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SUMMARY OF MATERIALS AND HARDWARE PERFORMANCE ON LDEF*

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ABSTRACT

A wide variety of materials and experiment support hardware were flown on the Long Duration Exposure Facility (LDEF). Postflight testing has determined the effects of the almost 6 years of low-Earth orbit (LEO) exposure on this hardware, and this paper is an overview of the results. Hardware discussed includes adhesives, fasteners, lubricants, data storage systems, solar cells, seals, and the LDEF structure. Lessons learned from the testing and analysis of LDEF hardware will also be presented.

INTRODUCTION

The extended duration of the LDEF mission presented a unique opportunity to learn more about the effects of long-term exposure to LEO on both materials and systems. Hardware discussed in this paper ranges from the Velcro™ used to fasten thermal blankets to the LDEF structure, to solar arrays used to actively charge a nickel-cadmium (NiCd) battery used to power a heat pipe experiment, to the LDEF structure itself. Testing results were assembled from the following sources: individual experimenters; the Materials, Systems, Induced Radiation, and Meteoroid and Debris Special Investigation Groups (SIG); the LDEF Science Office; the Boeing Material SIG and the Boeing Systems SIG Support Contracts; and from the hardware flown on the Boeing LDEF experiment and then tested at Boeing.

The discussion of these material and hardware investigations is divided into the four major engineering disciplines represented by the LDEF hardware: electrical, mechanical, thermal, and optical systems. Within each discipline there will be a brief description of the hardware, followed by an overview of the pertinent testing and analysis results and lessons learned. Because of the number of papers already presented that discuss findings within the optics and thermal disciplines, this paper focuses on mechanical and electrical hardware.

A detailed discussion of LDEF, its mission, and the environment seen by LDEF during its 69-month mission is presented in reference 1.

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MECHANICAL HARDWARE

This section discusses the effects of the 69-month LEO exposure on the LDEF primary structure, grapples, viscous damper, fasteners, adhesives, lubricants, seals, and composites.

Primary Structure

The LDEF primary structure is a framework constructed of welded and bolted aluminum 6061-T6 rings, longerons, and intercostals. The structure is approximately 30-ft long and 14 ft in diameter. A fusion welding process developed by NASA Langley Research Center (LaRC) for 6061 aluminum was used to fabricate the center ring. The remainder of the structure was mechanically fastened together. Figure 1 is a preflight photo of the structure prior to installation of experiments.

The welds were inspected postflight by dye penetrant and eddy current techniques following deintegration of the experiment trays. The welds were found to be nominal, with no evidence of any launch or flight-related degradation.

The potential for space exposure effects on the microstructural or mechanical properties of the aluminum primary structure was investigated by metallurgical analysis of the 6061-T6 aluminum experiment tray clamps. The tray clamps are representative of the primary structure (same aluminum alloy) and were distributed uniformly around the exterior of LDEF. Clamps from near leading edge (LE) and near trailing edge (TE) were cross sectioned and examined. The microstructures were found to be normal for 6061-T6 aluminum. *The lack of any differences between the samples and control specimens illustrates that LEO space exposure has no discernible effect on the bulk microstructures of typical structural metals.* Mechanical property changes are precluded in the absence of microstructural changes.

Primary Structure Fasteners

Following removal of the experiments, all primary structure fastener assemblies were retorqued to preflight values. The fastener assemblies consist of stainless steel bolts ranging in diameter from 1/4 to 7/8 inch with silver-plated locking nuts. Results showed that only 4 percent of the 2,928 assemblies had relaxed. Nut rotations, required to reestablish preflight torque levels for those that relaxed, ranged from 5° to 120°. The small number of relaxed fastener assemblies indicates that the reliability of bolted joints in space applications is very high. This conclusion must be tempered by the fact that LDEF was exposed to a rather benign thermal environment with minimal thermal swings. *Examination of the primary structure, the welds, and fasteners shows that the concept of a reusable bolted and welded spacecraft is a viable concept.*

Viscous Damper

Located on the center line of the space-end internal structure, the viscous damper provided attitude stabilization of LDEF from oscillations resulting from deployment. Postflight testing indicated that the damper performed flawlessly over the almost 6-year flight, even though the design life was 1 year. It was concluded that the damper suffered no discernible degradation from long-duration space exposure and that it can be flown again. The damper has been returned to NASA LaRC in a flight-ready condition.

Grapples

Both the rigidize-sensing (active) and the flight-releasable (passive) grapple fixtures have undergone postflight evaluation. The rigidize-sensing grapple was designed to activate the LDEF experiment initiate system (EIS) on or off via the remote manipulator system (RMS) with the LDEF still in the shuttle bay. The flight-releasable grapple was used to deploy and retrieve LDEF via the RMS. Both grapples performed as designed during deployment, and the passive grapple performed as designed during the retrieval of LDEF. Due to the extended mission length and consequent uncertain state of batteries, and the desire not to disturb the final state of certain experiments, it was decided not to reset the systems. Therefore, the rigidize-sensing grapple was not used during retrieval. Postflight testing of grapple components has shown nominal performance. However, post-flight functional testing has yet to be performed.

Fasteners—Tray Clamp Fasteners

The experiment trays were held in the structure openings in the primary structure by aluminum clamps. The clamps consisted of flat 0.25-in thick rectangular or "L" shaped plates with three mounting holes in them. They were attached to the structure with 0.25-28 A286 heat-resistant steel bolts. The bolts, with alodined aluminum washers under the head, were inserted into self-locking thread inserts installed in the primary structure. The bolts were cleaned with alcohol and installed with a preflight torque of 75 ±5 in-lb.

During deintegration of LDEF, unseating (breakaway) torque values were recorded for all 2,232 tray clamp fasteners, and prevailing (running) torque values were obtained for every third bolt (the middle of the three bolts in each clamp). The unseating torques averaged 72 in-lb, ranged between 10 and 205 in-lb, and the average values were similar throughout LDEF, indicating no pronounced effect of varying space exposure conditions on bolt torque behavior. The prevailing torques averaged 17 in-lb and ranged between 2 and 132 in-lb. Prevailing torque specifications for these threaded inserts called for torques ≤30 in-lb. Almost 10 percent of the 720 prevailing torques exceeded these specification.

The range in unseating torques is not surprising considering the unpredictable nature of fatigue, bolt stretching, corrosion, and particulate contamination. However, the amount of bolts exceeding the prevailing torque specifications was unexpected. Further testing and analysis was performed to determine why. Several causes were found, such as bolt shank contact with the clamp and shim holes during removal and the relative softness of these bolts. No clear correlation was made between thread condition, washer condition, and unseating torques. *No evidence of cold welding was observed.* All thread damage was consistent with galling damage.

Fasteners—Experimenter Fasteners

The LDEF Science Office suggested that experimenters use type 303 stainless steel bolts combined with self-locking nuts (AN, MS types). In fact, a wide variety of fastener assemblies and lubrication schemes were used. The following paragraph highlights some of the fastener removal difficulties encountered by experimenters during postflight hardware removal.

The most extensive fastener damage is shown in Figure 2. This photo shows both a sheared fastener and a severely damaged nut plate. It was reported that the majority of nut plates had the original MoS_2 dry-film lubricant removed by acid stripping prior to installation because of concerns with possible volatilization and contamination while in orbit. The MoS_2 was then replaced with cetyl alcohol. Initial speculation was that the A286 fasteners may have cold welded on orbit because of insufficient lubrication provided by the cetyl alcohol. However, testing and analysis of the fastener assemblies has shown that all removal difficulties were caused by galling (from lack of MoS_2) which had begun during installation.

Fasteners—Velcro™

Velcro™ was used to attach a variety of thermal blankets used on LDEF. In one instance, Velcro™ was stitched to the blankets with NOMEX thread. This thread, which was directly exposed to ultraviolet (UV), turned yellow. Tensile testing of the thread showed a 10-percent reduction. The mating side of the Velcro™ was successfully bonded to the tray structure using 3M's EC2216 adhesive. Qualitative tests carried out during disassembly showed a high level of separation resistance. On another experiment, the Dacron™ thread used to stitch the Velcro™ to thermal blankets failed.

Velcro™ was also used to fasten the 3- by 4-ft silverized Teflon™ thermal blankets used on 16 exterior surfaces throughout LDEF. Approximately 54 one-inch strips of Velcro™ were used for each thermal blanket. One surface of the Velcro™ was bonded to the backside of the blanket, and the other surface was bonded to aluminum surfaces on the tray. The experimenter responsible for the experiment deintegration reported that the Velcro™ retained its preflight disassembly parameters.

Velcro™ proved to be an excellent form of fastening low stressed hardware in space. However, it is critical to keep the adhesive or threads used to fasten the Velcro™ shielded from the LEO environment.

Adhesives

A variety of adhesives and adhesive-like materials were flown on LDEF. These included epoxies, silicones, conformal coatings, potting compounds, and several tapes and transfer films. Six different adhesive systems were evaluated using lap shear specimens exposed to leading and TE environments. All other adhesives were used in assembly of various experiments. Typically, these materials were shielded from exposure to the external spacecraft environment. *In most experiments, these adhesives were of secondary interest and were only investigated by visual examination and a "Did failure occur?" criteria. These adhesives performed as expected, holding the hardware* *together*. Several experimenters noted that the adhesives had darkened in areas that were exposed to UV. The following paragraphs document the results from testing epoxy lap shear specimens.

3M's EC 2216 (Boeing Materials Standard 5-92) along with 3M's AF 143 (BMS 5-104) epoxy adhesive lap shear specimens were flown on the TE. The EC 2216 is a room-temperature cure and the AF 143 is a 350F cure system. Both titanium-composite and composite-composite adherents were evaluated. The lap shear specimens were mounted such that one surface was exposed to the exterior environment. Visual examination of the specimens showed the exposed bondline to have become dark brown when compared to the shielded bondline on the backside of the specimens. Five specimens for each of the two epoxy systems were flown. The ultimate shear stress increased from 7 to 28 percent over preflight values. No control specimens were tested. The reason for the increase in strength compared to preflight values is speculated to be related to continued cure advancement.

Two separate experiments evaluated a third epoxy system, Hysol EA 9628 250F cure, using composite-composite and aluminum-aluminum adherents, respectively. A total of seven specimens were located on the LE with four shielded specimens located on the backside of the tray acting as in-flight controls. A similar arrangement was flown on the TE for a total of 22 specimens. In addition, eight ground control specimens existed. Postflight testing showed both the LE and TE in-flight control and the ground control specimens to possess equivalent shear values. However, the LE exposed specimens had decreased an average of 8 percent and the TE exposed specimens had a 28-percent decrease in shear when compared to the controls. These results were identical for both the composite and aluminum specimens. The reason for the decreases is unknown as the vast majority of the adhesive is between the adherents mating surfaces and, therefore, shielded from the detrimental effects of the atomic oxygen (AO) and UV. The only two LEO environments that could affect the adhesive strength are radiation and thermal cycling. While the temperature extremes seen by the exposed specimens were greater than the in-flight controls, the actual temperatures were well within the adhesive specifications. Also, the charged particle radiation environment seen by LDEF was minimal. While almost all other adhesives and tapes flown on LDEF showed no degradation and, in a significant number of cases, actually increased in mechanical properties, it is currently unknown why these particular adhesive shear properties degraded and why the TE specimens showed a much greater decrease than the LE specimens.

Lubricants

A variety of lubricants and greases were flown on LDEF. With the exception of three lubricants, all were components of functioning hardware and not the principal item of the investigation. The current status and test results of all lubricants flown on LDEF are listed in Figure 3. *The majority of the lubricants were shielded from direct exposure to space and performed their design function as anticipated.*

Seals

A variety of seals were also used on LDEF. These were generally O-rings, although sheet rubber was also used. All seals were shielded from direct exposure to the exterior environment. *These materials performed as designed, sustaining little or no degradation caused by exposure to the LEO environment.*

Composites

The most significant findings for fiber-reinforced organic composites were AO erosion and dimensional changes. Composites directly exposed to the LE environment exhibited erosion of up to one ply of material along with reduction of mechanical properties. *The following thin protective coatings were successfully used to prevent this erosion: 1,000 Å of sputtered nickel with a 600 Å sputtered SiO_2 overcoat; two white polyurethane coatings, BMS 10-60 and A276; and a carbon black polyurethane coating, Z306.* Composites located on the TE and on the LDEF's interior exhibited no erosion and did not display any reduction in mechanical properties. Chemical changes to composite systems were only a few microns deep on composites mounted on exterior surfaces and had no impact on the bulk performance properties of the materials. Microcracking has been reported for several nonunidirectional reinforced polymer matrix composites on both the leading and TE's.

ELECTRICAL HARDWARE

LDEF also carried a variety of electrical and electronic systems which were the result of the diversity in experiments. NASA provided certain guidelines and design review requirements, but responsibility for success (or failure) rested solely with the experimenters. The authors know of no LDEF components that were "space rated," i.e., they had not been subjected to the rigorous testing and inspections normally required of spacecraft system components (e.g., MIL-STD-883, Class S). Some were off-the-shelf, commercial quality parts, while most were MIL-STD-883, Class B or equivalent. LDEF provided a unique opportunity for evaluation of such components.

On-Orbit Data Storage Systems

LDEF was a passive satellite with no telemetry of data to Earth during the mission. However, several experiments required on-orbit collection of data. Seven Experiment Power and Data Systems (EPDS's) were supplied by NASA, and two other experiments used data storage systems of their own design and construction. All EPDS units were similar, consisting of a Data Processor and Control Assembly (DPCA), a tape recorder (the Magnetic Tape Module (MTM)), and two lithium sulfur dioxide ($LiSO_2$) 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 postflight functional testing showed that all EPDS functioned normally during and after the LDEF flight.

During postflight inspections, it was noted that the magnetic tape on all but one MTM unit had taken a "set" where it was wrapped around the phenolic capstan. The exception was the single unit which had operated periodically throughout the flight (experiment S0014). The MTM's were backfilled with dry nitrogen prior to flight. During postflight deintegration at Lockheed, the tapes were exposed to a controlled humidity, and the mechanical set gradually disappeared. Evidently some level of humidity is necessary in the sealed units to avoid this problem under long-term, inactive storage. Interestingly, it has been reported that a different type of tape (a ruggedized cassette) used in experiment A0180 did not encounter this problem even though it too had been backfilled with dry nitrogen. It has been speculated that outgassing of some other material in that tape recorder housing prevented excessive drying of the tape (ref. 2).

The University of Toronto used a custom-designed and built data storage system also based on the magnetic tape cassette concept. This unit performed as designed. *All magnetic tape cassette recorders worked well. They are simple, well proven, and reliable.*

The remaining data storage system was based on semiconductor technology using an Electrically Alterable Read Only Memory (EAROM)-based storage system. During postflight inspection, it was determined that on-orbit data did not exist. The resulting failure analysis showed that data had been stored on the EAROM at one time, but failed to identify the cause of data loss. However, this particular EAROM is thought to be radiation sensitive.

Solar Cells

Nine experiments involved solar cells, solar cell components, and/or solar array materials. The complexity of the experiments ranged from active on-orbit monitoring of solar cells, to recharging a NiCd battery used to power a heat pipe experiment, to passive exposure of cells and solar array materials. A total of over 350 cells representative of the late 1970's and early 1980's technology were flown. Eleven of these cells were gallium-arsenide and the remaining cells were silicon. A majority of these were actively monitored while on orbit. The following four major LEO environments, operating individually or synergistically, caused the vast majority of performance losses seen in the solar cells: meteoroid and debris impacts, AO, UV, and charged particle radiation.

The most extensive electrical degradation of the cells was caused by impacts and the resulting cratering. The extent of damage to the solar cells was largely dependent upon the size and energy of the impactors. Figure 4 shows the postflight current-voltage (IV) curves for three impacted cells (ref. 3). The first cell, M-3, has a small impact crater in the coverglass, but not penetrating the cell itself. From the curve, it is apparent that there is little change. The second cell, NA-9, has a large (about 1.8-mm diameter) impact crater which penetrated into the silicon cell. The cell was apparently shunted by this damage, resulting in a decrease in a open-circuit voltage (Voc) of approximately 100 mV. The third cell, M-9, has an impact crater in the coverglass which cracked the coverglass and the cell. The cell crack does not go all the way across the cell, but the resulting discontinuity in many of the current collection busbars on the front has caused an increase in series resistance and a drop in fill factor. The fill factor is a measure of how close to ideal (100 percent) the cell is performing. It is the ratio of the product of max-power-current and max-power-voltage divided by the product of short-circuit-current and open-circuit-voltage $(Imp \times Vmp)/(Isc \times Voc)$.

The other cause of cell degradation was reduced light reaching the cells. This was caused by contamination, UV degradation of the coverglass adhesive, and/or AO/UV degradation of the antireflection coating.

A variety of changes were reported by the various experimenters including silver oxidation on grid lines, some broken silver interconnects, and voltage and current drops. However, the fill factors were approximately the same as preflight and there was no delamination or loss of covers.

In general, the solar cells flown on LDEF proved to be robust. There were no significant changes in the performances of solar cells that had not undergone micrometeoroid or space debris impacts. Solar array designers need to account for individual cell loss caused by impacts. Results from some low-cost solar array 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 Dow Corning DC 93500 adhesive) is justified.

Wire Harnesses

The LDEF wire harness was essential to the success of all active experiments, as it carried the experiment initiate signals. It was assembled in-place on the LDEF frame, using Teflon™ insulated wire and nylon cable ties. Much of the harness also was protected by shielded braid and an outer Teflon™ jacket. The majority of the harness was well shielded from direct exposure to the external environment. Extensive testing included in-place visual inspection, connector disconnect torques, continuity measurements, and 500 Vdc insulation resistance. *All tests were nominal. There were no reported instances of experimenter-provided harnessing exhibiting deterioration of electrical properties.*

Batteries

Three different types of batteries were used on LDEF: $LiSO_2$, lithium carbon monofluoride (LiCF), and NiCd batteries. NASA provided a total of 92 $LiSO_2$ batteries that were used to power all but three of the active experiments. Ten LiCF batteries were used by the two active NASA Marshall Space Flight Center (MSFC) experiments. One NiCd battery, continuously charged by a four-array panel of solar cells, was used to power an active experiment from NASA Goddard Space Flight Center. A loss of overcharge protection resulted in the development of internal pressures which caused bulging of the NiCd cell cases. However, postflight testing showed that the battery still had 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.

Relays

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 platens, which were to sequentially rotate out of their exposed position at predetermined 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 MTM (the other six MTM's were two track). 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.

Electronic Support Hardware

Most of the electronics carried on LDEF were used to support active experiments, rather than being flown as part of an experiment. An exception was the Boeing Electronics Experiment, which was an investigation of the effects of LEO on inexpensive, commercial quality components. These included a number of plastic packaged integrated circuits and discrete components such as transistors, resistors, capacitors, and diodes. A total of over 400 components were mounted on a pair of circuit boards with half the components conformally coated with Hysol PC18. All hardware was mounted such that they were protected from direct exposure to the external environment, and many were powered up periodically during data collection periods. Postflight data were compared against preflight data. No failures or significant degradation were observed.

Many low cost, nonspace-qualified components performed quite well, without any measurable degradation. The question of whether to permit use of commercial or Class B parts in space applications is beyond the scope of this paper. However, it is evident that such components can survive long-term exposure to LEO and their use may often be justified for low cost systems when failures would not result in safety concerns or other major mission costs.

THERMAL HARDWARE

Thermal hardware flown on LDEF included a broad array of materials consisting of both experiment specimens and experiment support hardware. The largest component within the thermal discipline was the thermal control coatings. Also flown were three heat pipe experiments to evaluate a total of four different types of heat pipes.

Thermal Control Coatings

Over 50 percent of LDEF's exterior surfaces were chromic acid anodized (CAA). Extensive testing of these surfaces and several CAA test specimens was completed by numerous investigators, including the LDEF deintegration team. *Results show that for CAA with low to medium emissivities (0.2 to 0.7), any differences between pre- and postflight optical values were attributable to contamination, manufacturing, and/or measurement variations.* However, two high emissivity CAA test specimens showed signs of coating degradation (ref. 4).

S13G and S13G/LO white coatings had darkened significantly with UV exposure, but were partially "scrubbed" by AO to near original optical properties (ref. 5). Specimens of Z93 and YB71 white coatings were significantly less effected. The silicate-based coatings, even those containing carbon black pigments, indicate excellent stability in the AO environment. Silicone-based materials were also observed to be resistant to AO.

The loss of specularity of silverized Teflon™ thermal blankets, one of the earliest observations noted at the time of retrieval, was determined to have had no significant effect on the thermal performance. The increase in diffuse reflectance was greatest for materials closest to the LE. This loss of specularity is the result of first surface erosion and roughening caused by AO.

Analysis of thermal control coatings flown on LDEF greatly refined our knowledge of recession rates and changes in solar absorptance and thermal emittance due to long-term exposure to the LEO environment. The data showed that AO modifies and/or removes molecular contamination and UV degraded material.

Heat Pipes

Initial functional tests were successfully performed on all heat pipe experiments. All heat pipe experiments were found to be intact and were not degraded by the long-term LEO exposure.

OPTICS HARDWARE

In general, optical components showed some effects related to the space environment, unless well protected. The effects were often small, but sometimes had a significant effect on the respective hardware.

Four experiments flew fiber optics and a fifth experiment evaluated fiber optic connectors. Four of these five experiments recorded on-orbit data. Overall, the fiber optics performed well, with little or no degradation to 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 have indicated the need for additional study of the temperature effects on fiber optical performance. Postflight 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.

Dr. Don Blue (ref. 6) has listed general characteristics for both "weak" optical materials (susceptible to environmental effects) and "strong" optical materials.

Weak	Strong
Contains ionic bonds (halides) Potential for bond breaking (plastics) Thin precision layers degraded by - thermal cycling - oxidation - bond breaking (multilayer dielectric coatings)	Covalently bonded (silicon) Hard and brittle (Li NbO_3) Contains no plastic packaging, coatings, or filters

An LDEF Optical Experiment Data Base was created (using Claris™ Filemaker Pro data base software) that provides for quick and easy access to available experimenter's optics related findings. The data base contains a file for each of the LDEF experiments that possessed optical hardware (data base currently contains 29 files). Each file contains various fields that identify the optical hardware flown, describe the environment seen by that hardware, summarize experimenter findings, and list references for additional information. A paper copy of this data base is contained in reference 1.

CONCLUSIONS

LDEF carried a remarkable variety of mechanical, electrical, thermal, and optical hardware. The extended mission length provided a unique potential to refine our knowledge about the effects of long-term exposure to the LEO environment. No anomalies occurred that indicate any new fundamental limitations to extended mission lifetimes in LEO. To date, the data from LDEF have refined the knowledge of the LEO environment and serves as the benchmark for ground-based testing.

Shielding from the effects of AO, micrometeoroids, space debris, and UV radiation must be considered. If shielding is impossible, a thorough understanding of the surrounding environment and the materials response to that environment is necessary. Without this knowledge, it is impossible to accurately predict the material's lifetime.

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 preflight testing have been identified as the primary causes of all system failures.

The combination of any of the individual LEO environmental factors, such as UV, AO, thermal cycling, meteoroid and/or debris impacts, and contamination, can produce conditions that may accelerate the onset and rate of degradation of space-exposed systems and materials.

LDEF greatly refined our understanding regarding the possibility of on-orbit cold welding occurring. If the correct materials, tolerances, and lubricants are used such that galling does not develop during preflight fastener installation or removal, or during the launch environment, and the fastener remains undisturbed while on-orbit, no difficulty will be encountered during postflight removal. This also applies to an on-orbit replacement. No difficulty due to cold welding will be encountered if a nongalled fastener assembly is removed on orbit. However, repeated on-orbit removals and installations will require the use of appropriate lubrication schemes, shielding, and an understanding of the microenvironment to ensure that no thread or lubricant damage occurs.

This paper has been an overview of representative findings from the testing of LDEF material and hardware. References 1, 6, 7, and 8 provide additional detailed information on both hardware covered and not covered within this paper (ref. 8 is expected to be released in April 1993).

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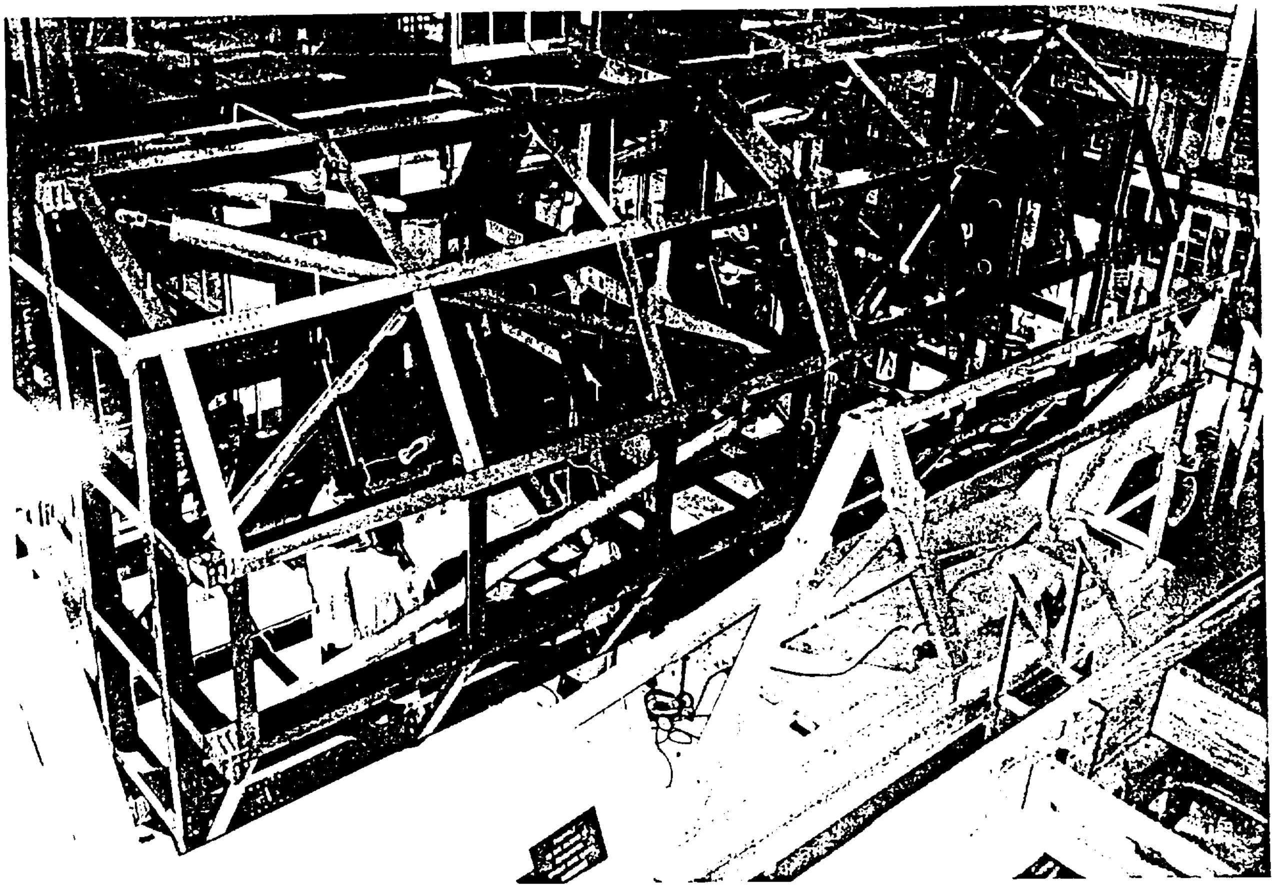

Figure 1. LDEF primary structure.

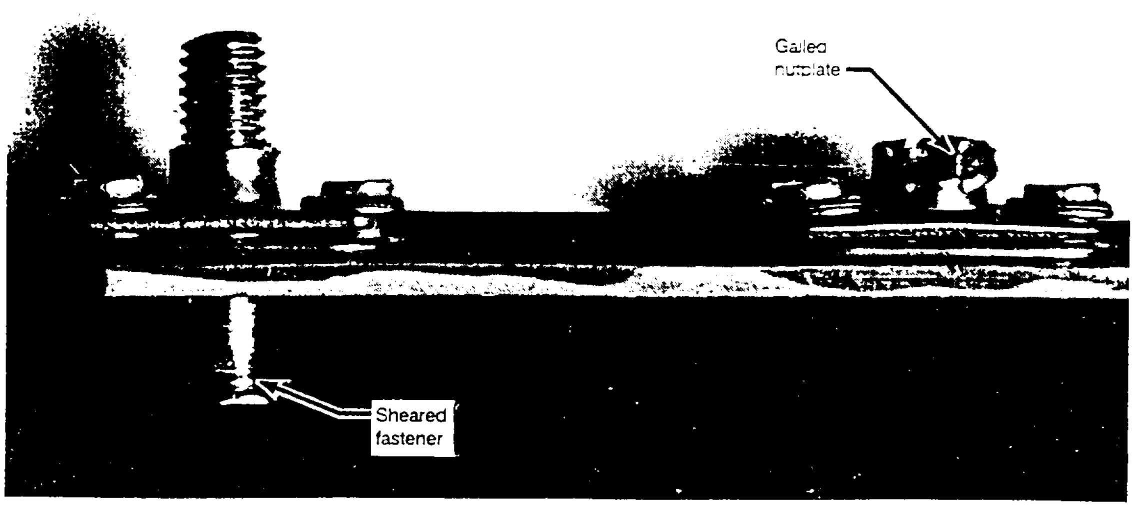

Figure 2. Sheared fasteners and galled nutplates.

LUBRICANTS

MATERIAL - DESCRIPTION	LOCATION	FINDINGS
Cetyl alcohol	A1 & A7	Failed
MoS_2	A1 & A7	Used on nut plates, appears to be nominal
MoS_2 – Air-cured dry film lubricant (MIL-L-23398)	EECCs (shielded and exposed)	Nominal, further testing required
MoS_2	B3 (shielded)	Not tested
WS_2 (tungsten disulfide)	Grapples	Bulk properties nominal
Apiezon H – thermal grease	F9 (shielded)	Outgassing tests nominal
Apiezon L – lubricant	D12	Not tested
Apiezon T – lubricant	H3 & H12 (space end)	Slight separation of oil from filler, some migration
Ball Aerospace VacKote 18.07 – MoS2 with polyimide binder	A9 (shielded)	Not tested
Ball Brothers 44177 – Hydrocarbon oil w lead naphthanate & clay thickener	EECCs (shielded)	Not tested, extensive outgassing
Castrol Braycote 601 – PTFE filled perfluoronated polyether lubricant	A3	Extensive testing, results nominal
Dow Corning 340 – Silicone heat sink compound	Shielded	IR spectra unchanged
Dow Corning 1102 – Mineral oil based heat sink compound	Shielded	Visual examination nominal
Dow Corning Molykote Z – MoS_2	Shielded	Not tested
DuPont Vespel 21 – Graphite filled polyimide	D3	Optical, EDX and friction tests nominal
DuPont Vespel bushings – polyimide	Various	Nominal
E/M Lubricants Everlube 620C – MoS2 with modified phenolic binder	D3	Complete binder failure
Exxon Andok C – Petroleum grease	Shielded	System test results nominal, lubricant not evaluated
Mobil Grease 28 – Silicone grease	MTM's (shielded)	System test results nominal, lubricant not evaluated
Rod end bearings with PTFE coated Nomex liner	D3	Extensive test results nominal

Figure 3. Lubricants and greases flown on LDEF.

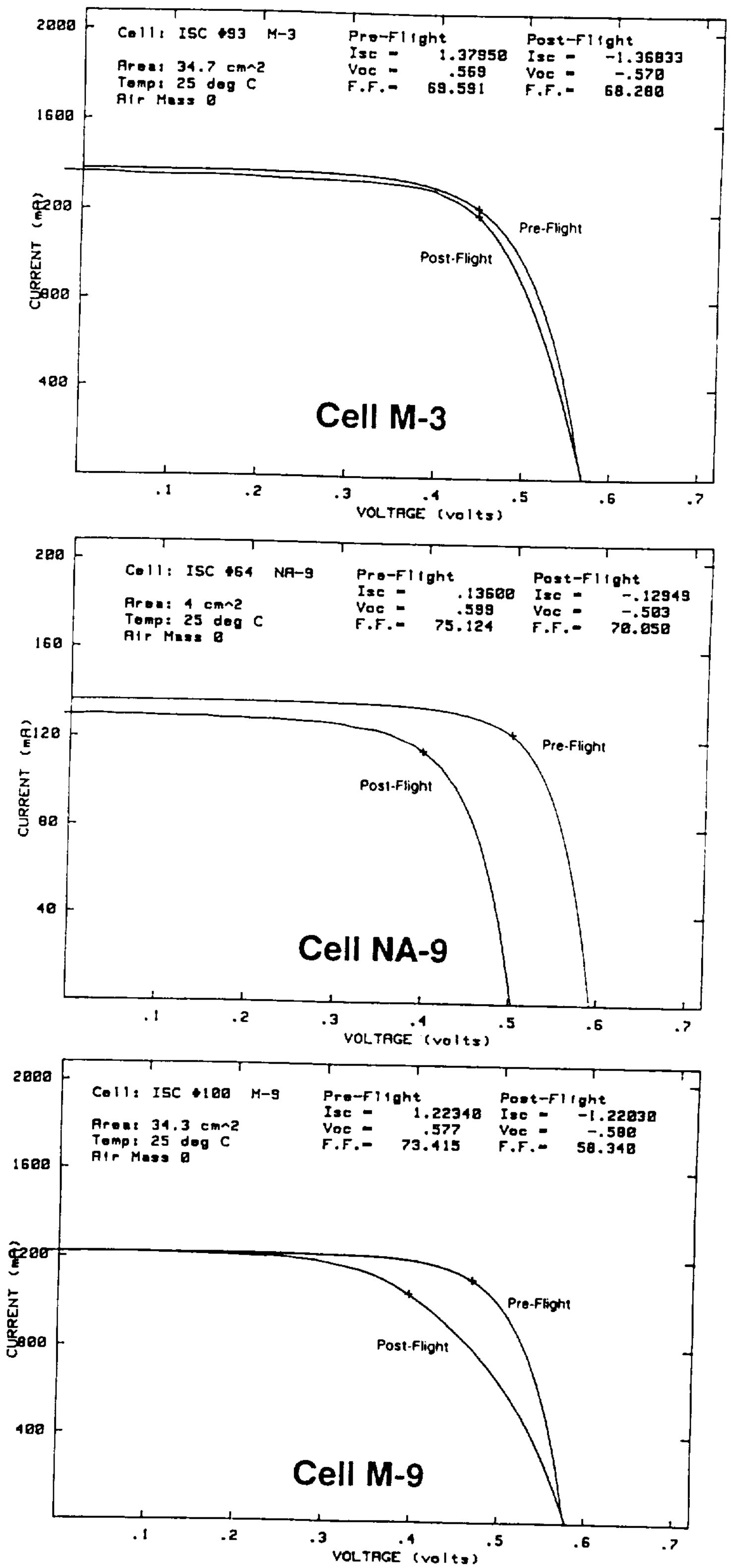

Figure 4. IV curves of cells impacted by micrometeoroids or space debris (courtesy of Dr. Dave Brinker).