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OVERVIEW OF THE SYSTEMS SPECIAL INVESTIGATION GROUP INVESTIGATION

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SUMMARY

The Long Duration Exposure Facility (LDEF) carried a remarkable variety of electrical, mechanical, thermal, and optical systems, subsystems, and components. Nineteen of the fifty-seven experiments flown on LDEF contained functional systems that were active on-orbit. Almost all of the other experiments possessed at least a few specific components of interest to the Systems Special Investigation Group (Systems SIG), such as adhesives, seals, fasteners, optical components, and thermal blankets.

Almost all top level functional testing of the active LDEF and experiment systems has been completed. Failure analysis of both LDEF hardware and individual experiments that failed to perform as designed has also been completed. Testing of system components and experimenter hardware of interest to the Systems SIG is ongoing. All available testing and analysis results have been collected and integrated by the Systems SIG. This paper provides an overview of our findings. An LDEF Optical Experiment Database containing information for all 29 optical related experiments is also discussed.

INTRODUCTION

The Systems SIG, formed by the LDEF Project Office to perform post flight analysis of systems hardware, was chartered to investigate the effects of the extended LDEF mission on both satellite and experiment systems and to coordinate and integrate all systems analyses performed during post flight investigations.

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The approach to the testing of hardware by the System SIG has always emphasized the testing of each system at its highest practicable level of assembly. The results at this level provided the direction for further testing in the form of either nominal or anomalous behavior. The Systems SIG divided the investigations into four major engineering disciplines represented by the LDEF hardware: electrical, mechanical, thermal, and optical systems. Almost all functional testing of the active experiments has been completed while system component hardware is still being evaluated. This paper discusses the results from System SIG investigations and those generated outside of the Systems SIG, e.g. by other SIGs or experimenters.

To disseminate LDEF information to the spacecraft community, the Systems SIG has completed the following activities: (1) distribution of a semi-quarterly newsletter containing updates on current results from all aspects of the various ongoing LDEF evaluations. Because of the newsletter's popularity (currently at 2400 copies), the LDEF Project Office has assumed responsibility of this activity; (2) development and release of standardized test plans for systems-related hardware, (3) release of the Systems SIG Interim Report in January, 1991; and (4) release of the Systems SIG Report in June, 1992.

For additional information regarding information presented in this paper, the reader is referred to the June, 1992 Systems SIG Report.

FINDINGS

General Observations

LDEF results demonstrate that shielding from the effects of atomic oxygen, micrometeoroids, space debris, and ultraviolet radiation must be considered for extended mission lifetimes in LEO.

There were several major system anomalies. However, the analysis to date has indicated that none of these can be solely attributed to the long-term exposure to LEO. Design, workmanship, and lack of pre-flight testing have been identified as the primary causes of all system failures. Degradations in system or component level performances due to the long-term exposure to the LEO environment were noted. The combination of any of the individual low Earth orbit environmental factors such as UV, atomic oxygen, particulate radiation, thermal cycling, meteoroid and/or debris impacts and contamination can produce synergistic conditions that may accelerate the onset and rate of degradation of space exposed systems and materials.

The most detrimental contamination process observed during LDEF's mission was the outgassing and redeposition of molecular contaminants which resulted in a brown film on the surfaces of LDEF. This brown film was widely dispersed over the trailing rows and both the Earth and space ends. Thermal control surfaces, optics hardware and solar cells were most susceptible to this contamination. Ram facing surfaces appeared "clean" due to atomic oxygen attack (i.e., cleaning) of the brown film.

Mechanical

The LDEF deintegration team and several experimenters noted severe fastener and hardware removal difficulties during post-flight activities. The Systems SIG has investigated all reported instances, and in all cases the difficulties were attributed to galling during installation or post-flight removal. To date, no evidence of coldwelding has been found. Correct selection of materials and lubricants as well as proper mechanical procedures are essential to ensure successful on-orbit or post-flight installation and removal of hardware.

The finding of no coldwelding indicated a need to review previous on-orbit coldwelding experiments and on-orbit spacecraft anomalies to determine whether the absence of coldwelding on LDEF was to be expected. The results of this investigation showed that there have been no documented cases of a significant on-orbit coldwelding event occurring on U.S. spacecraft. There have been a few documented cases of seizure occurring during on-orbit coldwelding experiments. However, the seized materials had been selected for the experiment because of their susceptibility to coldweld during vacuum testing on Earth. This susceptibility was enhanced by effective pre-flight cleanliness procedures.

All seals and the majority of lubricants used on LDEF were designed as functioning components of experiments and were, therefore, both shielded and hermetically sealed from exposure to the LEO environment. Post-flight testing has shown nominal behavior for these materials. However, several lubricants were exposed to the LEO environment as experiment specimens. Post-flight analysis showed a range of results for these specimens ranging from nominal behavior to complete loss of lubricant, depending on the particular lubricant and its location on LDEF. For example, Figure 1 shows Everlube 620, a MoS_2 lubricant within a modified phenolic binder, before and after the 69 months in LEO. Several specimens of this material, deposited on to a stainless steel substrate, were flown on the trailing edge as part of Boeing's materials experiment. Post-flight inspection of the specimens showed that none of the Everlube 620 remained. The binder apparently decomposed due to UV exposure and then outgassed (evaporated). This led to the MoS_2 becoming separated from the substrate. This is an example of failure of the lubricant system, not the lubricant.

With few exceptions, adhesives performed as expected. Several experimenters noted that the adhesives had darkened in areas that were exposed to UV. One of the most obvious adhesive failures was the loss of four solar cells. Two of the four solar cells were on the leading edge and the other two were mounted on a trailing edge using an epoxy adhesive. Upon retrieval of LDEF, it was noted that all four cells were missing. No adhesive remained on the two leading edge mounting plates but some remained on the trailing edge plate. This indicated that the bond failed at the cell/adhesive interface and then the exposed adhesive was attacked by atomic oxygen. Possible causes of failure include poor surface preparation and/or thermal expansion mismatch between the solar cell substrate and the aluminum mounting plate.

An additional adhesive failure involved polymeric lap shear specimens that used RTV 560 (+12% graphite) silicone adhesive. Four specimens were flown on the leading edge and four flown on the trailing edge. All eight specimens failed during the mission. Another finding involved composite lap shear specimens that used three different epoxy adhesive systems and were flown on the leading and trailing edges. Results ranged from post-flight increases in lap shear values (when compared to pre-flight values) for two of the three systems, to a decrease in shear strength for the third system.

One of the most notable observations made during the on-orbit photo survey was the loose silverized Teflon thermal blankets located on a space end experiment (Figure 2). 3M's Y966 tape was used to hold the edges of the thermal blankets to the experiment tray frame. The blankets apparently shrunk in flight causing the tape to fail. Portions of the tape were attached to both the blanket and frame, indicating that the tape had failed in tension. Post-flight adhesion testing showed that the tape retained adequate adhesive properties.

The viscous damper, used to provide stabilization of LDEF from deployment caused oscillations, performed as designed and exhibited no signs of degradation. The damper has undergone extensive post-flight testing and has been returned to NASA LaRC in a flight ready condition.

Both the rigidize-sensing grapple, used by the RMS to activate the active experiments prior to deployment, and the flight-releasable grapple, used by the RMS to deploy and retrieve LDEF, worked as designed. The grapples are currently awaiting functional testing to determine their post-flight condition.

The most significant finding for the fiber-reinforced organic composites was the atomic oxygen erosion of leading edge specimens. While the measured erosion was not unexpected, the detailed comparison of ground based predictions vs actual recession rates has not been completed. Thin protective coatings of nickel/SiO_2 and polyurethane based paints were used on leading edge specimens to successfully prevent this erosion.

Electrical

Electrical/mechanical relays continue to be a design concern. Two of the most significant LDEF active system failures involved relay failures. The Interstellar Gas Experiment was one of the more complex experiments on LDEF, with seven "cameras" located on four trays. Each camera contained five copper-beryllium foil plattens, which were to sequentially rotate out of their exposed position at pre-determined intervals. This experiment was never initiated due to a failure of the experiment's master initiate relay. The Thermal Control Surfaces Experiment recorded on-orbit optical properties of various thermal control coatings using a four-track Magnetic Tape Module. The latching relay which switched track sets failed to operate when switching from track 3 to track 4. Consequently, portions of the early flight data on track 1 were overwritten and lost.

The Experiment Initiate System (EIS) provided the initiate signal to the active experiments which directed them to turn on their power and begin their operational programs. Post-flight inspection and testing, using the original ground support equipment, showed the condition of the EIS to be nominal.

NASA supplied seven Experiment Power and Data Systems (EPDS) to record on-orbit generated data. All EPDS units were similar, consisting of a Data Processor and Control Assembly (DPCA), a tape recorder (the Magnetic Tape Module), and two $LiSO_2$ batteries, all of which were attached to a mounting plate designed to fit into the backside of the experiment tray. The EPDS components were not directly exposed to the exterior environment, being protected by their mounting plate and by external thermal shields. Although simple compared with today's data systems, the EPDS contained many elements common to most such systems, including various control and "handshake" lines, programmable data formats and timing, and a data storage system. EPDS electronic components were procured to MIL-SPEC-883, Class B standards, and were not rescreened prior to installation. Data analysis and post-flight functional testing showed that all EPDS functioned normally during and after the LDEF flight.

Three different types of batteries were used on LDEF: lithium-sulfur-dioxide ($LiSO_2$), lithium carbon monofluoride (LiCF), and nickel-cadmium (NiCd) batteries. NASA provided a total of 92 $LiSO_2$ batteries that were used to power all but three of the active experiments flown on LDEF. Ten LiCF batteries were used by the two active NASA MSFC experiments. One NiCd battery, continuously charged by a four-array panel of solar cells, was used to power an active experiment from NASA GSFC. A loss of overcharge protection resulted in the development of internal pressures which caused bulging of the NiCd cell cases. However, post-flight testing showed that the battery still has the capability to provide output current in excess of the cell manufacturer's rated capacity of 12.0 ampere-hours. All the LiCF and $LiSO_2$ batteries met or exceeded expected lifetimes.

LDEF provided valuable knowledge concerning the viability of using various solar cells and solar cell encapsulants (adhesives and coverglass materials). Coverglass materials such as ceria doped microsheet and fused silica withstood this particular environment. Measurable degradation of some widely used antireflection coatings was observed. Results from some low cost materials such as silicone, Teflon, and polyimide indicated that these materials will require additional research before full-scale replacement of the conventional encapsulants (fused silica coverglass and DC 93500 adhesive) is justified. Micrometeoroid and debris impacts will continue to be a significant solar cell performance degradation mechanism. Solar cell performance degradation due to the deposition of contamination on the surfaces was also well documented. However, the majority of electrical characterization and analysis of on-orbit data remains to be completed.

Pyrotechnic devices, flown on Experiment A0038, were successfully fired during post-retrieval ground testing.

Thermal

The change in performance of a wide variety of thermal control coatings and surfaces was moderate, with a few exceptions. A significant amount of these changes has been attributed to contamination effects. Certain metals (esp. chromic acid anodize aluminum), ceramics, coatings (YB-71, Z-93, PCB-Z), aluminum coated stainless steel reflectors, composites with inorganic coatings (Ni/SiO_2), and siloxane-containing polymers exhibited spaceflight environment resistance that is promising for longer missions. Other thermal control and silicone based conformal coatings, uncoated polymers and polymer matrix composites, metals (Ag, Cu) and silver Teflon thermal control blankets and second surface mirrors displayed significant environmental degradation. In addition, post-flight measurements may be optimistic because of bleaching effects from the ambient environment.

The results of thermal measurements on different samples of the same materials made at different laboratories have proven to be remarkably consistent and in agreement, lending additional credibility to the results. Confidence in designers' thermal margins for longer flight missions has been increased.

Initial functional tests were performed for each of the three heat pipe experiments flown on the LDEF, and the heat pipe systems were found to be intact and fully operational. No heat pipe penetration occurred due to micrometeoroid or debris impact.

Actual measured temperatures within the interior of the LDEF ranged from a low of 39°F to a maximum of 134°F and were well within design specifications. External thermal profiles varied greatly, depending on orientation, absorptance/emittance, and material mounting and shielding. The thermal stability of the LDEF adds to the accuracy of existing thermal models and enhances our ability to model the LDEF thermal history, as well as other spacecraft.

The loss of specularity of silver Teflon thermal blankets, one of the earliest observations noted at the time of retrieval, had no significant effect on the thermal performance of those materials. This loss of specularity is the result of first surface erosion and roughening by atomic oxygen.

The thermal performance (absorptance/emittance) of many surfaces was degraded by both line-of-sight and secondary contamination. The specific contamination morphology in various locations was affected by ultraviolet radiation and atomic oxygen impingement. Overall, the macroscopic changes in thermal performance from contamination appear to be moderate at worst. Limited measurements on surfaces from which the contamination was removed post flight suggest that the surfaces beneath the contamination layers have undergone minimal thermal degradation.

Over 50% of all LDEF's exterior surfaces were chromic acid anodized (CAA) aluminum. Extensive optical testing of LDEF's CAA aluminum tray clamps was performed because of their wide distribution around the LDEF and representation of a complete spectrum of spaceflight environmental exposures. The tray clamps provided a complete picture of the spaceflight environmental effects on this surface treatment. Comparison of front-side (exposed), backside (shielded) and control clamps showed slight changes in the optical properties. However, the variations in absorptance and emittance have been attributed to the inherent variability in anodizing, to variations in measurements, and to the effects of on-orbit contamination deposited on tray clamp surfaces.

Betacloth which was exposed to the atomic oxygen flux was seen to have been cleansed of the many minute fibers that normally adorn its surface. This has been observed to have no measurable effect on the thermal performance of the betacloth, although some associated contamination issues are raised.

Optical

Contaminant films and residue were widespread in their migration over LDEF and onto optical experiment surfaces, especially due to the decomposition and outgassing of several materials, at least two possible sources being identified as those from the vehicle itself, as well as those materials used in some of the experiments.

Four experiments flew fiber optics and a fifth experiment evaluated fiber optic connectors. Four of these five experiments recorded on-orbit data using the NASA provided EPDS. Overall the fiber optics performed well on-orbit, with little or no degradation to optical performance. Most environmental effects were confined to the protective sheathing. However, one fiber optic bundle was struck by a meteoroid or debris particle causing discontinuity in the optical fiber. Preliminary data has indicated the need for additional study of the temperature effects on fiber optical performance. Post-flight testing performed on fiber optics flown on the Fiber Optic Exposure Experiment showed an increase in loss with decreasing temperature, becoming much steeper near the lower end of their temperature range.

Four LDEF experiments contained a variety of detectors. Most detectors were not degraded by the space exposure, with one notable exception. The triglycine sulfide had a 100% detectivity failure rate on both the control and flight samples.

Several types of optical sources were flown on LDEF including solid and gas lasers, flashlamps, standard lamps, and LEDs. To date, the results indicate that most optical sources operated nominally except for two gas lasers (HeNe and CO_2) which would not fire during post-flight testing and a flickering deuterium lamp arc. During post-flight testing of the two gas lasers, no laser action could be obtained from the tubes. The characteristics of the tubes suggested that the mixture of fill gas had changed during the period between pre-flight and post flight tests. This result is consistent with changes expected due to gas diffusion through the glass tube. The tubes were in good physical condition, and survived the launch and recovery phases without apparent degradation.

Micrometeoroid and debris impacts on optical surfaces caused localized pitting, punctures, cracking, crazing, and delaminations. Examples of the effect of impacts are shown in Figure 3.

Spectral radiation from both solar and earth albedo sources was indicated both in the modifications of surface coating materials (chemical decomposition caused by ultraviolet radiation). This was particularly noticeable on an experiment located on the trailing edge where the holographic gratings had a 30% to 40% degradation of reflectivity from exposure to solar radiation and cosmic dust. Experimenters also noted that changes to coating interfaces as a result of infrared absorption may have contributed to mechanical stresses and failures from thermal cycling.

Atomic oxygen had a major effect in the oxidation of many physically "soft" materials, including optical coatings and thin films, as well as oxidation of uncoated, metallic reflective coatings (copper and silver). In general, "hard" uncoated optical materials were found to be resistant to the LEO environment.

Synergistic conditions of degradation resulted from the multiple and combined effects of environmental factors; for instance, UV and atomic oxygen attacked, changed, or even eroded away some of the overlaying contamination, modifying the broadband and spectral content of optical inputs to the sample beneath .

An LDEF Optical Experiment Database was created (using Filemaker Pro database software) that provides for quick and easy access to available experimenter's optic's related findings. The database contains a file for each of the LDEF experiments that possessed optical hardware (database currently contains 29 files). Each file contains various fields that identify the optical hardware flown, describe the environment seen by that hardware, summarizes experimenter findings and list references for additional information. A copy of this database is available upon request.

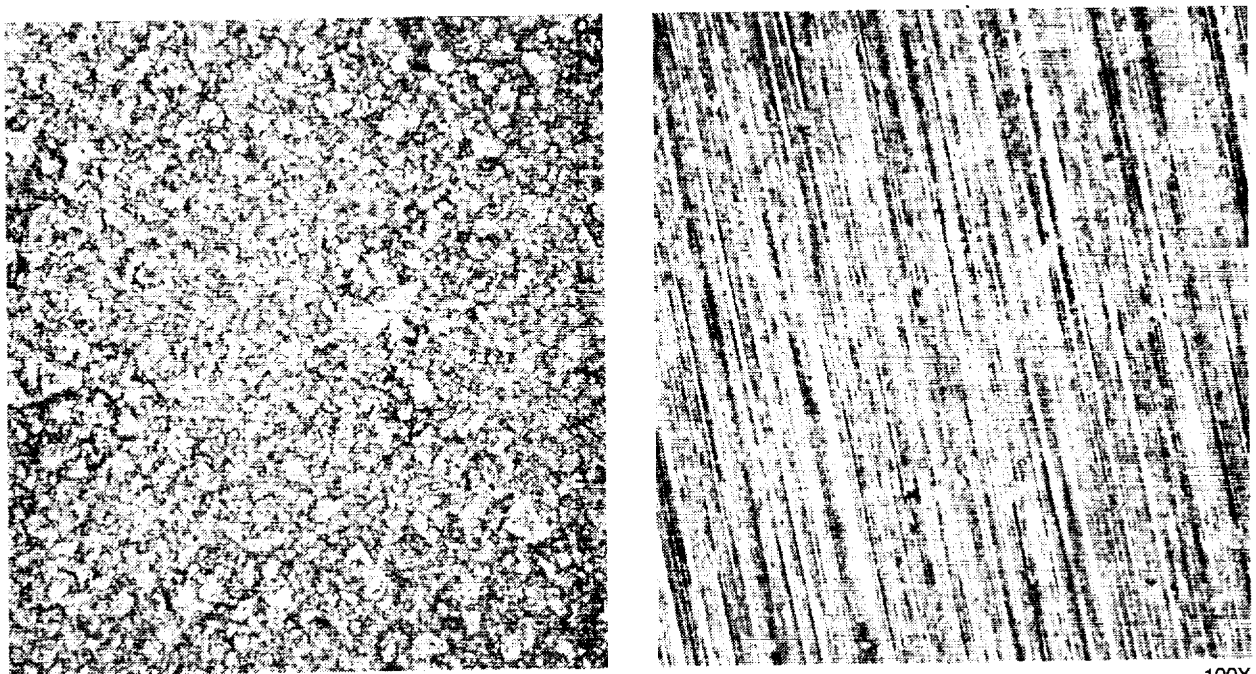
LDEF NEWSLETTER

The LDEF *Newsletter*, now in its third year, continues to see its distribution expand to increasing numbers of universities, corporations, government agencies, and countries. From its initial distribution of under three hundred names, the distribution (Figure 4) has reached a level of more than 2400; which includes pickup stacks at several NASA field center libraries and internal distribution in some corporations. This continuing circulation growth has been by word of mouth; there has never been any solicitation for increased distribution of the *Newsletter*.

The *Newsletter* has expanded from its initial eight-page issue to 24 pages or more as the LDEF investigation has begun to produce more results. The nominal length has hovered around an average of 16 pages which is near the limit for a one man level-of-effort but, more important, keeps the document at an easily readable and digestible length. The balance of size and frequency has appeared to be satisfactory for its specific purposes and there are no plans to deviate significantly in the foreseeable future.

The *Newsletter* has been serving as a useful interface between the engineering research and engineering applications communities (Figure 5), although with most of the information flow being LDEF research results transmitted to aerospace industry projects. There is some consideration being given to the notion of providing reverse information flow, since this communication "link" is well established, and using the *Newsletter* to transfer project information such as materials or design needs to the research community.

Several potential articles in this vein have been identified and are targeted for issues in the near future. However, as LDEF results continue to pour in, it will be a challenge to find time and space to present increased coverage within our current scope. At this time, significant LDEF activities have been slotted for each of the next four or five issues of the *Newsletter*, and in keeping with our charter, these will be receiving more attention and higher priority.



Non-flight Specimen 100X

LDEF Specimen 100X

Figure 1. Everlube 620C Lubricant

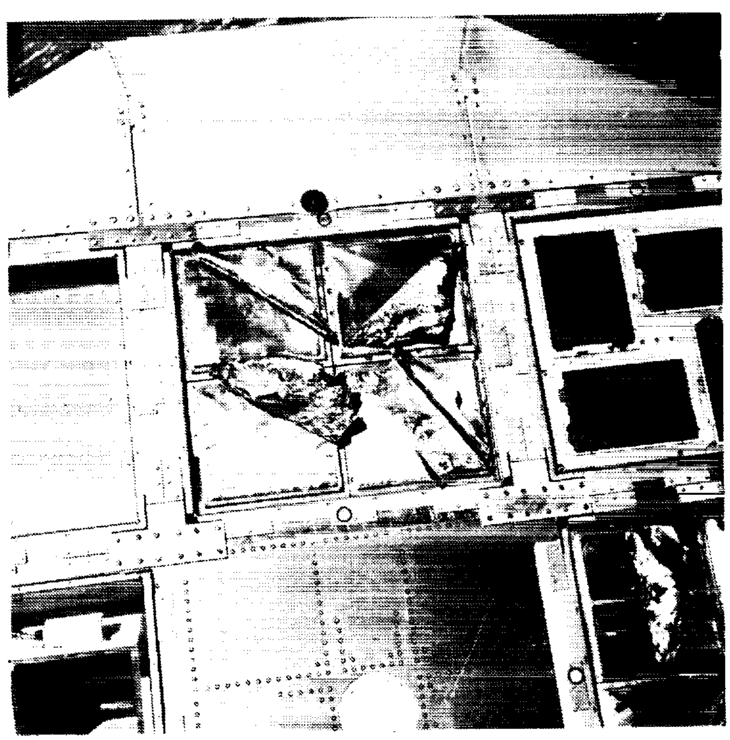


Figure 2. Loose Silverized Teflon Thermal Blankets

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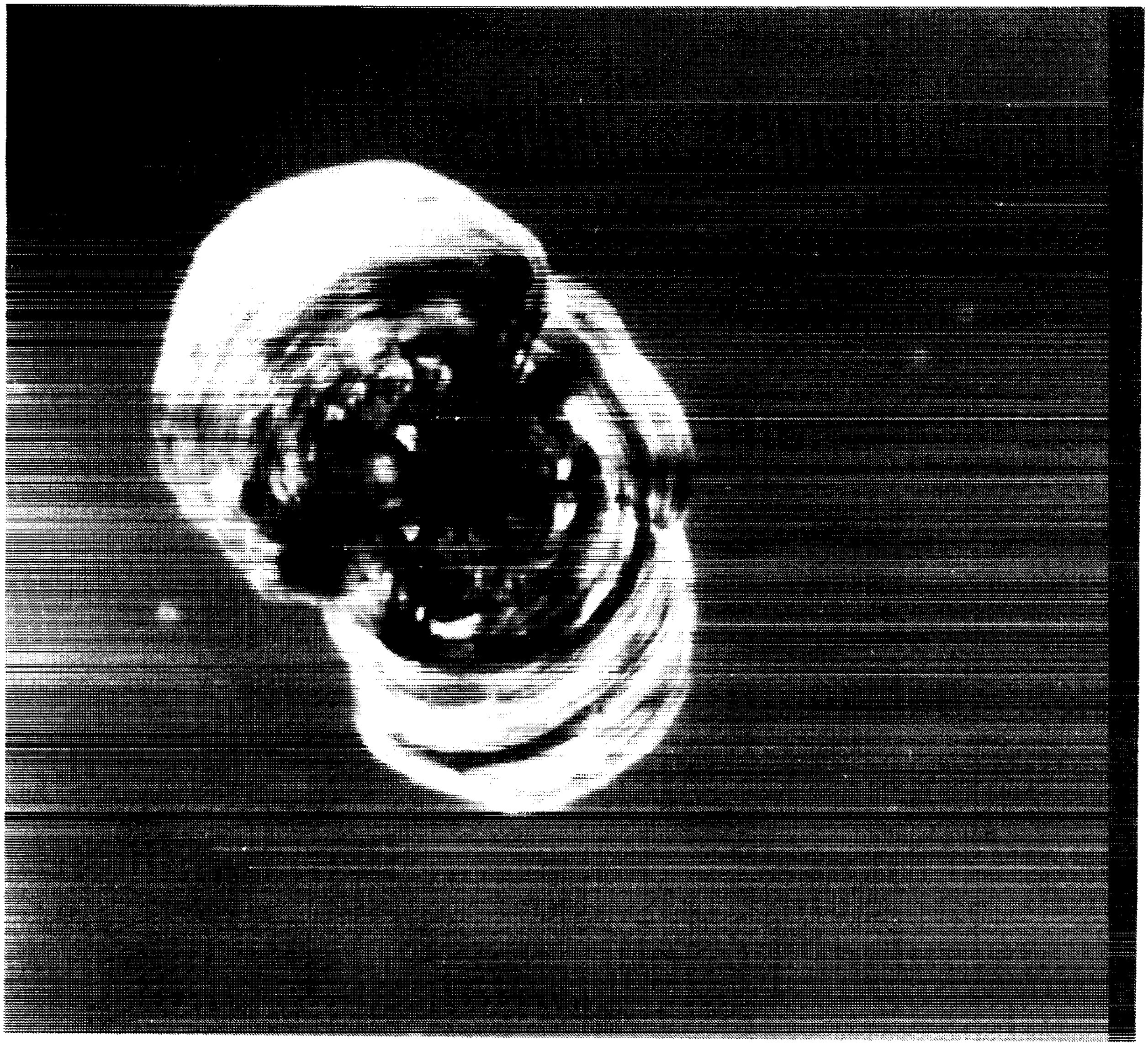

Figure 3. Effect of a Micrometeoroid on Debris Impact on a Quartz-Silver Second Surface Mirror

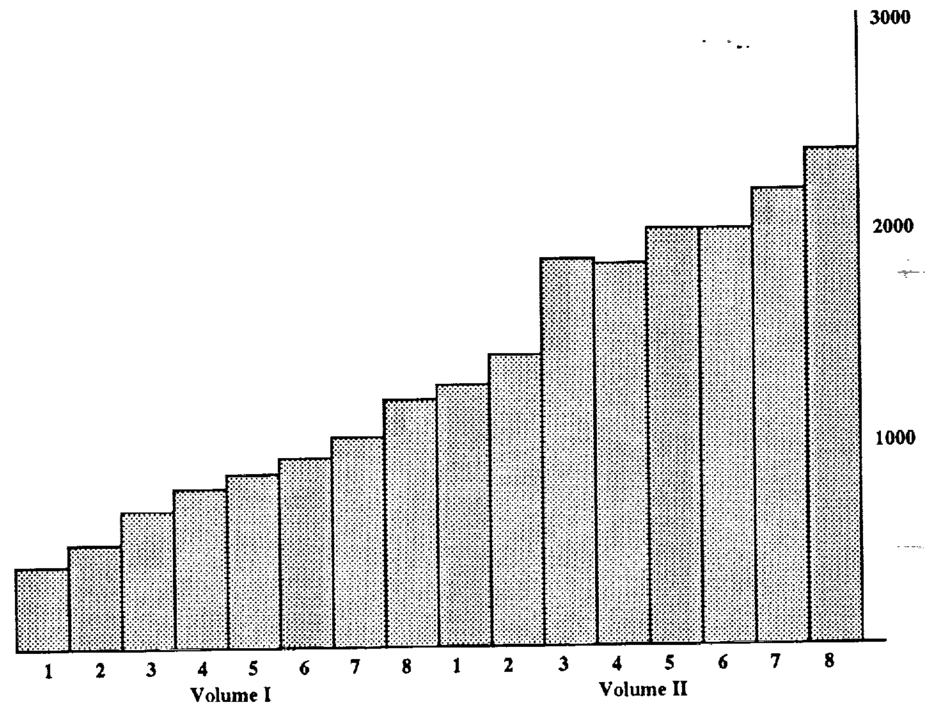

Figure 4
The chart above shows the continuing increase in the distribution of the LDEF Newsletter.

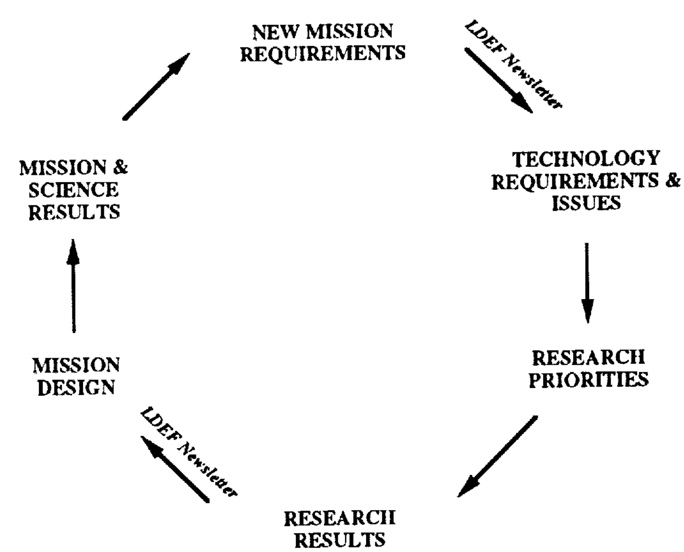

Figure 5
The chart above illustrates the dual role of the LDEF Newsletter in a simplified schematic of the relationship between the research and engineering communities.