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LEO MICROMETEORITE/DEBRIS IMPACT DAMAGE*

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The school bus sized LDEF (Long Duration Exposure Facility) was retrieved in 1990, after nearly six years of 250 nautical mile altitude LEO (Low Earth Orbit) environmental exposure (Figure 1). The recovery of LDEF experiments has provided extensive information on space interactions, including micrometeorite, debris, atomic oxygen, U.V. and particulate radiation.

JPL provided a test plate as part of SAMPLE (Solar-Array-Materials Passive LDEF Experiment). The test plate contained thirty thin silicon solar cell/cover assemblies. The cover samples included a variety of materials such as Teflon and RTV silicones, in addition to conventional microsheet. This paper discusses the nature of the approximately 150 micrometeorite/debris impacts on the cell/cover samples, cell interconnects and aluminum test plate.

Introduction

The JPL subplate consists of an 11" x 16.3" (28 cm x 41.4 cm) aluminum plate with thirty (30) cell/cover samples. The cells are 50 micron thick 2x2 cm^2 silicon devices fabricated by Solarex Corporation. Silver-plated Invar tabs are welded to the N and P contacts of each cell to facilitate pre and post flight electrical performance measurements. Each cell is bonded to a slightly oversize sheet of Kapton insulation bonded to the aluminum plate. The bonding materials are standard silicone RTVs. A protective cover is attached to the front surface of each cell. These covers consist of a variety of materials, including cerium doped microsheet, teflon film and various silicone-based encapsulants.

The preparation of samples and experiment assembly was performed by the G.E. Company. The LDEF flight provided a means to directly evaluate the behavior of the cover materials in the space environment, including their ability to protect cells from that same environment.

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The planned post flight review at JPL consisted of visual examination, cell electrical performance measurements and data analysis. The detailed visual examination (up to 200X power) has been completed and is discussed in this paper. The electrical performance measurements will be completed before the end of May, 1991.

Observation of the recovered test plate revealed a number of obvious changes (Figure 2). All exposed (uncovered by adhesive or encapsulant) tab surfaces darkened (black and dark blue) from the original shiny silver appearance. In many cases, the darkened silver tab surfaces showed signs of stress by the formation of platelets, much like dried mud in texture. The dark surface material is readily removed by gentle mechanical abrasion revealing a shiny, albeit rough, surface underneath. In some areas, it appeared that the original surface had flaked off. The resultant surface region was slightly lower than the surrounding regions and the color was less dark -- more gray than blue/black -- suggesting less exposure time to the pertinent environment.

As might be expected, the least disturbed cover system was that of the conventional microsheet platelet. Encapsulant behavior varied widely, with some materials appearing to have been essentially removed. In those cases, the cell grid lines darkened, probably through interaction with the space environment. In other cases, although encapsulant materials degraded, becoming embrittled for example, the cell grid lines were still protected sufficiently that they remained shiny. Areas of the aluminum plate appeared stained, most likely due to environmental interactions (atomic oxygen and/or UV) with the residue of materials used in assembly.

Survey of the plate reveals a large number of impact craters, predominantly in the aluminum plate, ranging in size from 0.05 mm (Figure 3) to 1 mm (Figure 4) in diameter. Most impacts appear to be normal to the plate (circular crater), although a small number of elongated craters indicate off normal incidence. The physical appearance of these impacts is discussed in the following section.

Micrometeorite/Debris Impacts

SAMPLE was located in a near ram position (direction of motion) on LDEF. The LDEF investigators have determined that the position was not only subject to a very high number of impacts, but also that the majority were due to manmade debris, such as solid fuel particles, and paint chips, rather than micrometeorites (reference 1). This is due to the fact that debris in the vicinity of LDEF tends to have the same magnitude of orbital velocity. Consequently, impacts from the forward direction will have large velocity differentials and impacts from the wake direction will have small velocity differentials. Ram impacts will then be highly energetic, leaving visible impacts or penetrations. By the same argument, wake impacts are unlikely to leave significant impressions.

Micrometeorites, being of extraterrestrial origin, will approach LDEF with high velocity differentials from many directions due to their high velocities. As a result, they will likely produce a comparable number of visible impacts in the ram and wake direction. Review of the entire LDEF structure has shown a roughly 10 to 1 ratio for ram to wake impacts. For the SAMPLE experiment, these considerations imply that the majority of impacts were of debris origin. Conversely, the majority of impacts on experiments in the wake are most likely due to micrometeorites.

Cratering in the Aluminum Plate

Since the majority of the test plate area consists of the uncovered aluminum mounting plate, the majority of impacts are located in the plate. These are generally similar visually, and typified by the example in Figure 4. The impact has formed a circular crater with a surrounding ridge ejected out from and over the plate surface. The crater bottom is crystalline in appearance, unlike the scratched and machined plate surface, showing evidence of melting and resolidifying. This crater pattern was observed for all sizes from 1mm diameter on down. Of the 157 impacts observed (over the entire test plate/sample surface), seven were 0.5mm or larger. Depth measurements of the seven indicated a crater depth (measured from crater bottom to top of surrounding ridge) ranging from one-half to one-third the crater diameter. Only a few craters were noted with an elliptical shape that might be attributable to an impact with a particle with a large non-normal velocity component.

Invar Interconnector Impacts

Although the total area occupied by the silver-plated Invar tabs was relatively small, the debris/micrometeorite fluence was sufficient that tab impacts did occur. The results of the impacts were visually surprising, but offer clear indication of the high particle impact velocities and corresponding impact energies. Figure 5 is a typical example of one such impact. It is observed that the tab has been completed penetrated. The region of Invar immediately surrounding the 0.5mm diameter through hole shows clear indication of melting and resolidifying. In addition, the impact generated gases have peeled the top silver plating away from the Invar and blown those layers out from the impact area. The silver/Invar separation is well-identified by the lack of any atomic oxygen darkened residual silver. Indeed, the inner surface of the peeled back silver plating has now darkened from atomic oxygen interaction. The remainder of the silver plated Invar tab still appears shiny due to a thin layer of silicone adhesive which has provided protection during the mission. This kind of impact well illustrates the nature of the typical LEO particulate impacts -- small and violent.

Impacts with Polymer Cell Covers

The appearance of impacts with a relatively thick polymer cell cover, such as Teflon FEP, shown in Figure 6, is remarkably similar to the above-described silver-plated Invar tab. For Teflon, the incident particle readily penetrates and impacts the silicon cell below. The impact with the silicon has generated gases which, in turn, lift the Teflon away from the cell and blow out the central area. The flexible Teflon, unlike the rigid silver metallization, settled back somewhat onto the cell surface. A light colored ring can be observed around the blowout region, corresponding to an area of Teflon/silicon delamination, where physical contact has been recovered, if not adherence. It is clear that the Teflon provides essentially negligible protection against the high energy impacts. Again, due to the small damage area, cell power degradation may not be significant. It is intended to examine for any impact/cell power loss correlation in subsequent electrical performance tests.

Impacts to Silicon and Microsheet

The silicon and microsheet impacts are discussed together because of the many similarities. Both materials are rigid and tend to shatter under severe loading. Figure 7 is a photograph of an impact in silicon (through a few micron thick polymer cover) and Figure 8 is a view of an impact into a microsheet coverslide. Both impact areas are comparable in size (~0.1mm central "hole"), the difference in the photographs being due to different magnification levels. In view of the limited number of such impacts, it is not clear if these are truly typical. However, both materials have a well-defined crater with any ejected material blown completely away. Both crater perimeters appear rectangular. For the silicon, this would reflect the crystalline nature of the material, however, this would not be expected for the microsheet. Of interest, the silicon cell has been completely penetrated, with the formation of a near hexagonal through hole. The microsheet impact appears well limited in size, and radiating cracks were not visible. In the case of the microsheet impact, it was not possible to determine with certainty that damage was limited to just the microsheet and immediately underlying silicone adhesive. However, it is believed that the impact was spent in the microsheet and that the adhesive was able to absorb any residual gas/debris, without a significant silicon interaction.

Conclusions

The LDEF experiment was subject to a wide variety of environmental interactions, in particular, space debris impacts and atomic oxygen. The extent of these interactions is strongly dependent on orbital altitude -- the LDEF orbit favored intensive interactions -- and care must be used in extrapolating to other, more commonly used higher altitude orbits. The advantage of LDEF is that the combination of long duration (~ 6 years) and environmentally active orbit altitude essentially accelerates interactions to better reveal the results.

For the particular case of debris/micrometeorite impacts, a relatively high fluence was observed for the SAMPLE experiment (~1300 impacts/m^2) over the mission duration. These typically were of small area

(0.05mm-1.0mm in diameter) and of high energy, allowing for penetration of Invar interconnector tabs and a thin silicon solar cell. At present, there is no evidence that these impacts incurred any significant electrical degradation in the solar cells. In particular, the Invar penetration only removed a small fraction of available interconnector material.

Although polymer-type covers may look attractive for low cost cell protection and may someday be suitable for protection against U.V. and low energy protons, there is negligible ability to shield against debris/micrometeorite impacts. If these impacts are cell degrading, then more robust covers, such as the standard fused silica or microsheet materials may be required at these low altitudes.

References

1. Ellis, David, "Micrometeoroid and Debris SIG is Focus for Many Issues", LDEF Spaceflight Environmental Effects Newsletter, Vol. 1, No. 8, January 23, 1991.

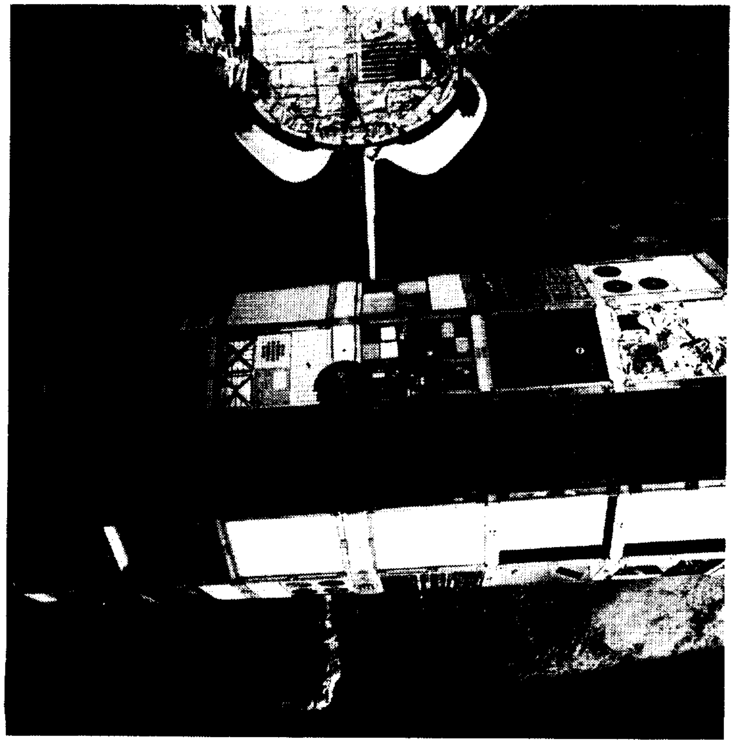

Figure 1. Retrieval of LDEF (Jan. 1990) - SAMPLE at upper left

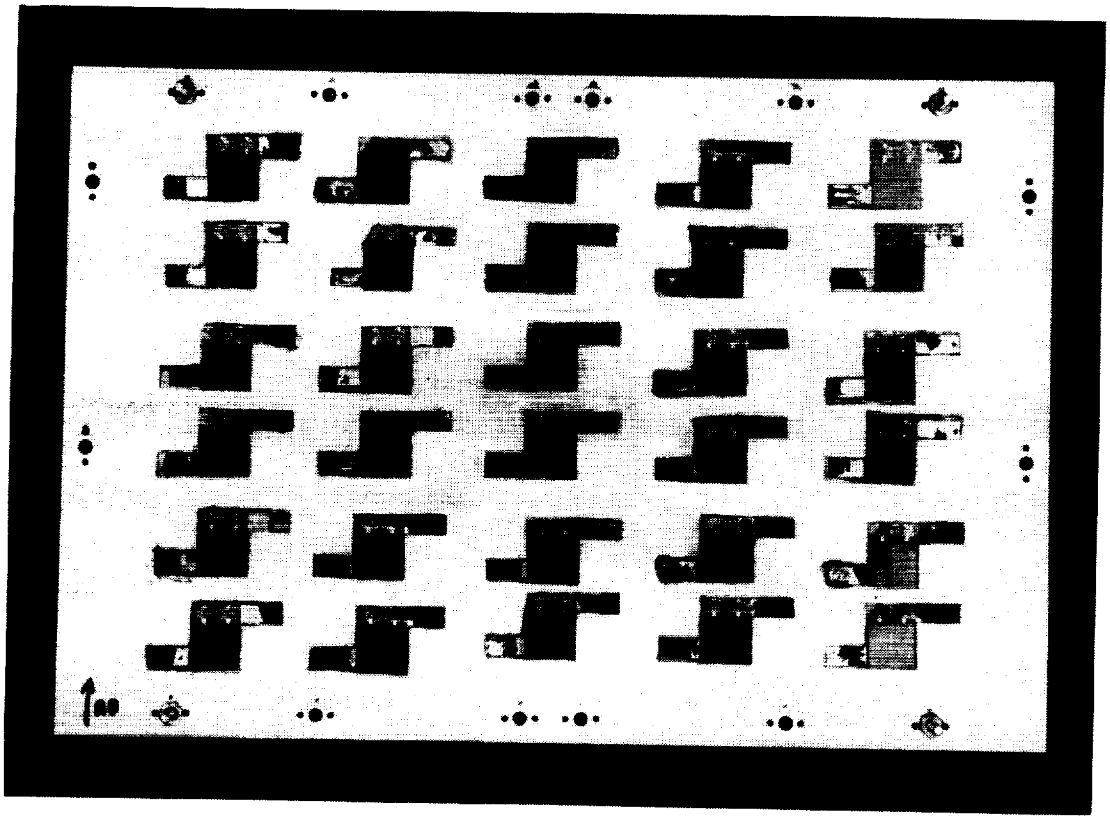

Figure 2. JPL SAMPLE Plate After Retrieval

Figure 3. Typical small Al craters ~0.05mm diameter

Figure 4. Largest crater ~1mm diameter

Figure 5. Invar Interconnector (~0.2mm diameter hole)

Figure 6. Teflon cover (~0.3mm diameter hole)

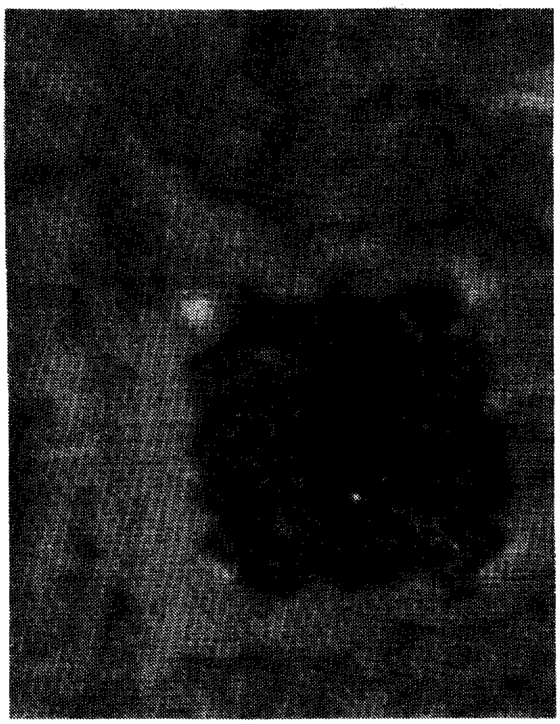

Figure 7. Impact in silicon (~0.1mm diameter hole)

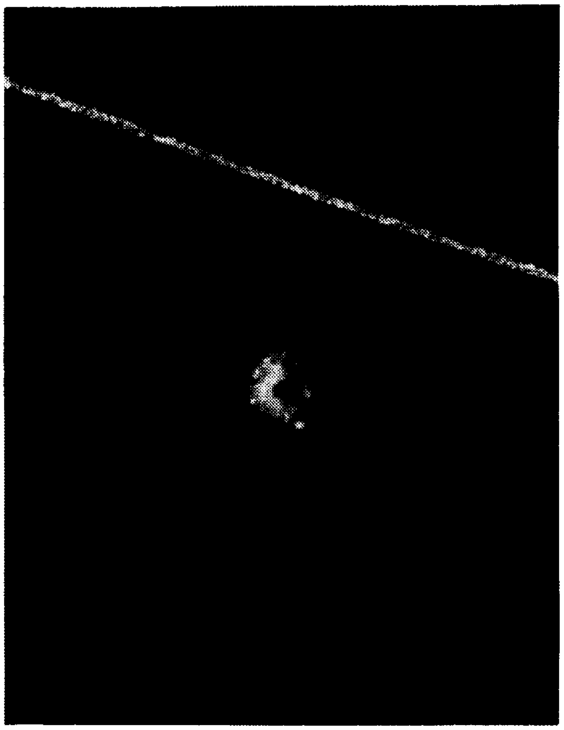

Figure 8. Impact in microsheet cover

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BLACK AND WHITE PHOTOGRAPH