Effects of space exposure on optical filters

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Optical transmittance characteristics of nine optical filters were remeasured after nearly 6 years in space aboard the NASA Long-Duration Exposure Facility. Three different filter types were included. In general, transmittance decreased for most filters. The center frequency and bandpass of a narrow-band filter under an aluminum cover were unchanged, while narrow-band filters exposed directly to the space environment tended to show a shift in center frequency and increased bandwidth. A pair of infrared-reflecting mirrors exhibited reduced transmittance in the visible, with a mirror under an aluminum cover less degraded than a mirror exposed to space. The bandpass was unchanged for both of these mirrors. Neutral density filters showed a slight increase in transmittance for an uncovered filter; essentially no change for the filter under the aluminum cover.

Key words: Optical filters, space exposure.

Introduction

The NASA Long-Duration Exposure Facility (LDEF) is a free-flying satellite that was designed to provide an economical means of achieving exposure to the space environment for experiments that can benefit from postrecovery measurements of the retrieved hardware. The measurements reported here are transmittance measurements on 1-in.- (2.54-cm)-diameter optical filters that were part of a set of electro-optic components located at one of the 86 experiment tray positions comprising the exterior of the satellite structure. The satellite was carried into space by the Space Shuttle Challenger and recovered by the Shuttle Columbia after it remained in orbit 5 years and 8 months.

The set of nine optical filters[1] included three different types as listed in Tables 1–3. Three of the nine filters were under an aluminum cover (numbers 2, 6, and 9), while the remainder were exposed directly to the space environment.

The filters were fabricated by using technology that was appropriate in the late 1970's. One of the wide-band hot-mirror filters was examined with scanning electron microscopy and secondary-ion-mass spectroscopy as part of the postrecovery measurements. It was found to be composed of 11 layers of thorium fluoride/zinc sulfide pairs deposited on a glass substrate. The topmost layer was thorium fluoride. The design and fabrication of optical filters was recently reviewed by Goldstein.[2]

The experiment tray was mounted on the starboard side of the LDEF in the four o'clock position relative to a twelve o'clock direction of motion. In this position, the components experienced reduced exposure to atomic oxygen and micrometeoroid impacts compared with the leading-edge position, but craters on the surface of most exposed components were nonetheless observed. The position of the tray on the LDEF is shown in Fig. 1. As this figure indicates, the experiment tray was divided into six subtrays, five of which were covered with sunscreens, each sunscreen with ~ 54% obscuration. Sunscreens were used on all but one subtray to minimize the excursions about the design temperature should the LDEF experience unplanned orientations or orbital parameters. Maximum temperatures were not a strong function of the percentage transmission of the sunscreens.

Maximum temperatures were near 66°C. Minimum temperatures were near −10°C. Minimum temperatures were not considered to be of concern to the survival of the set of components on the tray. The orbital altitude was in the 324–479-km range, with the lowest altitude reached at the time of recovery.

Exposed filters were subjected to temperature cycles, solar radiation, high energy and particle radiation, and (in the period just before recovery) increased amounts of atomic oxygen. The total radiation dose was not large. The total dose for unshielded samples was < 300 krads, mainly because of geomagnetically trapped electrons with a small amount of proton

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Table I. Optical Filter Properties of Narrow-Band Filters

	Center Wavelength (nm)		Band width (nm)		Transmission (%)	
Filter Number	Pre-launch	Post-recovery	Pre-launch	Post-recovery	Pre-launch	Post-recovery
1	486.2	487.2	1.2	1.4	32.3	25.4
2 (Covered)	513.9	513.8	1.05	1.9	58.3	28.6
3	633.6	632.5	1.0	5.5	45.1	18.3
4	545.8	544.2	10.7	10.7	62.4	33.0
5	544.7	545.3	10.7	10.8	70.1	33.0

irradiation.[3] The electron fluence for unshielded samples for all electron energies was $<2.5 \times 10^{12}$. Samples mounted under an aluminum cover received <300 rads. The total fluence of atomic oxygen was near 10^{13} atoms/cm^2.[4]

Experiment

Thin-film dielectric-stack narrow-band interference filters that were used in the experiment reported here were manufactured by cementing two filter halves together so as to protect the interference layers at the center of the sandwich. Neutral density filters had an Inconel coating that provided an optical density of ~ 1.4. As mentioned previously, the hot-mirror interference filters were deposited on glass with a ThF layer at the surface.

After measurement but before launch, the filters were mounted on the experiment tray that was then placed within a sealed metal shipping container with desiccant to ensure a dry atmosphere. A prompt launch and recovery were planned, and no filters were stored on the ground. Various delays and problems with the space shuttle turned a planned 6–10-month period in orbit into a 5.8-year orbiting period after an unplanned 7 years in storage in various locations before launch. As a result, data are limited to a set of prelaunch and postrecovery measurements.

Previous measurements on the effects of space exposure for these types of optical filter are limited. Nicoletta and Eubanks[5] studied the effect of electron, proton, and UV irradiation on the transmittance of various fused silicas, colored glass filters, and thin-film interference filters. They found that no significant changes occurred in the transmittance of fused silica as a result of exposure to electron and proton radiation equivalent to 1 year in space. There was also no change in transmittance of interference filters (shielded with fused silica) as a result of exposure to electron radiation equivalent to 1 year in space. For higher fluences and greater electron energies, transmittance losses in fused silica were observed. Their estimates of the total dose for 1 year, based on early NASA data, are close to the recent NASA estimates for the 5.8-year LDEF exposure. Therefore, one would not expect measurable changes in optical transmittance from the radiation dose received by the LDEF. Nicoletta and Eubanks did find that exposure to electron fluences of 2×10^{14} electrons/cm^2 or greater with electron energies of 1.0 MeV and higher caused significant losses in transmittance for fused silica. Such fluences are higher than the fluence received by the LDEF components.

Table 2. Optical Filter Properties of Neutral Density Band Filters

	50% On Wavelength (nm)		50% Off Wavelength (nm)		Transmission (%)	
Filter Number	Pre-launch	Post-recovery	Pre-launch	Post-recovery	Pre-launch	Post-recovery
6 (Covered)	415	38	700	780	96	78
7	386	385	695	702	98	86

Table 3. Optical Properties of Broadband Filters

Filter Number	Wavelength (nm)	Percent Transmission at Listed Wavelengths (nm) 350	400	500	600	700
8	Prelaunch		3.2	3.5	3.8	4.0
	Postrecovery		3.7	4.1	4.2	4.2
9	Prelaunch		3.0	3.2	3.5	3.7
(Covered)	Postrecovery	2.9	3.1	3.3	3.7	3.7

Reduction in transmittance as a result of UV irradiation was observed by these authors for interference filters, whereas the filters were unaffected by an initial irradiation by electrons. The authors' tenta-

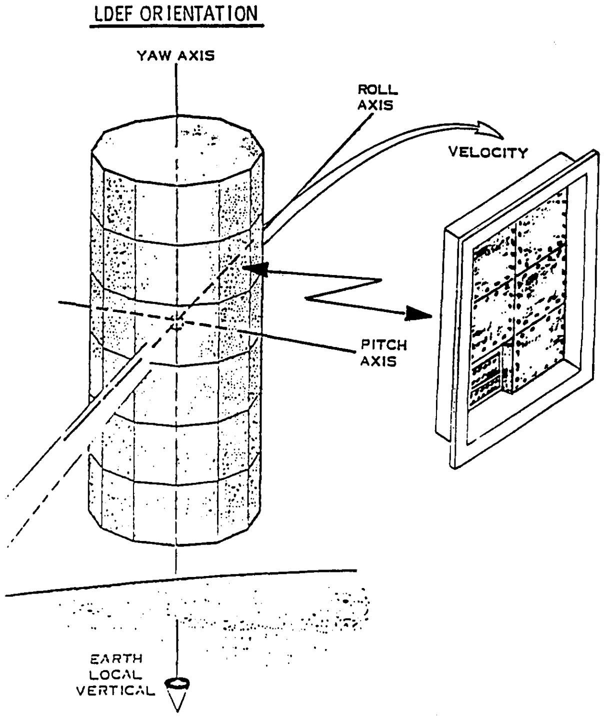

Fig. 1. Location of the Active Optical System Components experiment on the LDEF. In this location, expected effects from atomic oxygen and particle impacts are reduced from leading-edge locations.

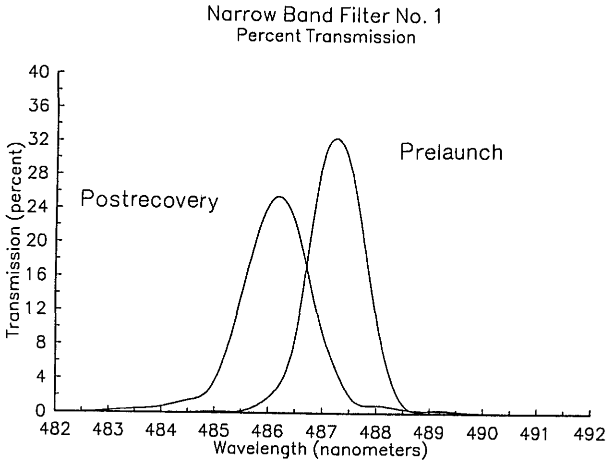

Fig. 2. Prelaunch and postrecovery transmission of narrow-band filter number 1.

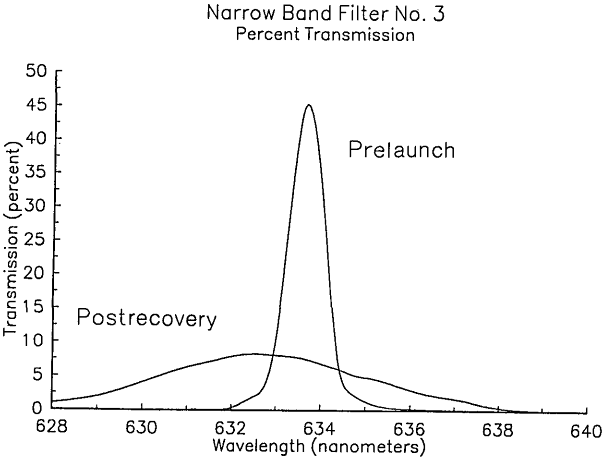

Fig. 4. Prelaunch and postrecovery transmission of narrow-band filter number 3.

tive conclusion with regard to the cause of the measured filter degradation was that the thin-film materials and/or the organic-based adhesive that was used to assemble the filters were responsible.

More recent measurements also indicate radiation-induced darkening in optical glasses and epoxies.[6–8] Typically, measurements are made immediately after irradiation so as to minimize spontaneous recovery. For the measurements reported here, the repeated temperature cycling to temperatures close to room temperature while in orbit followed by similar warming during recovery would permit some annealing of radiation-induced defects. For this reason also no significant effects on the filter properties resulting from ionizing radiation received while aboard the LDEF were expected.

Results

The narrow-band filter transmittance characteristics for our set of five filters are shown in Figs. 2–6. Filter 5 shows a slight but measurable shift toward longer wavelengths as a result of space exposure, but with the same bandwidth. For the other narrow-band filters, the shift is toward longer wavelengths and is more pronounced. The exception is filter number 2, which was under an Al cover. For filter number 2, the filter bandwidth was unchanged. For filter number 3, the filter bandwidth increased substantially. For the other two narrow-band filters, the filter bandwidth did not change appreciably with space exposure.

Although dielectric-stack laser mirrors on the tray showed evidence of deterioration (color changes and delamination from the substrate), the appearance of the filters was unchanged except for the presence of a thin deposited organic contamination layer. Deterioration that starts from the edge and moves toward the center, often seen in aged optical filters, did not occur with the filters in this set.

A bandpass shift toward the blue may be expected if the temperature cycling causes some realignment and adjustment within the multilayer interference films that tends to decrease the average film thickness. Any external effects that disrupt or disturb the interference layer uniformity will tend to broaden the

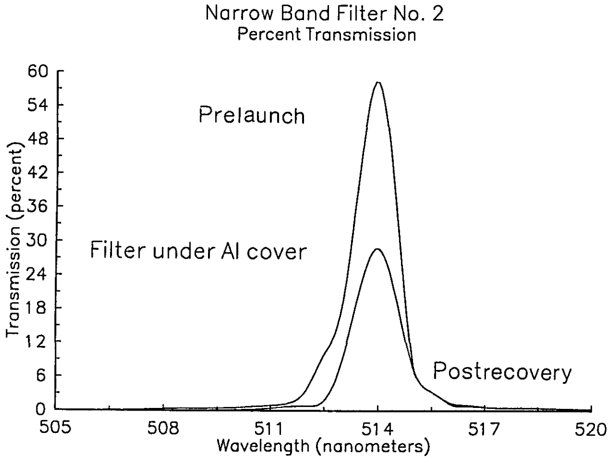

Fig. 3. Prelaunch and postrecovery transmission of narrow-band filter number 2. This filter was protected from the space environment by an Al cover.

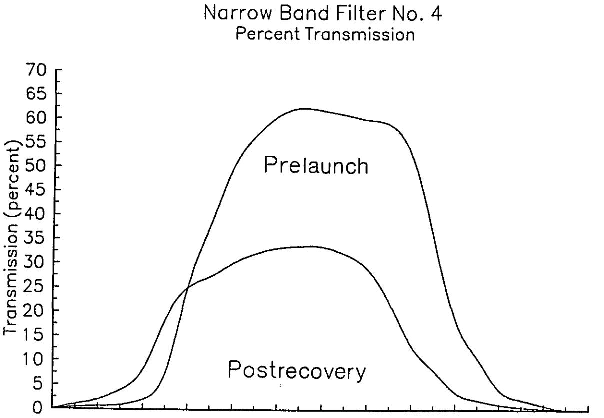

Fig. 5. Prelaunch and postrecovery transmission of narrow-band filter number 4.

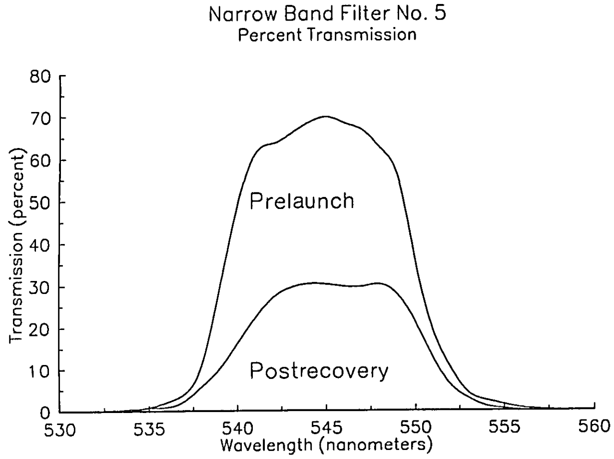

Fig. 6. Prelaunch and postrecovery transmission of narrow-band filter number 5.

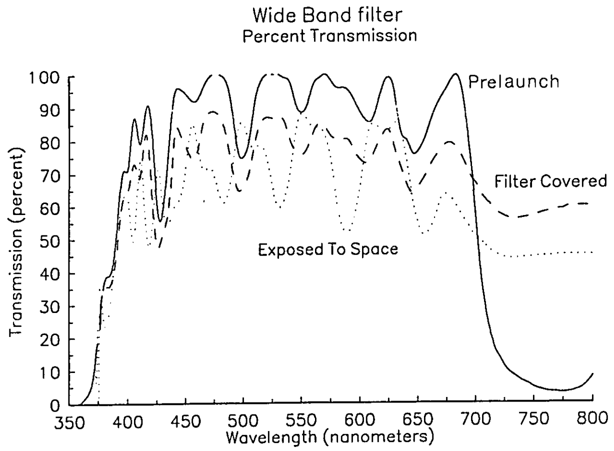

Fig. 7. Prelaunch and postrecovery transmission of two infrared-suppression filters. Filter number 9 was under an Al cover during the period in orbit and is shown as a dashed curve. The dotted curve is the postrecovery transmission of the filter directly exposed to the space environment.

filter bandwidth.[9] The results of our rather limited set of measurements indicate that such effects tend to be small although filter number 3 is the clear exception even to this attempt at a general statement with regard to these results.

The reduction in narrow-band filter transmittance is the most apparent change in the performance characteristics as a result of the years in space. A reduction in transmittance occurred for all narrow-band filters including the filter under cover. We believe that reduced transmittance is caused mainly by deterioration of the cement that was used to attach the two filter halves together. Deterioration of plastics and other organic materials on the LDEF has been noted by other NASA investigators[10] during preliminary investigations of the returned hardware. Concern with the behavior of plastics in space dates back several decades.[11]

For the two near-infrared suppression (hot-mirror) filters, the nearly 6 years of space exposure did not cause any shift in filter wavelength characteristics. However, the performance of the two filters had deteriorated. Both the transmission and the long-wave reflectance characteristics were degraded. As the results in Fig. 7 indicate, the covered filter has somewhat better performance than the filter exposed directly to space. For these filters, the degradation of the interference layers and the reduced interference effectiveness are indicated by the reduced transmittance through the visible region and increased transmittance on the long-wave side.[9] No apparent change in the filters is evident by visual observation.

The radiation exposure of <300 krads is below what would be expected to produce observable degradation, and the filter under the Al cover would have an exposure of $<1\%$ of this value. Yet the covered filter suffered significant degradation. The atomic oxygen fluence of $10^{13}/\mathrm{cm}^2$ provides only one oxygen atom for more than ten surface atoms, insufficient to produce the observed effects. UV irradiation would not affect the filter under cover, and normal aging of the hot mirrors should leave them in identical conditions. The thousands of temperature cycles would have nearly the same effect for the covered and exposed filters and do not provide an explanation for the performance differences between the pair. Possible changes in stoichiometry of the ThF surface layer would affect the filter performance, but no major change in stoichiometry was noted during the examination.

The pair of neutral density filters show somewhat different characteristics. The covered filter showed no performance changes to the accuracy of our measurements (0.1% detectable change in transmittance). The exposed filter showed an increase in transmittance of ~0.5%. Transmittance of this filter is shown in Fig. 8. The increased transmittance is possibly the result of erosion of the Inconel coating during the 69 months in low Earth orbit since oxide formation should be minimal. The only physical difference noted between this pair of filters was the

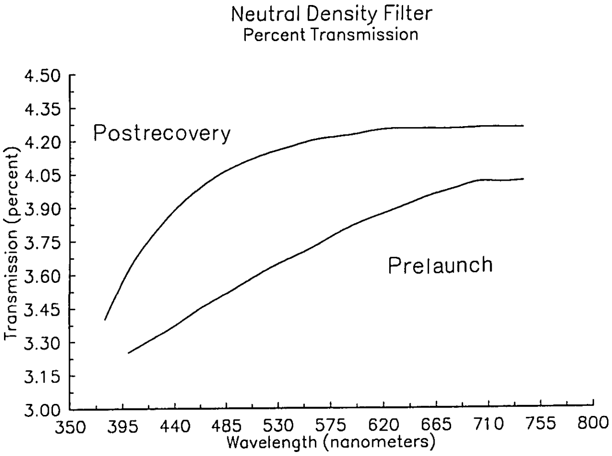

Fig. 8. Prelaunch and postrecovery transmission of one of two neutral density filters. The covered neutral density filter was unchanged. The exposed filter, shown here, showed increased transmission.

presence of a contamination layer on the exposed filter that stopped at the rim at which the surface was covered by the attachment hardware. The small amount of contamination would reduce transmittance. Erosion would result in increased transmittance.

Several filters were cleaned with isopropyl alcohol by using lens tissue after postrecovery measurements in order to determine if contamination deposited on the surface was responsible for any measurable changes in properties. The entire LDEF structure seemed covered by a yellow-brown stain of varying density that could possibly affect filter transmission. A CaF_2 window on the tray was found to have 0.2-mg/cm^2 organic residue. The source of a major portion of this contamination was traced to the black thermal control paint that was used in the interior of the LDEF. The deposition of the contamination was driven by temperature gradients, and retention of the film on surfaces was induced by solar UV radiation.[12]

Filter number 2 had black paint along the filter edge that had begun to peel somewhat. No organic residue was found on the lens tissue after cleaning. After cleaning, the transmittance of this filter was also unchanged. While in space, this filter was under an Al cover.

Filter number 3 showed no obvious contamination but some fogging was noted on one side that could not be cleaned off. No material was visible on the lens tissue after both surfaces were cleaned. The transmittance after cleaning was unchanged within the accuracy of the spectrometer.

Filter number 8, a neutral density filter, showed a faint brownish color upon reflection from its upper surface. The color appeared to be caused by a deposited nonuniform layer whose thickness varied slightly from one side of the filter to the other. The film was stubborn but could be removed by repeated passes with the lens tissue, leaving a brown stain on the tissue. This stain is consistent with the brown stain seen throughout the experiment tray surface and throughout the surface of the satellite. However, removal of the film left the filter transmittance unchanged.

As a result of these examinations, we do not find that the observed changes in filter transmittance in the visible spectral region are the result of absorption and scattering from impurities deposited on the surfaces.

The effects of erosion, compaction driven by temperature cycling, loss of volatile material from the film surface when permissible, degradation of organic materials, and contamination remain as the possible sources of the observed degradation. This combination of effects will produce results dependent on filter design and packaging.

Summary

Transmittance measurements for a set of nine optical filters that were exposed to the space environment for 5 years and 9 months aboard the NASA LDEF satellite indicate performance degradation.

Narrow-band interference filters show evidence of reduced transmittance, shift of center wavelength, and bandpass broadening. However, the results are not consistent for the five filters. In particular, the film under an aluminum cover, representative of conditions in the interior of a space vehicle, showed only a reduction in transmittance with no shift in center wavelength or bandwidth. The covered filter was protected from UV radiation, and its exposure to ionizing radiation was reduced by a factor of 10^3. Deterioration of the cement that was used to construct the filters is considered to be the source of the loss in transmittance for these filters.

Infrared suppression filters (hot mirrors) showed a reduction in transmittance and evidence of deterioration of the interference coatings as a result of space exposure. The filter under cover experienced a similar but a smaller amount of degradation compared with the exposed filters. No cement was used on the construction of these filters. Temperature cycling, erosion, changes in surface stoichiometry, and contamination are possible sources of the deterioration.

Neutral density filters are of different construction and reacted differently to the effects of space exposure. The sample exposed to the space environment had increased transmittance. The covered sample was unchanged. A small amount of erosion of the metal film of a few percent of the film thickness would be sufficient to cause the observed increase in transmittance.

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