WHAT LDEF MEANS FOR DEVELOPMENT AND TESTING OF MATERIALS

Ann F. Whitaker
NASA/Marshall Space Flight Center
Marshall Space Flight Center, AL 35812
Phone: (205) 544-2510, Fax: (205) 544-5786

Wayne K. Stuckey
The Aerospace Corporation
El Segundo, CA 90009-2957
Phone: (310) 336-7389, Fax: (310) 336-5846

Bland A. Stein
NASA/Langley Research Center
Hampton, VA 23665-5225
Phone: (804) 864-3499, Fax: (804) 864-7729

INTRODUCTION

The Long Duration Exposure Facility (LDEF) served as the ultimate laboratory to provide combined space environmental effects on materials. The LDEF structure and its 57 experiments contained an estimated 12,000 to 14,000 specimens of materials and materials processes. It not only provided information about the resistance of these materials to the space environment but gives us direction into future needs for spacecraft materials development and testing. This paper provides an overview of the materials effects observed on the satellite and suggests recommendations for the future work in space-qualified materials development and space environmental simulation.

A number of observations regarding space environmental effects was made for the first time from LDEF. The overall environmental response of the spacecraft and evaluations of materials at various experiment locations provided some insights into the relationship of spacecraft orientation and consequent environmental exposure. The contamination deposits on LDEF served to verify the pressure buildup from the return flux on the leading surfaces of the spacecraft and the resulting flow from the leading surface through 90°. New exposure phenomena and new synergistic effects in materials were noted; in some materials which were exposed to all environments, one dominant environmental effect determined the resultant material properties. Numerous micrometeoroid and small space debris "peppered" the spacecraft, creating some surface degradation. Complex contamination phenomena involving multiple environmental interactions were present. Surprisingly good performance was noted in a few space environmentally resistant materials and devices.

Space environments to which LDEF materials were exposed are shown in Table 1. The pressure level which was estimated would be expected to vary from the leading surface to the trailing surface. Material effects found on LDEF may have been influenced by the sequence of individual environmental exposures. LDEF was placed on orbit during a solar minimum, so that more space debris/micrometeoroid impacts would have occurred during that time and less atomic oxygen (AO) would have been present. During the last 10 percent of the mission, the spacecraft saw a higher flux of AO. Even though materials experience many thermal cycles, the temperature extremes would tend to be peculiar to materials, their optical properties, and their mounting configuration. From the standpoint of being a

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verifying spacecraft for contamination effects, molecular contamination appeared to have four major sources: uncontrolled components on individual experiments, bicycle reflectors on both ends of the spacecraft, electrical connectors, and the unbaked black urethane paint on the structure interior. In the absence of moderate levels of AO on the trailing surfaces, darkening of material from ultraviolet (UV) irradiation was prominent. While we characteristically think of LDEF as addressing issues related only to the low-Earth orbit (LEO) environment, the trailing surfaces of the spacecraft to a large extent, except for e^-, p^+ radiation levels, are relevant to what occurs to materials exposed to the geosynchronous-Earth orbit (GEO) environment.

Table 1. LDEF environments.

High Vacuum	10^{-6} to 10^{-7} torr (estimated) on leading edge; $<<10^{-6}$ torr trailing edge
UV Radiation	<2,000 ESH Earth end to ~15,000 ESH space end
Proton Fluence	10^9 p^+/cm^2 (0.5 to 200 MeV)
Electron Fluence	10^{12} to 10^8 e^-/cm^2 (0.5 to 3.0 MeV)
AO	9×10^{21} atoms/cm^2 on forward surface with less exposure through 90°; $<10^{17}$ atoms/cm^2 on trailing surfaces
Micrometeoroid/ Space Debris	~34,000 impacts > 0.1 mm, impact density varying over spacecraft
Thermal Cycles	~32,000 cycles, temperature extremes peculiar to material, mounting configuration

LDEF made significant contributions to the understanding of spacecraft durability issues. It renewed the emphasis for thermal vacuum bakeout of materials and components by identifying major sources of contaminants and their resulting effects on the spacecraft. Space exposure of a large number of engineering and model materials allowed for comparative grading of the materials durability. LDEF further sensitized us to spacecraft orientation in the relative partitioning of environmental effects. The approximate 6 years of exposure effects have assisted in identifying the combination of space environments for testing and the sequencing of individual environments in the testing of materials. As such, it confirms and identifies approaches to ground-based testing.

SIGNIFICANT LDEF FINDINGS

Several groupings of materials and components showed reasonable resistance to the space environment. Table 2 gives a qualitative description of how they fared in the LDEF environment. Ceramic-based materials and the fully oxidized glassy ceramic coatings demonstrated good stability. No radiation degradation was observed in solar cell covers probably because LDEF surface temperature of glasses would have annealed out any radiation-induced darkening. The structural metals, aluminum and steel, had no problems, but oxidation was noted in copper and silver, as anticipated. Silicone overcoats appeared to provide AO protection for ductile material, but additional testing is required to sort out subtle issues which could have consequences for durability longer than the 5.8 years of LDEF.

Table 2. Important LDEF materials findings.

- Materials and Components Durable Under Long Space Exposure
  - Ceramic coatings on rigid substrates—good stability
  - Solar cells/cover slips—limited degradation
  - Structural metals—no problems
  - Silicone overcoats on ductile materials—good AO protection although some cracking occurred
  - Acrylic and silicone adhesives—performed well
  - Fully oxidized glassy ceramic coatings—best protection for mirrors/reflectors
  - Beta cloth—limited degradation

- Materials and Components Requiring Modifications to Increase Space Durability Long Term
  - Beta cloth thermal blankets—replace threading/extend Beta cloth over Velcro™ fastening
  - Solar cells—cover slip to mask N wraparound/utilize fully oxidized AR coatings
  - Carbon fiber composites—require metallized/other tape coating

Silicone and acrylic adhesives functioned well. They underwent some aging evidenced by increased bond strength, but their companion control specimens in the laboratory also aged. Degradation of Beta cloth-covered multilayer insulation (MLI) was limited to some erosion of the TFE Teflon™, thread, and Velcro™. With a changeout of the thread to another AO resistive type and overlap protection of the Velcro™ by the Beta cloth, this MLI configuration should be durable for long exposures in the space environment. The maintenance of nominal optical properties requires that any silicones incorporated in the manufacture of the Beta cloth be restricted. Carbon fiber composites, particularly if they are thin, require some protection from AO. The protection chosen must be coupled with required optical properties. The incorporation of wraparound contacts and the selection of an environmentally resistant antireflection (AR) coating for the cover slide should yield durable solar cells. Even though fluorine is lost from magnesium fluoride in the space environment, principally to AO, it may still retain sufficient fluorine to be an acceptable AR coating for periods longer than LDEF's 6 years. Additional testing is required for this assessment.

DEVELOPMENT OF MATERIALS

Two general categories of materials and materials components come readily to mind when we consider development needs in materials for external spacecraft applications. Coatings and special function materials comprise the majority of these materials. New coatings are needed for AO protection of high reflectivity mirrors, as antireflective coatings, as paints in passive thermal control systems, and as high optical absorptivity telescope baffle materials.

Special function materials comprise a gamut of applications—space debris protection systems, tether composites, flexible booms, and nonoptically transmissive tapes. Lubricants form a special class of materials where existing dry films, fluids, and self-lubricating composites have space durability limits. In many instances, we can design around lubricant properties in thin film usage but not in all cases. Where a thin lubricating material is continually sheared during usage, it cannot afford additionally to lose mass in an AO environment.

LDEF CONTRIBUTIONS TO GROUND-BASED TESTING

While LDEF's principal contribution to the materials discipline has been the extensive and diverse materials exposure data, it has, further, contributed significantly to our approach to ground-based space environmental simulation. Table 3 describes the present approach to combined environments testing and the LDEF factors that contribute to update this approach.

Table 3. LDEF contributions to combined environments ground testing.

Present Approach To Ground-Based Combined Environments Testing	LDEF Contributed Testing Factors
• Generally, two parameters plus vacuum with configured materials	• Ground testing comparisons to LDEF results indicate qualitative damage can be reproduced in materials
• Sequential Environments Exposures – e.g., thermal vacuum cycling follows irradiation	• New synergistic effects • Fixing of contaminants by UV irradiation and/or AO
• Irradiation conducted as a series of parametric exposures at high intensities – Nonlinear response must be considered for accelerated exposures	• Many materials specific results – e.g., densification of glass ceramics – e.g., optically transmissive materials yield complex response
• Combining AO with UV irradiation and the sequencing/relative magnitudes of either yield different results	• All environmental parameters contributed to degradation – Dominant effect peculiar to material
• Space debris alone simulated to ~8 km/s	• Small particle/multiple velocity impacts of micrometeoroid/space debris must be considered; AO effects on impact areas

Historically, in our approach to combined environments testing, we utilize two parameters in a vacuum environment. We may also impose thermal cycle on our materials and/or either tension or compression on the test samples. In many cases, we tend to sequentially expose materials. For example, we thermal cycle materials after we irradiate with electrons or protons. Some testing, such as ground-based irradiation, is an accelerated process and, therefore, requires parametric exposures and data extrapolation.

We have noted more recently from LDEF and subsequent ground testing that when we combine AO and UV irradiation, the resulting properties obtained for the materials are dependent on the magnitude of the exposure parameters and also their sequencing. LDEF indicates to us that we can qualitatively reproduce the same kinds of damages with our laboratory test systems. We have observed new synergistic effects and phenomena not observed prior to LDEF such as the densification of ionic bonded materials. This densification effect can be severe when the material of concern is a 300 to 400 Å optical coating. Where greater thicknesses of these materials are utilized, some change in optical properties will be observed. In addition, we see complex phenomena in optically transmissive materials. Other issues that must be dealt with are the multitude of small particle impacts and their separate effects on ductile and brittle materials. Combined environments testing must be tailored to materials and specific orbital environments, a fact which is well known and has been reinforced by LDEF. This is the major reason that there are no general detailed specifications related to the testing of materials in this area. LDEF promotes the notion that we must pay more attention to sequencing of environmental exposures since we cannot combine all of them with the relative magnitudes that exist on orbit.

Now let us examine the issues of simulating individual space environments. Vacuum simulation alone is traditionally associated with addressing materials-generated contamination phenomena in the materials discipline. Sufficient specifications exist to address outgassing issues associated with materials, and special instrumentation is available to investigate finer questions. There is some work required based on observed LDEF contamination levels and locations that involves updating current predictive models for spacecraft contamination assessment. Pressure buildup on leading surfaces, gaseous flow around the spacecraft, distribution of molecular and particulate contaminants, and local source behavior contributions from LDEF should yield significant inputs to update these existing contamination models.

Particle impacts on materials from space debris, AO, electrons, and protons require their own unique simulations and peculiar protocols for specific materials exposures. Similar considerations are necessary for electromagnetic simulations. Many laboratories use thermal AO for materials evaluations because of availability and for rationale based on peculiar material response in simulation of orbital effects. The ideal AO simulation facility would be a 5 eV, large area exposure source for materials evaluation that can produce moderate and high fluxes. Some adjustments are needed in space debris simulation to account for the multiple velocities of small particles, and to cover evaluations across the gaps in ballistic limit curves. From an optical and mechanical effect on materials standpoint, few contributions were made to charged particle simulations by LDEF. Charged particle simulation is, of course, an accelerated testing parameter. Table 4 provides a summary of these simulation considerations.

Probably the area requiring the most systematic examination is UV irradiation simulation. Sources are limited by wavelength range, reliability, life, and competitive effects induced in materials from the UV and infrared regions. Disagreement of absorptivity changes induced in materials between ground and LDEF results is complicated both by simulation source and synergistic effects with other environmental parameters. Considerable additional research is required in this area. Fluorescence phenomena observed on LDEF may provide a new sensitive technique for surface analyses. Another aspect of LDEF exposure to be noted is that thermally activated and suppressed phenomena in materials were not addressed in the form of controlled thermal experiments.

RECOMMENDATIONS

There are a number of LEO materials durability issues that were not resolved by or were discussed on LDEF which must be considered for future long duration exposures of materials in space. There is a need for active in situ measurement of degradation rates for various materials at selected temperatures. The materials flown on LDEF represent those developed up to and during the 1970's; a new generation of materials and components are available for exposure. Investigation of synergistic effects and the verification of the space debris environment and contamination models should have a high priority. Finally, LDEF has alerted us to degradation mechanisms in materials arising from space exposures that must be understood—surface texturing, temperature dependence, involvement of stress, influence of microstructures, and the role of electrostatic interactions.

Table 4. Environmental simulations considerations for materials.

Single Environment	Present Approach	LDEF Generated Issues
Thermal Vacuum	10^{-5} to 10^{-9} torr; conventional and special tests and sensors for contamination	Pressure buildup on ram surfaces; localized source behavior; gaseous flow promoted distribution of contamination; contamination models update
AO	Thermal AO, small exposure areas for 5 eV at low fluxes	5 eV large area exposure required; long versus short exposures phenomena; competition of effects; synergism with contamination and incorporation of UV
UV Radiation	Sources: mercury xenon principally, hydrogen, krypton, deuterium	Conflict of absorptivity results between ground simulations and LDEF perhaps involving synergism; severity and dominance of effects
Particulate Radiation	e^- and p^+ (a few KeV to 2½ MeV)	Little attention paid to effects although bulk polymers show free radical generation
Micrometeoroid/Space Debris	Space debris velocities to ~8 km/s for particle diameters to 3/8 in	New simulation required for multiple velocities of small particles; brittle versus ductile materials behavior

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