LONG DURATION EXPOSURE FACILITY (LDEF) SPACE ENVIRONMENTS OVERVIEW

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SUMMARY

The LDEF was retrieved from Earth orbit in January 1990 after spending almost 6 years in space. It had flown in a near-circular orbit with an inclination of 28.5 degrees. Initially the orbit altitude was approximately 257 nautical miles; however, when the LDEF was retrieved the orbit altitude had decayed to approximately 179 nautical miles. The LDEF was passively stabilized about three axes while in free flight, making it an ideal platform for exposing experiments which were measuring the environments of near-Earth space and investigating the long-term effects of these environments on spacecraft. This paper presents a brief overview of the encountered environments that were of most interest to the LDEF investigators.

INTRODUCTION

National Aeronautics and Space Administration (NASA), Department of Defense (DOD), and other government agencies need accurate knowledge of the near-Earth space environments and the effects of these environments on spacecraft to efficiently and reliably implement their space programs. Uncertainties, for example, in our current knowledge of the man-made debris, the natural meteoroid, or the radiation environments, and the effects these environments can have on spacecraft may result in the installation of thousands of pounds of unnecessary shielding on spacecraft such as Space Station Freedom. An even more critical concern, however, is the fact that the uncertainties in our current knowledge of these same environments and their effects may also result in the development of spacecraft that will fail to accomplish their mission objectives. This would result in the loss of large national investments.

Accurate knowledge of the space environments is also highly desirable science to better understand the origin and evolution of our universe.

In-space experiments are a necessary part of research programs to define the environments of space, and in many cases are also a necessary part of research programs to define the effects of these environments on spacecraft. For example, the effects of atomic oxygen impingement and effects of hypervelocity meteoroid and debris impacts on spacecraft cannot be very well simulated in the laboratory. The effects of other environments such as reduced gravity and the synergistic effects of all of the environments found in space are impossible to study in the laboratory; they can only be studied with in-space experiments. The LDEF was developed to provide opportunities for these types of needed in-space environment and environmental effects experiments.

The environments that were of most interest to the Principal Investigators of the LDEF experiments were atomic oxygen, ionizing radiation, natural meteoroids, man-made debris, ultraviolet (UV) radiation, vacuum, and the very low gravity. This paper provides a brief overview of these environments as they are defined in pre-LDEF influenced models. The contributions from individual LDEF experiments to our knowledge of these environments, and to our knowledge of the effects of these environments on spacecraft, have been and will continue for some time to be reported by the respective LDEF experiment Principal Investigators in various publications. In a few cases, however, early reported significant contributions from LDEF experiments to the definitions of these environments are noted in this paper.

It is the intent of this paper to provide the reader with an introductory composite picture of the environments of space which the LDEF and the experiments encountered for the prolonged 69 months' stay in orbit.

BACKGROUND

The LDEF was launched into Earth orbit in April 1984 at a time of near-minimum activity in the Sun's 11-year solar cycle, and it was retrieved almost 6 years later in January 1990 at a time of near-maximum solar activity. The variation in the 10.7cm radiation levels over the mission life is shown in figure 1. The widely varying levels of solar activity, which were monitored by the 10.7 cm radiation, by counts of solar flares and Sun spots, and by measurements of the geomagnetic index, had a major effect on the near-Earth space environments encountered by the LDEF and the onboard experiments.

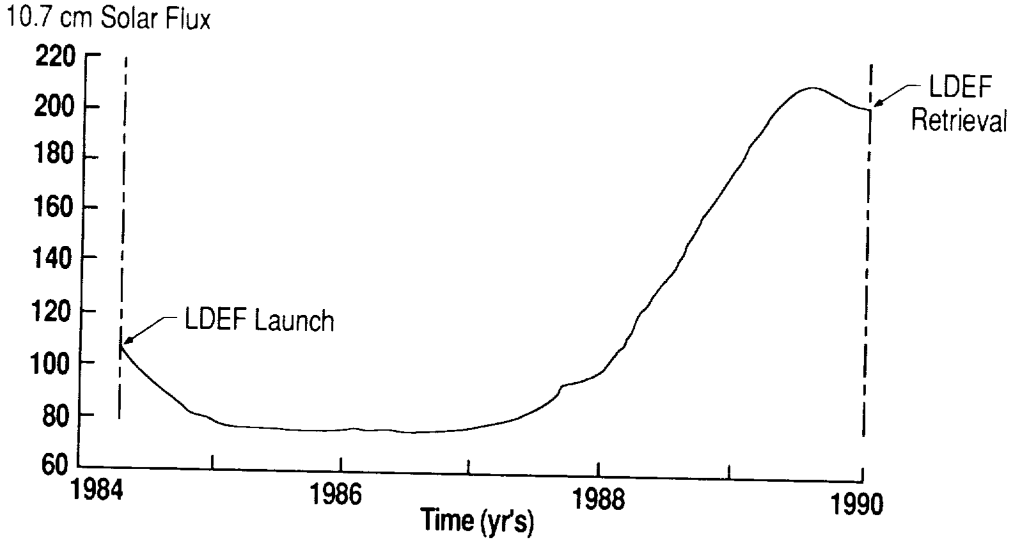

Fig. 1.- Solar activity as indicated by the 10.7 cm flux recorded during the time of the LDEF mission.

During LDEF's stay in space, it flew in a circular orbit having an inclination of 28.5 degrees. The orbit altitude was initially approximately 257 nautical miles. When the LDEF was retrieved, the orbit had decayed to an altitude of approximately 179 nautical miles. The history of the decay of the LDEF orbit altitude is illustrated in figure 2 (ref. 1).

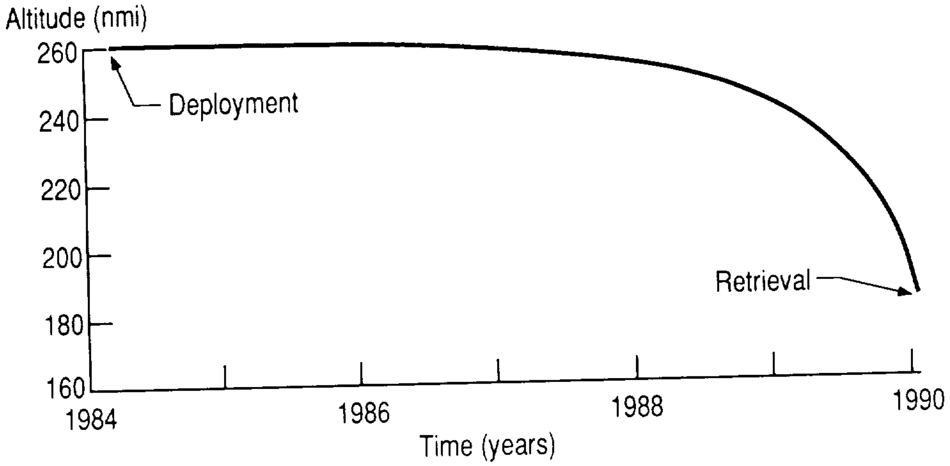

Fig. 2.- LDEF orbit altitude history.

The altitude decay, as can be seen in figure 2, was very slow during the first 4 years of the mission. The intense UV radiation from the Sun which occurred during the very high solar activity in 1989 (see fig.1) greatly expanded the effective atmospheric density at the LDEF orbital altitude, and thus the LDEF orbit was decaying very rapidly by the January 1990 recovery date. In fact, the LDEF would have reentered and been destroyed within another few months (see fig.3). The situation was so critical that some individuals in fact began to play the part of "Chicken Little" and literally cry out, "*The LDEF is falling!*"

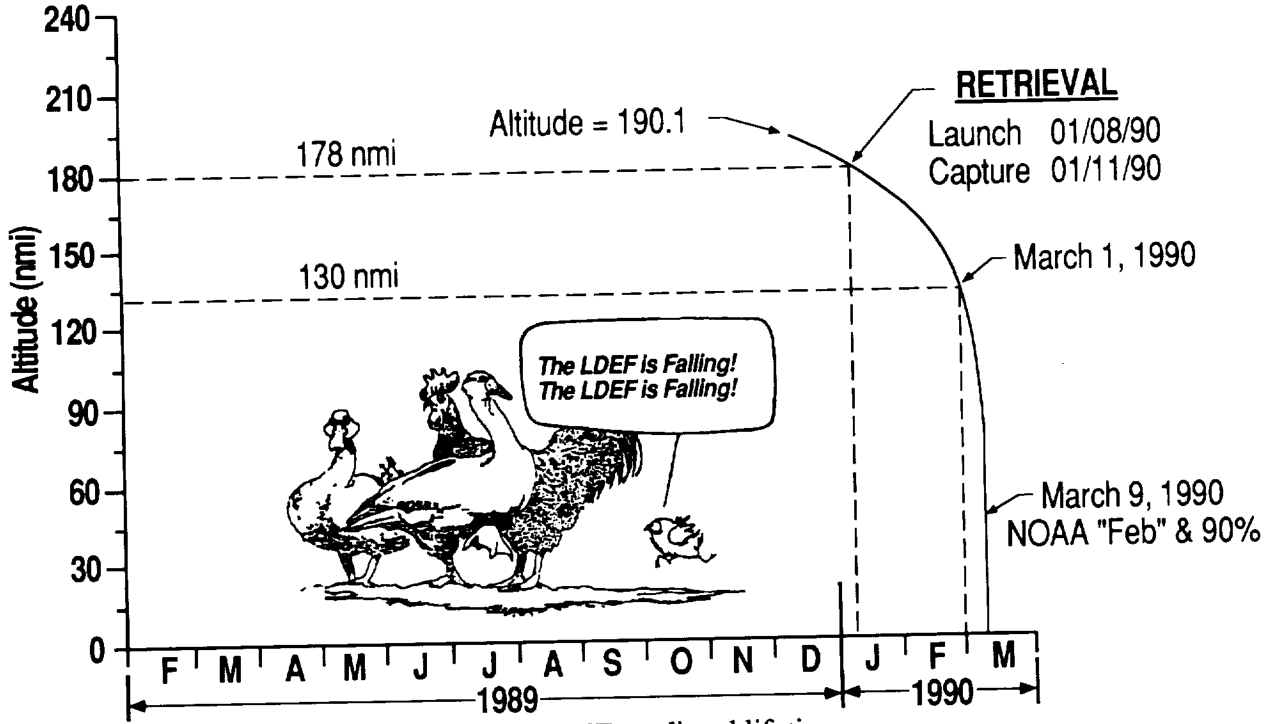

Fig. 3.- The LDEF predicted lifetime.

The orientation and stability of LDEF was such that it had a constant drag coefficient throughout the mission. Because of the constant drag coefficient, the LDEF tracking data obtained by North American Air Defense Command (NORAD) and the measurements of the solar 10.7 cm radiation and magnetic indexes obtained by the National Oceanic and Atmospheric Administration (NOAA) during the LDEF mission can be used to generate a unique set of measurements of the atmospheric density at the LDEF orbital altitude as a function of solar activity from solar minimum to solar maximum. This data set can be used by atmospheric scientists to check the current models of the Earth's upper atmosphere and its response to solar activity and to guide revisions in the models if necessary. Accurate models of the atmospheric densities are critical to the design and operation of large precision-pointing spacecraft such as the Hubble Space Telescope and Space Station Freedom.

The very rapid changes that can occur in the atmospheric density with changes in the solar activity are reflected in the LDEF altitude decay rate curve presented in figure 4 (ref. 2) for a period of rapidly changing solar activity.

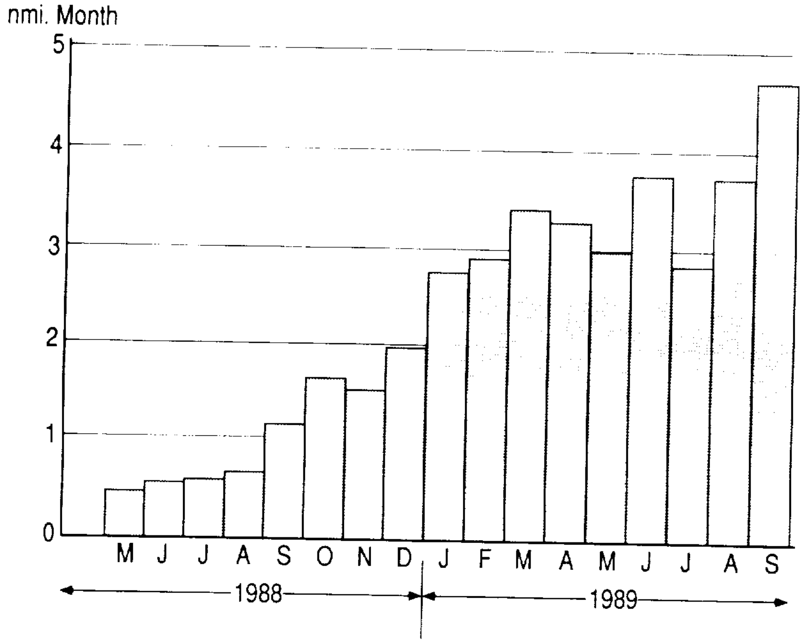

Fig. 4.- The LDEF orbit decay rate as a function of time during a period of rapidly changing solar activity.

The LDEF was passively stabilized about three axes while in free flight. Its orientation, as illustrated in figure 5, remained essentially such that one side always faced east in the direction of travel (velocity vector), one side always faced west in the trailing direction, and two sides were parallel to the velocity vector (one facing north and one facing south). One end of the LDEF always faced essentially toward the center of the Earth and the other end always pointed away from the Earth into deep space. Postflight observations of the LDEF surfaces* have revealed that the facility actually flew with a slight yaw (the most eastward LDEF face was canted 8 degrees toward the north), and the LDEF had a very slight pitch (the space end of the eastward face was also canted forward approximately 2 degrees). The postflight observations have also revealed that the facility, late in the mission, had essentially no oscillations about any of the three axes. The facility may have had some slight slow oscillations for a brief period just after it was deployed.

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* Private communication from Bruce Banks, NASA Lewis Research Center, Cleveland, Ohio.

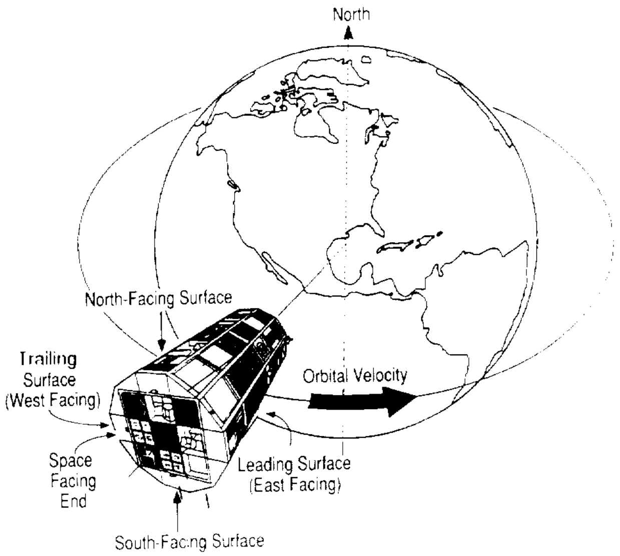


Fig. 5. - LDEF orientation.

Since many effects of the environments of space are orientation or velocity-vector dependent (meteoriod, man-made debris, trapped proton, and atomic oxygen environments for example), the very stable LDEF orientation with respect to the velocity vector was an extremely important LDEF feature.

ATOMIC OXYGEN

Atomic oxygen is the predominant species present at the LDEF orbital altitudes and thus the LDEF drag data can be viewed as an indication of the magnitude of the atomic oxygen fluence the LDEF encountered at any given time. The fluence of atomic oxygen striking a given LDEF surface was a function of the LDEF altitude, the orientation of the surface with respect to the LDEF velocity vector, the solar UV radiation, and the Earth's magnetic index. The 10.7 cm solar flux (fig.1) is used as an indicator of the UV radiation since there are no active satellites capable of monitoring the UV radiation. The UV radiation cannot be monitored from the ground because of atmospheric absorption.

The history of the atomic oxygen flux striking the leading surfaces of the LDEF during the mission is presented in figure 6. This flux history* was calculated using current upper atmospheric models, the history of the tracked LDEF altitude, and the monitored 10.7 cm solar radiation and magnetic indexes. As can be noted, the atomic oxygen flux during the latter months of the mission was almost two orders of magnitude greater than the flux encountered early in the mission.

The thermal velocity of the atomic oxygen in near-Earth space is low compared to the orbital velocity of the LDEF and, for that reason, the atomic oxygen total fluence on the leading surfaces of the LDEF was much greater than that on the trailing surfaces. Figure 7 shows the calculated distribution of the total atomic oxygen fluences on each of the 12 sides of the LDEF.* As can be seen, the fluence on the forward-facing east side is approximately 19 orders of magnitude greater that that on the trailing west. The fluence on the south side is slightly higher than that on the north because of the slight yaw in the LDEF orientation.

*See footnote on previous page.

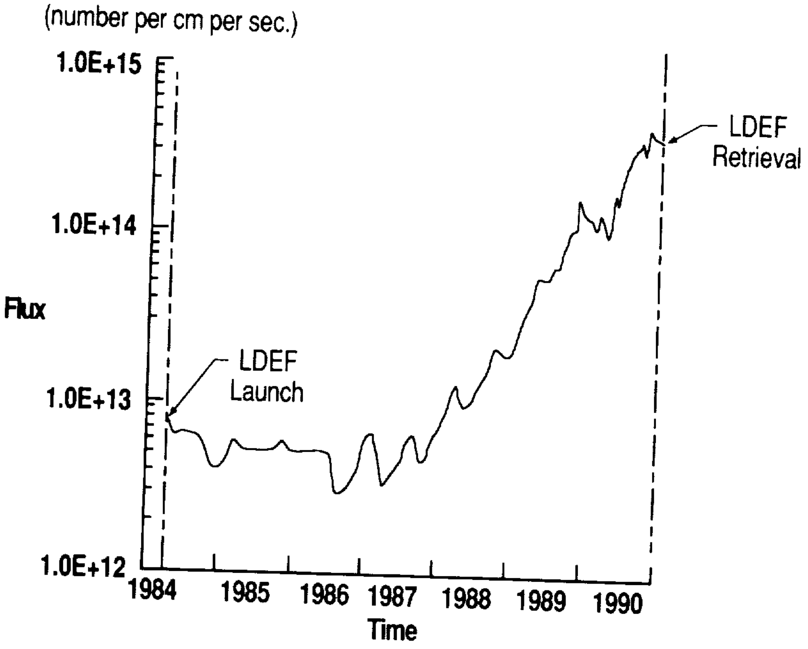


Fig. 6.- History of atomic oxygen fluence on LDEF leading surfaces.

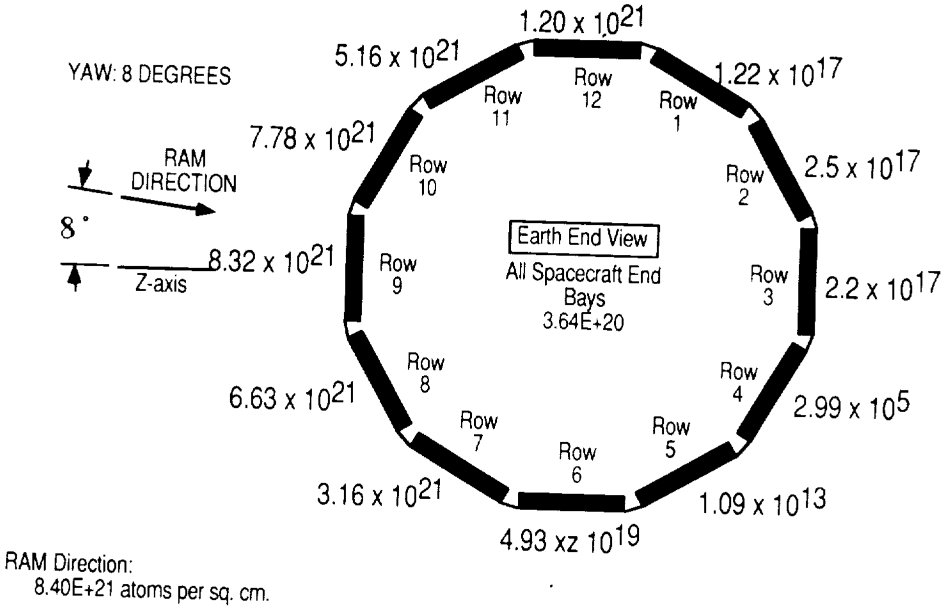


Fig. 7.- Calculated distribution of the total atomic oxygen fluence on each of the LDEF surfaces.

Because the LDEF orbit altitude was well below the Earth's Van Allen radiation belts, except at the small region of the belt that is generally referred to as the South Atlantic Anomaly, the LDEF and the onboard experiments were exposed to only modest levels of ionizing radiation. The penetrating ionizing radiation the LDEF did receive resulted primarily from protons trapped in the South Atlantic Anomaly region of the Van Allen belts and, to a much lesser degree, from galactic cosmic rays. The predicted trapped proton integral fluence for the LDEF is presented in figure 8.

The geomagnetically trapped electrons dominated the LDEF surface absorbed radiation dose. The integral fluence of the trapped electrons on the LDEF is presented in figure 9.

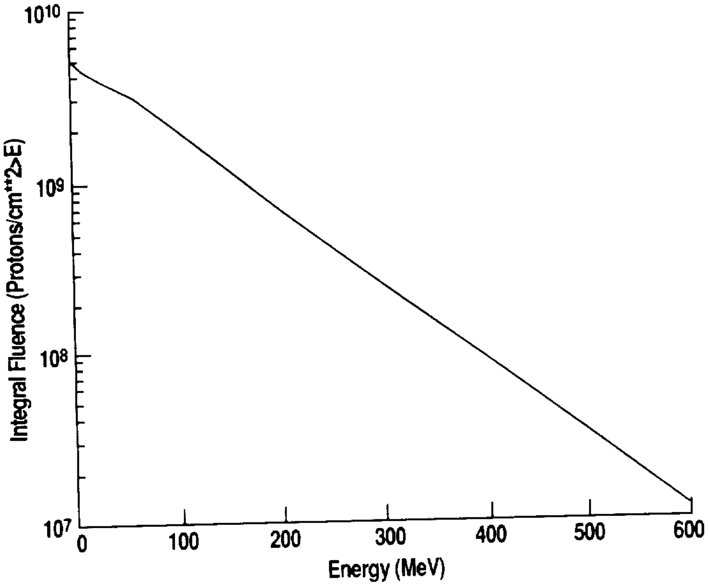


Fig. 8. - Predicted integral fluence of trapped protons striking the LDEF.

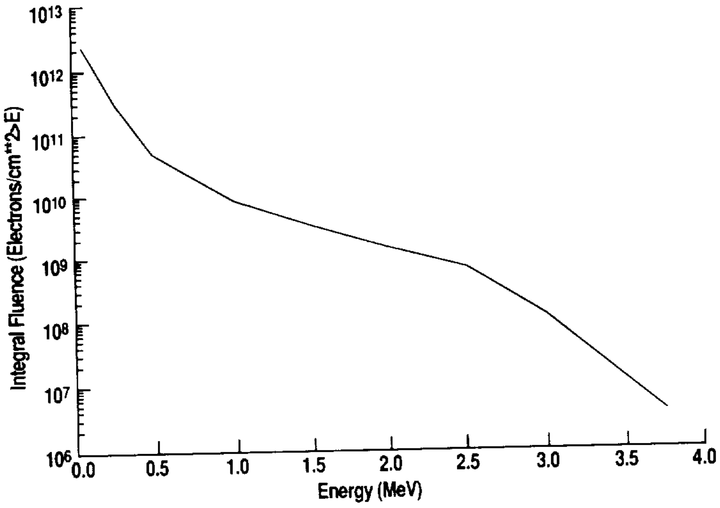


Fig. 9. - Predicted integral fluence of trapped electrons striking LDEF surfaces.

Primary ionizing passive radiation detectors were included in 15 of the LDEF experiments and these detectors along with postretrieval measurements of the induced radiation in LDEF materials have and will continue to provide valuable information for refining the current models of the radiation environment near Earth and the calculations of the ionizing radiation the LDEF actually received. Measurements of the induced radioactivity in selected aluminum experiment tray clamps from the LDEF have, for example, confirmed an anisotropy situation in the trapped protons in the South Atlantic Anomoly. The west-facing LDEF surfaces received a higher trapped proton fluence than did the east-facing surfaces.

NATURAL METEOROIDS AND MAN-MADE DEBRIS

The current models which are most frequently used to predict natural meteoroid and man-made debris impacts on spacecraft are shown in figure 10.

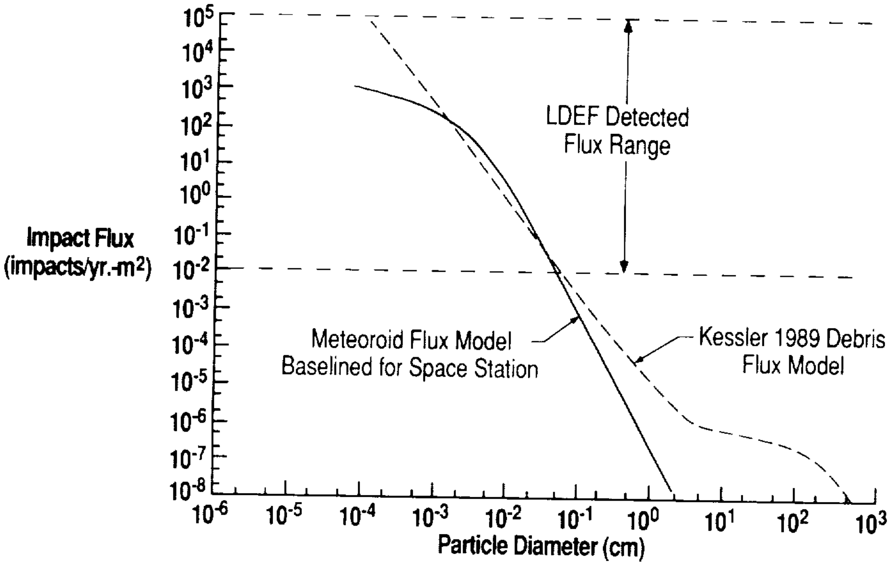


Fig. 10.-The most frequently used models for predicting meteoroid and man-made debris impact fluxes as a function of particle size.

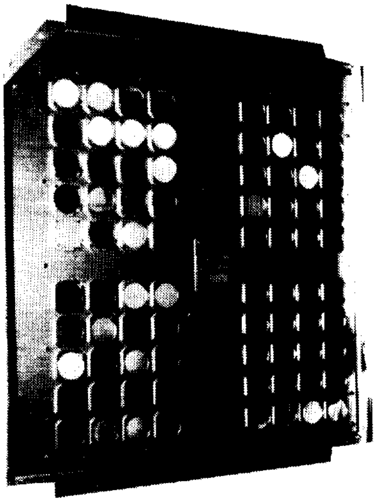
Based on these models the largest man-made debris particles or the largest natural meteoroid particles one should expect to have impacted on the LDEF would be approximately .5 mm in diameter. An impact by a particle of this size is consistent with the size of the largest craters observed on the retrieved LDEF. These models also indicate that in the particle size range from approximately .02mm to .2mm more of the impacting particles would have been natural meteoroids rather than man-made debris. In the size range less than .02mm in diameter, the models indicate that man-made debris particles should have dominated the impacts.

The man-made debris model includes an assumption that the small debris particles are in orbits similar to the orbits observed for the large trackable Earth orbiting debris objects. This assumption means that debris particles would have impacted primarily on the leading surfaces of the LDEF and that no debris impacts should be expected on the trailing LDEF surfaces (craters with man-made debris residue in them, however, have been found on the trailing LDEF surfaces).

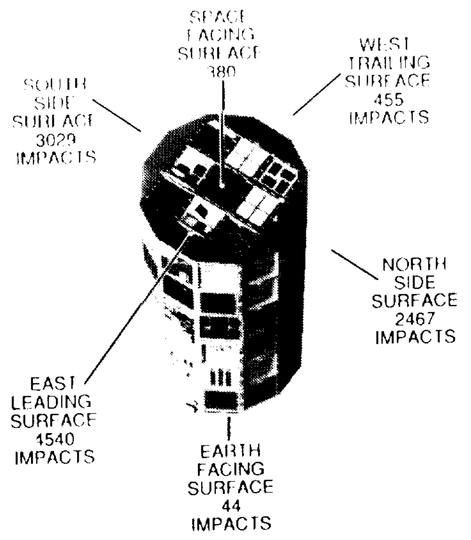
The model for the natural meteoroids assumes that they approach the Earth randomly from all directions with a distribution of velocities that averages about 20 km per sec. This assumption means that the leading surface of the LDEF would also have been impacted more frequently by meteoroids than the trailing LDEF surfaces. The meteoroid models (ref. 3), unlike the debris models, indicate that a substantial number of meteoroid particles will strike the trailing surfaces of the LDEF (this is generally consistent with the distribution of the craters found on the LDEF).

The Interplanetary Dust Experiment which was flown on the LDEF had very sensitive detectors mounted around the LDEF such that they faced east, west, north, south, toward the Earth, and out toward deep space. The impact counts recorded by the more sensitive of the two types of detectors flown in this experiment during the first year in orbit are presented in figure 11.†

• Detector Arrays Mounted on 6 Sides of LDEF



DETECTOR ARRAY MOUNTED ON EARTH SIDE OF LDEF



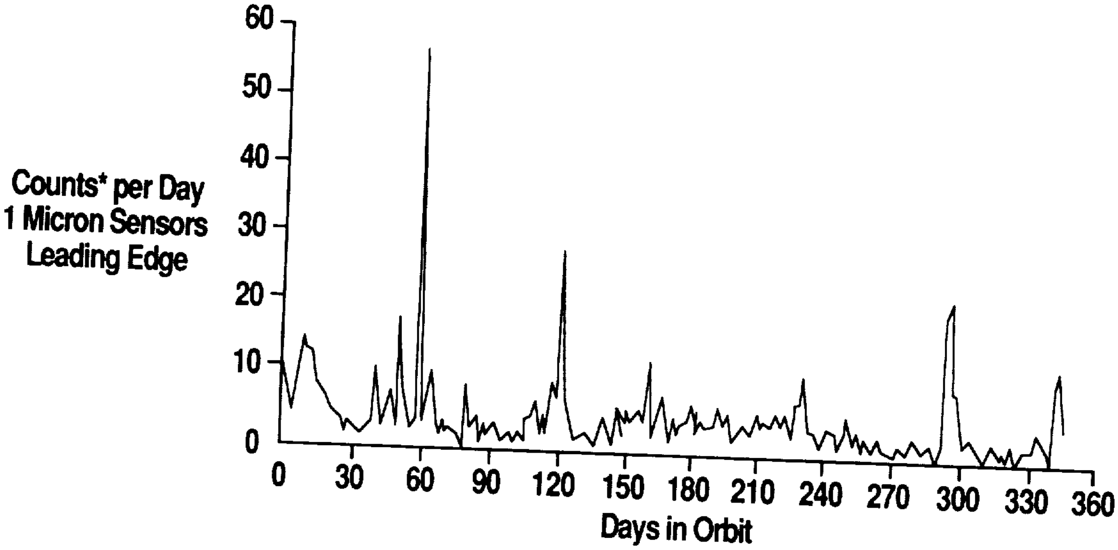
FLUX COUNTS FROM 4,000 ANGSTROM THICK MOS DETECTORS

Fig.- 11. Distribution of impacts counted by LDEF Interplanetary Dust Experiment detectors mounted on the respective sides of the facility.

The Interplanetary Dust Experiment also recorded the precise time each of these impacts occurred as illustrated in figure 12. It can be noted that the events are certainly not random in time.

Measurements of the chemistry of the impactor residue that is present in most of the craters on the LDEF surfaces, which have just begun, will be extremely valuable in separating the man-made debris impacts from the natural meteoroid impacts. This separation will allow the two models (meteoroid and debris) to be evaluated independently. The preliminary indications are that errors exist in both models.

† Private communication from J. Derral Mullholland, Institute for Space Science and Technology, Gainsville, Florida.



* Flight data from the LDEF Interplantary Dust Experiment

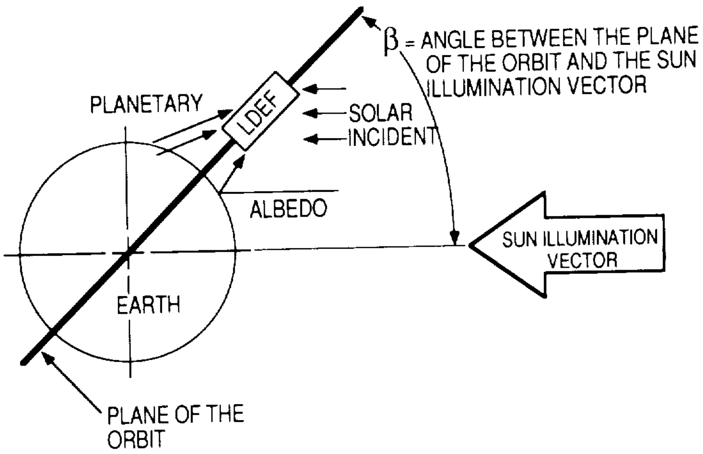
Fig.- 12. Distribution of impacts counted by LDEF Interplanetary Dust Experiment detectors as a function of time during the first year in orbit.

SOLAR FLUX

All of the exterior LDEF surfaces received direct solar illumination for periods of time during the 69-month mission. The cumulative times for the illumination of individual surfaces on the facility varied from 10 percent to 25 percent of the total mission time. The cumulative illumination time per orbit varied as the angle between the Sun's illumination vector and the plane of the LDEF orbit varied. The minimum cumulative illumination occurred when the LDEF orbit plane was in the ecliptic plane, and the maximum occurred when the LDEF orbit plane was at the maximum inclination to the ecliptic (see fig. 13).

VACUUM

Neglecting the contribution from LDEF-generated contamination, the molecular density adjacent to individual LDEF surfaces at any given time was dependent on the LDEF orbital altitude, the solar activity, and the orientation of the surface with respect to the LDEF velocity vector. The density increased as the altitude decreased and as the solar activity increased. The density also built up adjacent to leading surfaces as a result of ram effects, and it diminished adjacent to trailing surfaces as a result of wake shielding effects.



Beta Angle = (β) Angle between the plane of the orbit and the sun illumination vector.
Solar Incident = (BTU/Hr-Ft^2) Heat due to direct illumination from the sun.
Albedo = (BTU/Hr-Ft^2) Heat due to the portion of the solar incident energy reflected from the planet into the LDEF.
Planetary = (BTU/Hr-Ft^2) Heat due to energy emitted from the planet.

Fig.- 13.- Variation of the Sun's illumination vector with the plane of the LDEF orbit.

The ambient molecular density along the LDEF orbit was lowest early in the mission while the LDEF orbital altitude was above 250 nautical miles and the solar activity was near minimum (approximately 1.86×10^7 molecules per cubic centimeter). The predominent molecular species at that time were atomic oxygen (approximately 1.56×10^7 molecules per cubic centimeter), and nitrogen (second in abundance with a density several orders of magnitude lower than the atomic oxygen).

The ambient molecular density along the LDEF orbit was highest (approximately 6.58×10^8 molecules per cubic centimeter) late in the mission when the orbital altitude had decayed to approximately 179 nautical miles and the solar activity had increased to near-record highs. The predominant molecular species at that time was still atomic oxygen (5.42×10^8 molecules per cubic centimeter) and nitrogen was still second in abundance (1.06×10^8 molecules per cubic centimeter).

The ram effects made the molecular density adjacent to surfaces on the leading side of the LDEF approximately an order of magnitude higher than the ambient density. The wake shielding effects reduced the molecular density adjacent to surfaces on the trailing side of the LDEF more than an order of magnitude. The molecular densities presented above were calculated using the model described in Smithsonian Astrophysical Observatory Special Report 375 (ref. 4).

GRAVITY/ACCELERATIONS

The LDEF experiments were exposed to very low accelerations during the mission since the facility was passively stabilized and there were no systems on board to generate vibrations or shocks. The acceleration level at the center of the LDEF remained less than 10^{-7} g's throughout the mission.

CONCLUDING REMARKS

The LDEF flew in an orbit very similar to the orbits planned for many future near-Earth orbiting spacecraft such as the Space Station Freedom and the Earth observation satellites. Therefore the LDEF encountered the same environments as these future spacecraft will encounter, and the data obtained from the LDEF experiments and hardware will be directly applicable to the design of these spacecraft.

As stated in the introduction to this paper, the current uncertainties in a number of the near-Earth environments are a concern in the development of these future spacecraft. With the knowledge gained from analysis of the LDEF data, these current uncertainties can be appreciably reduced. When the LDEF data on the environments of space and the effects of these environments on spacecraft are completely analyzed and placed in accessible data bases, it will be obvious that the LDEF mission has provided "*Product Assurance* " for many of the future space missions.

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