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A FINAL LOOK AT LDEF ELECTRO-OPTIC SYSTEMS COMPONENTS

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SUMMARY

Postrecovery characteristics of LDEF electro-optic components from the GTRI tray are compared with their prelaunch characteristics and with the characteristics of similar components from related experiments. Components considered here include lasers, light-emitting diodes, semiconducting radiation detectors and arrays, optical substrates, filters, and mirrors, and specialized coatings. Our understanding of the physical effects resulting from low earth orbit are described, and guidelines and recommendations for component and materials choices are presented.

INTRODUCTION

As the LDEF program was developing in the early 1970's, the ability of optical systems to survive in the space environment had been demonstrated by successes with interplanetary probes such as Mariner II in 1962. Ground-based testing had been the method used to simulate the expected major effects of the space environment, while the consequences of any unexpected effects were assumed minor. Confirmation of these assumptions was difficult to obtain, particularly for effects related to the near-earth environment. The availability of the LDEF satellite provided an opportunity to expose a set of state-of-the-art components to the space environment and look carefully for unexpected degradation effects in both familiar and novel materials and devices. This report summarizes the results of this experiment, discussing both the components which were unchanged, and the components whose properties were altered during the nearly six years in space.

Figure 1 shows the position of the tray containing the components on the LDEF satellite. This location, on the rear portion of the satellite, resulted in a lower fluence of atomic oxygen and fewer micrometeorite impacts than was the case for the leading edge trays. Five of the six subtrays were covered with a sunscreen (with ≈ 50% transmission) which provided some temperature stability in the event of an undesired orbit. The environmental parameters for this tray position, as determined from data supplied by NASA, are presented in Table 1.

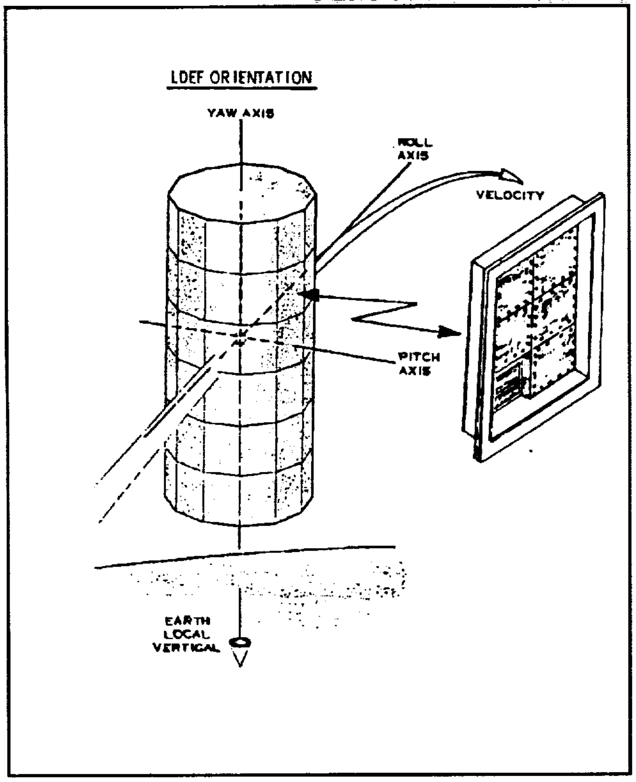


Figure 1. Location Of The Active Optical Systems Components Experiment On The LDEF.

TABLE I. THE LDEF ENVIRONMENT FOR THE COMPONENT SET

Maximum Temperatures From NASA Estimates For The First Year	66°C (105°F)
Atomic Oxygen Fluence	1.1 X 10^{13} atoms/cm^3
Radiation Dose At The Tray Position Of Figure 1. From NASA Reports	< 300 Rads(Si)

The total radiation dose for components protected by the sunscreen was less than 300 krads which is well below the value where degradation is observed in many materials and components. No effects of radiation on component properties were found with the exception of the silicon CCD array. The location of the tray on the rear of the satellite minimized effects from micrometeorite impact as well as effects of atomic oxygen. The oxygen flux represents less than one oxygen atom per 100 surface atoms, a negligible amount.

The components typically were mounted in such a manner as to simulate a minimum level of protection to be expected in a realistic application except that, in a few cases, no protection was provided merely to satisfy our curiosity.

OPTICAL COMPONENTS

In addition to the windows, filters, and mirrors in the GTRI tray, similar optical components from several other experiments were carried on the LDEF. Common results were found for optical substrates, filters, and mirrors covering wavelength regions from the ultraviolet to the infrared. Most components survived space exposure quite well, and space-induced degradation was not a major factor for most optical component properties. Some of our results have been published.[1,2]

Window materials including SiO_2, MgF_2, Al_2O_3, CaF_2, and LiF, were returned from space with a thin brown or yellow-brown contamination layer.[3] The contamination layer or layers could usually be removed by cleaning. Infrared spectroscopy of all window materials except SiO_2 indicated the presence of methyl and methylene bands. Their absence on SiO_2 indicates substrate selectivity for the deposition of contaminant.[4] Optical filters on the GTRI tray were coated with a slight contamination layer, but did not show measurable transmittance changes attributable to this contamination.

The results of these and other measurements[3,4,5,6] reveal that the contamination layer absorbs strongly in the ultraviolet region, but has negligible absorption in the visible and infrared regions: a result independent of the location of the contamination on the satellite. The spectral transmission of the substrate materials is similar to results for transparent substrates subjected to heavy doses of radiation.[7]

KRS-5 windows used on pyroelectric radiation detectors degraded[8] as did KRS-5 and KRS-6 uncoated material and filter substrates from the University Of Reading experiment (unpublished work). When these two materials were used as substrates for multi-layer dielectric stack filters, delamination occurred.

Thin-film dielectric-multilayer narrow-band filters and mirrors showed a band shift, increase in band width, and reduced throughput or reflectance after return from the space environment.[1,2,9] Figures 2 and 3 show the results for an optical narrow-band filter from the GTRI set, and a long-wave infrared filter from the Reading University set. Both filters show the three effects mentioned above. The band shift is small, but may be important for certain space-borne systems. These effects appear to be result of temperature cycling expediting the realignment and compaction of the deposited dielectric layers which tend to decrease the average film thickness and shift the peak transmittance toward the blue. Similar effects occur in a laboratory environment, although at a lower rate in most cases. Interdiffusion between layers increases bandwidth, and lowers transmittance. Deterioration of cement used to attach filter substrates together can also lower transmittance.

Among the effects considered but not found important in the deterioration of the GTRI set of filters and mirrors were surface contamination, atomic oxygen flux, and radiation dose.

The substrates, filters, and mirrors aboard LDEF provided a rich source for information about the effects of space exposure, stability of various types of substrates, coatings, and films, and performance of these optical elements in various configurations and constructs. Additional information on this topic may be found in the other 1993 NASA symposium papers on this topic and in the references.

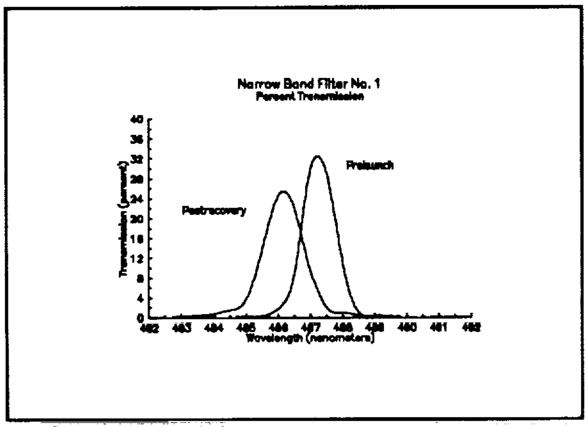


Figure 2. Prelaunch And Postrecovery Transmittance Of A Narrow-Band Filter From The GTRI Set.

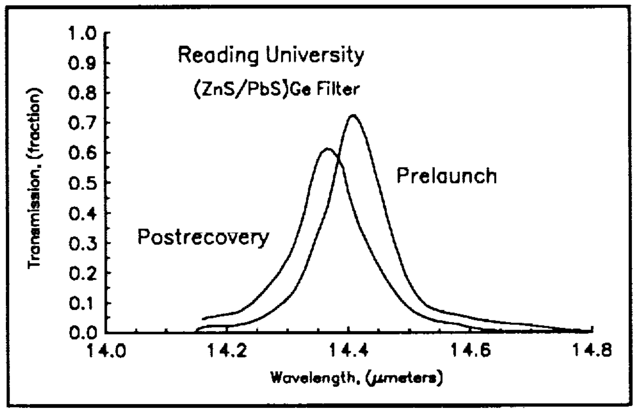


Figure 3. Prelaunch And Postrecovery Transmittance For A Narrow-Band Filter From The Reading University Set.

OPTICAL RADIATION DETECTORS

The LDEF carried a variety of radiation detectors which were of interest in the 1970-1980 time frame. All detectors were maintained at ambient temperature. Regarding their survivability in space, postrecovery measurements support the general conclusion that their detection properties were not degraded. However, degradation unrelated to direct intrinsic loss of detector sensitivity, such as degradation of detector assembly windows or loss of electrical contact can occur. These effects are of a mechanical origin and do not contradict the general conclusion that the detector element survives. The assortment of detectors supporting our conclusions included a group of pyroelectric detectors, Si, PbS. PbSe, InSb, HgCdTe, GaAsAlP, and two Pd_2Si Schottky-barrier IRCCD imaging-array chips.

The only exceptions to this typical result concern TGS (triglycine sulphate) material used in pyroelectric detectors and CCD readout structures. TGS detectors either failed or deteriorated for both the control and the space-exposed samples. This material is to be avoided. The results for the set of pyroelectric detectors have been described by Robertson.[8]

CCD structures can be damaged by the natural radiation in space. Silicon CCD readout or scanning circuitry is associated with image frame sensors. As will be discussed further, CCD's are arguably examples of the most radiation-sensitive semiconductor devices.

Six silicon large-area photovoltaic (pv) detectors were mounted so that the sensitive photosurface was exposed to the space environment. After recovery, small scars from the apparent impact of micrometeorites could be observed by eye.

Properties measured for these detectors included spectral noise density, responsivity, and reverse leakage current.Only one detector showed any increase in leakage current, and the amount was less than 2 microamperes per cm^2. Figure 4 shows the prelaunch and postrecovery capacitance for one of the detectors. Despite the micrometeorite impacts and the lack of radiation protection, the detectors survived without notable change in properties.

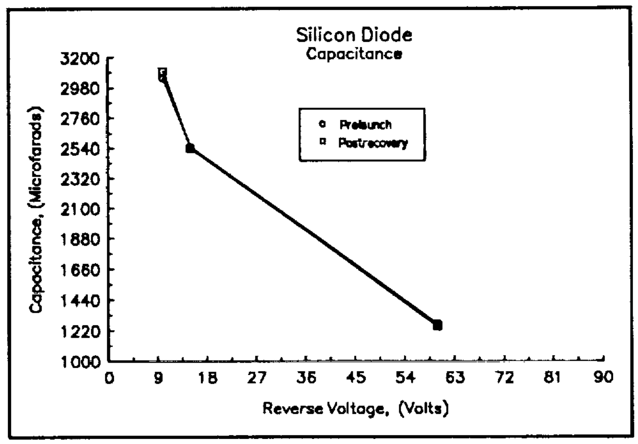


Figure 4. Prelaunch and Postrecovery Capacitance for a Large-Area Silicon Photodiode.

The postponed launch date of the LDEF permitted addition of two Pd_2Si arrays to the collection of radiation detectors in 1983. Two different chips were used. The first chip contained process test devices, while the second chip contained a Schottky-barrier 32X63 IRCCD imaging array. Postrecovery characterization compared the recovered chips with a control from the same silicon wafer.

Radiation produces three different types of permanent degradation in CCD arrays. First, radiation effects can increase the thermal generation rate of minority carriers which increases the dark current and shortens the storage time of the device. Second, because of a tendency for some charge to be left behind in each transfer step from gate to gate, there is an inherent charge transfer loss in CCD's. This transfer loss or transfer inefficiency is enhanced by radiation and works to degrade image resolution. Finally, irradiation of a CCD causes a shift in the range of bias voltages in the propagation and transfer gates over which satisfactory operation can be obtained.

A major damage mechanism in these devices is the production of positive charge which can be trapped in the SiO_2 insulator or at the semiconductor-insulator interface. Because the amount of energy required to create a hole-electron pair in SiO_2 silicon is 18 eV, the total received dose must be corrected to include only the radiation with energy above this value. This correction is negligible for LDEF. For 18 eV/pair, it can be calculated that 7.6 X 10^{12} pairs/cm^3 are created per rad(Si) dose. The calculated received dose was 68 krads(Si).

This calculated dose is about two orders of magnitude greater than originally expected because of (1) the extended time in orbit, and (2) a higher radiation flux than originally expected. In a more realistic setting, these arrays would be mounted inside a cryogenic assembly and mechanical structure at the focal plane of a telescope, all of which would provide extensive radiation protection.

From the thickness of the oxide and area of the electrodes, the volume of insulator and, therefore, the number of hole-electron pairs per electrode created by the radiation can be calculated. Most of the charge pairs recombine quickly (about 95%) and most of the defects produced by the remainder would be expected to be removed by the annealing resulting from the periodic temperature cycling experienced by the LDEF along its orbital path. A reasonable assumption is about 1% if the irradiation dose results in permanent trap creation. As a result, the expected number of traps per electrode is estimated to be 1.5×10^6. These traps cause transfer inefficiency. Injection of additional charge to fill these traps is one means of improving operation.

For these devices, a charge injection equivalent to 2×10^6 electrons per pixel restored most of the lost transfer efficiency. This number is to be compared to the estimated trap density. The reasonable agreement obtained suggests that the received radiation dose is the major source of the reduced device performance.

The construction of these chips represents technology over ten years old. Since these arrays were produced, alternative insulating systems were produced which provide greater radiation hardness. Newer devices also have shorter gate lengths and greater transfer efficiency which suggests better performance in a radiation environment. As mentioned above, additional radiation protection would be afforded by the required cryogenic support and necessary mechanical structures.

MISCELLANEOUS COMPONENTS

In the category of miscellaneous components, we examined lasers, flashlamps, LED's, black paints in the extreme-IR region, and an electro-optic modulator.

Our interest in black paints was stimulated by interest in sensor technology in the extreme-IR region (20-1000 μm) and the lack of measurements on dielectric properties of materials in this wavelength region. In particular there was a lack of information in the early 1970's regarding black surface finishes necessary for stray light rejection in radiometer systems. Moreover, the stability of the materials in a space environment was also unknown, and was of considerable interest. Some of the results of our normal reflectance measurements[10] for coatings on aluminum substrates are shown in Figures 5 and 6 where wavelength is plotted on a logarithmic scale to better display the short-wavelength reflectance.

Measurements at cryogenic temperatures (near the temperature of liquid helium) indicate increased reflectance of five percent to ten percent at wavelengths where the coatings become partially transparent (wavelengths beyond 100 µm) and negligible differences at shorter wavelengths where the films are strongly absorbing.

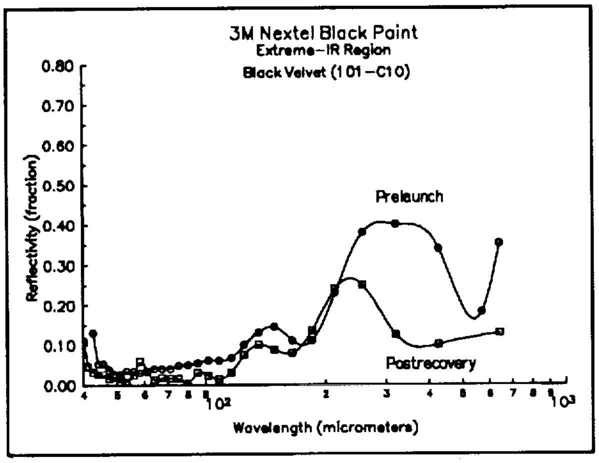


Figure 5. Prelaunch and Postrecovery Normal Reflectance Of 3-M Black Velvet Paint From 40 µm to 600 µm at room temperature. Postrecovery data indicate reduced reflectance.

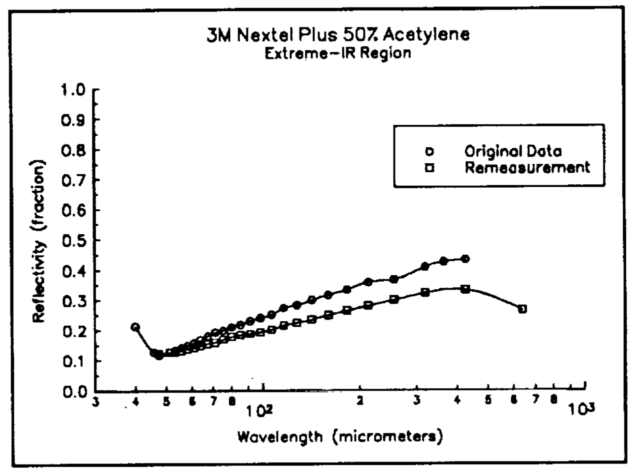


Figure 6. Original And Remeasured Normal Reflectance For A Sample Of 3-M Paint Containing 50% Acetylene. Period between Measurements Was approximately 13 Years.

Figure 6 represents results for one of our special coatings designed to improve performance at the longer wavelengths. This sample provides an indication of the effect of storage in a laboratory for thirteen years on normal reflectance, and also provides an indication of any calibration problems arising as a result of instrument modifications during the years between measurements. Samples from this set showed slightly increased or slightly decreased reflectance (Fig. 6), but do not exhibit the striking changes that appear in the spectra of the space-exposed samples. The reflecting-layer model of Smith[11] was used to analyze the reflectance data. While the assumptions in this model limit its applicability at wavelengths beyond 250 µm, the short wavelength spectra could be reproduced and the interference fringes could be roughly reproduced without allowing the dielectric properties to vary with wavelength. The results suggest that the imaginary component of the refractive index of the coatings increased by about 0.15.

The data could not be fitted with a change in surface roughness or coating thickness, indicating that surface roughening or loss of material from erosion or other effects of space dust and debris were not responsible for the change in properties.

These results suggest that increased absorption may be related to loss of volatile components in the coating binder, and degradation of the pigment and binder by UV radiation providing an increased density of absorption sites in the paint films. While these effects could occur during natural ageing, space exposure may accelerate them.

Less spectacular effects were found for the lasers, flashlamps, LED's, and modulator. The extended time in orbit is believed the cause of the inability of our gas lasers (HeNe and CO_2) to operate, although they arrived in otherwise excellent condition.

Two or three years is the maximum time these lasers will operate without replacing the laser gas mixture. However, no changes in the characteristics of the YAG laser rods, the semiconducting laser-diodes, or the LED's could be found.

Figure 7 shows the prelaunch and postrecovery characteristics of a recovered LED compared with the original and remeasured characteristics of a stored LED. The original and later measurements are in excellent agreement. The stored LED continues to have greater radiation output than the space-exposed unit. The space exposed units could be distinguished from stored units because of the small indentation on the plastic domes, a result of the impact of small micrometeorites which left their mark on soft surfaces on all components.

Other components in this category, such as the modulator and flashlamp, did not show any changes in performance. For the modulator, transmittance, half-wave retardation voltage, and frequency response were measured. For the flashlamp, spectral output was measured.

All members of this set of miscellaneous components survived without change except for the black paints and the sealed gas lasers. The lasers require periodic refills wherever their location.

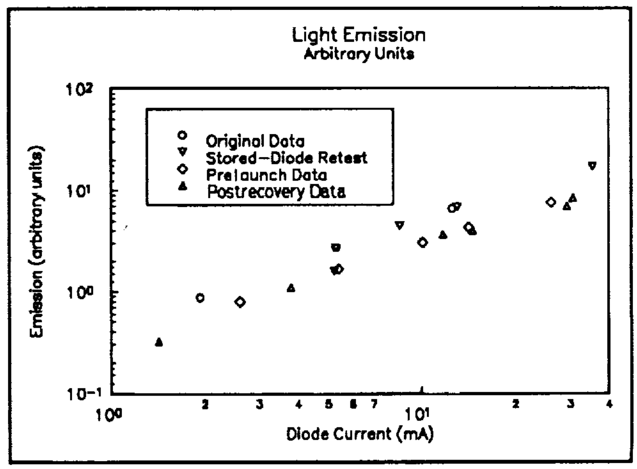


Figure 7. Light-emitting Diode Output vs Drive Current. Note That The Control Diode Has Slightly Greater Output Than The Flight Unit.

CONCLUSIONS

A review of results from several different experiments is required in order to arrive at any general conclusions regarding effects of space exposure on optical materials and components. Some general conclusions for a group of experiments related to optical and electro-optical components are listed in Table II. The LDEF, with its planned six to eighteen months in space, was not expected to provide a test of radiation hardness. With the extended stay in orbit, comparison with predicted effects is more meaningful. The results are in agreement with expectations for these materials.

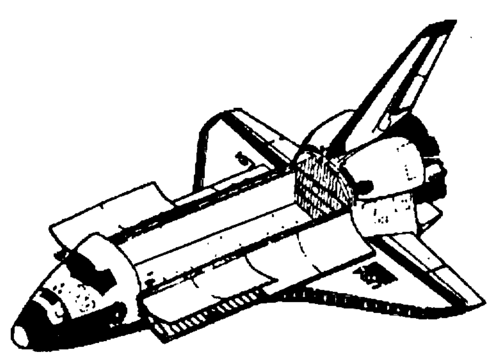
TABLE II. GENERAL CONCLUSIONS

(1) Radiation effects for LDEF materials and components do not differ from ground-testing results. Results are consistent with previous radiation-effects studies.
(2) Radiation creates additional absorption sites which increase the attenuation for radiation from the UV to the Far-IR. Black paints become increasingly black and thus, more effective.

TABLE III. CONCLUSIONS REGARDING OPTICAL MATERIALS

STABLE SUBSTRATE MATERIALS
Si, SiO_2, Al_2O_3, Quartz, ULE Glass
POOR SUBSTRATE MATERIALS
KRS-5, KRS-6
SUSPECT SUBSTRATE MATERIALS
Fluorides such as MgF_2, CaF_2

Table III lists conclusions relating to materials. Other investigators at this symposium have reached similar conclusions. Multilayer dielectric-stack narrow-band filters and mirrors prepared using substrate materials listed as poor or suspect in Table III are expected to suffer greater degradation in performance than similar components fabricated from materials listed as stable. Simply put, covalently-bonded materials should be more stable over time in the low-earth environment than ionically-bonded materials.



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