonvolatile memory location. A timer sequencer was designed to delay the application of high voltage until day 32 (to allow for satellite outgassing), to power up the memory system every 20 min for 0.6 s, and to shut the high voltage down on day 243 (or upon retrieval, in case retrieval took place first).

## Postexposure Evaluation

### Physical

The mass and the overall dimensions of sections selected for mechanical tests were accurately determined prior to the final cutting. Mass was normalized for dimensions of length and width, and a comparison was made between the flight space and the flight control specimens. The mass deficits of the flight space sections were used to estimate surface erosion. Surface roughness was determined using a profilometer. The Kapton film was bonded to a polished aluminum plate. The Kapton surface was scanned over a distance of 200 $\mu$m with a stylus mass of 9 mg. Each surface roughness value represents the average of five measurements.

### Mechanical

To provide a discrete reference for permanent elongation measurements, three 0.5-mm-diam holes were precisely located along each flight space and flight control tensile panel centerline, the first two holes being 2.54 cm apart with the splice region between them. The third hole was located 8.26 cm away from one hole and 10.80 cm from the other. Permanent elongation under load was determined from pre- and postflight measurements of hole spacings of tension panels.

Tensile tests to destruction were conducted using a universal test machine with pneumatically actuated grips. The initial distance between grips was 4.06 cm, and this value was used as the gauge length. A crosshead speed of 0.254 cm/min was used for all of the tests. Strain was derived from crosshead movement. The laboratory temperature ranged from 22 to 25°C and the relative humidity ranged from 31 to 47% during the period of testing.

### Chemical

Energy dispersive spectroscopy (EDS) was used to identify contaminants on the surface of flight space panels and surrounding areas. The 20-kV electron beam of a scanning electron microscope (SEM) was used to excite fluorescence of surface elements. Fluorescence was collected using a SiLi detector interfaced to a spectrometer capable of detecting elements with atomic numbers greater than or equal to that of fluorine ($Z = 9$).

An unshielded, high-purity germanium detector was used to acquire 4096 channel gamma spectra. To isolate a specific section of the package, the detector was positioned 1.27 cm directly in front of a vertical array of tension assembly rollers that provided support for the tension panels. Each roller was a cylinder made of 6061-T6 alloy (97.9% aluminum) with a radius of 2.45 cm. The rollers were oriented in such a way that the detector viewed the sides of the cylinders. A measurement was made for 16 h and was followed immediately by a background run of similar duration.

Transmission Fourier transform infrared (FTIR) spectra were obtained from 125-$\mu$m-thick films over the energy range of 400–4000

$cm^{-1}$. Infrared spectra of the background atmosphere were collected under identical conditions and have been subtracted from all of the spectra. Transmission FTIR spectra were also obtained from the brown residue found on the ram-facing surface of the trailing side of the aluminum tray downstream of the tensile panels.

An Amray model 1810 SEM, operating at 10 kV, was used to determine surface morphology of flight specimens. All polyimide films examined in the SEM were first sputtered with gold to a thickness of about 100 Å.

## Results

Preliminary radioactivity survey measurements of short duration (30 min) at various points along the facing plane of the experimental package gave little indication of discernible gamma emissions above background levels. A spectrum obtained from the tension assembly roller contains a gamma ray line at 1274 keV, which does not appear in the background spectrum. Gammas of this energy are from the decay of $^{22}Na$, which are produced by activation of $^{27}Al$. No other significant features were noted in the gamma spectrum that spanned the energy range from 100 keV to 3 MeV.

The meteoroid and debris special investigation group reported 206 visible features on the experiment tray and experiment surfaces.[5] Figure 2 illustrates an impact feature in a 1.27-cm-wide glass/Kapton strip. Delamination damage extends several diameters around the penetration site, typical of impact events in a bonded structure. For comparison, a reference hole machined in the strip before flight is also visible in Fig. 2.

Two striking manifestations of contamination appeared throughout visual inspection of the experiment tray: fine shiny particles clinging to the Kapton and brownish staining of many light-colored surfaces. The particles were probably metal from degraded thermal insulation systems elsewhere on LDEF, but we did no analysis to confirm this. Such particles were clearly present as airborne debris during deintegration of the experiment tray from LDEF.

Brown stains were seen on unpainted aluminum surfaces, typically in locations exposed to direct sunlight and ram plasma. Distinct shadowing patterns could be observed where adjacent upstream parts interfered with the ram and/or the sunlight. The EDS spectra (not shown) indicated the presence of only silicon; however, elements lighter than fluorine cannot be detected with our spectrometer. A mottled pattern of brown staining was observed on the white-painted ceramic electronics modules of the antenna ground plane. Here, the complicated geometry of the antenna plane and dipole drop lines above the ground plane may have contributed to a complex, less distinct pattern of staining. Several surface particles noticed on flight space Kapton panels during SEM examinations were also determined to be predominantly silicon.

The Kapton upper surfaces of the flight space Kapton and glass/Kapton panels suffered significant weathering, as is evident by the diffuse appearance of these surfaces. This is in contrast to the flight control panels that had a specular appearance (see Fig. 3). Kapton surfaces shielded from the ram by the lip of tension assembly rollers retained a specular appearance very similar to control panels, as can be seen in Fig. 3. The diffuse appearance of flight space Kapton is likely the result of surface erosion by the atomic/molecular fluence. The SEM photomicrograph of Fig. 4a shows a region of the leading edge of a flight space glass/Kapton panel that was shielded from the ram flow. The sandwich structure of the glass/Kapton and the reasonably good condition of this surface are clearly evident in the photograph. Figure 4b shows an SEM photomicrograph obtained a few centimeters removed from the region of Fig. 4a; the only difference is that this region experienced direct normal exposure to the ram flow. This region shows significant surface erosion and cratering, as compared to shielded regions. Figures 4c and 4d show oblique views of the leading edge for shielded and direct ram exposure, respectively. The SEM photomicrograph displayed in Fig. 4f shows the typical triangular erosion pattern observed for Kapton exposed to low-angle-of-incidence ram flow.[6] The triangular erosion patterns point in the direction of the satellite's velocity vector. A photomicrograph of a shielded region on the same panel and obtained under the same conditions as the photograph in Fig. 4f shows no such erosion; this is evident from inspection of Fig. 4e.

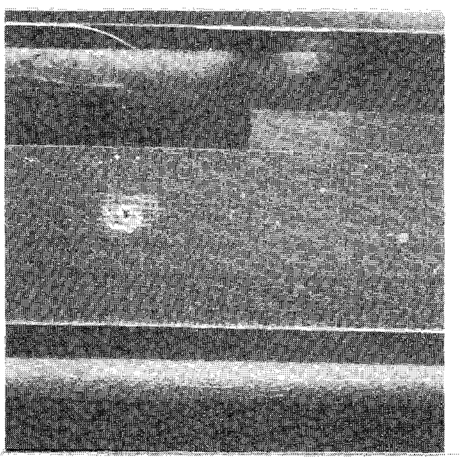

**Fig. 2 Impact site in glass/Kapton panel.**

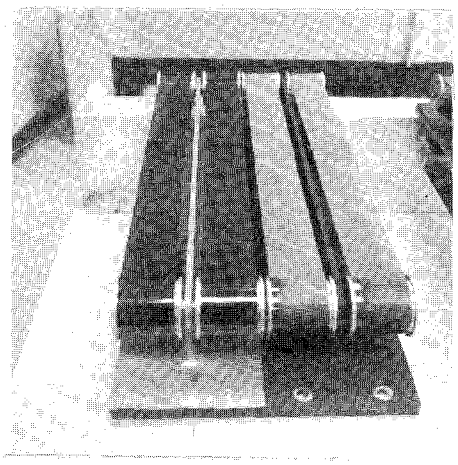

**Fig. 3 Kapton panels showing specular appearance of flight controls in assembly 1 and diffuse appearance of flight space specimens in assembly 3.**

The surface roughness of the flight space panel was significantly greater than for either flight control or ground control specimens. The values (average ± standard deviation; $n = 5$) obtained from profilometry were 287 ± 35 nm, 72 ± 32 nm, and 62 ± 15 nm for flight space, flight control, and ground control specimens, respectively. The surface erosion suffered by the Kapton exposed to the space environment is estimated to be 8.0 ± 1.4 $\mu$m (average ± standard deviation, $n = 6$) from mass loss data. The space end of LDEF was pitched forward about 1 deg[7,8] so the near-parallel, grazing incidence of the atomic/molecular flux apparently undercut and eliminated surface contaminant features that otherwise could have been used to determine erosion depth by SEM or profilometry.

Creep elongations were measured in the plain Kapton and the glass/Kapton. The creep strains for the plain Kapton were slightly higher and somewhat more stress dependent than the glass/Kapton. With one exception, all creep strains in the unspliced areas of the panels were less than 0.0012. There was little or no significant difference in creep between the flight space specimens and the flight controls. The spliced portions of the panels experienced elongations on average 30% higher than the unspliced regions.

Representative stress-strain curves for the Kapton and the reinforced Kapton strips are shown in Fig. 5. The reinforced Kapton shows a yield point, after which stress increases slowly with strain. This is in contrast to the plain Kapton strips, which do not show yield points. The ultimate strength and elongation at break of the polyimide films as determined from tensile tests are presented in Fig. 6. The error bars indicate standard deviations.

The infrared spectra, x-ray diffraction (XRD) patterns, and differential scanning calorimetry (DSC) thermal traces of flight space-

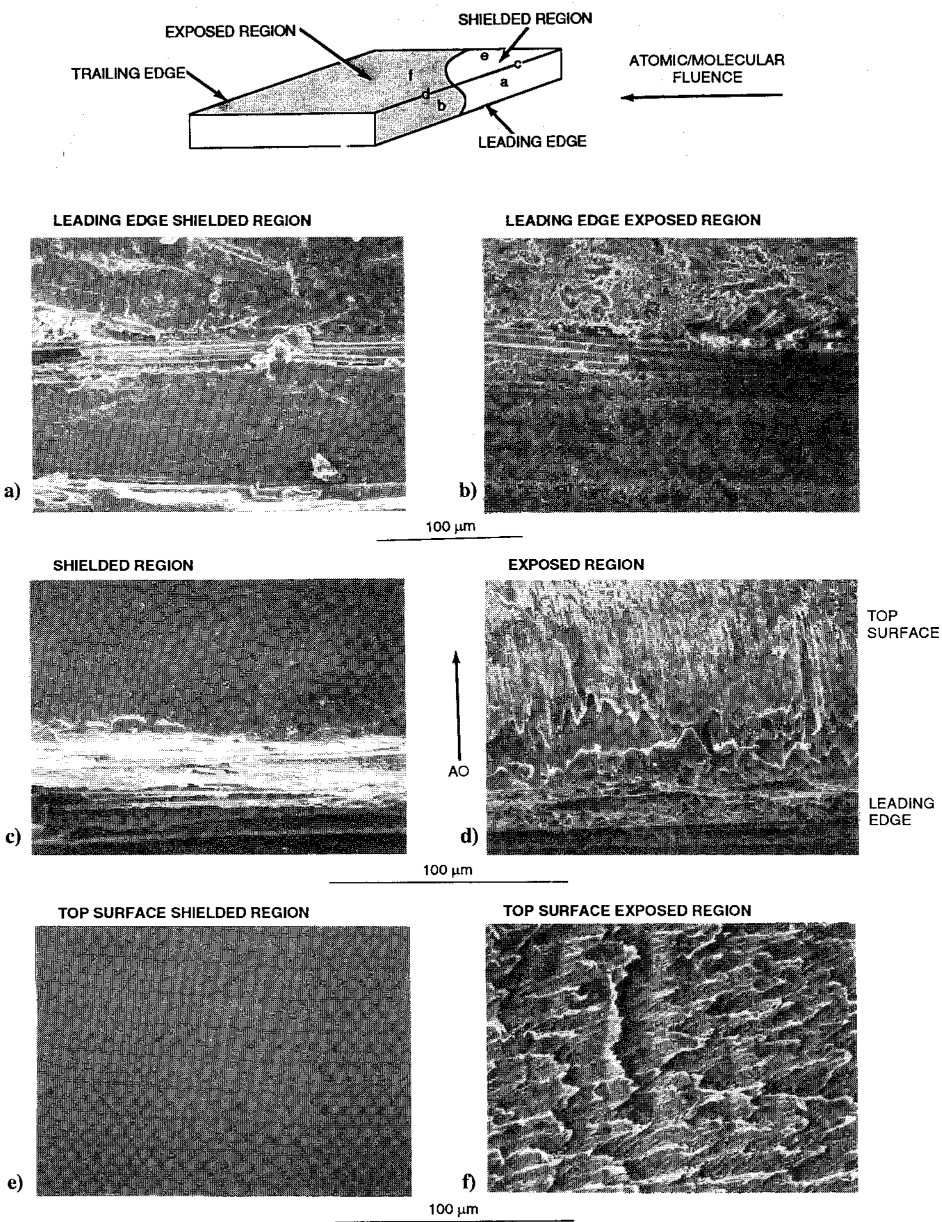


**Fig. 4 SEM photomicrographs of flight space glass/Kapton.**

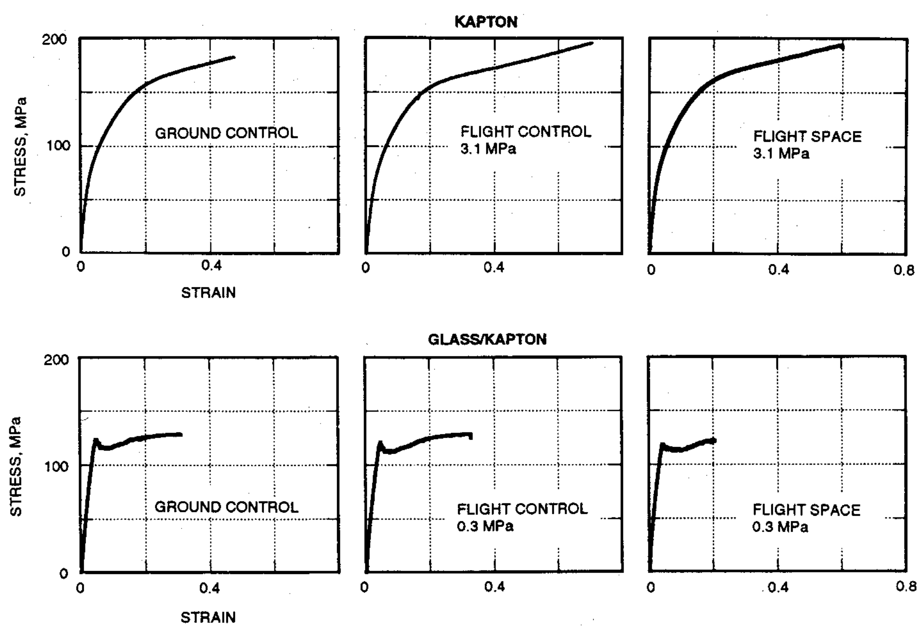


**Fig. 5 Representative tensile stress-strain curves.**

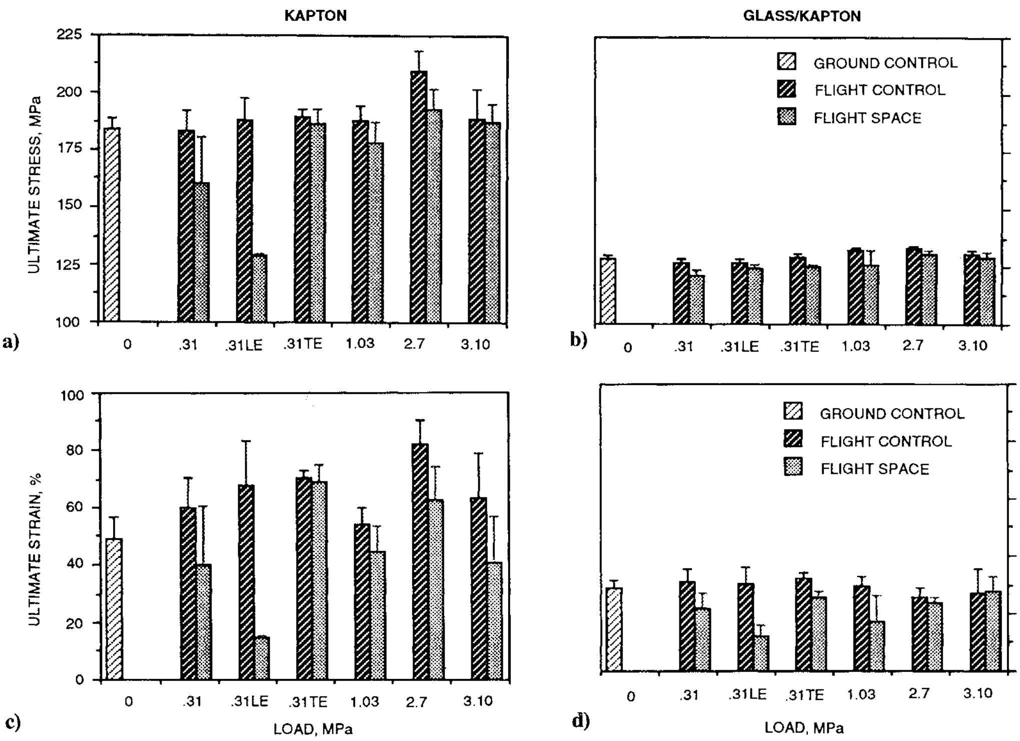


**Fig. 6 Ultimate strength as determined from tensile tests: a) ultimate tensile stress of Kapton, b) ultimate tensile stress of glass/Kapton, c) ultimate tensile strain of Kapton, and d) ultimate tensile strain of glass/Kapton. (LE is leading edge; TE is trailing edge.)**

**Table 1 High-voltage discharge events recorded in experiment memory**

| | 1.5-kV Counts | | 3-kV Counts | |
|---|---|---|---|---|
| Hour | Gap A | Gap B | Gap A | Gap B |
| 768.0 | Experiment on | | | |
| 1642.0 | 0 | 0 | 1 | 0 |
| 2069.6 | 1 | 0 | 0 | 0 |
| 2076.0 | 1 | 0 | 0 | 0 |
| 2114.0 | 0 | 2 | 0 | 0 |
| 2138.6 | 0 | 2 | 0 | 0 |
| 2143.0 | 0 | 2 | 0 | 0 |
| 2155.0 | 1 | 0 | 0 | 0 |
| 2161.3 | 1 | 0 | 0 | 0 |
| 3330.3 | 1 | 0 | 0 | 0 |
| 5832.0 | Experiment off | | | |

exposed, flight control, and ground control specimens showed no significant differences and are not shown.

Very few discharge events were recorded during the active experiment time. The numbers and times of events are included in Table 1. One event was recorded for gap A of the 3-kV experiment, and none for gap B of the 3-kV experiment. Five events were recorded for gap A of the 1.5-kV experiment, and six events for gap B of the 1.5-kV experiment (two at each of three sample times). Although sparse, counts appear for three out of the four gaps. These data indicate low counts, which are consistent with data in other cells of zero counts. Thus, a single-event upset in these few cells, although possible, is unlikely.

## Discussion

The most striking difference between flight-exposed and control Kapton surfaces is the severe weathered appearance evident on exposed surfaces. This weathering has previously been observed on short-duration exposures of organic films during Shuttle flights,[3] and has been attributed to the impact of atmospheric constituents of high relative velocity in the fixed reference frame of the satellite.[3,4] The primary constituent of the atmosphere at altitudes between 200 and 600 km is atomic oxygen.[9] The kinetic energy of the 8-km/s atomic oxygen fluence is approximately 5 eV and is sufficient to rupture chemical bonds within the molecular structure of the polyimide film. Continued bombardment by atomic oxygen can lead to significant erosion of organic surfaces. We estimate that the surface erosion of the flight-exposed Kapton during the 2106 days in orbit is $8.0 \pm 1.4$ $\mu$m. This is less erosion than predicted, say, 13.8 $\mu$m from reported Kapton erosion yield of $3.0 \times 10^{-24}$ $cm^3$/atom (Ref. 9) and reported fluence at the space end of LDEF of $4.59 \times 10^{20}$ atoms/$cm^2$ (Ref. 7).

Creep deformations experienced by the Kapton were slightly above those estimated from time extrapolation of short-term, room-temperature, ground tests. The space environment appeared to have little or no detrimental effect on the creep behavior of the Kapton or glass/Kapton. As expected, the creep strain of the thermoplastic adhesive splice regions was greater than the basic membranes.

The mechanical properties of the flight Kapton were, in general, no different from those of ground-based controls. Flight space-exposed specimens typically showed reductions in ultimate stress and elongation compared to ground and flight controls; however, in most cases differences were not significant. The reductions are thought to be the result of a higher incidence of surface defects associated with the exposed specimens, although these differences could also be explained by increased exposure to a high-radiation environment.[10,11] However, a large percentage of the flight space-exposed specimens failed quite early during mechanical tests. Thus, although the average values of mechanical properties of the flight space-exposed specimens are less than those of the flight and ground controls, the associated standard deviations are large, and in most instances no statistical significance could be established. Specimens that contained an original leading edge showed a reduction in mechanical integrity, with an ultimate elongation that was about 30% of control values. These specimens were eroded not only on the upper surface, but also at the leading edge. In contrast, the properties determined for flight space-exposed specimens containing the trailing edge were quite similar to specimens taken from the middle regions. The fact that many flight space-exposed specimens displayed a mechanical integrity equal to that of the control specimens supports the argument that surface defects cause these reductions.

No significant differences between flight space-exposed, flight control, and ground control have been detected using DSC, transmission FTIR, or XRD. This is perhaps not surprising since these techniques measure bulk properties, and it is likely that the greatest change in material properties will be localized to the surface regions of space-exposed specimens. Although these surface regions were exposed to the space environment for nearly six years, the erosion process continually refreshed the surface, which maintains a steady-state composition, and gross changes in chemical properties due to the atomic/molecular fluence are likely to be small. In fact, even ESCA studies of Kapton film exposed to LEO showed very little difference from control specimens.[12] This is in contrast to Kapton etched in an Earth-based oxygen reactor, which did show significant differences.[12]

The EDS spectrum of the brown residue indicates silicon as the primary elemental constituent. Elements lighter than fluorine could not be detected with our energy-dispersive spectrometer. However, EDS spectra of a similar brown residue recovered from other locations on the LDEF satellite show that carbon and oxygen also are present.[13] The peaks in the FTIR spectrum at 2900–3000 $cm^{-1}$ (perhaps a C-H stretch) suggest the presence of aliphatic groups within this residue. This residue is thought to result from the condensation of outgassed silicon and organic products on cold surfaces followed by ultraviolet catalyzed polymerization.[14]

Side-by-side radio frequency test comparisons with a ground-based antenna constructed at the same time as the flight article showed no significant differences due to the LDEF environment.

The high-voltage experiment was designed specifically to record discharges initiated across spark gaps by environmental interactions, e.g., contaminant transport and/or coupling to the space plasma. The experiment timer sequencer apparently functioned perfectly. It powered up the experiment on day 32 and powered it down on day 243. This is corroborated by the block of ones in the appropriate memory cells. There was no evidence of any single-event upset in these cells. There was no charring of the Kapton or other damage visible at the gaps. An increase in surface conductivity was observed in the space-exposed Kapton tension panel surfaces,[15] but this was not sufficient to have influenced the discharge results.

## Conclusions

The most important environmental factor was the atomic oxygen erosion experienced at low altitudes. The survivability of the Kapton is largely attributable to the stability of LDEF and the orientation, close to 1-deg grazing incidence. This extreme orientation produced surface and leading-edge erosion and some interesting surface features. The surface recession was estimated to be 8 $\mu$m.

The mechanical properties of the Kapton and the glass/Kapton experienced only slight degradation except for specimens taken from areas containing eroded edges. The eroded edges had significant effects on tensile strength and strain to failure.

The active circuitry to control the high-voltage discharge experiment and record the number and time of electrostatic discharges apparently functioned as intended, although full systems functional tests have not been accomplished. The memory locations reserved for diagnostics were unchanged. Few discharges, one at 3 kV and 11 at 1.5 kV, were recorded.

The experiment demonstrated the functionality and the durability of the Kapton antenna plane materials and other materials and systems onboard A0133.

## Acknowledgments

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