

PERFORMANCE OF SELECTED POLYMERIC MATERIALS ON LDEF

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SUMMARY

The NASA Long Duration Exposure Facility (LDEF) provided a unique environmental exposure of a wide variety of materials for potential advanced spacecraft application. This paper examines the molecular level response of selected polymeric materials which flew onboard this vehicle. Polymers include polyimide, polysulfone, and polystyrene film and polyimide, polysulfone, and epoxy matrix resin/graphite fiber reinforced composites. Several promising experimental films were also studied. Most specimens received 5.8 years of low Earth orbital (LEO) exposure on LDEF. Several samples received only 10 months of exposure.

Chemical characterization techniques included ultraviolet-visible and infrared spectroscopy, thermal analysis, x-ray photoelectron spectroscopy, and selected solution property measurements. Results suggest that many molecular level effects present during the first 10 months of exposure were not present after 5.8 years of exposure for specimens on or near Row 9. Increased AO fluence near the end of the mission likely eroded away much environmentally induced surface phenomena. The objective of this work is to provide fundamental information for use in improving the performance of polymeric materials for LEO application. A secondary objective is to gain an appreciation for the constraints and limitations of results from LDEF polymeric materials experiments.

INTRODUCTION

The longer missions envisioned for the U.S. Space Program have placed increased demands on materials, particularly polymeric materials. Until now, most spacecraft have been launched with relatively short life expectancy, from a few days to a few years. Confidence has developed in materials which support these short-term missions. However, the 25 to 30 year Space Station *Freedom* mission and other planned space programs with long-term LEO exposures are driving additional concerns and challenges. Quite simply, we don't know how all nonmetallic materials are going to perform in space for extended periods of time.

Polymeric materials offer a number of electrical resistivity, thermal expansion, weight, and strength to weight advantages over metallic materials. Figure 1 compares several physical and mechanical properties of metals and nonmetals. The figure was extracted from an article written 30 years ago (ref. 1). The two extremes in relative properties have widened considerably in the intervening years with the development of space-age polymers. The application of these materials is critical to the success of long-term space activities.

Fortunately, the NASA LDEF is filling much of the data void concerning long-term space environmental effects. The LDEF story is continuing to unfold through a series of conferences, workshops, technical sessions and discussions, and journal articles (refs. 2-5). The present paper is an

effort to increase the body of knowledge on space environmental effects on materials resulting from the LDEF mission by summarizing the performance of selected polymeric materials which flew on that vehicle.

Through the cooperation of the Environmental Effects on Materials Special Investigation Group (MSIG) and several LDEF experiment Principal Investigators, a representative number of nonmetallic specimens have been assembled for examination at the Langley Research Center. Table I summarizes these materials, identifies their source, and gives respective LDEF tray and row locations in the foot-notes.

The chemical characterization of most of these specimens is now complete. The objective of this effort has been to assess the molecular level response of a broad variety of experimental and commercially available polymers to the extended LEO exposure provided by LDEF. A secondary objective is to gain an appreciation for the limitations and constraints of LDEF polymer experimental results. The benefit is intended to be fundamental knowledge for use in developing new and improved space-stable materials and for enhancing our understanding of ground-based simulation of LEO environmental effects.

EXPERIMENTAL

Materials used in study were contributed by several Principal Investigators and are summarized in Table 1. The fabrication of Langley Research Center composite materials has been previously discussed (ref. 6). PMR-15/C6000 polyimide matrix composite was fabricated by Rockwell International, Tulsa, OK. Films were obtained from commercial sources or synthesized in-house at Langley. The LDEF location of specimens is included with information in Table 1. Environmental exposure conditions for specimens at these locations may be obtained from several sources familiar to the LDEF community (refs. 2,7,8).

Characterization. Several analytical techniques were used to characterize specimens. Ultraviolet-Visible (UV-VIS) spectra were recorded on a Perkin-Elmer Lambda 5 spectrometer. Infrared spectra were obtained on a Nicolet 60SX Fourier Transform Infrared System (FTIR) in the transmission or diffuse reflectance modes. Glass transition (T_g) determinations were conducted on a DuPont 9900 Computer/Thermal Analyzer-Model 943 Thermomechanical Analyzer (TMA).

The approach used to make solution property measurements has been previously reported (ref. 9). Gel Permeation Chromatography (GPC) was performed on a Waters Associates GPC interfaced with a Viscotek Model 100 Differential Viscometer (DV). A standard $10^6/10^5/10^4/10^3$ Å microstyragel column bank was used. Solvents for polysulfone, polyimide, and polystyrene specimens were chloroform, 0.0075M LiBr/DMAC, and toluene, respectively.

X-Ray Photoelectron Spectroscopy (XPS) measurements were conducted at the Virginia Tech Surface Analysis Laboratory, Department of Chemistry, VPI & SU, Blacksburg, VA (ref. 10). A Cambridge StereoScan 150 was used for Scanning Electron Microscopy (SEM).

RESULTS AND DISCUSSION

Much of the value of materials exposure on LDEF emanates from the remarkable attitude stability of the vehicle in orbit. As documented in several sources (refs. 2,11), one end of the spacecraft always faced space, one end faced Earth, and one row (Row 9) flew nominally in the leading edge or RAM direction for the duration of the 5.8-year flight. This orbital orientation dictated that most of the environmental exposure a specimen received depended on where it was located on the vehicle.

Figure 2 is an expanded version of a contribution to the LDEF Materials Workshop '91 held at the Langley Research Center (ref. 12). The figure identifies the same polymer matrix composite material at different LDEF locations. It also lists various environmental parameters at those locations and gives a sketch of the vehicle. In some instances, a particular material has been identified at five different LDEF locations. Thus, these specimens received several orders of magnitude difference in atomic oxygen (AO) fluence as well as different vacuum ultraviolet (VUV) exposures. A remarkable opportunity exists for LDEF investigators to compare the response of the same polymer to varying LEO environmental parameters.

Figure 3 clearly illustrates this directionality for Kapton film from three different LDEF locations. UV-VIS spectra are given for thin film which received 5.8 years of exposure on Tray C, Row 3 or C3, 5.8 years of exposure on the space end at H7, and 10 months of exposure at B9. Environmental effects are quite different for the three specimens. The C3 film, probably saw primarily VUV. The UV-VIS transmission spectrum for that sample did not change significantly from that of the control. The H7 specimen experienced considerable AO in addition to VUV. A significant change in transmission was noted for that film. A change was also noted in the spectrum of the film after 10 months of exposure of B9. Thus, materials test results reported by LDEF investigators will be influenced by where those materials were located on the vehicle. Even with this restriction, many results reported to date have been remarkably consistent. Figure 3 makes an additional point about information being derived from LDEF. We may have an orbit for a spacecraft, but where a particular material is located on that spacecraft may become critical.

Composite Materials. The characterization of 934/T300 and 5208/T300 epoxy/graphite, PMR-15/C6000 polyimide/graphite, and P1700/C6000 polysulfone/graphite composites has been discussed in a series of articles (refs. 6,13-16). While details of that characterization may be found in the referenced publications, several more significant results are summarized here. Uncoated composites protected or shielded from direct exposure exhibited no detectable weight loss or change in measured mechanical properties. In contrast, uncoated composites which received direct LEO exposure exhibited significant loss of both resin and fiber. Essentially one ply of the four ply composites was lost after 5.8 years in LEO. A proportional reduction of 25 percent in tensile strength and tensile modulus was noted with these specimens.

No real differences were noted at the molecular level for composites exposed for 5.8 years on or near Row 9. Figure 4 summarizes data obtained for polysulfone composites. Infrared spectra of exposed and protected surfaces were essentially identical. The subtraction of exposed from control spectra resulted in a straight line in many instances. This also suggested little difference between the specimens. No changes were noted in the glass transition temperature with exposure. A detailed molecular weight characterization of control, flight protected, and flight exposed polysulfone composite specimens resulted in identical molecular weight distributions for all samples. One conclusion of this assessment of 5.8-year exposed composites was that molecular level effects resulting from UV exposure in the LEO environment were apparently lost in the surface material eroded away by AO.

Thin silicon dioxide, metal, and metal oxide coatings appeared to protect composite surfaces from effects of the harsh LEO environment. No significant erosion or weight loss was noted for several coated specimens. Figure 5 shows SEM photomicrographs at two magnifications for 934/T300 specimens coated with 1,000 Å of nickel followed by 600 Å of SiO₂. A 10-month exposed specimen is included in the figure for comparison with a 5.8-year exposed specimen. Minimal evidence of AO erosion was noted for these coated composites.

As noted in several Langley publications (refs. 6,13,14), stripes developed in some exposed composite specimens. These white to charcoal-colored stripes run in the fiber direction and are probably a row wide. Further research needs to be done to adequately explain this phenomenon.

Films. An assessment of selected films on LDEF has also been reported. Silvered FEP Teflon thermal blanket material, which provided thermal protection for 17 LDEF experiments, is probably the most studied material on LDEF. Since FEP Teflon has been the subject of numerous publications within the LDEF community (refs. 2-4, for example), it will not be addressed in the present paper.

No films survived 5.8 years of exposure on Langley's Row 9 experiment. However, films which received 10 months of exposure in the experiment exposure control canister (EECC) did survive and have been extensively characterized (refs. 4,16,17). One EECC specimen, P1700 polysulfone, was subjected to in-depth analysis (ref. 16). Figure 6 summarizes pertinent results from that study.

The upper left side of Figure 6 shows an SEM photomicrograph of 10-month exposed polysulfone film. Partial surface contamination apparently protected underlying resin from AO, resulting in the relief pattern visible in the micrograph. As with 5.8-year exposed polysulfone composite specimens, no change in T_g was noted with exposure. The lower left portion of Figure 6 gives the result of subtracting the FTIR spectrum of exposed film from that of unexposed film. A downward inflection in the difference spectrum means more of a particular component in the exposed film. A large -OH band which resulted from exposure is noted around 3,400 cm⁻¹.

Solution property measurements also revealed changes at the molecular level for 10-month exposed specimens. The GPC-DV molecular weight distributions for polysulfone control, protected edge, and exposed specimens are included in Figure 6. The distribution broadened with exposure, indicative of both chain scission and crosslinking. Various molecular weight parameters for LDEF-exposed polysulfone specimens are given in Table 2. Film values were calculated from the GPC-DV distribution given in Figure 6. Note the decrease in film solubility with exposure, decrease in number average molecular weight (M_n), and increase in weight (M_w) and z-average (M_z) molecular weights. This is clear evidence for both chain scission and crosslinking. VUV likely played a major role in these processes. Data for control and 5.8-year exposed composite specimens showed no change in molecular weight, as discussed earlier with Figure 4. However, the analysis of a 10-month exposed composite specimen suggested the same molecular weight trends as the 10-month exposed film, as it should.

An indisputable result of comparing 10 month polysulfone data with 5.8 year data is that many molecular level effects are present after 10 months of LEO exposure but not after 5.8 years of LEO exposure. This potentially contradictory result is best understood by considering the orbit of the spacecraft. LDEF was deployed into an essentially circular 257 nautical mile orbit in April 1984 (ref. 18). It was retrieved 69 months later at an altitude of 179 nautical miles. Atomic oxygen fluence differs greatly at these two altitudes. EECC samples were exposed for 10 months early in the mission when AO levels were at a minimum and then sealed inside the vacuum canister. Specimens outside the EECC received significant AO exposure near the end of the mission after the orbit had decayed.

Approximately 50 percent of the total AO exposure was received during the last 6 months of flight. Thus, molecular level effects observed after 10 months of exposure, primarily related to changes in surface chemistry, were most likely eroded away by the time the spacecraft was retrieved. An earlier retrieval from a higher orbit may have provided different results.

Polyimide-polysiloxane Copolymers. The chemical characterization of a series of polyimide-polysiloxane copolymer films flown inside the EECC also provided insight into molecular level effects of LEO exposure. Preliminary results obtained on these experimental materials have been given in previous reports (refs. 15,17). In general, they discolored somewhat but did not exhibit significant weight loss. SEM, scanning tunneling microscopy (STM), and limited XPS data may be found in the referenced articles.

Table 3 gives detailed XPS results for three different siloxane-containing copolymers. Data for both control and exposed film is included in the table. Several points are made concerning these data. Note the decrease in surface carbon content with exposure and subsequent increase in surface oxygen content. Note also the increase in silicon and that the silicon to oxygen ratio is about 1:2 after exposure. Finally, note the increase in the silicon 2p electron binding energy with exposure from approximately 102 electron volts (eV) to 103 eV. This data is consistent with the following interpretation. Upon AO exposure, the surface of these siloxane-containing copolymers is eroded to expose silicon atoms. These atoms are initially present as an organic silicone, as evidenced by the 102 eV binding energy. Upon exposure to AO, organic silicone (102 eV B.E.) is oxidized to inorganic silicon (103 eV B.E.), most likely, an SiO₂ type of silicate. At this point, further AO erosion is retarded. Inorganic silicates are known to be effective barriers to AO erosion. These observations suggest an exciting potential for designing AO protection into the backbone of certain polymers. This protection could likely be achieved by periodic incorporation of siloxane groups into the molecular structure of the host polymer.

High Performance Films. Several experimental high performance polymer films which received 10 months of exposure on Langley's Row 9 experiment have also been characterized. Since these films are the subject of a future publication, only limited results will be presented in the current paper. Table 4 gives the molecular structure and color for five of the polyimide films. Commercially available Kapton film was included in this study as a reference material. The films were synthesized as part of a broad program to develop polymeric materials for a variety of potential space applications.

UV-VIS transmission properties were affected by the 10-month LEO exposure. Figure 7 gives spectra from 200 to 600 nm for the six films. As described in earlier research, 6F-DDSO₂ and 6F-BDAF were developed in an effort to obtain essentially transparent films and coatings (refs. 19-21). These two films exhibit a shorter UV cutoff than other films in Figure 7 and, thus, possess less color. Figure 8 gives corresponding spectra for LDEF-exposed film. While some UV and AO degradation of the polymer backbone no doubt occurred, the dramatic decrease in transmission with exposure is considered due to AO-induced roughening of the film surface. The roughened, diffuse-appearing surface reflected much of the impinging radiation and, thus, less light was transmitted.

Only the 6F-BDAF and 6F-DDSO₂ films were potentially soluble in non-degrading solvents. Solution property measurements were performed only on these two materials. Table 5 summarizes molecular weight data determined by GPC-DV. Analyses were conducted on control film, the edge of a flight specimen shielded from direct exposure, and a 10-month exposed specimen cut from the center of the film. All samples contained residual insoluble material. The insoluble gel was recovered by filtration and dried to constant weight. Analyzed concentrations were then adjusted to account for the insoluble portion.

An inspection of data for 6F-BDAF suggests that various molecular weight parameters were not effected by the 10-month LEO exposure provided by LDEF. In contrast, 6F-DDSO₂ exhibited significant changes at the molecular level. Solubility decreased from 94.5 to 60.9 percent with exposure. The number average molecular weight (M_n) remained fairly constant while the z-average molecular weight (M_z) doubled. Changes in the polydispersity ratio (M_w/M_n) are also noted for this material. These observations, particularly solubility and M_z behavior, are considered evidence that the 6F-DDSO₂ structure crosslinked during exposure. Hill noted that M_z is the neglected parameter for evaluating crosslinking in environmentally exposed polymers (ref. 22). The molecular weight change for 6F-DDSO₂ is considered primarily a result of VUV damage to the -SO₂-group in the backbone of the polymer. Previous research has shown this material to be affected by exposure to UV in the laboratory (refs. 20,21). Sulfur and, thus, the -SO₂-group was the suspected weak link in those earlier studies.

Traditional Polymers. The chemical characterization of more traditional polymers listed in Table 1 has also been completed. The results of this study will also be the subject of a future publication. However, pertinent data obtained for polystyrene and polyvinyl toluene is summarized in Figure 9 as examples of the type of information obtained. The specimens in Figure 9 flew on Row 3 and saw significant VUV for the duration of the LDEF flight.

The decrease in UV-VIS transmission with exposure for polystyrene on Row 3 was not nearly as dramatic as that observed for films obtained from other LDEF locations, for example, Row 9. Significant changes in transmission probably reflect considerable AO erosion. The decrease in transmission observed for polystyrene is considered primarily due to VUV damage. The result obtained by subtracting the FTIR spectrum of exposed polystyrene from that of unexposed polystyrene is also given in Figure 9. Bands centered around 3545, 3365, and 2084 cm are indicative of degradation in the exposed specimen. However, the origin of these bands has not been established.

The molecular weight and molecular weight distribution for both polystyrene and poly-vinyl toluene are included in Figure 9. The decrease in M_n and increase in M_w and M_z for polystyrene is consistent with chain scission and crosslinking. The solubility of polyvinyl toluene decreased from 90.1 to 56.5 percent with exposure. That observation, coupled with a decrease in M_n , is also considered as evidence for chain scission and crosslinking.

Contamination and Post Exposure Effects. As documented in numerous LDEF publications, much of the vehicle surface was coated with varying amounts of a molecular contamination film commonly referred to as the "nicotine stain." This stain was often found to contain silicon, either in the form of organic silicone or inorganic silicate. This layer of contamination likely had an effect on how various polymeric materials behaved. UV probably contributed to the discoloration of some contaminated specimens. Upon exposure to AO, the resultant silica/silicate layer probably affected the manner in which the material was eroded. We consider that contaminated samples probably performed differently than had they not been contaminated.

The possibility that some LDEF polymeric materials have changed or degraded after the spacecraft was returned to Earth has been raised on several occasions. At the first post retrieval conference, we reported that two thin films flown on STS-8 in 1983 had changed significantly in appearance since they were initially examined (ref. 14). We gave additional information on these two specimens at the LDEF Materials Workshop '91 (ref. 15). One of these films, an experimental polyimide designated PMDA-DAF, also flew on LDEF. It too has continued to change after deintegration in Spring 1990.

Some environmentally exposed thermal control paints are known to partially recover their deteriorated optical properties upon return to ambient laboratory conditions. The authors first observed this phenomenon with selected white paints associated with the Lunar Orbiter program in the 1960's. Alain Paillous made an effective argument for caution in the use of LDEF data obtained after deintegration during the LDEF Results for Spacecraft Application Workshop held October 27-28, 1992, in Huntsville (ref. 23). His observations spawned additional comment on this subject (ref. 24). For practical, logistical, and budget considerations, the chemical characterization of all LDEF polymeric materials could not be completed immediately after deintegration. Although analytical work proceeded with deliberate speed, many analyses were delayed for months for various reasons. Thus, we must be aware and appreciate the possibility that certain characterized effects may have occurred in the laboratory while the specimen awaited analysis and did not occur in space.

A Perspective. Lessons being learned from the LDEF mission concerning space environmental effects on materials are continuing to be refined. Panel sessions at the LDEF Materials Workshop '91 concerning several materials themes provided an excellent summary of findings to that date (ref. 3). Two expanded summary articles have also focused on LDEF materials results (refs. 25,26). Confirmed results, confusing or unexplained results, and new ground simulation testing requirements may be found in the cited references. The present article restricts the discussion to expectations and limitations of LDEF results as they apply to polymeric materials only.

As a result of work on LDEF polymers, several opportunities have been identified for the development of new space-stable polymers. LDEF has shown that flexible AO-resistant coatings and noncontaminating AO and UV resistant materials are needed. LDEF has also provided guidance for the chemistry and syntheses of such materials. They may originate as copolymers with mainchain or pendant siloxane groups, siloxane-modified polyimides, and thermoset siloxane resins, all of which are potentially intrinsically stable to AO. Highly fluorinated polymers and colorless polyimides hold promise as being potentially stable to UV. New polymeric materials developed after LDEF was flown should also be examined. These include various phosphorus-containing polymers as well as inorganic polymers.

Several points should be kept in mind when interpreting or applying LDEF results. Anticipated molecular level effects are present in many 10-month exposed specimens that are not apparent after 5.8 years. The relative intensity of AO versus VUV is a key to the resulting effects. The performance of polymeric materials on or near Row 9 is heavily biased by increased AO fluence near the end of the mission. In some instances, an earlier retrieval from a higher altitude may have provided different results.

An interfacial layer of a silicon-containing contaminant was often being exposed to the LEO environment. Was this layer degraded by VUV or oxidized by AO to affect the performance of the underlying polymer? Many questions concerning synergistic effects remain unanswered. Did one environmental parameter generate a lesser or greater response to another environmental parameter? Finally, which specimens have changed since retrieval? An appreciation for limitations of polymeric materials studies from LDEF exposures is necessary for their successful application.

A significant amount of fundamental information has been generated on several polymers which received 10 months or 5.8 years of LEO exposure. For example, Figure 6 gives molecular weight data for P1700 polysulfone after 10 months of exposure. Table V gives similar data for 6F-BDAF and 6F-DDSO₂ polyimides. Figure 9 gives solution property data for polystyrene and polyvinyl toluene after 5.8 years on Row 3. The latter specimens are two very well understood polymers. UV-VIS and IR data are available for all these samples. Can this information be used as a benchmark to calibrate the

ground-based simulation of LEO space environmental effects? If effects on materials described in this report can be duplicated, then the same conditions can be used to simulate the effects of LEO exposure on other polymers having more immediate potential for space application. Synergistic and accelerated effects may also then be better understood.

CONCLUDING REMARKS

Current studies indicate LDEF to be the definitive source for long-term exposure verification of LEO environmental effects on polymeric materials. A wide variety of materials have been characterized. No significant change at the molecular level has been noted in many 5.8-year exposed polymers. However, changes have been noted in the chemistry of selected polymeric films which received 10 months of exposure. Environmental effects for these specimens are primarily surface phenomena. That surface was eroded away by AO for many 5.8-year specimens on or near Row 9.

The performance of polymeric materials on LDEF may be biased by contamination, increased AO fluence near the end of the mission, and by post exposure effects. A unique opportunity exists for using LDEF data as a baseline or a "sanity check" on the ability of ground tests to adequately simulate LEO effects on polymeric materials. The ultimate benefit of data derived from the LDEF program will be its influence on future spacecraft design and new materials development.

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Table 1. Polymeric materials.

Characterization Complete

^aComposites:

P1700/C6000 Polysulfone
934/T300 Epoxy
5208/T300 Epoxy
PMR-15/C6000 Polyimide

^aFilms:

FEP Teflon
Silvered FEP Teflon
Kynar Fluorocarbon
P1700 Polysulfone
Kapton Polyimide

^bHigh Performance Polymers:

Polyimide-Polysiloxane Copolymer
BTDA-ODA Polyimide
BTDA-ODA-Al³⁺ Doped polyimide
6F-DDSO₂ Soluble polyimide
6F-BDAF Soluble polyimide
PMDA-DAF Polyimide

^cTraditional Polymers:

Polystyrene
Polyvinyl toluene
Polytetrafluoroethylene
Polymethylmethacrylate
Nylon
Polyethylene terephthalate

^dCharacterization Pending

Polyurethane
Various Silicones
Polyethylene terephthalate

Kevlar Aromatic polyamide
Teflon PTFE
Kapton Polyimide

Source: ^a W. Slemp, PI, Expts. A0134/S0010 (B9) and LDEF MSIG (various LDEF locations).

^b W. Slemp and A. St. Clair, PI, Expt. S0010 (B9).

^c J. Gregory, PI, Expt. A0114 (C9/C3).

^d A. Whitaker, PI, Expt. A0171 (A8).

Table 2. Molecular weight of LDEF-exposed P1700 specimens.

Film	% Soluble	^a M _n	^a M _w	^a M _z	M _w /M _n	^b IV
Control	100	18,100	53,600	92,600	2.97	0.48
10 month, edge	96	12,700	73,500	183,000	5.77	0.47
10 month, center	87	12,500	90,900	326,000	7.27	0.49
Composite	% Resin					
Control, top ply	30.3	15,800	57,400	100,600	3.62	0.43
10 month, top ply	27.5	14,300	61,200	115,600	4.28	0.39
5.8 year, top ply	32.9	15,400	57,300	99,800	3.71	0.45

^a Molecular weight average, grams/mole.

^b Intrinsic viscosity, dL/g.

Table 3. XPS analysis of 10-month LDEF-exposed polyimide-polysiloxane copolymers.

PHOTOPEAK	PIPSX-6		PIPSX-9		PIPSX-11	
	CONTROL	EXPOSED	CONTROL	EXPOSED	CONTROL	EXPOSED
C 1s B.E. ^a (eV)	285.0/287.6/288.7	285.0/286.1	284.7	284.6	285.0/286.5/288.6	283.7 ... 287.8 ^c
A.C. ^b (%)	57.5	15.5	54.4	16.8	69.2	19.0
O 1s B.E. (eV)	532.6	532.9/533.8	532.5	533.0	532.2/533.7	532.7/533.8
A.C. (%)	23.4	53.8	23.7	52.4	19.2	53.0
N 1s B.E. (eV)	400.1	—	—	—	400.4	—
A.C. (%)	1.6	NSP ^d	NSP	NSP	2.5	NSP
Si 2p B.E. (eV)	102.6	103.8	102.2	103.4	102.2	103.6
A.C. (%)	17.6	27.1	21.6	30.8	9.2	28.0
F 1s B.E. (eV)	—	—	—	—	—	—
A.C. (%)	NSP	—	—	—	NSP	NSP
Na 1s B.E. (eV)	—	1073.1	—	—	—	—
A.C. (%)	—	2.1	—	—	—	—
Cl 2p B.E. (eV)	—	200.1	—	—	—	—
A.C. (%)	—	1.3	—	—	—	—

^a Binding Energy

^b Atomic Concentration

^c Multiple Peaks

^d No Significant Peak

Table 4. High performance polyimide films.

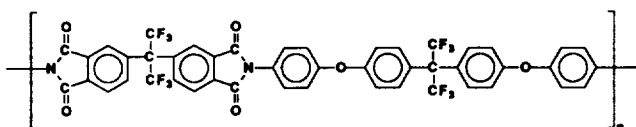
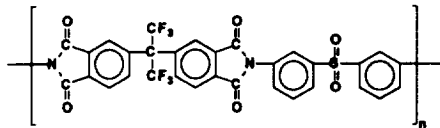
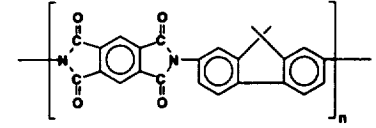
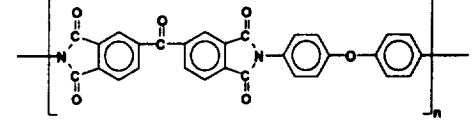
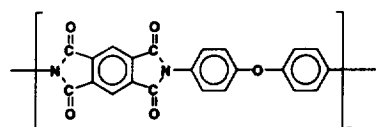
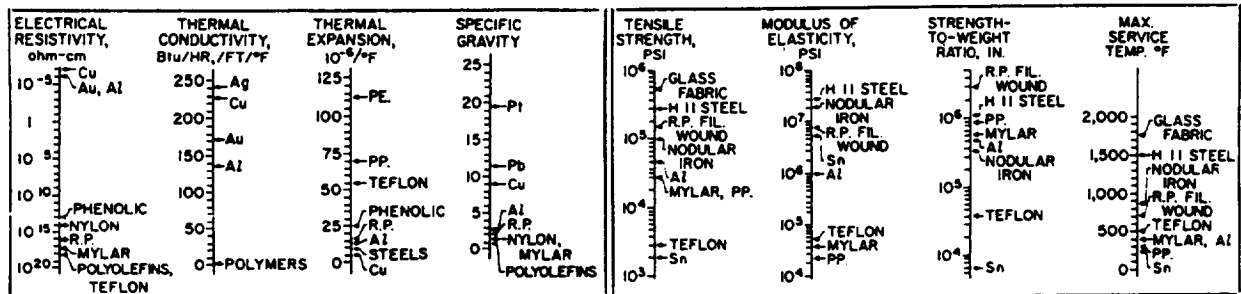
SAMPLE	STRUCTURE	COLOR
6F-BDAF		pale yellow
6F-DDSO ₂		colorless
PMDA-DAF		reddish-yellow
BTDA-ODA		yellow
BTDA-ODA-AP ⁺	BTDA-ODA + Al(acac) ₃	brownish-yellow
KAPTON		yellow

Table 5. Molecular weight of LDEF-exposed polyimide films.

SAMPLE	% SOLUBLE	^a M _n (x10 ⁻⁴)	M _w (x10 ⁻⁵)	M _z (x10 ⁻⁵)	M _w /M _n	I.V. ^b
6F-BDAF						
Control	98.8	8.56	2.18	7.10	2.54	0.829
		8.75	2.18	6.59	2.49	0.816
Edge ^c	98.7	7.65	2.12	7.67	2.77	0.846
		8.40	2.25	8.00	2.68	0.805
Center ^d	96.8	8.05	2.19	6.51	2.72	0.824
6F-DDSO₂						
Control	94.5	6.69	1.81	4.38	2.70	0.715
		4.65	1.76	4.07	3.79	0.732
Edge ^c	86.8	8.07	3.02	9.04	3.74	1.048
		7.62	3.09	9.66	4.06	1.042
Center ^d	60.9	4.18	3.06	11.10	7.32	0.619
		5.22	2.74	8.02	5.25	0.598

- ^a Molecular weight average, grams/mole
- ^b Intrinsic Viscosity, dL/g
- ^c Shielded from direct exposure
- ^d 10-month direct exposure



AEROSPACE APPLICATIONS

- Filament wound structures
- Erectable structures
- Thermal control surfaces
- Reduction of satellite weight

Figure 1. Some relative physical and mechanical properties of metals and nonmetals (ref. 1).

Row no.	Angle off RAM (°)	AO fluence (10 ²¹ a/cm ²)	VUV (ESH x 10 ³)	Epoxy				Polyimide		Bismaleimide	Polysulfone
				934/T300	934/P75	CE339/GY70	5208/T300	PMR/C6000	LARC/C6000	F178A/T300	P1700/T300
9	8	8.72	11.1	✓	✓	✓	✓	✓			✓
8	-38	6.93	9.4	✓	✓	✓	✓	✓			
7	-68	3.28	7.2					✓		✓	
12	82	1.28	6.9	✓			✓				
1	112	0.0002	7.5	✓					✓		✓
3	172	0.0001	11.1	✓	✓	✓	✓	✓			

Additional Environmental Parameters

Thermal Cycles: ~34,000 (-20 to 160°F, ±20°)

Particulate Radiation:

e- and p+: 2.5 x 10⁵ rad

Cosmic: <10 rad

Vacuum: 10⁻⁶ - 10⁻⁷ torr

Micrometeoroid and Debris: 34,336 impacts (0.5mm - 5.25mm)

Altitude/Orbital Inclination: 255-180 nm/28.5°

LDEF Sketch and Orbital Orientation

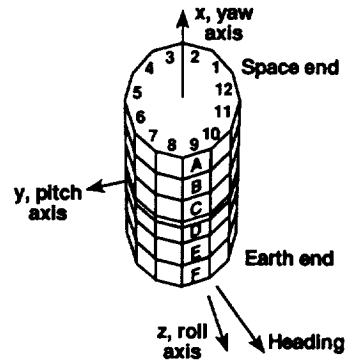


Figure 2. Selected LDEF-exposed composite materials.

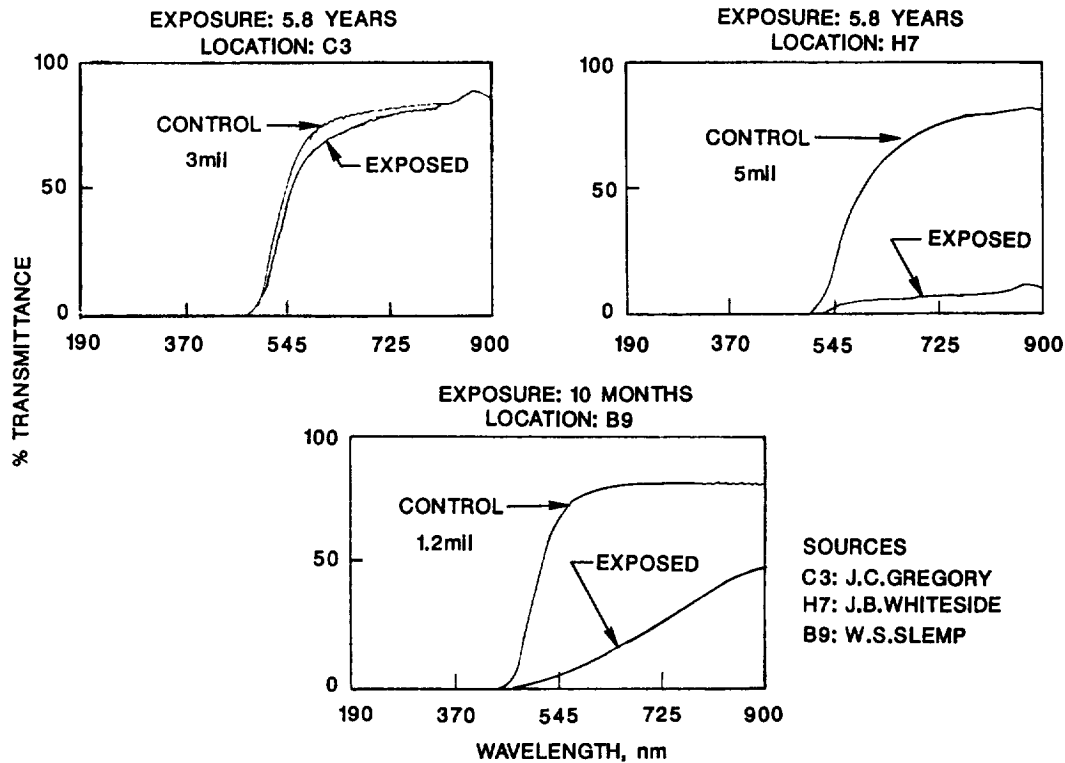
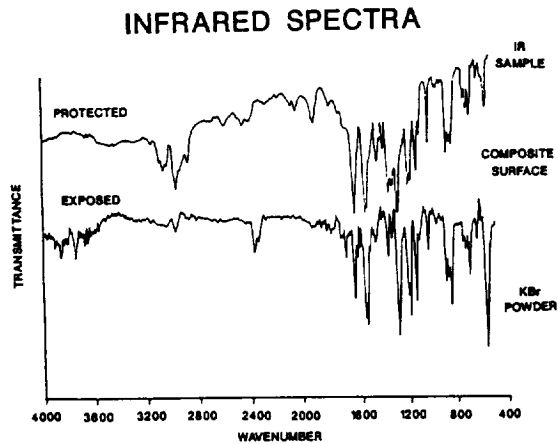


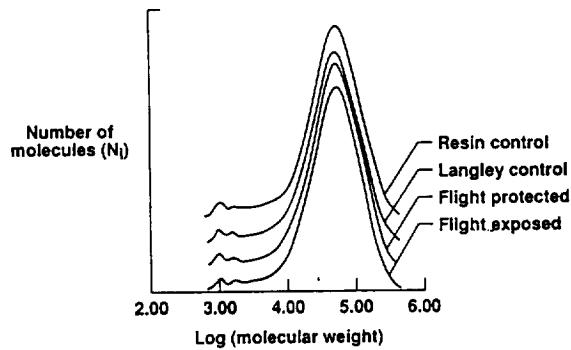
Figure 3. UV-VIS spectra of LDEF-exposed Kapton film.



GLASS TRANSITION TEMPERATURE

Sample	T _g (°C)	Contacted side
Langley Control	167°	} Random
	167°	
	170°	
	166°	
Flight Protected	164°	Side A
	166°	Side B
Flight Exposed	170°	} Exposed side
	171°	
	169°	} Nonexposed side
	171°	

MOLECULAR WEIGHT DISTRIBUTION



MECHANICAL PROPERTIES

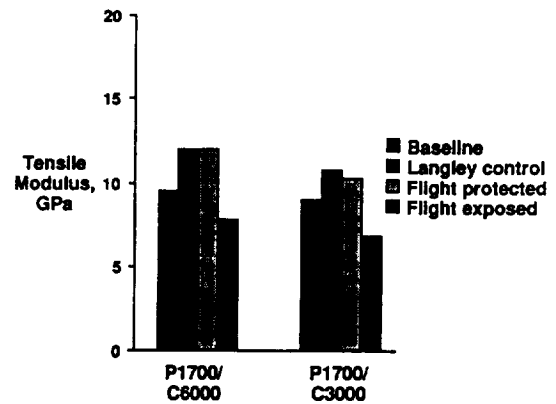


Figure 4. A summary of polysulfone composite characterization results; 5.8 years of Row 9 exposure.

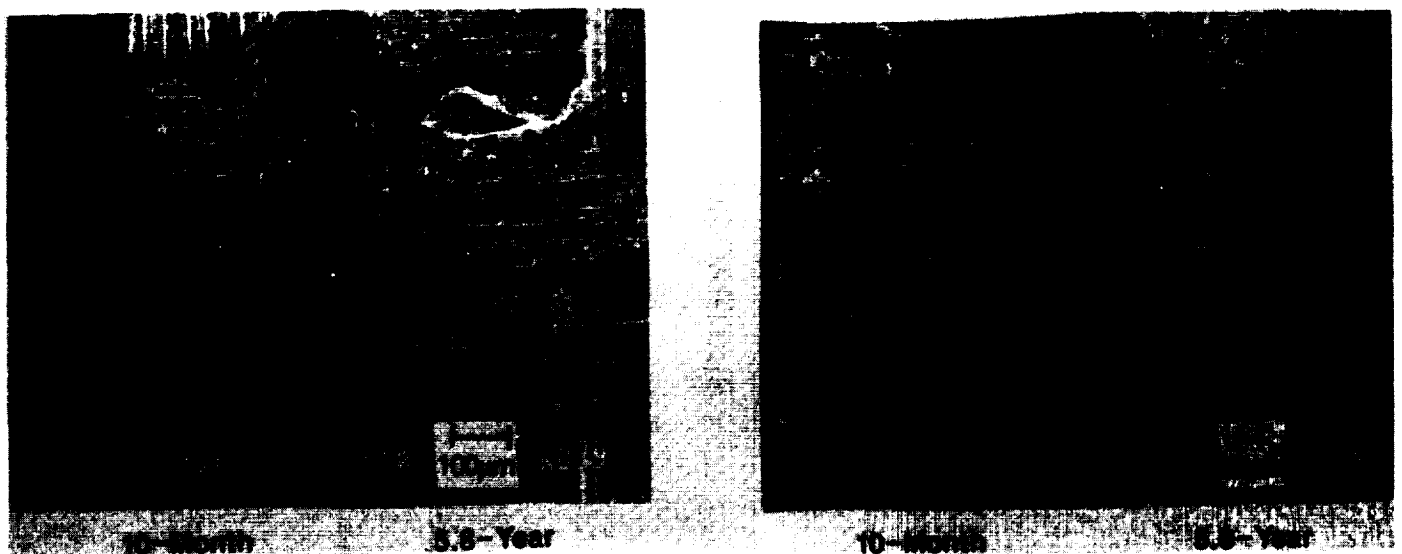
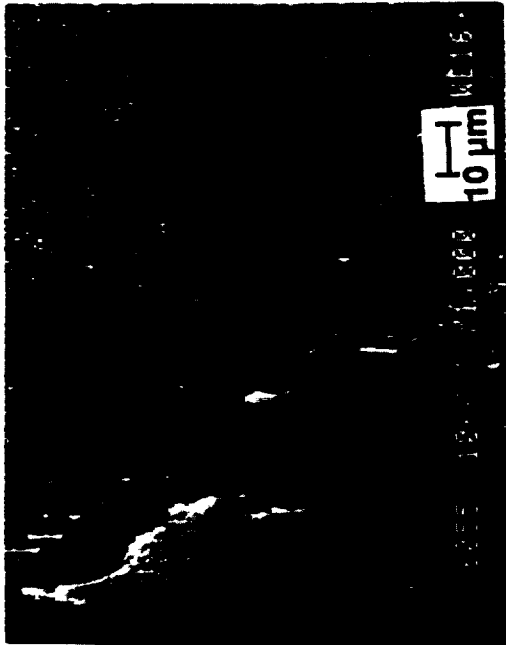


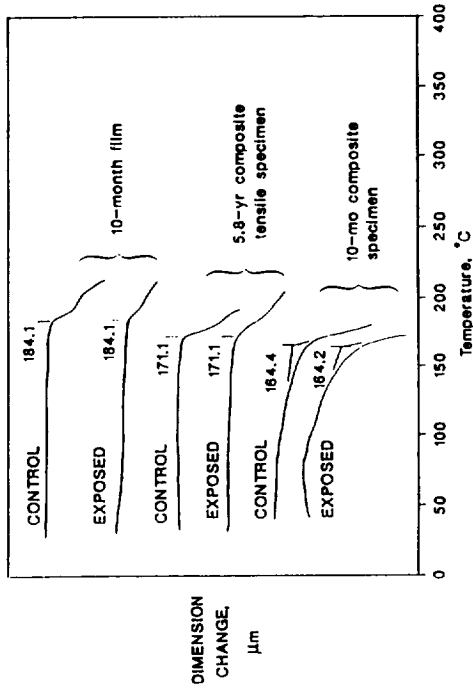
Figure 5. Scanning electron microscopy photomicrographs of coated 934/T300 epoxy composites; 600 Å SiO₂/1,000 Å nickel/composite.

SEM

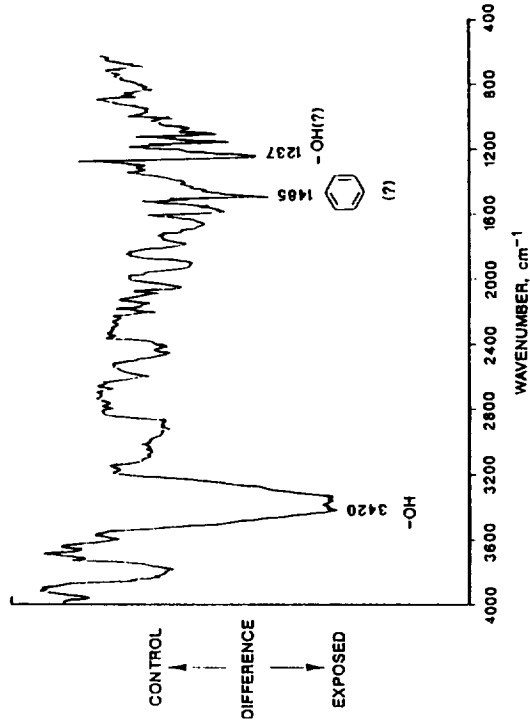


10-Month Exposure

TMA



SUBTRACTION SPECTRUM



MOLECULAR WEIGHT DISTRIBUTION

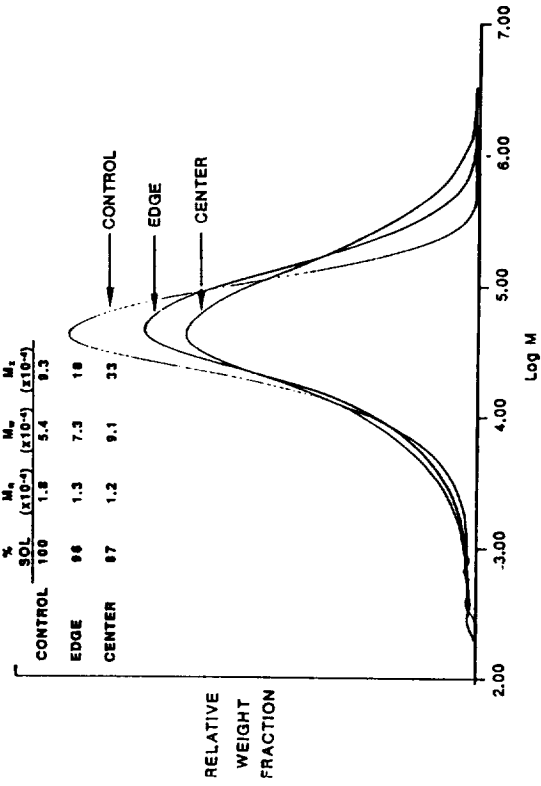


Figure 6. A summary of polysulfone film characterization results; 10 months of Row 9 exposure.

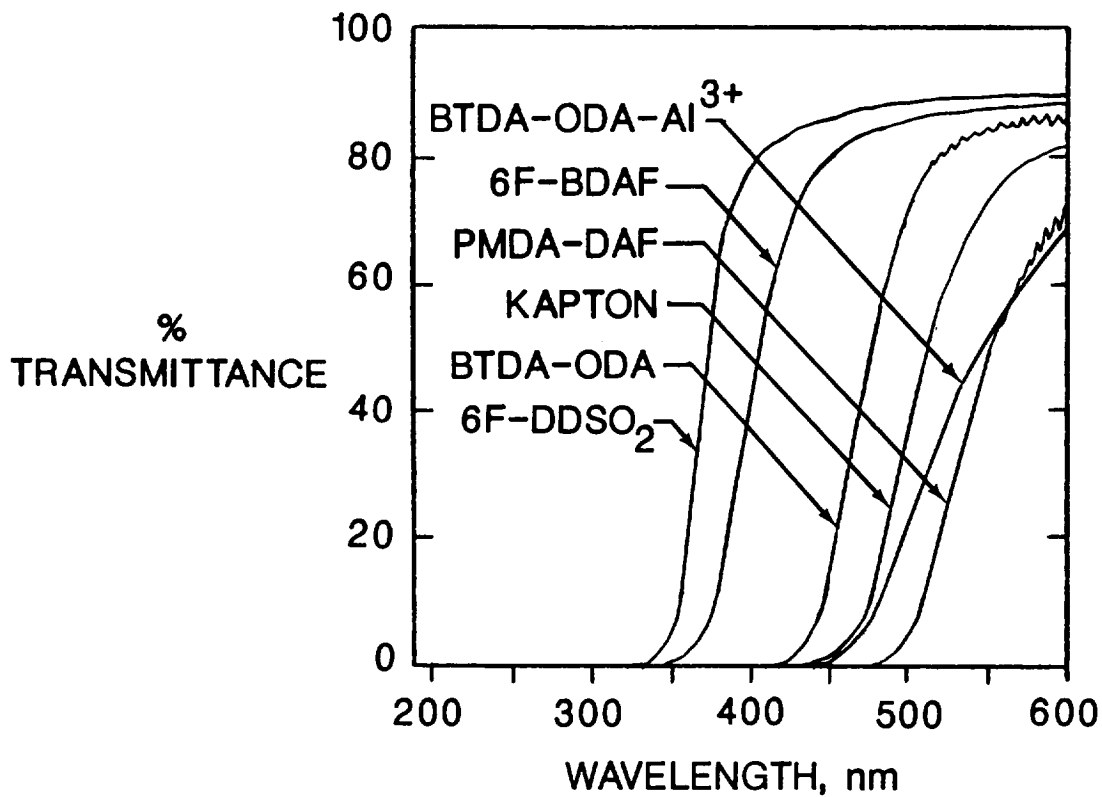


Figure 7. UV-VIS spectra of unexposed polyimide films.

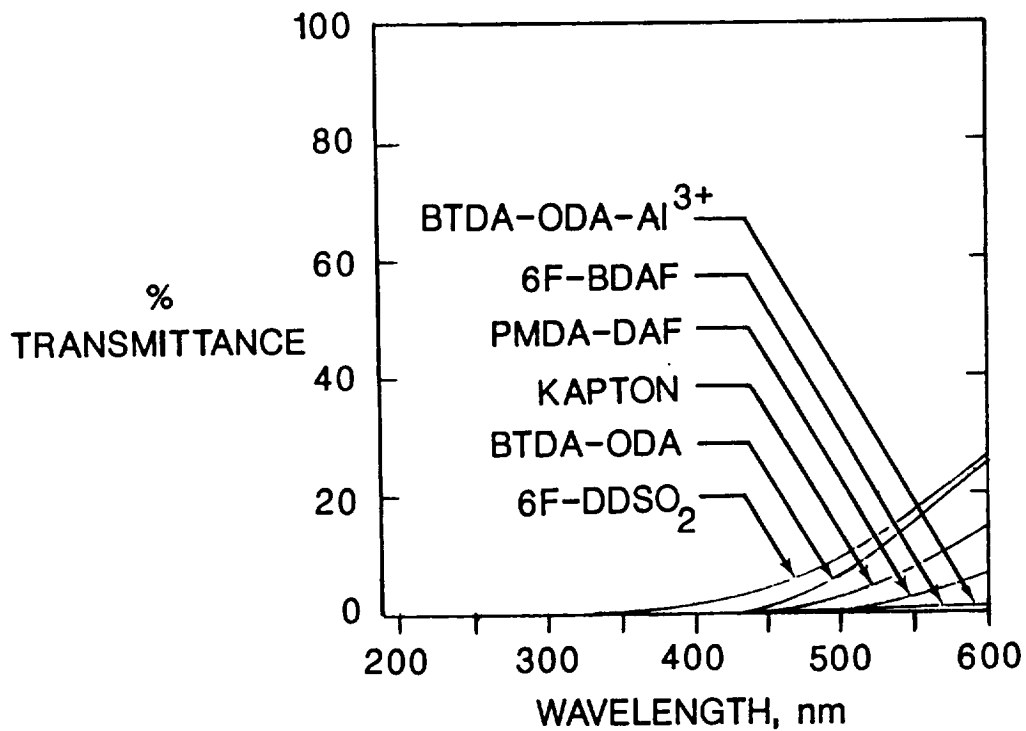
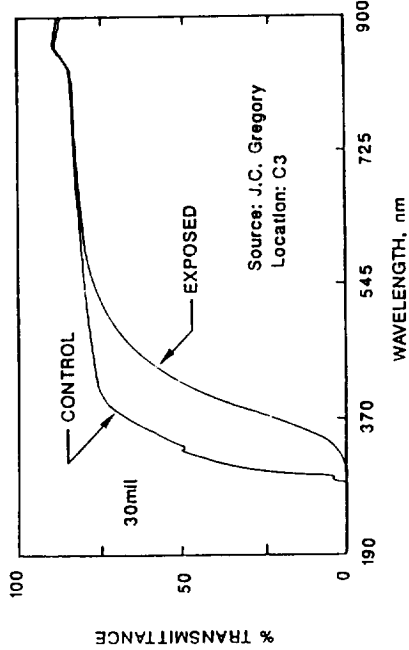
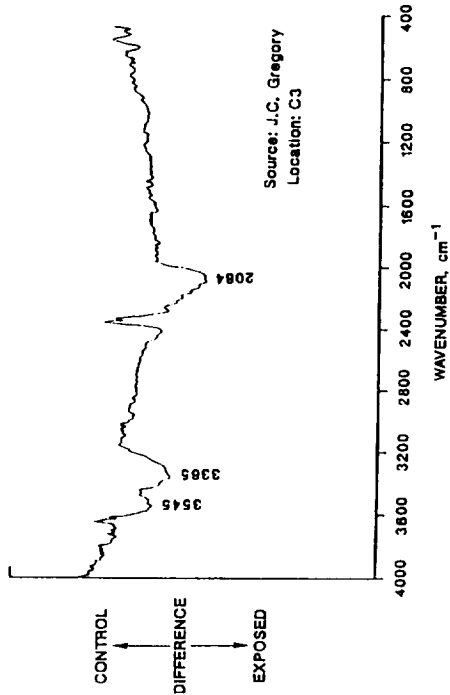


Figure 8. UV-VIS spectra of polyimide films exposed for 10 months on LDEF.

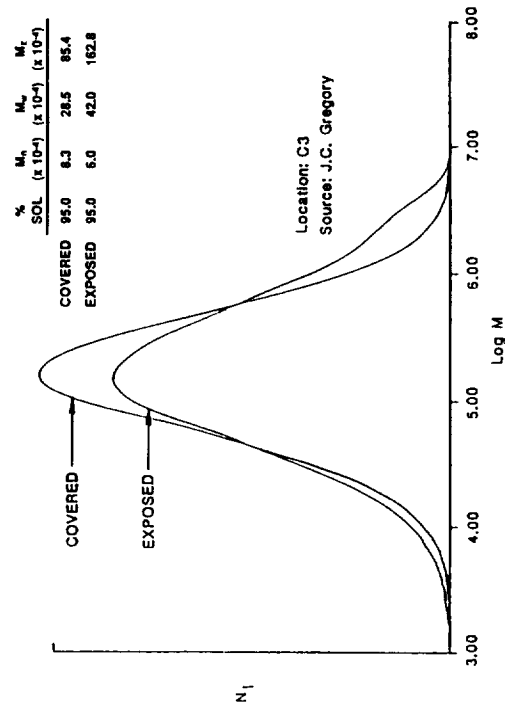
POLYSTYRENE UV-VIS SPECTRA



POLYSTYRENE SUBTRACTION SPECTRUM



MOLECULAR WEIGHT DISTRIBUTION
-POLYSTYRENE-



MOLECULAR WEIGHT DISTRIBUTION
-POLYVINYL TOLUENE-

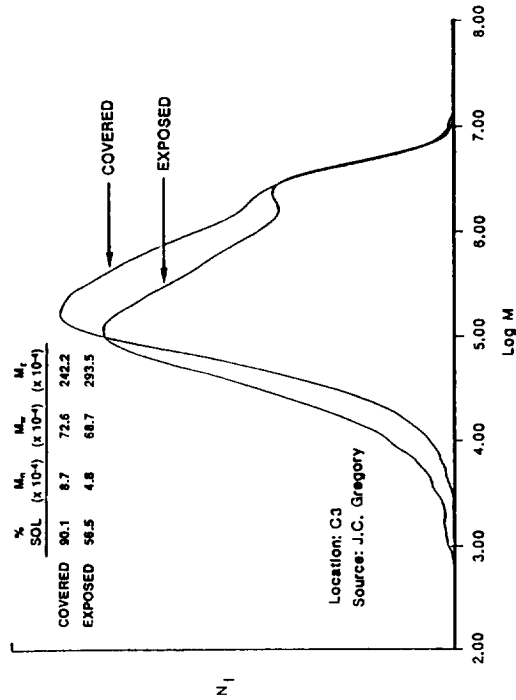


Figure 9. A summary of polystyrene and polyvinyl toluene characterization results; 5.8 years of Row 3 exposure.