N93-29687

LEO EFFECTS ON CANDIDATE SOLAR CELL COVER MATERIALS

501719 P- 12

Paul M. Stella
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

SUMMARY

In 1984, the LDEF (Long Duration Exposure Facility) was placed in LEO (Low Earth Orbit) for a mission planned to last approximately one year. Due to a number of factors, retrieval was delayed until 1990. An experiment, prepared under the direction of JPL, consisted of a test plate with thirty (30) individual thin silicon solar cell/cover samples. The covers consisted of conventional cerium doped microsheet platelets and potential candidate materials, such as FEP Teflon, silicone RTVs, glass resins, polyimides, and a silicone-polyimide copolymer encapsulant. This paper discusses the effects of the LDEF mission environment (micrometeorite/debris impacts, atomic oxygen, UV and particulate radiation) on the samples.

INTRODUCTION

The JPL experiment was part of SAMPLE (Solar-Array-Materials Passive LDEF Experiment), experiment number A0171, which included contributions from NASA-MSFC, NASA-LeRC and NASA-GSFC. SAMPLE was located at A08, a near ram position.

The JPL subplate consisted of an 11" x 16.3" (28 cm x 41.4 cm) aluminum plate with thirty (30) cell/cover samples. The cells were 50 micron thick 2x2 cm^2 silicon devices fabricated by Solarex Corporation. Silver-plated Invar tabs were welded to each cell to facilitate pre and post flight electrical performance measurements. Each cell and tab assembly was bonded to a slightly oversize sheet of 25 micron thick Kapton insulation bonded to the aluminum plate. The bonding materials were standard space-type silicone RTVs. Protective covers were attached to the front surface of the cell. These covers consisted of a variety of materials, including cerium doped microsheet, teflon film and various encapsulants.

The G.E. Company prepared the samples and assembled the experiment. The LDEF flight test was part of an evaluation to develop a protective cover alternative to the conventional fused silica or microsheet platelet covers. Although the conventional covers are not expensive (compared to the cell), the process of covering the cell is time-consuming and expensive. Ideally, a spray-on or roll-on coating would significantly reduce the cost and assembly time for array fabrication. It is important that such a cover not only protect the cell from radiation and enhance the cell emissivity, but that it not be degraded. The LDEF flight provided a means to directly evaluate the behavior of the cover materials in the space environment, including their ability to protect the cells. The post flight experiment review consisted of visual examination, cell electrical performance measurements and data analysis. The results are discussed below.

VISUAL OBSERVATIONS

Observation of the recovered test plate revealed a number of changes (Figure 1). All exposed (uncovered by adhesive or encapsulant) tab surfaces darkened from the original shiny silver appearance as the result of atomic oxygen interactions. In many cases, the darkened silver tab surfaces showed signs of stress by the formation of platelets. The dark surface material was 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 during the mission. 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. Although initially it appeared that the damage to the silver plating did not extend to the Invar, recent efforts to rub off additional blackened regions showed that this was not completely correct. There were a few small areas on the tabs where removal of the darkened surface revealed the Invar surface, suggesting that a minimum thickness of unreacted silver remains on the exposed interconnector. The initial silver thickness was not noted (the problem of atomic oxygen not anticipated at the time of experiment assembly), but typically ranged from four to six microns.

The initial view of the test plate quickly revealed many changes had occurred. Although no major damage was noted, the test plate and samples looked contaminated, with brownish-orange stains particularly apparent around the test samples. This was apparently the residue of silicone adhesives and/or encapsulants that had reacted with the LDEF space environment. The samples with Teflon covers appeared "charred" with the Teflon surface appearing brownish-gray. The cell gridlines were visible as yellow brown lines. Various samples with encapsulants were distinct in the lack of the normal dark blue cell appearance. Instead, colors varied from medium to very light blue (almost green), with clear indication of encapsulant crazing, peeling and flaking. Some cells with silicone encapsulants had exposed areas free of coating where the cell surface was clearly visible (with AR coating intact), although exposed silver grid lines were now blackened. Beyond these rather large scale changes, some of the larger impact craters were evident, such as an impact with a cell covered by Teflon (Figure 2). On a smaller scale, some light-colored, hazy areas evident along the sides of the test samples were most likely attributable to outgassing of cell to Kapton or Kapton to substrate silicone adhesives.

Upon completion of the initial visual examination, photographs were made to record the appearance, especially since it was possible that ambient reactions might be further altering the materials' conditions. (However, no significant changes have been noted during the two years following the initial observations.) Following this, a microscope-aided inspection of impact craters was performed followed by a measurement of test cell electrical performance. These are discussed in the following sections.

As might be expected, the cover system appearing the least changed was that of the conventional microsheet platelet. These samples generally appeared as if newly assembled.

DEBRIS/MICROMETEORITE IMPACTS

Inspection of the plate revealed a large number of impact craters, predominantly in the aluminum plate, ranging in size from 1 mm (Figure 3) to 0.05 mm in diameter. Most impacts appear to be normal to the plate (circular crater). The physical appearance of these impacts is discussed for various impact surfaces in the following sections.

Cratering in the Aluminum Plate

Since the majority of the test plate area consisted of the uncovered aluminum mounting plate, the majority of impacts were located in the plate. These were generally similar in appearance, and typified by the example in Figure 3. The impact formed a circular crater with a surrounding ridge ejected out from and over the plate surface. The crater bottom was crystalline in appearance, unlike the scratched and machined plate surface, showing evidence of melting and resolidification. This crater pattern was observed for all sizes from 1 mm diameter on down. Of the 157 impacts observed (over the entire test plate/sample surface), seven were 0.5mm or larger. Depth measurement 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 small, 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 4 is a typical example of one such impact. It is observed that the tab has been completely penetrated. The region of Invar immediately surrounding the 0.5mm diameter penetration 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 away from the impact still appears shiny due to a thin layer of silicone adhesive which has provided protection during the mission.

Impacts with Polymer Cell Covers

The appearance of impacts with a relatively thick polymer cell cover, such as Teflon FEP, shown in Figure 5, is remarkably similar to the above-described silver-plated Invar tab. For Teflon, the incident particle readily penetrated and impacted the silicon cell below. The impact with the silicon has generated gases which, in turn, lifted the Teflon away from the cell and blew out the central area. The flexible Teflon, unlike the rigid silver metallization, has 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, if not adherence, has been recovered. It is clear that the Teflon provides negligible protection against the high energy impacts. However, it was noted that the electrical performance of this cell was not noticeably different from other similarly covered cells, indicating minimal effects from the impact.

Impacts to Silicon and Microsheet

The silicon and microsheet impacts are discussed together because of the many similarities. Both materials are brittle and tend to shatter under severe loading. Figure 6 is a photograph of an impact in silicon (through a few micron thick polymer cover) and Figure 7 is a view of an impact into a 100 micron thick 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 nearly rectangular. For the silicon, this reflects the crystalline nature of the material, although this would not be expected for the microsheet. Of interest, the silicon cell was completely penetrated, with the formation of a near hexagonal-shaped through hole. The microsheet impact is limited in area, 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. No degradation was noted in the electrical performance of the covered solar cell.

ELECTRICAL PERFORMANCE

As mentioned earlier, the experiment consisted of thirty (30) solar cells. Six (6) had 100 micron thick microsheet covers, using five (5) different cell/cover silicone adhesives, including the widely used DC 93500. Ten (10) cells had 50 micron thick FEP Teflon covers, bonded with five (5) different silicone adhesives. Ten (10) cells were covered with six (6) different silicone encapsulants. Of the ten, six employed soft coatings, such as DC93500, and the other four had hard coat silicone encapsulants. Two cells were covered with GE X-76 polyimide, and the remaining two (2) cells with Bergstron and Associates/GE BE-225HUP silicone-polyimide copolymer. The encapsulant thicknesses ranged from a low of approximately 12 microns to a high of 75 microns. The large number of sample variations and relatively small number of samples meant that in a few cases only one sample of a particular combination was tested. In general, however, at least two of each combination were tested.

Rather than present the results of the electrical performance measurements on each cell, the cells have been grouped by cover/encapsulant type. There are obviously some variations in performance due to actual material differences and the significant variations will be noted. Table 1 lists the categories and changes in Isc (short circuit current). Little change was noted in Voc, other than that due to the decreased currents.

An additional source of measurement error was attributable to the extreme length of time over which this experiment was conducted, i.e., more than ten years from experiment assembly to final tests. As a result, the original simulator and standard cell were not available for the post flight tests. Fortunately, JPL possesses balloon calibrated solar cells from the same production run as the test cells and one was selected as a new standard. A Spectrolab pulsed xenon simulator was used for these tests. The electrical tests were performed by Spectrolab, Inc. with JPL assistance.

The smallest percentage loss measured was for the cerium doped microsheet samples and the BE-225HUP copolymer samples. The latter, however, had very low initial output current and the post flight samples had cell areas clearly free of encapsulant. The next lowest losses were measured on the polyimide encapsulant, soft silicone encapsulants and the hard coat silicone encapsulants. For the X-76 polyimide, the cell was extensively denuded of encapsulant, so the current shown is in some part that of a bare cell (Figure 8). The hard coat silicones also exhibited some coating loss and crazing (Figure 9). In general, minimal cell exposure was noted for the various soft silicone encapsulants and only at the cell corners. Thickness measurements of the encapsulants were not taken post flight due to the lack of sufficiently accurate pre-flight data, so that the only assessment of coating removal was based on noting any visible exposure of the underlying solar cell.

The largest current loss was exhibited by the Teflon covered samples, although the variation was extremely high, ranging from a loss of 10 percent to a loss of 43 percent. In one case the Teflon cover was missing with only a layer of RTV remaining on the cell. Whether this occurred during flight or during retrieval is not known. The cell current with only an RTV layer left showed an Isc loss of 10 percent equal to the best of the remaining Teflon covers. The variation in losses for the Teflon covers is not understood. However, UV reaction with Teflon has been well-documented and the top surface of the Teflon covers exhibited considerable damage as defined earlier. In review, the surface appearance varied from a hazy white to a brownish discoloration. The later samples showed the greatest Isc loss. In addition, the surface was soft and somewhat tacky (Figure 10). In terms of electrical performance then, no encapsulant or Teflon cover system provided output at the end of the mission comparable to the microsheet covered system. All of the non-microsheet cover systems exhibited visible erosion or reaction with the space environment.

CONCLUSION

The LDEF experiment provided a unique opportunity to view and evaluate the effects of a wide variety of environmental interactions. These included micrometeorite/space debris impacts, UV and particulate radiation and atomic oxygen. The relative importance of these interactions is highly dependent on orbital altitude. In addition, the LDEF experiment did not remain at a fixed altitude throughout the mission. Consequently, the extrapolation of these results to other orbits must be made with care. At present, numerous investigators are reviewing a wide variety of experiments in order to approach a comprehensive understanding of the LDEF results. Recent data indicates that the total fluence of atomic oxygen in the vicinity of this experiment was on the order of 6×10^{21} atoms/cm^2(1).

For the JPL experiment, a relatively high fluence of debris/micrometeorite impacts (~ 1300 impacts/m^2) of size $\geq$ 0.05 mm diameter was observed over the mission duration. These were typically of small size and of high energy, as evidenced by penetrations of materials such as Invar tabs and thin silicon solar cells. There is no indication that the impacts with the test samples (including solar cells) caused any electrical degradation. Evidence from a number of LDEF experiments suggests that the majority of the impacts observed on this experiment were of space debris, rather than micrometeorite origin (2).

Although the concept of polymer-type cell covers may look attractive for low cost cell protection, all tested samples exhibited losses in performance. In many cases, coating erosion was sufficient to remove most of the polymer material, allowing damage to occur to the cell grid metallization by atomic oxygen. The most durable polymer material was FEP Teflon, which continued to provide protection against atomic oxygen to the cell below. However, the Teflon material was not free of damage and exhibited visible surface darkening and softening, with some material loss. The best Teflon systems, i.e., those bonded to the cells with high quality silicone adhesives, displayed approximately eight percent greater cell current loss than the samples employing conventional cover glass material. For the latter, material integrity after nearly six years' space exposure was outstanding. Overall cell current losses were typically on the order of three percent, within the range expected from UV darkening. Clearly, the optical qualities of the conventional platelets remain unmatched by the other materials. In addition, only the relatively hard conventional covers appear to provide any protection against incident micrometeorite or debris. For orbits containing similar types of environmental threats, conventional coverglass materials are preferred, and a quality polymer replacement has yet to be demonstrated.

Acknowledgment

The work reported herein was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.

References

1. Bourassa, Roger J. and James R. Gillis, "Atomic Oxygen Fluence for Each LDEF Tray", LDEF Spaceflight Environmental Effects Newsletter, Vol. 111, No. 1, March 30, 1992.

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

Cover/Encapsulant	Isc (mA)		Δ(%)	Comments Cover/Encapsulant
	Preflight	Postflight		
Microsheet (Ceria)	136.5	132.4	-3	
FEP Teflon	136.8	106	-22	Darkened top surface loss varies from -10% to -43%
Silicone (soft)	132	115	-13	Crazing, some loss near cell edges
Silicone (hard coat)	135	112	-17	Crazing, flaking, close to complete removal
BE-225 HUP Polyimide-silicone Copolymer	125	121	-3	Partially removed - Voids
GE X-76 Polyimide	129.5	119	-8	Encapsulant significantly removed

Table 1. Solar Cell Assembly Electrical Performance

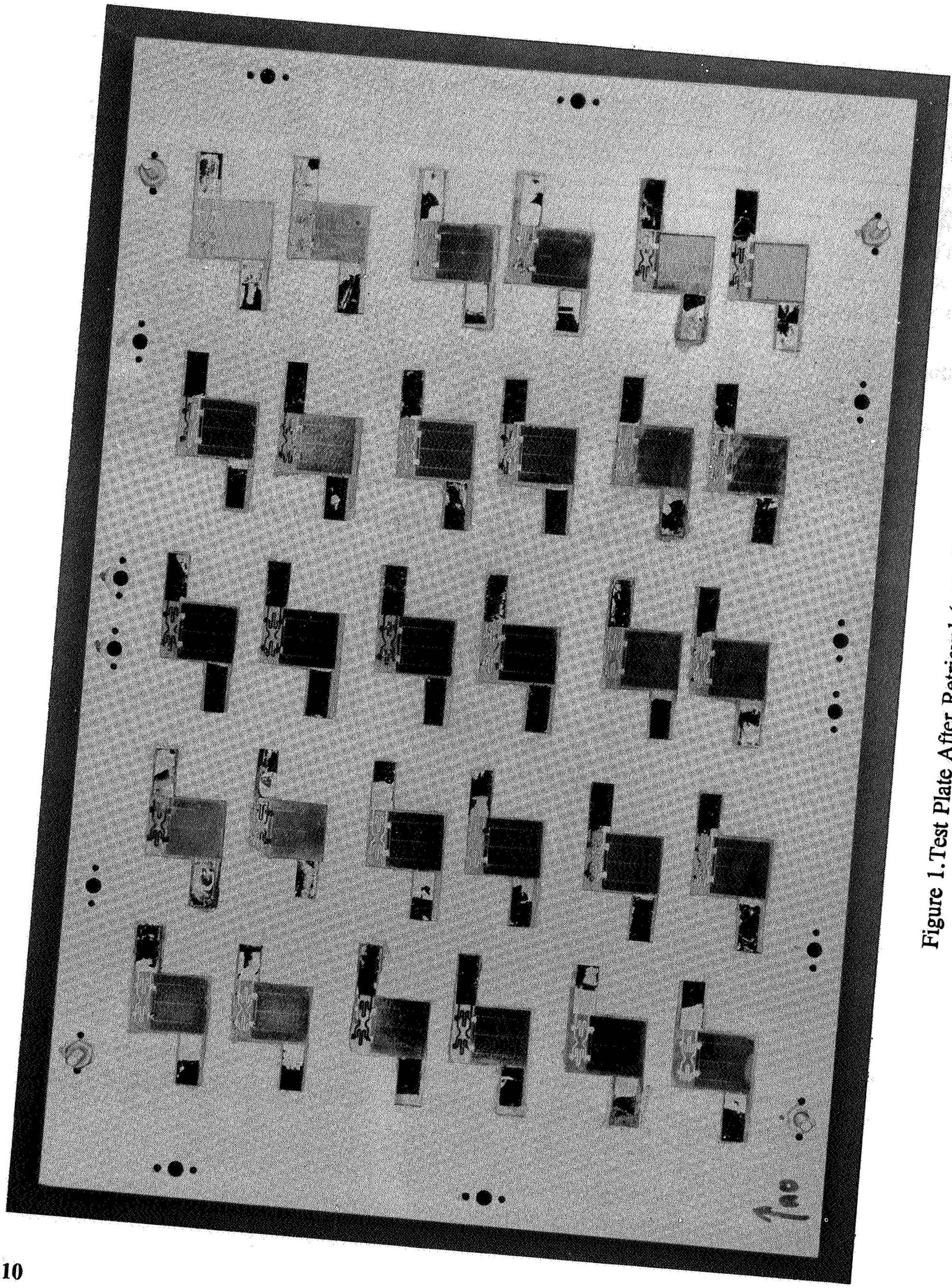

Figure 1.Test Plate After Retrieval (note darkened tabs)

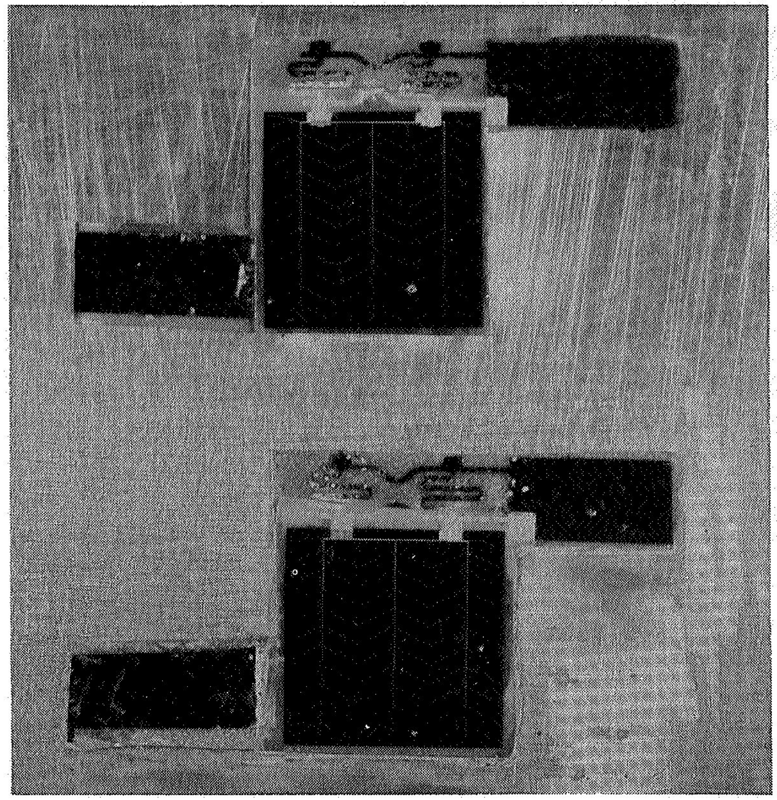

Figure 2.Impact with Teflon Cover (Lower Part of Upper Cell)

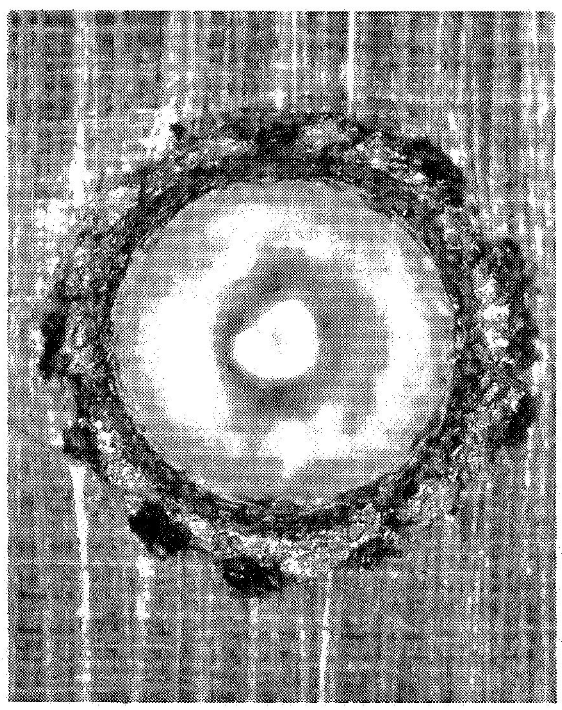

Figure 3.Largest Impact Crater (~1 mm diameter)

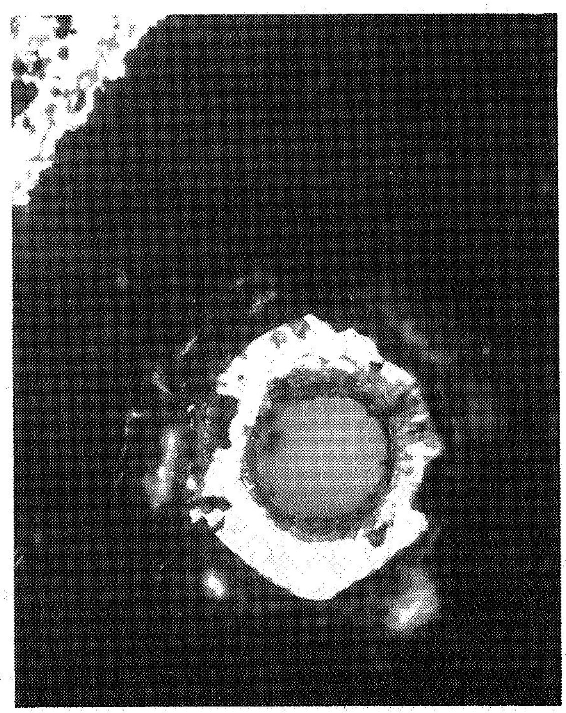

Figure 4.Ag Plated Invar Impact

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Figure 5.Teflon Cover Impact

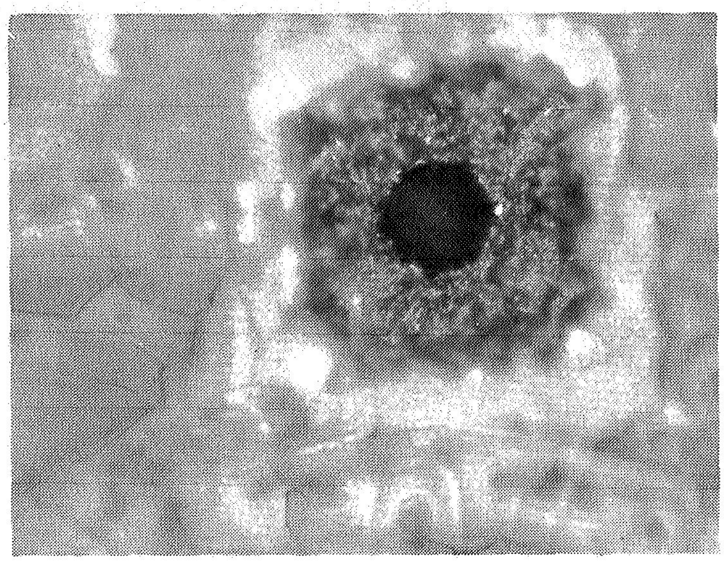

Figure 6.Silicon Impact (200X)

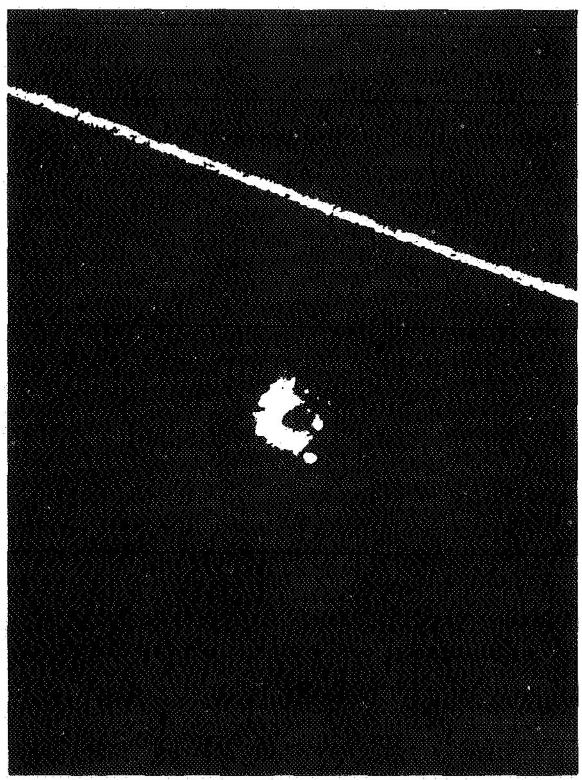

Figure 7.Microsheet Cover Impact (7X)

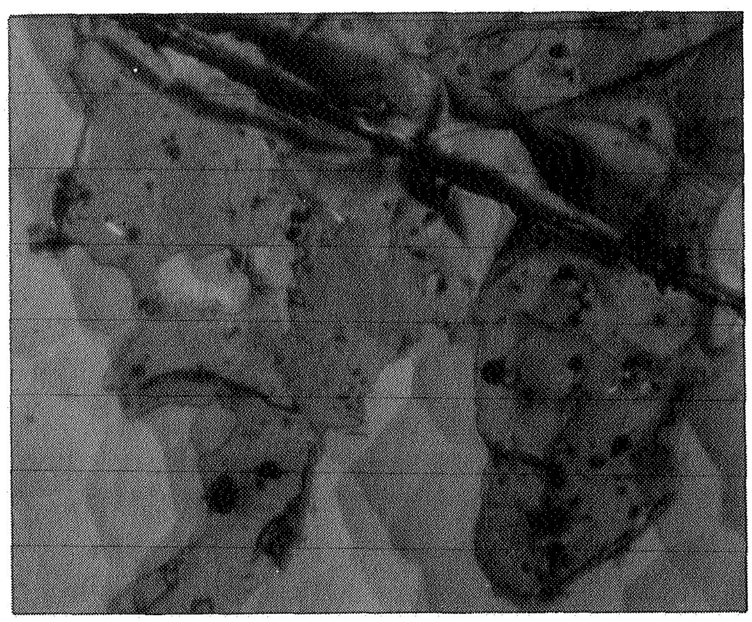

Figure 8.Polyimide Encapsulant Degradation

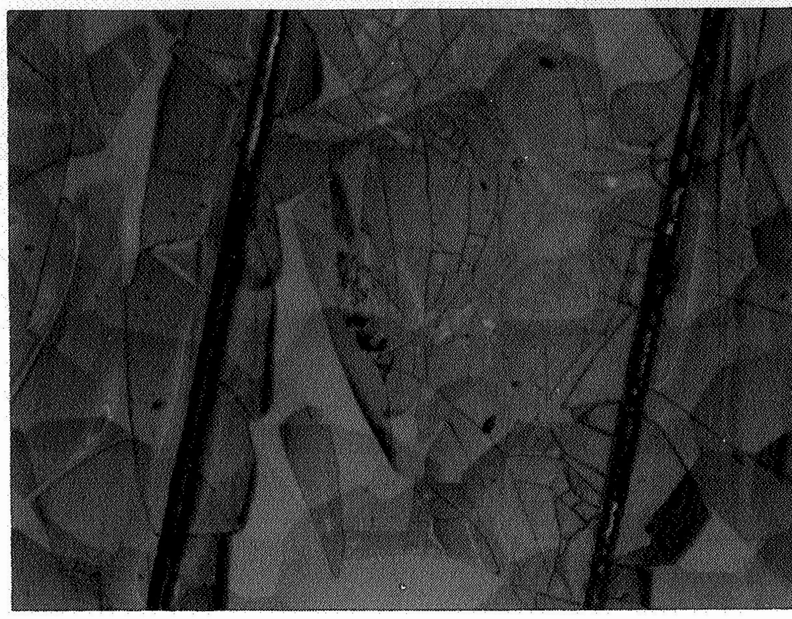

Figure 9. Hard Coat Silicone Degradation

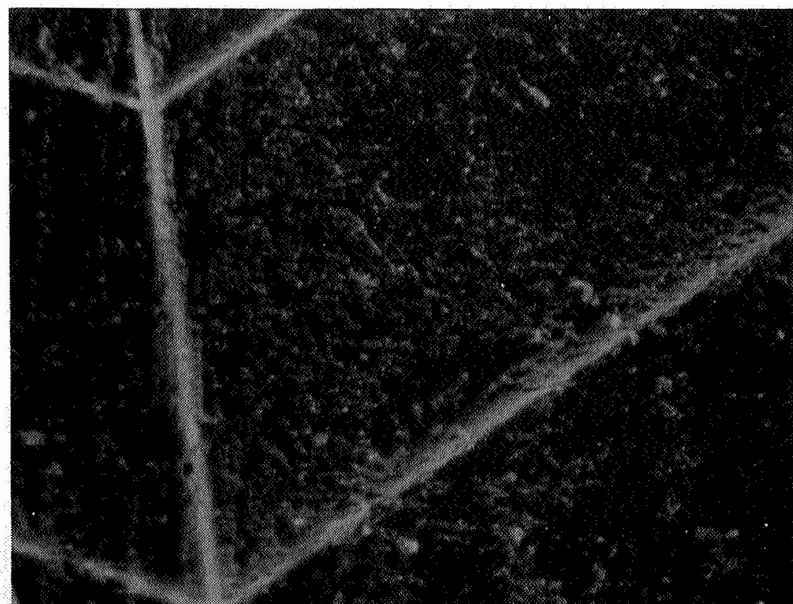

Figure 10. Softened Teflon Cover