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LDEF Materials Results for Spacecraft Applications—Executive Summary

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EXECUTIVE SUMMARY OF THE

LDEF MATERIALS RESULTS FOR SPACECRAFT APPLICATIONS CONFERENCE

OCTOBER 27-28, 1992; VON BRAUN CIVIC CENTER, HUNTSVILLE, ALABAMA

Foreword

The space environment once was viewed as relatively benign and simple because it was characterized by an absence of atmospheric and gravitational stresses, or by a handful of extremes like ultraviolet and particulate radiation. Even the anticipated danger of micrometeoroids abated as Pegasus, the first large space exposure test program, registered fewer hits than expected. A few missions in the 1960s and 1970s registered concerns about ultraviolet radiation and contamination effects.

To address the challenges of space environmental effects, NASA designed the Long Duration Exposure Facility (LDEF) for an 18-month mission to expose thousands of samples of candidate materials that might be used on a space station or other orbital spacecraft. LDEF was launched in April 1984 and was to have been returned to Earth in 1985. Changes in mission schedules postponed retrieval until January 1990, after 69 months in orbit.

Analyses of the samples recovered from LDEF have provided spacecraft designers and managers with the most extensive data base on space materials phenomena. Many LDEF samples were greatly changed by extended space exposure. Among even the most radically altered samples NASA and its science teams are finding a wealth of surprising conclusions and tantalizing clues about the effects of space on materials. Many were discussed at the first two LDEF results conferences and subsequent professional papers. The *LDEF Materials Results for Spacecraft Applications Conference* was convened in Huntsville to discuss implications for spacecraft design. Already, paint and thermal blanket selections for space station and other spacecraft have been affected by LDEF data. This volume synopsizes those results and their implications. It is not a substitute for detailed papers found in NASA CP-3257 or which may be found in professional journals.

Finally, I want to thank the many people who helped make this conference such a success: Marshall Space Flight Center Director Jack Lee; MSFC's Materials and Processes Laboratory personnel; MSFC's sponsoring organizations—Space Station, Space Systems Projects, Payloads Projects, Program Development, and Safety and Mission Assurance—NASA Associate Administrator Richard Petersen; LDEF Project Office personnel; LDEF Chief Scientist William Kinard; The University of Alabama in Huntsville's Office of Conferences and Marketing; and all the government, industry, and academic investigators.

Dr. Ann F. Whitaker
Conference Chair

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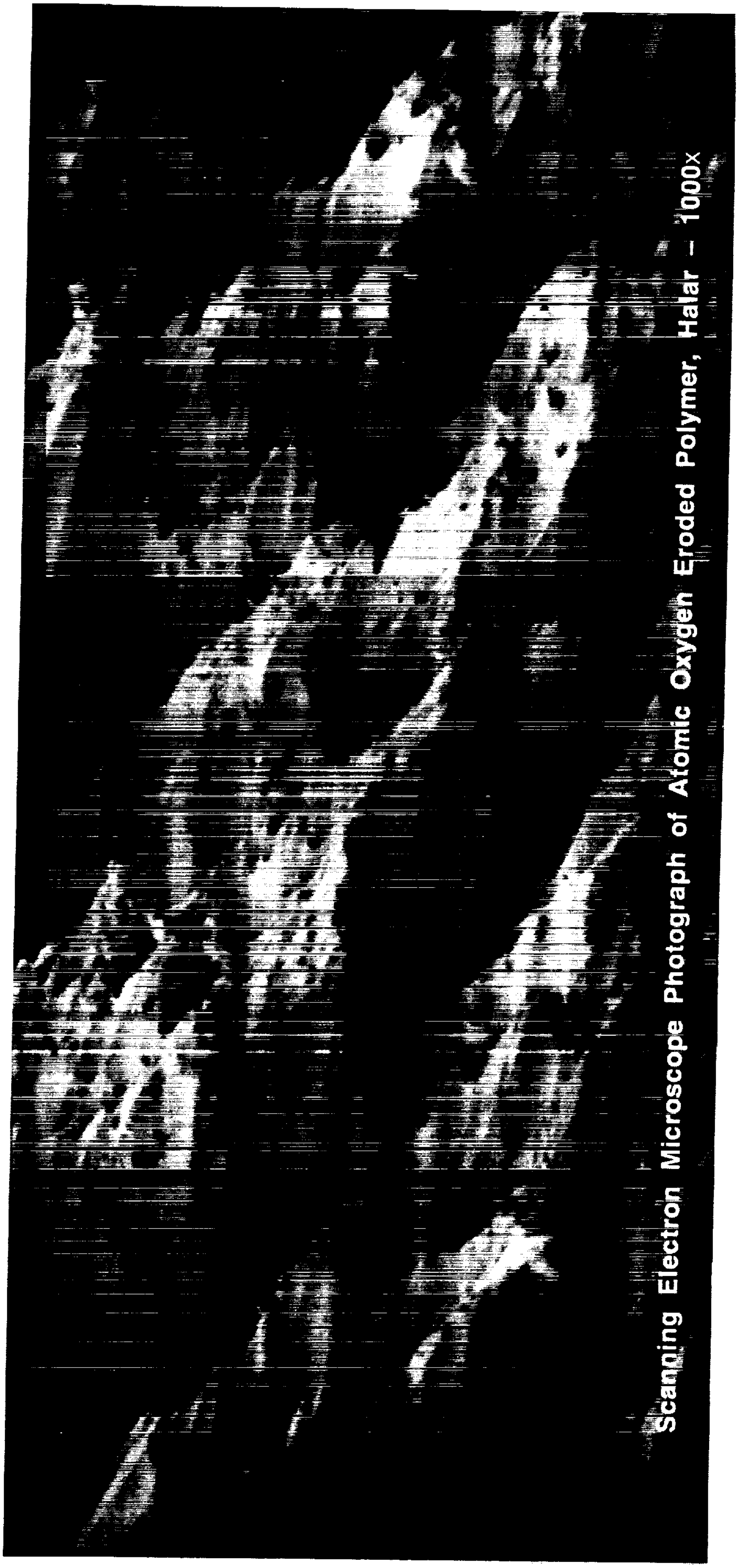

Scanning Electron Microscope Photograph of Atomic Oxygen Eroded Polymer, Halar – 1000x

LDEF-1 Summary Data

Size: 4.3 m x 9.1 m (diameter x length)
Mass (launch): 11,000 kg
Launch: April 7, 1984
Orbit:467 x 470 km/28.5°
Recovery (planned): February 1985
Recovery (actual): Jan. 20, 1990
Orbit:296 x 361 km/28.5°
Exposure: 32,000 orbits; 9 x 10^{21} oxygen atoms/cm^2; 10^9 protons/cm^2 (0.5 to 200 meV), 10^{12} to 10^{19} electrons/cm^2 (0.5 to 3 meV); <2,000 estimated sun hours (ESH, earth end), >15,000 ESH (space end); 34,000 impacts with particles > 0.1 mm diameter

Key references:

Long Duration Exposure Facility Mission 1 Experiments. Washington: NASA, 1984. SP-473.

LDEF—69 Months in Space. First Post-Retrieval Symposium. Proceedings of a Workshop Held at Kissimmee, Fla., June 2-8, 1991. Hampton, Va.: NASA, 1992. CP-3134.

LDEF Materials Workshop '91. Proceedings of a Workshop Held at Langley Research Center, Nov. 19-22, 1991. Hampton, Va.: NASA, 1992. CP-3162.

69 Months in Space. Second Post-Retrieval Symposium. Proceedings of a Workshop Held at San Diego, Calif., June 1-5, 1992. Hampton, Va.: NASA, 1993. CP-3194.

For copies of these and other publications, contact:
Jim Jones, Experiment Manager, Langley Research Center, MS 404, Hampton, VA 23665-5225 (☎ 804-864-3795)
LDEF Spaceflight Environmental Effects Newsletter. P.O. Box 10518, Silver Spring, MD 20914.

Overview: Plenary, Opening Sessions

The Long Duration Exposure Facility (LDEF), launched in April 1984, was the first large satellite designed specifically to expose samples to the space environment then allow retrieval for analyses on Earth. LDEF was a passive satellite in that it was designed without active controls or sophisticated systems. It might be thought of as a laboratory bench to which dozens of investigators attached trays full of test materials, some common, some exotic, and some with active systems.

When LDEF was placed in orbit by Space Shuttle *Columbia,* recovery was expected 18 months later. That retrieval came some 69 months later in no way invalidated the results. Indeed, following the initial analyses that revealed what happened to which samples, the space community found itself facing the daunting challenge of how to apply the results to spacecraft design. The *LDEF Materials Results for Spacecraft Applications Conference* addressed a number of those issues. Technical details of the various investigations are in the session summaries. First, LDEF's lessons were reviewed in the plenary session that ended the conference and in the keynote speech by NASA Associate Administrator Richard Petersen (see page 2).

Expanding on the experience theme, Ann Whitaker of Marshall called LDEF and its 12,000 to 14,000 specimens "the consummate laboratory" for studying space environmental effects (Pl.2). Among other lessons, it reconfirmed the need to vacuum bake exterior spacecraft components, and to be aware of the composition of materials on ram and lee spacecraft surfaces. Bicycle reflectors, electrical connectors, Z306 paint (from the interior), and several experiment trays were major sources of volatiles that condensed on parts of LDEF, she noted.

Needs raised by LDEF include:

- A new generation of materials,
- Space debris and contamination models need development or updating,
- New techniques are needed for accelerated ground-based testing of candidate spacecraft materials,
- Deeper understanding of degradation mechanisms, and
- Further investigation of synergistic effects.

Results from LDEF already are impacting the design of a wide range of spacecraft, as described by Robert Schwinghamer, former director of Marshall's Materials and Processes Laboratory (now Deputy Director of Science and Engineering for the Space Transportation System; Pl.1). The first of these is the international space station *Alpha* which had a number of representative materials aboard LDEF. Significant benefits are expected in *Alpha's* lightweight solar arrays which will carry thousands of solar cells. Contamination data will help the Advanced X-ray

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Dr. Ann Whitaker, MSFC, Engineering Physics Division, EH11, Huntsville, AL, 35812 (205-544-2510, 205-544-5786)

Speakers

Pl.1 *MSFC Orbital Spacecraft Development Emphases for this Decade.* Robert J. Schwinghamer, MSFC, EA01, Huntsville, AL, 35812

Pl.2 *What LDEF Means for Development and Testing of Materials.* Dr. Ann Whitaker, MSFC, Engineering Physics Division, EH11, Huntsville, AL, 35812 (205-544-2510, 205-544-0212)

Pl.3 *Future Direction of NASA's Space Research Program.* Robert Hayduk, NASA/Headquarters, Code RSR, 600 Independence Ave., SW, Washington, DC, 20546 (202-453-2760, 202-755-4068)

Pl.4 *NASA's Space Platform Technology Thrusts: Ongoing and Planned Programs.* Dr. Gary Bennett, NASA/Headquarters, Code RS, Washington, DC, 20546

Pl.5 *Design Application and Development of Spacecraft in LEO Utilizing LDEF Results.* George Rauch, The Boeing Company, P. O. Box 240002, M/S JR36, Huntsville, AL, 35824-6402

Pl.6 *LDEF Science and Education.* Dr. John Gregory, The University of Alabama in Huntsville, Chemistry Department, MSB 111, Huntsville, AL, 35899-2900 (205-895-6028, 205-895-6349)

Pl.7 *Concepts of LDEF II.* Dr. Vernon Keller, MSFC, PS-02, Huntsville, AL, 35812 (205-824-2470, 205-544-5861)

Welcome Address. Jack Lee, Director, MSFC, DA01, Huntsville, AL, 35812 (205-544-1910, 205-544-5228)

Keynote Speaker. Richard Peterson, NASA-R, Washington, DC, 20546 (202-453-2693, 202-755-3283)

Banquet Speaker. Dr. William Kinard, NASA/ Langley Research Center, MD-LDEFSO, M/S 404, Hampton, VA, 23665-5225 (804-864-3796, 804-864-3796)

LDEF's impact on spacecraft design

Results from LDEF are just the beginning of a long, demanding journey for the materials sciences community that must provide structures and surfaces for future spacecraft. Richard Petersen, NASA associate administrator for space technology, told the conference that a wide range of materials development and testing challenges is flowing from the results of LDEF samples. As a follow-on, a new National Space Environmental Effects program is being developed to address the development of new space durable materials.

In the past conservative designs were used because of a lack of materials data, Petersen said. "Clearly, the results of LDEF will be relevant and beneficial to many future missions, including Space Station *Freedom*."

With 57 experiments—representing more than 200 investigators from 33 companies, 21 universities, 16 NASA and defense centers, and 8 nations—LDEF covered a broad range of science and engineering investigations. The results are generating an extensive database that will significantly improve spacecraft design practices.

A strong contribution is provided by erosion effects—both striking and subtle—caused by steady exposure to energetic (5 eV) atomic oxygen (AO). Erosion was greatest on the LDEF panels facing the ram direction, or the line of flight, and extended as far as 100° (radially) from the ram vector rather than just 90° as a simple application of the cosine law would predict.

Petersen also noted that LDEF has contributed to our knowledge of the natural and manmade debris environment in low Earth orbit, by providing the first statistically large data set showing the true nature, structure, and dynamics of these particles.

Significantly, these data indicate that pre-LDEF debris models were inadequate. Analysis of debris arriving at LDEF after 12 months (when active experiments closed) shows a sharp drop in impacts after 1986 when launch accidents sharply curtailed space activity. The data also show that debris comes in clouds or clusters denser than the

Astrophysics Facility which will have the most stringent optical contamination requirements of any spacecraft. Other programs that will benefit include the Laser Atmospheric Wind Sounder and the Lunar Ultraviolet Telescope Experiment. Schwinghamer called a second LDEF mission "a worthy objective," but cautioned that in the interim experimenters will have to learn as much as they can by using opportunities in the Shuttle manifest.

NASA's Robert Hayduk (Pl.3) said the new Office of Advanced Concepts and Technology Development wants to accelerate the insertion of new technology into NASA missions. Its goals include reducing transportation costs and supporting long-duration missions, Earth observation and planetary missions, and extraterrestrial bases. Key design requirements are low launch weight, long-term environmental stability, improved performance, and survivability.

An intriguing possibility is development of smart structures that change shape or properties, or transform energy inputs, in response to environmental factors.

average flux, and also arrives from highly elliptic orbits, thus placing the lee side of spacecraft at greater risk than anticipated.

"LDEF has provided the first opportunity to observe firsthand meteoroid and debris impact damage on a wide variety of materials and systems," Petersen observed, "and, these observations have revealed that designers must consider not just the impact damage, but also the synergistic effects of multiple environments on the impact-damaged region of the spacecraft."

LDEF also carried detectors which are yielding information about long-term radiation exposure and are changing pre-1970 radiation models which had been the standard. Among many effects is a previously unknown component, low-energy, high-mass ions which may have solar or galactic origins. Conversely, analysis of the LDEF structure "has allayed concerns about induced radioactivity" on *Alpha*. An extraordinary find is radioactive beryllium (^{7}Be) on the ram side of LDEF. This isotope is created by cosmic rays striking the stratosphere, but its migration to orbital altitude is a mystery.

None of the few mechanical systems that failed aboard LDEF point to any cause in long-term exposure; most appear to be caused by design, workmanship, and lack of preflight testing.

By far the worst problem appears to have been self-contamination by outgassing from organic materials, Petersen said: "This brown film was widely dispersed over the trailing rows and both the Earth and space ends," while ram surfaces were somewhat cleaned by AO.

Finally, LDEF stands as an outstanding example of cooperation between disciplines and nations.

"LDEF paved the way for international cooperation on a large scale with a very modest budget," Petersen said. "It was built on the cheap by a dedicated bunch of engineers and scientists led by [Project Scientist] Bill Kinard." LDEF's success also comes from the international teams of Special Investigation Groups which have shared hardware and specimens among themselves.

Monitors imbedded in structures will help operators determine whether the spacecraft's health is affected by AO or other chemicals, and assist in real-time assessment of the stiffness and strain response. Intelligent microspacecraft will use materials that are adaptive, thermally stable, AO resistant, and radiation hardened.

LDEF was part of NASA's program in space platform technology thrusts, as described by Gary Bennett (Pl.4) of OAST's Transportation and Platforms Division at NASA headquarters. "Like NACA [NASA's predecessor], NASA should invest in platform technologies that benefit everyone," he said. Such investments have included large space structures, multipropellant resistojets, large solar cells, nickel-hydride batteries, arcjet thrusters (now going into Telstar 4 satellites), and LDEF. Controlled Structures Interaction, for example, has special challenges since its success in holding a large structure stable will depend on the control system "knowing" the response characteristics of each part.

A new NASA priority is to reduce the launch weight of satellites and thus reduce launch costs. The Thermal Ion and Mesosphere Dynamics (TIMED) Explorer is a test case with a goal of reducing its weight from 1,100 kg to 100 kg so it can be launched on a Pegasus rather than Delta. As *Alpha* and science programs continue to be drivers in this area, materials exposure needs are important. Ten-year objectives include a lightweight solar dynamic system (a 2 kW Brayton-cycle unit is to be tested at NASA's Lewis Research Center), advanced heat rejection systems, improved solar arrays, high-density NiH batteries, and spacesuits with fewer parts. OAST's fiscal 1993 funding is only $325 million, so not all projects can be accommodated. Bennett said that the new Office of Space Systems Development (formed shortly before the conference) wants to develop generic technologies which all payloads need to survive.

LDEF is doing just that, having returned "just in time to help with Space Station *Alpha*'s design phase," said George Rauch (Pl.5) of the Boeing Co. But long-term life predictions still are elusive, and the results have not been fully disseminated to potential users. Part of the latter challenge lies in establishing accessible, user-friendly data bases.

"We haven't fully characterized all the materials on LDEF," Rauch said. "Less than half the results are reported, and even less are documented."

Further, additional in-flight results are needed—perhaps from LDEF-like trays attached to *Alpha*—to fully understand exposure effects. Most specimens on LDEF were designed for 18 months of exposure; some were destroyed by the 69-month exposure, so survivability often is determined on a yes/no basis without understanding the damage mechanism which might lead to improved materials.

Rauch said that materials susceptibility data are most needed during the conceptual phase of a project. During the design phase materials protection and selection guidelines are based on analysis and limited testing. LDEF showed that lifetime prediction models need verification.

John Gregory, speaking as director of the Alabama Space Grant Consortium (Pl.6) urged the LDEF community to use LDEF samples as a means of getting students involved in science and math at all levels. "Business continues to regard education as a source of fodder and expect students to be supplied without [their] interaction," he said. Meanwhile, university teachers complain about the quality of incoming students. The space community is at the top of the education tree, Gregory said, and "We can't say it's not our problem."

He cited LDEF as "an outstanding example of NASA-academic cooperation," and pointed to the Seeds in Space experiment as "one of NASA's most successful efforts in reaching thousands of students [in grades K through 12]. We have to have more of this." NASA soon will publish new guidelines in which education becomes an integral component of mission-related R&D. Gregory called for education to play a bigger role in NASA's technology research.

A1
Thermal control materials

A special burden is carried by thermal control materials which must protect a spacecraft from excessive heat loads even as the exterior is assaulted by atomic oxygen (AO), solar ultraviolet (UV), and particulate radiation. A few coatings such as Z93, YB71, and D111 survived LDEF's 69 months in space, but substantial issues were raised about their gradual degradation on *Alpha* and other long-life vehicles. Many of the data from LDEF samples are qualitative and not quantitative, cautioned Don Wilkes of AZ Technology (A1.2) because control specimens were not set aside or properly maintained; some preflight data were lost when investigators moved during the five-year wait; and newer instruments were used for post-flight analysis. "Nevertheless, we obtained the most comprehensive space environmental effects data ever gathered," Wilkes said.

Silicone materials were changed to SiO_x materials with microscopic cracking. Silicone contamination was found in many areas in trace quantities not large enough to have a significant effect for thermal control coating applications. Significant contamination was found near vents or known outgassing sources. Hydrocarbon contamination was found principally on the wake side of LDEF.

Various thermal control paints exhibited a range of changes on an experiment carousel which rotated samples under an optical spectroreflectometer for the first 18 months, Wilkes continued. Z93 white paint—selected for *Alpha* based on performance, weight, and cost—showed only small changes between exposed and unexposed samples. A slight, significant shift in the spectral absorption band probably indicates that some complex chemical changes are occurring in the surface.

The implications are that "You have limited choices for how you design your spacecraft," Wilkes said. "Few coatings passed the LDEF test," and conservative end-of-life estimates must be used to ensure spacecraft margins.

Silverized Teflon films and tapes work well despite mechanical and chemical changes, said Gary Pippin of Boeing (A1.1), but the tapes must be applied carefully to prevent stressing that can cause degradation in the space environment. Damage to silverized Teflon—silver-backed fluorinated ethylene propylene (Ag/FEP)—was similar to that seen on materials from the Solar Maximum Mission satellite. Pippin said the combination of AO and UV eroded the Ag/FEP tape and increased its absorption/emissivity (a/

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Speakers

A1.1 *Performance of Silvered Teflon Thermal Control Blankets on Spacecraft.* Gary Pippin, Boeing Defense and Space Group, P. O. Box 3999, M/S 82-32, Seattle, WA, 98124-2499 (206-773-2846, 206-773-4946)

A1.2 *The Performance of Thermal Control Coatings on LDEF and Implications to Future Spacecraft.* Donald Wilkes, AZ Technology, Inc., 3322 Memorial Parkway, SW, Suite 93, Huntsville, AL, 35801 (205-880-7481, 205-880-7483)

A1.3 *Space Environment Durability of LDEF Beta Cloth.* Miria Finckenor, MSFC, EH15, Huntsville, AL, 35812 (205-544-9244, 205-544-0212)

A1.4 *Thermal Control Materials for M0003-5.* Charles J. Hurley, University of Dayton Research Institute, 300 College Park Ave., Dayton, OH 45469-0137 (513-255-3220)

A1.5 *Anodized Aluminum on LDEF.* John Golden, Boeing Defense and Space Group, P. O. Box 3999, M/S 82-32, Seattle, WA, 98124-2499 (206-773-2055, 206-773-4946)

A1.6 *Follow-up on the Effects of Space Environments on UHCRE Thermal Blankets.* Dr. Francois Levadou, European Space Agency, European Space Research and Technology Centre, P. O. Box 299, Noordwijk, The Netherlands, 2200 AG [(31) 1719-83915, (31) 1719-84992]

A1.7 *Space Station WP-2 Application of LDEF MLI Results.* Dr. Charles Smith, McDonnell Douglas Space Systems Co., 5301 Bolsa, M/S 17-4, Huntington Beach, CA, 92647-2048 (714-896-4015, 714-896-1313)

e) ratio. Reflections from the tape were diffuse rather than specular, and mechanical properties varied, such as a 33 percent drop in tensile strength (on the trail side) and an increase in percentage elongation to failure. The recovered tapes delaminated easily. Several tapes failed under thermal cycling in post-recovery tests, although those parts held by Velcro did not fail. No large-scale tears were associated with debris impact craters (one crater had darkened edges and was starting to delaminate).

"But Ag/FEP works well as a thermal control material," Pippin said, if it is applied gently. He suggested that improper application of Ag/FEP tapes may be to blame for a number of premature spacecraft failures where no immediate cause could be found. And, he cautioned that "designs that work for the short term may be inadequate for the long haul."

Beta-cloth, a durable quartz-fiber mat impregnated with Teflon, withstood the space environment well, said Miria Finckenor of Marshall (A1.3). Only 0.24 mil of Beta-cloth was lost vs. up to 0.61 mils predicted before recovery. Although the surface was eroded, as shown in scanning electron microscope (SEM) images, most of the Teflon stayed between the glass fibers. No through-erosion was found except where micrometeoroid impacts opened a channel for AO. Even so, the quartz fibers pulled up but did not release. The a/e ratio showed no apparent change. The worst damage occurred to Dacron threads (holding Velcro™) at the edges: they easily pulled apart on deintegration of the samples. The Velcro™ also appeared severely bleached and many of its nylon hooks were eroded to nubs. Finckenor predicted that with AO-resistive threads in place of Dacron, Beta-cloth should last far longer than the 69 months it was aboard LDEF.

Similar materials have been selected for the more than 1,000 MLI blankets that will be installed on *Alpha*, said Charles Smith of McDonnell Douglas Space Systems Co. (A1.6). Data from blankets on LDEF's Cascaded Variable Conductance Heat Pipe Experiment (tray F-9) were extrapolated to support the blanket design. The heat-pipe experiment worked well, providing temperature control within 0.3°C, but on recovery the MLI blanket color was silver, not gold.

The outermost 3 mil Kapton coating and the polyester scrim cloth were gone, and some of underlying aluminum had fragmented and drifted away (as seen in some recovery photographs). Micrometeoroid hits on the MLI opened pinholes allowed AO to enter the aluminum undercoating and erode the underlying Kapton layers. SEM images also show vent hole shadows and cloudy areas where vaporized material condensed. Nevertheless, the MLI blankets still protected the heat pipes.

Blankets planned for *Alpha* comprise:

- Outer cover: Beta-cloth with an aluminized inner surface.
- Reflective layers: Kapton (0.0076 mm), double-aluminized, perforated to allow venting, interleaved with Dacron or Nomex (depending on site temperature).
- Inner cover: Kapton (0.076 mm), aluminized on both sides and perforated.

The edges will be bound by a Beta-cloth strip that overlaps each side by an inch and is stitched by glass fiber. The blankets will be held by Velcro and mechanical snaps in protected and unprotected areas, respectively. The complete assembly is expected to last the space station's lifetime.

The primary coating on the LDEF structure—thin chromic acid-anodized aluminum—survived the AO environment well, said John Golden of Boeing Defense and Space Group (A1.5). Two other types of anodized surfaces also were flown. Changes that were noted include:

- Chromic acid anodize—small absorption changes ranging from less than 0.02 to 0.07, mostly due to contamination (manufacturing variations can be on the order of 0.02). The primary concern for this material is that its porous surface might trap contaminants.
- Sulfuric acid anodize—high emissivity increase, and small increases in absorptivity. A small area with a chromate seal had an emissivity increase from 0.75 to 0.84
- Dyed sulfuric acid anodize—increased absorptance. This anodizing process is used for optical baffles.

Understanding the effects of AO erosion also requires understanding self-contamination effects, said Francois Levadou of the European Space and Research Technology Centre in Noordwijk, The Netherlands (A1.6). Levadou is looking at silicone contamination in a number of samples including FEP.

(Although the most severe effects were generally found on the ram side of the vehicle, an abstract by Charles Hurley of the University of Dayton Research Institute (A1.4) reported that thermal control coatings (which were state-of-the-art in 1982) changed more on the lee side than on the ram side. Solar absorptance changed the most on the lee side, apparently due to contamination and radiation effects. Contamination on the ram side was cleaned by AO.)

A2
Spacecraft environment

LDEF has provided the largest single physical data set—a benchmark—on the space environment, showing that the environment is more dynamic than simple, averaging models indicate, said William Kinard in reviewing the LDEF micrometeoroid and debris environments (A2.1). The LDEF

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M. Ralph Carruth, Jr., MSFC, Physical Sciences Branch, EH12, Huntsville, AL, 35812 (205-544-7647, 205-544-0212)

Speakers

A2.1 *An Overview of the LDEF Micrometeoroid and Space Debris Environment.* Dr. William Kinard, NASA/Langley Research Center, MD-LDEFSO, M/S 404, Hampton, VA, 23665-5225 (804-864-3796, 804-864-3796)

A2.2 *The Ionizing Radiation Environment of LDEF-1.* Dr. Thomas Parnell, MSFC, ES62, Huntsville, AL, (35812 (205-544-7960, 205-544-7754)

A2.3 *Induced Activation Study on LDEF.* Dr. Alan Harmon, MSFC, ES62, Huntsville, AL, 35812 (205-544-4924, 205-544-5800)

A2.4 *An Overview of LDEF Contamination.* Dr. Wayne Stuckey, The Aerospace Corporation, P. O. Box 92957, MS: M2/250, Los Angeles, CA, 90009 (310-336-7389, 310-336-5846)

A2.5 *Modeling of LDEF Contamination Environment.* M. Ralph Carruth, Jr., MSFC, Physical Sciences Branch, EH12, Huntsville, AL, 35812 (205-544-7647, 205-544-0212)

A2.6 *Spacecraft Contamination Lessons From LDEF: Issues for Design.* Gary Pippin, Boeing Defense and Space Group, P. O. Box 3999, M/S 82-32, Seattle, WA, 98124-2499 (206-773-2846, 206-773-4946)

A2.7 *Model of Spacecraft Atomic Oxygen and Solar Exposure Microenvironments.* Roger J. Bourassa, Boeing Defense and Space Group, P. O. Box 3999, M/S 82-32, Seattle, WA, 98124-2499 (206-773-8437, 206-773-4946)

data set includes sensitivities down to 10^{-2} impacts per square meter per year for particles down to 10^{-4} cm in size. More than 30,000 impacts, from less than a micron to 5 mm in size, have been recorded on LDEF itself, "plus hundreds of impacts on other specimens." The impact record indicates that the debris and micrometeoroid environment will not cause catastrophic failures on *Alpha*, "but it will be impacted repeatedly and cause small failures" over the course of the station's life.

At a gross level, LDEF has confirmed the simple micrometeoroid model established by Pegasus in the 1960s. The data were established by the Pegasus satellites and, while it is "remarkable that the curves had held up as well as they have over the years ... LDEF has provided a lot more information so we can refine these models," Kinard said.

Impacts on LDEF's ram side were 10 times those experienced on the lee side. Surprisingly, the distribution was not constant with time, but came in clusters. Some active experiments (which shielded specimens after a few months in orbit) had periods when impact frequency was "orders of magnitude greater" than at other times, Kinard said. In particular, the flux for the first year was higher than the average for the next four years, possibly in connection with changes in space activities in 1986 when several launch mishaps changed space operations. Impacts from manmade debris on LDEF's lee side also indicate that debris in highly elliptical orbits is 30 times greater than once expected. Further, many craters are hemispherical, indicating hypervelocity impacts. Distinguishing manmade from natural impacts can only be done by chemical analysis, Kinard added, and not readily by inspection as some investigators had hoped.

Kinard also cautioned that investigators seeking to simulate LDEF impacts must include synergistic effects from exposure to the rest of the space environment—especially AO and UV radiation—before and after the surface is hit. "We need to be careful in impact simulations and include synergistic effects," he said. Even spalling (secondary impact particles) must be considered.

Lessons for designers are as complex as the sources of contamination seen on LDEF. Gary Pippin (A2.6) of Boeing Defense and Space Group, reviewed a number of possible sources and their impact on spacecraft. Contamination—the transport of unwanted material from one location to another—can affect spacecraft in a number of ways, Pippin recounted. It can block apertures or ports, interfere with (or abrade) moving parts, change thermal properties, and cause other effects.

Many deposits can be explained as line-of-sight contamination from vents that were parallel to the spacecraft surface. "We have to think about vent paths that are normal to the surface," Pippin said. "Materials will outgas for long periods" and, with substances like RTV and shrink tubing, the total quantity can be significant over the years. An unusual effect noticed during recovery was a cluster of particles floating in formation with LDEF. "These most likely came from the leading edge," Pippin said, "and we need a mechanism to sweep them into the wake." Such particles can confuse or obscure star trackers and science instruments, degrade optical and thermal control properties on *Alpha* or other spacecraft.

Another challenge is to predict the effects that the space environment may have: AO can clean some materials off surfaces while UV may cause others to cross-link and become more tenacious. Designers need to think about how to prevent contamination such as locating vent paths away from sensitive instruments, cleaning the spacecraft before launch, and warming it early in the mission (with apertures still closed) to drive out volatiles before activating sensitive systems.

Spacecraft designers long have worried about induced radiation that a spacecraft might acquire through long-term exposure to space radiation. LDEF data have altered thinking about shielding on *Alpha* and has spurred work on a new three-dimensional radiation model, said Tom Parnell of Marshall Space Flight Center (A2.2). LDEF carried 14 experiments with radiation detectors, some as astrophysics experiments, others as monitors. These were analyzed as a set to understand potential effects on crews and electronic devices on *Alpha.*

A principal concern is the South Atlantic Anomaly (SAA), a region where the Earth's magnetic field pulls the radiation fields closer. Until recently SAA models were omnidirectional and required spherical shielding. Instead, a distinct east-west symmetry has been found with protons trapped on field lines and generate a "pancake-shaped flux." Two LDEF experiments indicate that these protons are energetic enough to penetrate some 6 mm of aluminum, Parnell said. Analysis of aluminum tray clamps shows the east-west anisotropy of the protons, too. Linear energy transfer recoils that can cause single-event upsets in electronics exceeded predictions, Parnell said. A new 3-D radiation model is to be ready in late 1993 as data from the various LDEF experiments are organized and compiled, he added.

While most of LDEF and its samples were built in sheets or layers, the support trunnions and other primary structures were large enough to allow analysis of radiation effects to a depth of several centimeters, said Alan Harmon (A2.3) of Marshall. This allows more detailed analysis of radiation energy spectra. Half-lives of radiation products allow limited information about flux history. However, the combination of SAA anisotropy and shielding on LDEF give the radiation complex patterns. One surprise was the discovery of beryllium-7 on the leading surfaces of the trunnions (etching the surface confirmed that it was scavenged by impacts and not caused by decay in the structure). This is believed to be a by-product of cosmic rays striking oxygen atoms in the upper atmosphere. Sodium 22, an aluminum daughter product, was found inside the trunnions on the trailing side.

The structures were analyzed soon enough after retrieval to allow detection of products with short (<14 days) half-lives inside steel. Intensity profiles around the trunnion show SAA exposure on the west and south sides of LDEF, and greater manganese-54 on the Earth side. Significant activation from primary and secondary particles was also seen deep inside the trunnions. Neutron activation of cobalt, nickel, and tantalum was recorded, but not at the levels expected. Harmon said the data are still being archived, but additional measurements are needed to normalize variations of 10 to 20 percent that were seen even at the same laboratories.

Self-contamination from outgassed products was one of the major effects noticed on LDEF. "The unique thing to learn is how to pick out the flight portion of the contamination [from] assembly, launch, and recovery," said W. K. Stuckey of The Aerospace Corporation (A2.4). Emphasizing a lesson repeated by several speakers, he said that the synergism of deposition mechanisms with AO and UV radiation should be understood better. Further, contamination should be minimized by using models to predict outgassing products better and to select the correct materials for spacecraft.

"Just because it's been flown or meets specifications doesn't mean it doesn't have the potential to cause contamination problems," he cautioned. Most outgassing was driven by temperature differences, exposure to sunlight, and AO effects, he said. The D8 tray, where he had samples, showed thick brown stains—mostly carbon compounds and silicon oxides—with glassy structures around vents. On the other hand, his ram side samples were greatly reduced in carbon compounds, and showed gross Kapton erosion from AO exposure, which created a lot of debris.

Applying the Integrated Spacecraft Environments Model (ISEM) to LDEF demonstrated the need to have a full, comprehensive model of the ambient environment and contamination sources, said M. R. Carruth of Marshall (A2.5). Conditions and effects were modelled for three points in the mission: early, when the overall environment is dominated by outgassing, even on the ram side; middle, when outgassing dominates only on the lee side; and late, when materials are being gettered onto the lee side as a result of AO erosion. Carruth said that some materials contaminated LDEF by return flux scattering when they were released from the satellite and encountered the ambient atmosphere around it. Investigators also found flows into LDEF and sample trays. In one case, enough material was deposited (in a pattern matching a thermal flow through the vent) that it easily flaked off the structure. "The results have important implications for future spacecraft designs and how they are modelled," Carruth said, "especially with respect to combined environments."

Variations in the atmosphere, solar activity, and even the attitude of the spacecraft surface to the ram vector shifted the rates at which materials were affected by AO, said R. J. Bourassa of Boeing Defense and Space Group (A2.7). AO density varied by a factor of 100 as LDEF's altitude slowly decreased, he said. As a result, the last year of exposure accounted for almost 85 percent of the erosion due to AO. Pre-retrieval predictions of damage varied by as much as 25 percent due to co-rotation of the atmosphere and errors in the original simulation codes, Bourassa continued.

An application of the cosine law did not predict AO effects that were seen up to 110° from the ram edge rather than just 90°. Microenvironmental effects such as shadowing and specular and diffuse reflection also caused local variations in the AO plume. An angle bracket holding the F9 experiment tray, for example, saw the most AO erosion in a recessed corner due to AO being reflected into that spot. The same effect caused extensive erosion for the edge of thermal control blankets on the B7 and D11 trays. Bourassa said that such variations must be included if spacecraft designers are to evaluate design options and establish maintenance schedules.

B1
Materials erosion, radiation damage, and fluorescence

Atomic oxygen exposure caused a wide range of damage effects to LDEF samples as described by Rachel Kamenetzky of Marshall (B1.1) in discussing the effects on some 300 specimens in experiment A0171 (tray A8), mounted just 38° from the ram direction. Among the changes noted were missing solar cells and thin films and darkened composites and polymers. Epoxy fiberglass was less reactive than expected, with the glass apparently providing some protection.

Kamenetzky said that FEP polymers were more reactive with AO than anyone expected. She also noted that pure polymers have a linear erosion rate, and damage to Kevlar™ suggests that stresses within the material may play a role in its reactivity. Glassy ceramics showed small decreases in reflectivity, and SiO was found to have oxidized to SiO_2. The surface of paints such as Z302 were covered by an ash structure that is not fully understood. In general, paints became darkened or blackened, and all polymer coatings except S13GLO lost mass. Oxides of metals are still being studied, but reactivity seems to vary with temperature and stress. Some metals gained mass through oxidation (not all oxides have been fully identified), and the surface morphology of silver changed radically.

Many factors affect the linearity of oxidation rates for different materials, said John Gregory of the University of Alabama in Huntsville (B1.2). Materials that have gaseous oxides disappeared from the samples; those with refractory oxides remained. Profilometry traces of polymers with -CH_2- backbones showed erosion ranging from 33.5 μm (for polyfluorotetraethylene or PFTE) to 566 μm (polymethylmethacrylate, PMMA or Lucite™). Ridge marks on Kapton™ (possibly stress lines from manufacture) propagated into linear grooves that eroded into the material. Gregory cautioned that data comparisons with previous flights may be affected by contamination of the samples on earlier missions. Ultraviolet radiation may exacerbate AO effects on materials such as -CF_2- polymers. Samples atop hot plates carried on the recent Concap-2 payload indicate that temperature may be a more significant factor for metal oxides than for polymers.

The microenvironment of space is becoming more important, said Philip R. Young of Langley Research Center (B1.3). Selected polymers he examined had suffered some 34,366 micrometeoroid impacts and large fluxes of electrons and protons. One of the mysteries that returned with LDEF is why some epoxy composite samples returned with stripes at a 45° angle to the ambient flux. Analysis at the University of Queensland shows that polysulfones are essentially unchanged. AgFEP tapes also show little surface chemistry change and still have the same total reflectivity even when the surface changes from specular to diffuse. About 20 materials were seen to shift from light to dark color—or the reverse—and to show some surface erosion. Young also found specimens of SiO oxidized to SiO_2. He said that the experience with a number of specimens offers "the exciting possibility" of designing AO protection into polymers so they adapt through exposure in space.

In particular, he said he is excited about polysulfone, a commercially available material, which showed strong exposure effects after 10 months (for samples withdrawn into a control canister) and no effects after 69 months. "We may be able to develop stable AO and UV [resistant] materials," he said. However, "We need to fly well-characterized materials to establish criteria." Prompt analysis plus a full understanding of post-flight materials changes also are important, especially in light of the decay, in terrestrial storage, of samples flown on STS-8 and other missions, he said. Understanding the separate and combined effects of AO and vacuum UV is also needed.

An intriguing finding was the discovery that caverns were hidden behind pinholes in Kapton™ polyimide and graphite epoxy coatings. Bruce Banks of Lewis Research Center (B1.4) said these cavities seemed to be out of proportion to the pinhole and slit apertures which admit the oxygen atoms. After entering the aperture the AO either reacts with the material or is scattered a second or third time until is it is reacted or loses its energy thermally. As the cavity grows, so do the chances of reactions (which varies with thermal accommodation) since the internal surface area is far greater than the aperture where the atom might exit. Banks suggested that this repeated erosion behind the scenes caused aluminum film that covered graphite to break up when it was repressurized on return to Earth. Computer modeling is consistent and shows the aluminum film remaining intact while the width of the undercut increases faster than the size of the aperture.

Changes in the fluorescence of materials is emerging as a new tool for detecting and diagnosing the effects of space exposure, said Roger Linton of Marshall (B1.5). Fluorescence is the nonthermal reradiation of photons absorbed by an atom's outer electrons. Generally it is stimulated by UV radiation and expressed as visible light in wavelengths unique to each material. In general, Linton said, the fluorescence of LDEF materials was quenched (reduced) or shifted to another part of the spectrum. A spectrafluorometer measured responses to short and long UV radiation (254 and 365 nm). A276 white polyurethane paint, for example, was totally quenched by loss of the polymer binder. But an A276 sample under an UV window, and thus protected from AO, responded in a different part of the spectrum than did a control specimen.

Z306 black polyurethane paint and white YB-71 zinc orthotitinate were exceptions to the strong quenching found in most specimens. RTV-511 showed stimulated emissions, PMR neat resins showed enriched emissions, and polyether-ether-ketone (PEEK) had a shifted wavelength response. Linton also found that temperature and humidity in the laboratory can affect responses obtained with the spectrafluorometer (exposure to UV was limited, also, to minimize damage to the specimens). Other changes may be caused by variations in materials preparation or morphology.

(Ralph Hill of Southwest Research Institute was unable to present his paper. Hill is using laser-induced fluorescence, at 488-nm, to study space-exposed polyurethane [B1.6]. Degradation variations were more apparent, and anomalies

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Speakers

B1.1 *Atomic Oxygen Erosion Considerations for Spacecraft Materials Selection.* Rachel Kamenetzky, MSFC, EH12, Huntsville, AL, 35812 (205-544-1089, 205-544-0212)

B1.2 *On the Linearity of Atomic Oxygen Effects with Fluence: A Comparison of STS-8 and LDEF Experiences.* Dr. John Gregory, The University of Alabama in Huntsville, Chemistry Department, MSB 111, Huntsville, AL, 35899-2900 (205-895-6028, 205-895-6349)

B1.3 *Performance of Selected Polymeric Materials on LDEF.* Dr. Philip Young, NASA/Langley Research Center, M/S 226, Hampton, VA, 23665-5225 (801-864-4265, 801-864-8312)

B1.4 *Atomic Oxygen Interaction at Defect Sites in Protective Coatings on Polymers Flown on LDEF.* Bruce Banks, NASA/Lewis Research Center, Electro-Physics Branch—M/S 302-1, 21000 Brookpark Rd., Cleveland, OH, 44138 (216-433-2308, 216-433-6106)

B1.5 *Fluorescence Observations of LDEF Exposed Materials as an Indicator of Induced Materials Reactions.* Roger, Linton MSFC, Space Environmental Effects Branch, EH12, Huntsville, AL, 35812 (205-544-2526, 205-544-0212)

B1.6 *Laser-Induced Fluorescence of Space-Exposed Polyurethane.* Dr. Ralph Hill, Jr., Southwest Research Institute, Instrumentation and Space Research Div., 6220 Culebra Road, San Antonio, TX, 78238-5166 (512-522-3358, 512-647-4325)

B1.7 *Spacecraft Thermal Control Coatings: Comparison Between Flight Results Obtained on LDEF and Mir.* Dr. Alain Paillous, CERT-ONERA, Space Technology Department, BP 4025, Toulouse-Cedex, France, 31055, [(33) 61 55 71 19, (33) 61 55 71 72] between fresh and control samples were easily detected. Video cameras and fiber optics were used to reveal defects that standard blacklight inspection could miss.)

Lasers were used by Joan Pallix of Eloret Institute (P1.8) to gently detach "ash" for analysis in a mass spectrometer. (The technique was borrowed from the semi-conductor industry.) The ash was found on the surfaces of polymer-matrix composites on LDEF's ram and lee sides. A pulsed YAG laser freed or mobilized the material, and an electron gun ionized it for easy transport into the mass spectrometer. Samples included C/polysulfone, C/polyimide, and C/epoxy. In every case, the molecular signatures could be assigned to fragments of heavier, complex materials such as polysulfone and PMR polyimide, although a sodium peak appeared in some samples. C_3 fragments were not detected.

The combination of UV radiation and AO flux can be more damaging than either alone, according to A. Paillous of the CERT-ONERA/DERTS research center in Toulouse, France (B1.7). Paillous had samples aboard LDEF and, more recently, for a year aboard the Russians' Mir space station. The Mir samples were exposed and protected by various windows. The two missions do not compare directly because of environmental, orbital, and other differences. Further, some of the Mir samples were boxed before their return to Earth vs. exposure to air after LDEF returned to Earth; high temperatures (85°C) inside the canister on LDEF may also have played a role. Paillous cautioned that the latter may have changed reflectance values on LDEF samples. He also said that LDEF data cannot be used as an unrestricted qualification for general space use because synergistic effects of different environments and localized effects can alter the effects on materials.

B2
Optical elements and materials

A common effect experienced by many optical materials was the loss of UV transmission and a reduction in visible light transmission, said M. Donald Blue of the Georgia Tech Research Institute (B2.1). Hardened materials survived in the best shape. Glass, quartz, silicon, and germanium generally stood up well, he said, and cadmium telluride and zinc selenide came through "in good shape." Magnesium fluoride and calcium fluoride, though, appear to be less robust with various investigators reporting different results. KRS5 and KRS6 glasses (in the thorium bromine iodine family) work well as infrared windows in the laboratory, "but they don't work well in space." Those on LDEF returned with mottled, milky surfaces caused by bromine depletion. Dielectric coatings did not fare well, either. The best ones lost UV transmission, and some became opaque. In general they experienced drops in transmission, broadening of bandwidths, and shifts to the blue in peak transmission.

A late addition to Georgia Tech's sample tray was a 32 x 64-element charge-coupled device (CCD) representing advanced infrared detector technology of the early 1980s. Electrical property changes in the chips were still within manufacturing tolerances, Blue said, but the charge transfer efficiency dropped from 0.999 to less than 0.995, an unacceptable condition. However, Blue said that electrically charging the chips can solve the problem, and in actual use the chips would be protected inside a dewar.

Photovoltaic cells, though, must operate exposed to the space environment. Leighton E. Young of Marshall said that of six solar cell modules (from Lockheed Missiles & Space Co.) flown on LDEF, three were lost during the mission (B2.2). One was missing before retrieval, one drifted away while the robot arm was grappling LDEF, and one detached and fell to the bottom of the shuttle payload bay where it was found after landing. Those with exposed kapton experienced severe erosion, Young said, and in one case only the copper interconnects were holding the module together. Cell output degraded by 4.3 to 80 percent while series resistance increased (from less than $0.01\ \Omega$ to $2.8\ \Omega$), depending on erosion of the contacts. Little degradation was noted on ground control samples that underwent 50,000 thermal cycles.

"In general, the solar cells did well," Young said. "I think the solar cell samples performed well for the conditions they were in." Interconnects helped hold them together, and electrical performance was good except where silver contacts were oxidized by AO (in some cases, the silver oxide was removed by micrometeoroid impacts).

Palmer Peters of Marshall reported on changes in chemical and optical properties of thin film metal mirrors on LDEF (B2.3). Fused silica optical flats were coated with a variety of different metals in 200 to 1000 Å thicknesses and optical densities of 1 to 2. Half of each specimen was covered by a protective aluminum retainer.

Specimens on the trailing face showed an increase in SiO_x compounds, while those on the leading face became thicker as the metals were oxidized (some, like osmium, were completely cleaned off).

James M. Zwiener (B2.4) of Marshall, said that micrometeoroid impacts on LDEF can now provide worst-case calculations for long-term exposure. Of some 34,000 impacts recorded on LDEF, Zwiener examined 4,000 ranging in size from 0.5 mm to 5.25 mm (sizes down to 0.1 mm were extrapolated). At a gross level, LDEF experienced about 140 hits/m^2/year on the ram side, and 16 on the lee side. Spalling and debris condensation caused little change to solar absorption of paints, although the emissivity increased

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B2.1 *Degradation of Optical Components in Space.* Dr. M. Donald Blue, Georgia Tech Research Institute, EOL Dept.—Baker Bldg. Rm. 3064, 925 Dalney Street, Atlanta, GA, 30332-0800 (404-894-3646, 404-894-6285)

B2.2 *Impact of LDEF Photovoltaic Experiments Findings On Future Spacecraft Solar Cell Assembly Design and Development Requirements.* Leighton Young, MSFC, EJ-33, Bldg. 4200, Huntsville, AL, 35812 (205-544-0707, 205-852-0561)

B2.3 *Changes in Chemical and Optical Properties of Thin Film Metals Mirrors on LDEF.* Dr. Palmer Peters, MSFC, ES63, Bldg. 4481, Huntsville, AL, 35812 (205-544-7728, 205-544-7754)

B2.4 *Micrometeoroid/Space Debris Effects on Materials.* James Zwiener, MSFC, Space Environmental Effects Branch, EH15, Huntsville, AL, 35812 (205-544-2528, 205-544-0212)

B2.5 *Physical Properties of Glasses Exposed to Earth-Facing and Trailing-Side Environments.* Dr. Donald Kinser, Vanderbilt University, Department of Materials Science & Engineering, Box 1689-B, Nashville, TN, 37235 (615-322-3537, 615-343-8645)

B2.6 *Micrometeoroid/Space Debris Effects—Studies on Impact Features on Germanium Targets of Experiment A0187-2 & Their Experimental Simulation.* Klaus G. Paul, Universitat Munchen, Lehrstuhl fur Raumfahrttechnik, Richard-Wagner-Str. 18/III, Munchen, Germany, D-8000, [(49) 89-2105-2578, (49) 89-2105-2468]

B2.7 *Morphology Correlation of Craters Formed by Hypervelocity Impacts.* Gary Crawford, Auburn University, Space Power Institute & Materials Engineering, Ross Hall, Auburn, AL, 36849-5351 (205-844-4822, 205-844-3400) dramatically. Silver-Teflon™ showed relatively little change because of the AO erosion that quickly follows (it starts to debond and the Teflon™ either cracks or separates from the adhesive). Composites like aluminum-coated epoxy were less affected by the AO erosion that followed impacts. Solar cells also were relatively unaffected, including samples of Hubble Space Telescope cells which lost Kapton but still generated electricity.

While space exposure eroded coatings or deposited new ones, it had no apparent effect (absent impacts) on the physical properties of glasses and glass-ceramics, said Donald L. Kinser of Vanderbilt University (B2.5). Five glass samples (out of 120 flown) and one ceramic sample (out of 20 flown), each 25.4 mm wide and 3 mm thick, were mechanically tested until they fractured. No detectable changes were found in mechanical properties compared to control specimens. Seven samples that had impacts were tested, to the extent allowed by the shape of the remaining pieces, and showed no degradation other than that caused by the impact itself.

Impact craters generally showed a melted pit surrounded by a lip extending upward. A fused quartz specimen had several 100 μm-long, 0.5 μm-wide glass fibers that had to form in the space of a few nanoseconds as the molten glass sprayed outward from the impact, Kinser said. One impact had no melt zone, indicating a low-speed impact (<5 km/sec). Other than a loss in UV due to apparent photolysis of the internal coatings, optical transmission for lee-side specimens was unchanged. No radiation damage was apparent.

Two LDEF investigations have evolved simulation techniques to duplicate micrometeoroid damage and thus understand the shape and chemistry of the particles that impacted LDEF. Experiment A0187-2 (bay E-8) provided germanium targets to capture debris for post-flight analysis. K. Paul of the Lehrstuhl for Raumfahrttechnik, University of Munich, Germany, said that a plasma gun firing particles weighing 84 micrograms at 17 km/sec has produced impacts similar to those found on LDEF (B2.6). Crater shapes change with the particle velocity—below 5.6 km/sec the rims become less visible, for example—and the velocity distribution of the particles might be determined by looking at the crater cross sections, Paul said. Scaling the impact velocities may also be possible with sufficient modeling, he added.

Gary Crawford of the Space Power Institute at Auburn University, Auburn, AL, has used Auburn's debris simulation facility morphology to correlate craters formed by hypervelocity impacts (B2.7). "It's obvious that we have a lot of junk in space," he said, "and spacecraft have to be designed to deal with that environment." Crawford used microspheres of olivine (magnesium iron sulfate) to closely match the composition of many micrometeoroid particles and fired them into a copper sheet. Copper, coated with carbon to help visualize impacts, was selected because its fracture mechanics are well known and its chemistry is easily separated from the rest of the debris. A Mylar screen was placed in the path to confirm the size of olivine particles before impact (in some cases it caused the microsphere to break up), and a special solid-state camera determined the velocity. A laser makes 10 to 20 precise scans of the crater at 5 μm increments.

Crawford said a clear, linear relationship can be seen between particle momentum and crater volume. Olivine debris could be distinguished in collisions ranging from 5.6 to 8.7 km/sec. He plans to extend his research to use LDEF-type materials and then match their craters to in-flight impacts, and to see if he can reach a velocity where no particle debris is left in the crater.

C1

Composites and structural materials; databases

Boron and graphite epoxy samples flown aboard LDEF appeared to adapt to the space environment after about 80 days, according to Rod Tennyson (C1.1) of the University of Toronto. Tennyson said the temperature and strain coefficients of the composite samples were sampled every 16 hours for 200 days at the start of the mission. Changes in their coefficient of expansion probably stabilized after the samples finished outgassing, he said. This raises the question of "Can you design to compensate for outgassing" and predict dimensional changes as a function of time and temperature, he said. Laboratory tests indicate that the process cannot be easily simulated or accelerated. Doing so led to nonuniform saturation of the samples. Tennyson also believes that future experiments must test the samples every 10 minutes rather than 16 hours to get an adequate measure of change.

Graphite-fiber reinforced composites generally survived various types of damage, according to Gary Steckel (C1.2) of the Aerospace Corp. A total of 299 impacts on graphite aluminum samples had the same effect as impacts on aluminum metal, he said, and the projectile barely penetrated to the matrix. However, thermal fatigue cracks spread from the impact crater. Aluminum foil provided good protection to the surface, but some samples also showed extensive surface foil cracking, and silicone contamination embrittled the foil of samples on the trail side (all cracked samples were on the trail side). Graphite magnesium showed surface cracking and a brittle-phase material on the surface. Steckel believes that the cracking is associated with an oxide coating that the surface acquired in the two years before launch (it was cleaned off before flight) and with AO erosion in orbit. Magnesium and epoxy samples proved to be more susceptible than aluminum, but graphite/borosilicate glass showed no significant mass loss or changes.

Pete George (C1.3) of Boeing Defense and Space Group cautioned that some of the results "may be scaring a lot of people from designing with composites" since those specimens that were protected did well. (He also called Tennyson's outgassing results most useful.) George analyzed the cover of a module on the D9 tray; it was made of T300/934 graphite/epoxy unidirectional prepreg tape in a multi-oriented layup. Three of four quadrants had thermal control coatings; the fourth was bare. George noted that composite fibers can help shield the matrix from UV exposure, as does ash from AO. He also cautioned that designers facing AO exposure "cannot take a knockdown based on thickness" of the material because bending modes may be adversely effected. White coatings (such as A-276 paint) protected some structures through heating variations caused by thickness. But, "once you damage it [with an impact], you'll keep on damaging it." Less than 1% of the panel was damaged by major impacts, though.

LDEF Data bases

The wealth of information from LDEF is being entered into several date bases so they can be accessed by a wide range of potential users. Three data bases were discussed at the LDEF conference. Only the first data base is represented by a proceedings paper. The second was added on the day of the conference, and the third was an exhibitor.

- J. Strickland (C1.5) of BAMSI Inc., said the LDEF materials data base on the Materials and Processes Technical Information System (MAPTIS), at MSFC, was introduced at the Second LDEF Post-Retrieval Symposium. Several changes have since been incorporated at user requests. MAPTIS is a retrieval system rather than a data manipulation system. Users can search by a wide array of features such as specific or general properties, materials types, sample location on LDEF, type of use, exposure, etc. BAMSI Inc., 150 West Park Loop, Suite 107, Huntsville, AL 35806 (☎205-544-7375; fax, -7372).
- Boeing Defense and Space Group has developed a data base on FileMaker Pro to capture information on specific areas including Ag/FEP materials, treated aluminum, thermal control panels, the LDEF environment, composites, metals, and contamination. Because of concerns that the space environmental effects community is working "in splendid isolation," Boeing's Gary Pippin said copies are available if you send a blank 3.5-inch disk. Boeing Defense and Space Group, Seattle, WA 98124-2499. (☎206-773-2846; fax, -4946)
- A materials data base that can be manipulated is available through the M/VISION materials system builder, according PDA Engineering, the manufacturer. M/VISION is a hybrid hierarchical/relational data base for examining trends in the data. It has imaging and graphics capabilities and supports engineering spreadsheets. It also offers SQL interfaces for experienced users. Contact PDA at 2975 Redhill Avenue, Costa Mesa, CA 92626 (☎714-540-8900).

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Speakers

C1.1 *Space Environmental Effects on Composite Structures.* Dr. Rod Tennyson, University of Toronto, Institute for Aerospace Studies, 4925 Dufferin Street, Downsview, Ontario, Canada, M3H 5T6 (416-667-7710, 416-667-7799)

C1.2 *Impact of LDEF Results on Space Application of Metal Matrix Composites.* Dr. Gary Steckel, The Aerospace Corporation, P. O. Box 92957, MS: M2/242, Los Angeles, CA, 90009 (310-336-7116, 301-336-5846)

C1.3 *Low Earth Orbit Effects on Organic Composite Materials Flown on LDEF.* Pete George, Boeing Defense and Space Group, P. O. Box 3999, M/S 73-09, Seattle, WA, 98124-2499 (206-234-2679, 206-237-2525)

C1.4 *Summary of Materials and Hardware Performance on LDEF.* Harry Dursch, Boeing Defense and Space Group, P. O. Box 3999, M/S 82-32, Seattle, WA, 98124-2499, 206-773-0527 (206-773-4946)

C1.5 *The LDEF Materials Data Base on the Materials and Processes Technical Information System.* John Strickland, BAMSI, Inc., 150 West Park Loop, Suite 107, Huntsville, AL, 35806 (205-544-7375, 205-554-7372)

Harry Dursch (C1.4), who works with George at Boeing, said that LDEF's reusable aluminum structure endured its journey in good shape. In summary, no anomalies or shortfalls were found that might limit LEO missions, but some areas for hardware protection were highlighted. Fewer than 45 of the 3,000 fasteners had relaxed. They were torqued to 72 inch-pounds on installation; an average of 72 in-lbs was needed to unseat them. No evidence of cold-welding was found, although extensive galling was found on fasteners where lubricant had been removed preflight.

Most lubricants fared poorly either due to evaporation in a vacuum or AO erosion: molybdenum sulfide(MoS_2) was lost to UV, and the phenolic binder in Everlube 620 failed.Adhesives had lap shear increases due to the extended cure in space. Only one of LDEF's experiment mechanisms failed. Shielded seals survived. Tape recorders worked well, but volatile memory devices failed. Solar cells took a battering from impacts; old cells with copper substrates were the most robust, while lightweight, flexible arrays need more work to be as durable. Electrical systems worked, but relays continue to be a challenge. Fiber optics survived except where they were hit by debris.

(The LDEF Materials Data Base, presented as a part of this session, is discussed on page 18.)

C2
Advanced approaches to spacecraft materials issues

Several ground-based simulation techniques are being applied to LDEF results.

While AO erosion rates are not yet established, opportunities still exist to set materials selection guidelines for composites, said Bor Z. Jang of Auburn University's Materials Engineering Department. Jang, speaking from a self-proclaimed outsider's perspective, discussed approaches to evaluating space effects on composites (C2.2) which have been tested only in limited size and quantity to date. "Even though only a few materials have been tested, you can see significant changes in properties," he said, "But results are qualitative. We need more [data] to quantify them." Differences between tough and brittle materials need to be quantified. The effects of moisture, differences in impacts on composites vs. homogeneous materials, thermoset material cure rates, and the differences in tension and compression mechanics within composites also must be better understood.

A sophisticated simulation facility at Los Alamos National Laboratory in New Mexico can provide a number of diagnostic capabilities at once, said Jon Cross (C2.3) of Los Alamos National Laboratory. Tests have yielded results similar to those of LDEF, but more work is needed to develop accelerated tests that will yield valid results. The Los Alamos facility can observe gas phase and surface phase reaction products *in situ* during AO/VUV/electron exposure, and can measure angular and recoil velocity distributions of reactants and products scattering from a material surface. Most of the LDEF-related work at Los Alamos has focused on FEP Teflon materials. Exposure to radiation and (separately) to energetic argon yielded CF_4, CF_3, and C_2F_4. Cross is also using a chopper in an attempt to understand what is an immediate by-product of exposure what results from metastable compounds forming and decaying fractions of a second later. He said that the time histories of the products are complicated and that it appears that some products are diffusing from the bulk of the material to replace losses at the surface.

The first major exposure experiment after the return of LDEF was the Energetic Oxygen Interaction with Materials—Third Phase (EOIM-III) flown on the STS-46 shuttle mission (C2.4). Lubert Leger of Johnson Space Center said the specimens were returned just two months before the conference and "the computers are still chewing on the data." EOIM-III included a number of samples provided by NASA, ESA, Canada, and Japan and mounted on a carousel to expose them at different intervals, plus a mass spectrometer and a quartz crystal microbalance to measure ambient conditions. Some 42 hours of exposure data were collected as the shuttle flew at about 230 km with the payload bay facing in the ram direction. About 48,000 spectra were taken by the mass spectrometer at that altitude and at two higher altitudes.

Leger said measuring the composition of the ambient atmosphere is a challenge because the AO constituents themselves react with the interior of the mass spectrometer. The instrument is now being recalibrated to improve confidence in its readings which included CO_2, N_2, O_2, H_2O, shuttle engine exhaust products, and FEP Teflon reaction products.

Even as LDEF contamination sources are being identified, possible methods to clean the contaminants *in situ* are being investigated. Steve Hotaling of the U.S. Air Force's Rome Laboratory at Griffiths Air Force Base, N.Y., (C2.5), described the use of CO_2 snow jets and aerogel collectors to clean optical windows and mirrors. Hotaling said that samples from the D3 and D9 trays were selected for cleaning. These had Deluron, nylon and Chemglaze siloxane contaminants, plus a wide distribution of fibrous and other particles, including "jellyfish particles"—unspent microdroplets of hydrazine fuel. Such coatings can be disastrous to telescopes and other optical devices, and cleaning can be difficult. Hotaling and others have demonstrated a CO_2 snow jet to bump the particles off an optical substrate; the CO_2 then sublimes without affecting the substrate's optical qualities. "We have had good success on a

Chairs

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Dr. Richard, Sudduth, Boeing Defense and Space Group, P. O. Box 240002, Mail Stop: JR36, Huntsville, AL, 35824 (205-461-5787, 205-461-5600)

Speakers

C2.1 *Programmatic Effects of LDEF REsults.* Safety and Mission Quality Manager, NASA-QP, Washington, DC 20546 (202-453-1877)

C2.2 *Space Environmental Effects on Composites.* Dr. Bor Jang, Auburn University, Materials Engineering Program, 201 Ross Hall, Auburn, AL, 36849 (205-844-3324, 205-844-3307)

C2.3 *Ground-Based Simulations of LEO Environment: Investigations of Select LDEF Materials—FEP Teflon.* Dr. Jon B. Cross, Los Alamos National Laboratory, Chemical & Laser Sciences Division, CLS-2, M/S J565, Los Alamos, NM, 87544 (505-667-0511, 505-665-4631)

C2.4 *Overview of Evaluation of Oxygen Interaction with Materials—Third Phase (EOIM-III) Experiment: Space Shuttle Mission 46.* Dr. Lubert Leger, NASA/Johnson Space Center, Materials Branch, Mail Code ES-511, Houston, TX, 77058 (713-483-8916, 713-483-2162)

C2.5 *Analysis of Leading Edge and Trailing Edge Optical Samples Before and After Treatment with Advanced Contamination Removal Techniques.* Steven P. Hotaling, U.S.A.F. Rome Laboratory, Surveillance & Photonics Directorate, Griffiths AFB, NY, 13441-5700 (315-330-2147, 315-330-7901)

C2.6 *Space Simulation: Contamination in Ashers.* Ron Synowicki, University of Nebraska—Lincoln, Center for Microelectronic & Optical Materials Research, 209N Walter Scott Engineering Ctr, Lincoln, NE, 68588 (402-472-1975, 402-472-7987)

LDEF-2?

An important result from LDEF is a better understanding of what questions must be addressed to fully understand the effects of the space environment on materials. Several materials samples have been or will be flown on the Space Shuttle during the 1990s, but durations longer than Shuttle missions—and active, monitored experiments—are needed. Simply reflying LDEF is not enough to answer the present challenge, especially given the shuttle's crowded manifest.

Marshall's Program Development Office has formed an LDEF-2 study team, headed by Vernon Keller (Pl.7), to find a way around the problem. Keller said the design guidelines include a 4.4m diameter and length less than 4.5m, and a launch mass of 6,000 kg (of which half would be structure and spacecraft), less than a third that of LDEF-1. These criteria were selected to use the same moments of inertia as LDEF-1.

The design which has evolved has a core with two end sections that rotate on hinges to form a 13m-long satellite. Keller said the design offers more ram and lee area than LDEF-1 but at less weight. LDEF-2 would carry 3,000 kg of instruments in 40 or so trays. Power options are being examined with a goal of supplying 50 to 60 watts to the experiments. Because the Tracking and Data Relay Satellite System is an expensive resource, telemetry would be sent direct to a ground station when in sight. Passes would average 5.2 minutes each, yielding 300 kilobits of data per day (equivalent to a 9600-baud line).

"This would be an ideal mission of opportunity if we keep it simple," Keller said, and could be done in four years.

However, the program remains a study project for the near future.

"It needs the enthusiastic support of the science community," he continued, "and it needs the financial support of NASA."

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number of mirror types in returning them to pristine condition," he said. Electron and neutral or ionized oxygen beams can be used to clean molecular contamination. A challenge that remains is to make sure that the removed materials do not redeposit or recondense nearby. Hotaling said the laboratory has invented an aerogel collector that traps particles and retains them even when vibrated or heated to 200 to 350°C. Aerogels are low-density foams with densities approaching that of ambient air and bubbles only 100 nm wide. Hotaling said the laboratory is hoping that a flight version of the CO_2 snowjet might be used on LDEF-2 to clean quartz crystal microbalances when they become saturated.

A challenge to ground tests is the problem of contamination from the simulator. Ron Synowcki of the University of Nebraska described such a problem in using asher cans, a device normally used to photoetch thin films in electronics manufacture (C2.6). For that purpose, he said, the contamination is low enough, but for space studies it is quite high. For space simulations "it is cheap and easy," but siloxanes were being deposited at the rate of 160 Å/hour. After varying his apparatus, he determined that the Viton seals on the asher can were the source of the siloxane, and he reduced the deposition rate to 3 Å/hour by using a flat urethane seal with Vaseline as a sacrificial barrier.

Poster Presentations

Po.1 *Preliminary Results from the EOIM-3 and CONCAP-2 Experiments on STS-46.* Dr. John Gregory, The University of Alabama in Huntsville, Chemistry Department, MSB 111, Huntsville, AL, 35899-2900 (205-895-6028, 205-895-6349)

Po.2 *The Reaction of Silver with Atomic Oxygen.* Dr. Mohan K. Bhan, The University of Alabama in Huntsville, Chemistry Department, MSB 111, Huntsville, AL, 35899 (205-895-6881, 205-895-6349)

Po.3 *Effects of Orbital Exposure on RTV During the LDEF Mission.* Dr. William E. Brower, Jr., Marquette University, Department of Mechanical & Industrial Engineering, 1515 West Wisconsin Avenue, Milwaukee, WI, 53233 (414-288-7081, 414-288-7082)

Po.3 *Effects of Translational Energy on Atomic Oxygen Erosion Yields.* Robert Krech, Physical Sciences, Inc., 20 New England Business Center, Andover, MA, 1810 (508-689-0003, 508-689-3232)

Po.4 *An Active Materials Probe.* Scott Spearing, Ken Lienemann, Teledyne Brown Engineering, Cummings Research Park, Huntsville, AL 35807 (205-726-6149 or 6146)

Po.5 *Oxygen Atom Dosimetry on Spacecraft: An Affordable Approach.* Dr. John Gregory, The University of Alabama in Huntsville, Chemistry Department, MSB 111, Huntsville, AL, 35899-2900 (205-895-6028, 205-895-6349)

Po.6 *Preliminary Results from the EOIM-3 and CONCAP-2 Experiments on STS-46.* Dr. Ganesh Reiker, The University of Alabama in Huntsville, Chemistry Department, MSB-103, Huntsville, AL, 35899 (205-895-6076, 205-895-6349)

Po.7 *Characterization of Polymer Decomposition Products by Laser Desorption Mass Spectrometry.* Dr. Joan Pallix, NASA/Ames Research Center, Mail Stop 234-1, Moffett Field, CA, 94035-1000 (415-604-0332, 415-604-0487)

Po.8 *Solar Absorptance and Thermal Emittance Data on Selected LDEF Materials.* Michael T. Beecroft, Surface Optics Corporation, 9929 Hibert Street—Suite #C, P. O. Box 261602, San Diego, CA (92131, 619-578-8910, 619-578-0484)

Po.9 *Vacuum Deposited Thermal Control Coatings for Space Applications.* Donald Fisher, Surface Optics Corporation, 9929 Hibert Street—Suite #C, P. O. Box 261602, San Diego, CA, 92131 (619-578-8910, 619-578-0484)

Po.9 *Atomic Oxygen Profilar in LEO Simulator and In Space.* William Morrow, Resonance Ltd., 171 Dufferin Street South, Unit #7, Allison, Ontario, Canada, LOM 1AO (705-435-2577, 705-435-2585)

Po.10 *Initial Results from the EOIM-3 Experiment.* Roger Linton, MSFC, Space Environmental Effects Branch, EH12, Huntsville, AL, 35812 (205-544-2526, 205-544-0212)

Po.11 *Photo Thermal Scanning of Atomic Oxygen Damaged Samples.* Dr. Aled W. Williams, University of Wales, Department of Physics, Singleton Park—Swansea, Wales, U.K., SA2 8PP (44-0792-205678, 44-0792-295324)

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Editor's note: At the time of this conference the U.S./international space station was called *Freedom*. During production of these proceedings it was changed to *Alpha* as the program went through major revisions. For convenience, we have changed the name to *Alpha*.

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13. ABSTRACT *(Maximum 200 words)*

To address the challenges of space environmental effects, NASA designed the Long Duration Exposure Facility (LDEF) for an 18-month mission to expose thousands of samples of candidate materials that might be used on a space station or other orbital spacecraft. LDEF was launched in April 1984 and was to have been returned to Earth in 1985. Changes in mission schedules postponed retrieval until January 1990, after 69 months in orbit.

Analyses of the samples recovered from LDEF have provided spacecraft designers and managers with the most extensive data base on space materials phenomena. Many LDEF samples were greatly changed by extended space exposure. Among even the most radially altered samples, NASA and its science teams are finding a wealth of surprising conclusions and tantalizing clues about the effects of space on materials. Many were discussed at the first two LDEF results conferences and subsequent professional papers. The LDEF Materials Results for Spacecraft Applications Conference was convened in Huntsville to discuss implications for spacecraft design. Already, paint and thermal blanket selections for space station and other spacecraft have been affected by LDEF data. This volume synopsizes those results.

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