

## MICROMETEOROID/SPACE DEBRIS EFFECTS ON MATERIALS

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## SUMMARY

The Long Duration Exposure Facility (LDEF) micrometeoroid/space debris impact data has been reduced in terms that are convenient for evaluating the overall quantitative effect on material properties. Impact crater flux has been evaluated as a function of angle from velocity vector and as a function of crater size. This data is combined with spall data from flight and ground testing to calculate effective solar absorptance and emittance values versus time. Results indicate that the surface damage from micrometeoroid/space debris does not significantly affect the overall surface optical thermal physical properties. Of course the local damage around impact craters radically alter optical properties. Damage to composites and solar cells on an overall basis was minimal.

## INTRODUCTION

The purpose of this report is to provide useful information to the spacecraft designers and managers about meteoroid/space debris impacts and their effects on materials, as was learned from the LDEF. Various materials on LDEF were impacted, including thermal control coatings, thin films, solar cells, and composites. Results of impact damage to these materials and their effects are examined in this report.

LDEF was exposed to a meteoroid/space debris environment consisting of numerous natural and man-made particles which impact orbiting spacecraft with closing velocities ranging in the tens of kilometers per second. Those larger than 1 cm in diameter can cause major damage to a spacecraft, but have a low probability of impact. The LDEF satellite was impacted by particles smaller than ~1-mm diameter. Emphasis in this report is only on these high probability small impacts which caused significant surface damage.

Orientation of the LDEF during its 5.75 years flight is shown in Figure 1. During the 5.75 year mission, the LDEF experienced a maximum of approximately 140 significant impact craters/m<sup>2</sup>/year. These impacts have been quantified in terms of size distribution and flux. Impact data were evaluated for impact craters having diameters from 0.1 mm to less than 3 mm. Approximately 10 times more impact craters occurred on the leading edge (RAM) of LDEF compared to the trailing edge. The largest impact was 5.25 mm in diameter. Simple empirical relationships were derived to conveniently model the impact flux in terms of crater diameters and crater size distributions.

Although the LDEF data appear extensive, they are in fact limited in terms of specific damage such as spall to crater ratios for specific paints. For this reason, the LDEF flight data have been supplemented with ground tests at hypervelocities.

## LDEF METEOROID/SPACE DEBRIS DATA

Cataloging of all meteoroid and space debris impacts on the satellite surface was performed by the LDEF Meteoroid/Debris Special Investigation Group (M&DSIG). This extensive cataloging was performed during de-integration of the satellite trays at the Spacecraft Assembly and Encapsulation Facility No. 2 (SAEF-2) at Kennedy Space Center. All exposed surfaces of the LDEF, including the experimental trays and all of the exterior satellite surfaces, were optically scanned for impact features.

All impacts, greater than 0.1 mm in diameter as seen with a 10× magnifier, were cataloged. Selected images were recorded by digitizing the video image from a stereo microscope system and storing on a WORM (write once, read many) compact laser disk. The criteria for image storage by digitization was 0.5-mm diameter or larger crater when measured along the major axis, 0.3 mm or larger penetration, and unusual impacts. Preliminary results from this satellite survey are published in reference 1, which is the data source for all the impact crater flux and size evaluations reported in this paper.

At KSC, 34,336 impacts were found, and approximately 4,000 of these impact images were stored on laser disk. The total number of impact features has increased with the discovery of numerous smaller impacts and the analysis of the approximately one-fourth of the experiment trays designed for meteoroid/debris investigation. However, these impacts will not be included in the survey since many of the smaller impacts have no significant damage to material surfaces which could affect the design of spacecraft and selection of spacecraft materials. In addition, results of this report demonstrate that even a factor of two in flux would not significantly affect the overall surface properties, except at the very localized damage sites.

### Impact Crater Flux Calculation

In order to calculate the overall surface damage effects from impacts to large surface areas, the flux must be known, ideally, in terms of crater diameters versus the angle from the velocity vector. D. Humes (ref. 2) has shown the significant dependence of meteoroid/orbital debris flux versus angle from velocity vector as derived from model calculations and from the LDEF experiment S0001 data.

Since impact data for LDEF were not reduced in the form required for the calculations, the raw counts of crater impacts were summarized utilizing the data in reference 1. All impact craters above 0.3 mm were summed for each row. This analysis is intended to obtain reasonable (conservative) crater fluxes on surfaces as a function of their surface normal to the velocity vector.

Figure 2 defines the angle "Beta" as the angle from the velocity vector (or RAM) to the normal to each row. Note that Beta increases with increasing row number in a positive value up to 180°. Negative values mean the direction is as shown in Figure 2, with decreasing row number up to a -180°. As an example, row 9 is a minus 8° (ref. 3).

A summary of the crater impact data is provided in Table 1. The "count" column lists the total number of craters (diameter  $\geq 0.1$  mm) reported for each type of surface in each row. "Area" column lists the area (square meters) used to calculate flux values. "Flux" column provides the reduced counts of impact craters per square meter per year, for each type of surface.

Directional dependence of meteoroid/debris impacts, as a function of the angle from the velocity vector, can be seen from the count and flux data. Apparent flux variations occurred within the same row for different materials. Flux values derived from impacts on experiment surfaces are normally lower than those from the structure or thermal panels. Each experiment was composed of a variety of different materials. Impacts on some surfaces exhibited excellent contrast, making identification for counting fairly easy, while other materials, such as composites, exhibited very poor contrast, making it much more difficult to identify impacts. The LDEF structure and thermal panels have smaller exposed areas than the experiment surfaces, but each consists of the same type material and coating, resulting in a more reliable and consistent count. Attempting to count impacts on such a variety of materials on 24-hour shifts on a tight schedule could account for the variations in flux values listed in Table 1.

All of the flux data listed in Table 1 are plotted graphically in Figure 3. Notice that the flux data for the structure surfaces are skewed from velocity vector zero degree reference. This skewing resulted from assuming the longerons pointed in the same direction as the rows, and combining their count data with that for the intercostals (which do face in the same direction as each row). The offset in angle is 15° which would restore part of the symmetry. It was found that a simple function, defined as the “baseline,” encompasses all of these curves as a worst case value.

A simple relationship for the total number of impacts is approximated by equation (1) which is also plotted in Figure 3.

$$\text{Flux } f(\text{Beta}) = a + b \cos^2(\text{Beta}/2) \quad (1)$$

where:

$$a = 15$$

$$b = 125$$

Beta = degrees from velocity vector or RAM direction.

#### Impact Crater Size Distribution

A relationship between total number of impacts per crater diameter is required in order to determine the total damage area based on the impact flux. This relationship was determined by summing all of the impacts on LDEF for each crater diameter. Table 2 lists impacts summed on each row for diameters between 0.1 mm up to 2.5 mm. This count includes impacts on experiments, trays, clamps, structures, and thermal panels. The total count for each diameter was summed for all rows and plotted in Figure 4. This size distribution can be approximated by the following relationship given by equation (2) plotted in Figure 2.

$$\text{Ln } (d) = C1 + (C2 * N) \quad (2)$$

where:

$N$  = number of impacts craters

$\text{Ln}$  = natural logarithm

$d$  = diameter of crater in mm.

$C1 = +8.693612$

$C2 = -3.532209$  .

This approximation permits an estimation of the actual number of impacts below 0.5 mm where incomplete counting occurred. A summation was made using this relation for all diameters between 0.1 and 3.0 mm. The total sum was used to normalize the size distribution data into a fractional distribution.

### Coating Spall Effects

Other information required in order to calculate the overall optical effects of multiple impact craters is the ratio of crater diameter to coating spall diameter. Dependent upon the bond strength and type of coating different, amounts of coating will be removed during impact. Figure 5 schematically defines crater diameter versus spall diameter. The shock waves from the impact can cause coatings to spall, as shown in Figure 5. An example of this spall effect is shown in Figure 6, comparing impact spall on an LDEF flight sample (ref. 4) YB71 ceramic type paint to spall from a similar Z93 white ceramic paint from a ground simulation impact tests at hypervelocity.

As was previously mentioned, impact crater spall data were very limited, even on LDEF samples after almost 6 years in orbit. Most experiment flight samples were about 1 inch in diameter. A flux rate of 140 impact craters per year results in only 0.07 impacts per year on a 1-inch disk. This explains why very few impacts occurred on specific types of experiment sample coatings, which had preflight characterization and normally ground control samples. Of course large areas of LDEF consisted of conversion coatings and silver Teflon™ (Ag/FEP), which provides a large data base for determining spall or effective damage area.

To obtain better spall data for the paint coatings, including Z93 (white ceramic binder type paint) and S13GLO (white silicone binder type paint), a series of hypervelocity impacts were performed by Auburn University (AU) by Dr. F. Rose under contract to MSFC (ref. 5). The hypervelocity impact (ref. 6) system at AU is a plasma drag type accelerator shown schematically in Figure 7. This HVI system is capable of providing a particle impact velocity distribution somewhat similar to Kessler's model (ref. 7), as shown in Figure 8. Another example of impact spall is shown in Figure 9 for S13GLO coatings. This ground simulation sample compares favorably to an impact on LDEF experiment M0003 (ref. 8). Spall to crater diameter ratio is greater for the LDEF exposed sample material.

Impacts on Ag/FEP bonded to aluminum with acrylic adhesive (ref. 9) is shown in Figure 10. An Ag/FEP layer has been lifted up and blown back from the impact site. The adhesive layer was debonded from the aluminum substrate, leaving the bare aluminum exposed. This was one of the larger impacts on experiment S0069.

In comparison, impacts on conversion coatings such as chromic acid anodize (CAA) did not produce any apparent spall. An example is the CAA sample from LDEF experiment S0069. Figure 11 is an enlargement of the impact on the thermal guard ring of the calorimeter flight sample. Even for a very thick conversion type coating, as shown in Figure 11, no measurable spall occurred.

Results for spall to crater ratios, from flight and ground tests, are summarized in Table 3.

## EFFECT ON THE THERMAL RADIATIVE PROPERTIES OF COATINGS

### Calculative Approach

Since the flux levels as a function of Beta angle, crater size distribution, and spall/crater ratio are known, the change in effective (average) thermal radiative properties can be calculated with respect to time using equation (3).

$$A_s(\text{Beta}) = A_o - [D_{a,e} * F_a * T_{yr}] \quad (3)$$

where:

$A_s$  (Beta, time) = effective or average value of solar absorptance or emittance at each Beta angle

$A_o$  = solar absorptance or emittance of original coating

$D_{a,e}$  = difference between coating and substrate absorptance or emittance

$F_a$  = fraction of damaged surface area per year

$T_{yr}$  = number of years exposed.

The fraction of damaged surface area ( $F_a$ ) is derived by summing for each angle "Beta" the product of flux, size distribution, and spall area, for crater diameters from 0.1 to 3.0 mm. For convenience a selection of values for " $F_a$ " are provided in Table 4. These values for  $F_a$  can be used with equation (3) to predict long-term optical property changes from impact craters. Remember that the values provided in Table 4 are actually the total area in square millimeters of substrate exposed from the impact per square meter (refer to Figure 5) and subsequently includes a multiplication factor of  $10^{-6}$  (as indicated in Table 4). Values in Table 4 are listed for spall to crater diameter ratios ranging from 1 to 15, and for selected Beta angles in the range from  $0^\circ$  through  $180^\circ$ .

### Results of Calculations

#### White Paints (Z93 and S13GLO)

Figures 12 and 13 show the results of impacts on Z93 white coating for three different Beta angles of  $0^\circ$ ,  $90^\circ$ , and  $180^\circ$ , for up to 30 years in orbit. Both solar absorptance and thermal emittance decrease slightly with time. The larger spall/crater diameter ratio for Z93 and other ceramic binder paints does not significantly affect the solar absorptance or thermal emittance values. When the coating and substrate thermal radiative properties are significantly different, then the effect of impacts is greater. This effect is shown in Figures 12 and 13, by comparing the larger change in emittance than in absorptance. Bare aluminum substrate has a very low emittance ~4 percent, compared to the Z93 value of ~92 percent. In comparison aluminum absorptance is ~4 percent (low value) and Z93 ~14 percent. Actually, the exposed aluminum absorptance in the spalled area is probably closer to the Z93, which means the changes shown on Figure 12 are even less.

Effects on S13GLO are even less than on the Z93, see Figures 14 and 15, since the spall to crater ratio is much less. The overall effect on S13GLO would be difficult to measure. For these

coatings, the atomic oxygen, ultraviolet radiation, and contamination will have a greater long-term effect than meteoroid/debris impacts (ref. 4).

#### Conversion Coatings such as CAA

Chromic acid anodized aluminum exhibited no spall on either flight or ground test samples, resulting in changes much less than 0.1 percent in even 100 years for effective absorptance and emittance. Of course, this assumes the orbital debris environment does not change significantly from what LDEF experienced.

#### Silver Teflon™ Blankets

Changes to the thermal radiative properties of silver Teflon™ (Ag/FEP) blankets utilized the damaged area measured by Nerren (ref. 10). Photograph of a Ag/FEP blanket flown on LDEF as shown in Figure 16, was analyzed for percent of area darkened from impacts. This analysis was performed by Nerren and Sullivan (ref. 9). The photograph image of the silver Teflon™ blanket flown on LDEF experiment No. A0178 on row 10E was scanned to determine the damage area. The Ag/FEP blanket analyzed was positioned +22° from the velocity vector (Fig. 2). A total of 322 penetrations were counted and their associated darkened area measured. The darkened area includes the impact penetration hole area and the discolored area surrounding the impacts, resulting in a 1.44-percent damaged surface area. The darkened area has a higher solar absorptance than the original Ag/FEP, which increases the overall effective solar absorptance. The overall effect to thermal radiative properties is plotted in Figures 17 and 18 utilizing equation (3).

### IMPACT EFFECT ON SOLAR CELLS

Electrical properties of solar cells appear to be minimally affected by meteoroid/debris impacts as reported by Young and Trumble (ref. 11). Cracking of the cover glass and even penetrations only have a local effect. Certainly a high level of damage by impacts would cause significant loss in solar cell array outputs. At this time, the damage effect threshold is being determined by impact testing on arrays at Auburn University utilizing their hypervelocity facility and at MSFC (ref. 12) utilizing a light gas gun for impact tests with particles up to 0.5 in (12 mm).

### IMPACT EFFECTS ON COMPOSITE MATERIALS

Composite specimens flown on LDEF were carefully examined for impacts before tensile testing. The graphite/epoxy samples did experience several small impacts, but these craters did not serve as crack propagation sites nor had any discernible effect on the tensile test. Erosion of the graphite/epoxy induced variability to the tensile strength measurements which was greater than the effect of meteoroid/debris impacts.

Several small impacts were also found on fiberglass/epoxy samples covered with aluminized thermal control tape. No debonding of the tape was observed. Peel tests of the thermal control tape were not perceptibly affected by the impacts.

## CONCLUSION

Overall average effects of meteoroid/space debris (M/OD) impacts on most spacecraft surfaces are not significant even for extended periods. This is true only for non-penetrating small high probability impacts causing craters in the 0.1 to 3 mm range. Even at this minimal average effect, up 140 impacts/year/square meter can be expected and must be planned for and considered in spacecraft designs requiring long periods of exposure in the low earth orbital environment.

For very stable materials where a few percent change in overall properties is critical, then the impact and spalling can be important. Example, is if the overall average emittance of a radiator must be stable for 30 years (change <2 percent), then the effects of the M/OD must be included in life predictions.

Localized damage, if it occurs in the wrong place can cause severe degradation. Although the overall effect of impacts on solar cells is small, impacts that sever connections will cause loss of those cells. These types of events are rare, but they will occur, and redundancy by physical separation can all but eliminate local damage failures.

Optical surfaces such as lenses and mirrors were not discussed, but the flux values can be used to assess the magnitude of impacts these surfaces will experience with time. By always exposing optical systems in the trailing direction the flux can be reduced by a factor of 10. The type of impacts evaluated in this report will normally not cause penetration of optical surfaces, but they will create scatter sites for light.

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Table 1. Crater impact data.

| ROW NO.   | EXPERIMENTS & TRAYS |                        |       | LDEF STRUCTURE |                        |        | THERMAL PANELS |                        |        | ANGLE BETA |
|-----------|---------------------|------------------------|-------|----------------|------------------------|--------|----------------|------------------------|--------|------------|
|           | COUNT               | AREA (m <sup>2</sup> ) | FLUX  | COUNT          | AREA (m <sup>2</sup> ) | FLUX   | COUNT          | AREA (m <sup>2</sup> ) | FLUX   |            |
| 1         | 622                 | 6.58                   | 16.43 | 112            | 1.22                   | 15.95  | 46             | 0.316                  | 25.33  | + 112°     |
| 2         | 126                 | 6.58                   | 3.33  | 68             | 1.22                   | 9.68   | 36             | 0.316                  | 19.83  | + 142°     |
| 3         | 399                 | 6.58                   | 10.54 | 74             | 1.22                   | 10.54  | 10             | 0.316                  | 5.49   | + 172°     |
| 4         | 311                 | 6.58                   | 8.22  | 96             | 1.22                   | 13.67  | 15             | 0.316                  | 8.26   | - 158°     |
| 5         | 846                 | 6.58                   | 22.36 | 184            | 1.22                   | 26.20  | 29             | 0.316                  | 15.97  | - 128°     |
| 6         | 915                 | 6.58                   | 24.15 | 442            | 1.22                   | 62.94  | 12             | 0.316                  | 6.60   | - 98°      |
| 7         | 2108                | 6.58                   | 55.71 | 572            | 1.22                   | 81.46  | 170            | 0.316                  | 93.62  | - 68°      |
| 8         | 3289                | 6.58                   | 86.92 | 939            | 1.22                   | 133.72 | 175            | 0.316                  | 96.37  | - 38°      |
| 9         | 3077                | 6.58                   | 81.40 | 924            | 1.22                   | 131.59 | 246            | 0.316                  | 117.53 | - 8°       |
| 10        | 3118                | 6.58                   | 82.40 | 652            | 1.22                   | 92.85  | 204            | 0.316                  | 112.34 | + 22°      |
| 11        | 2435                | 6.58                   | 64.35 | 493            | 1.22                   | 70.21  | 168            | 0.316                  | 92.52  | + 52°      |
| 12        | 1620                | 6.58                   | 42.81 | 321            | 1.22                   | 45.71  | 132            | 0.316                  | 72.56  | + 82°      |
| SPACE END | 112                 | 5.966                  | 3.26  | 79             | --                     | --     | 165            | 4.65                   | 6.16   | ~ 90°      |
| EARTH END | 1095                | 5.966                  | 31.92 | 649            | --                     | --     | 1200           | 4.65                   | 44.82  | ~ 90°      |

FILE:99/LDEF92/TABL801

Table 2. Impact crater size distribution.

| TOTAL NUMBER OF IMPACT CRATERS PER ROW AND PER DIAMETER |          |      |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
|---------------------------------------------------------|----------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| ROW #                                                   | DIAM(mm) | 50.1 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 | ≥15 |
| 1                                                       | 10       | 32   | 34  | 25  | 25  | 13  | 15  | 5   | 0   | 1   | 2   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 1   | 0   | 0   | 0   |
| 2                                                       | 25       | 25   | 7   | 10  | 12  |     | 3   | 2   | 1   | 1   | 1   | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 3                                                       | 22       | 9    | 13  | 9   | 10  | 4   | 3   | 2   | 2   | 1   | 0   | 2   | 1   | 0   | 2   | 1   | 1   | 0   | 0   | 0   | 0   | 0   | 1   |
| 4                                                       | 29       | 20   | 11  | 5   | 7   | 2   | 2   | 6   | 3   | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 5                                                       | 29       | 29   | 21  | 13  | 15  | 5   | 4   | 4   | 2   | 0   | 1   | 3   | 1   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 6                                                       | 68       | 45   | 43  | 33  | 19  | 16  | 15  | 5   | 2   | 4   | 2   | 3   | 2   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 7                                                       | 65       | 106  | 72  | 61  | 32  | 28  | 15  | 11  | 3   | 8   | 2   | 4   | 2   | 1   | 0   | 2   | 0   | 0   | 2   | 1   | 0   | 1   | 1   |
| 8                                                       | 85       | 132  | 97  | 75  | 42  | 29  | 22  | 9   | 13  | 13  | 5   | 6   | 1   | 1   | 0   | 1   | 0   | 0   | 0   | 1   | 0   | 4   | 4   |
| 9                                                       | 100      | 125  | 95  | 75  | 51  | 24  | 22  | 27  | 15  | 9   | 10  | 8   | 6   | 1   | 5   | 0   | 0   | 1   | 0   | 1   | 0   | 7   | 7   |
| 10                                                      | 124      | 149  | 107 | 79  | 51  | 24  | 30  | 20  | 15  | 11  | 4   | 7   | 5   | 1   | 5   | 2   | 7   | 4   | 1   | 2   | 0   | 6   | 6   |
| 11                                                      | 66       | 104  | 83  | 109 | 55  | 22  | 22  | 9   | 12  | 7   | 3   | 3   | 6   | 2   | 2   | 0   | 0   | 1   | 0   | 1   | 1   | 5   | 5   |
| 12                                                      | 65       | 51   | 46  | 54  | 33  | 11  | 18  | 4   | 9   | 1   | 2   | 4   | 2   | 2   | 1   | 0   | 0   | 0   | 2   | 0   | 0   | 3   | 3   |
| TOTALS:                                                 |          | 688  | 829 | 629 | 548 | 352 | 178 | 171 | 104 | 76  | 56  | 32  | 41  | 24  | 9   | 16  | 6   | 8   | 6   | 5   | 7   | 1   | 27  |

FILE:99/LDEF92/TABL802

Table 3. "CN" spall diameter to crater diameter ratio.

| COATING MATERIAL | RATIO OF SPALL TO CRATER DIAMETER |                     |
|------------------|-----------------------------------|---------------------|
|                  | LDEF FLIGHT SAMPLES               | GROUND TEST SAMPLES |
| S13GLO           | 3                                 | 1.5 to 3.0          |
| YB71             | 4 to 8                            | 5 to 8              |
| Z93              | na                                | 5.5 to 8            |
| Ag/FEP           | 2 to 6                            | na                  |
| CAA              | 1                                 | 1                   |

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Table 4. " $F_a$ " fraction of damaged surface per year.

| Beta<br>D/D <sub>c</sub> | VALUES FOR $F_a \times 10^4$ |         |         |         |         |         |        |        |
|--------------------------|------------------------------|---------|---------|---------|---------|---------|--------|--------|
|                          | 0°                           | 10°     | 30°     | 60°     | 90°     | 120°    | 150°   | 180°   |
| 1                        | 21.07                        | 20.93   | 19.81   | 16.37   | 11.66   | 6.96    | 3.52   | 2.26   |
| 2                        | 84.28                        | 83.71   | 79.24   | 65.47   | 46.65   | 27.84   | 14.07  | 9.03   |
| 3                        | 189.63                       | 188.34  | 178.29  | 147.30  | 104.97  | 62.65   | 31.66  | 20.32  |
| 4                        | 337.12                       | 334.83  | 316.96  | 261.87  | 186.62  | 111.37  | 56.28  | 36.12  |
| 5                        | 526.75                       | 523.18  | 495.24  | 409.17  | 291.59  | 174.01  | 87.94  | 56.44  |
| 6                        | 758.52                       | 753.37  | 713.15  | 589.21  | 419.89  | 250.58  | 126.64 | 81.27  |
| 7                        | 1032.43                      | 1025.43 | 970.68  | 801.97  | 571.52  | 341.07  | 172.37 | 110.62 |
| 8                        | 1348.47                      | 1339.33 | 1267.82 | 1047.48 | 746.48  | 445.48  | 225.13 | 144.48 |
| 9                        | 1706.66                      | 1695.09 | 1604.59 | 1325.71 | 944.76  | 563.81  | 284.93 | 182.86 |
| 10                       | 2106.99                      | 2092.70 | 1980.97 | 1636.68 | 1166.37 | 696.06  | 351.77 | 225.75 |
| 11                       | 2549.46                      | 2532.17 | 2396.98 | 1980.39 | 1411.31 | 842.23  | 425.64 | 273.16 |
| 12                       | 3034.07                      | 3013.49 | 2852.60 | 2356.82 | 1679.57 | 1002.33 | 506.55 | 325.08 |
| 13                       | 3560.82                      | 3536.66 | 3347.84 | 2765.99 | 1971.17 | 1176.34 | 594.49 | 381.52 |
| 14                       | 4129.70                      | 4101.69 | 3882.71 | 3207.89 | 2286.09 | 1364.28 | 689.47 | 442.47 |
| 15                       | 4740.73                      | 4708.58 | 4457.19 | 3682.53 | 2624.34 | 1566.13 | 791.48 | 507.74 |

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## LDEF Orbital Flight Orientation

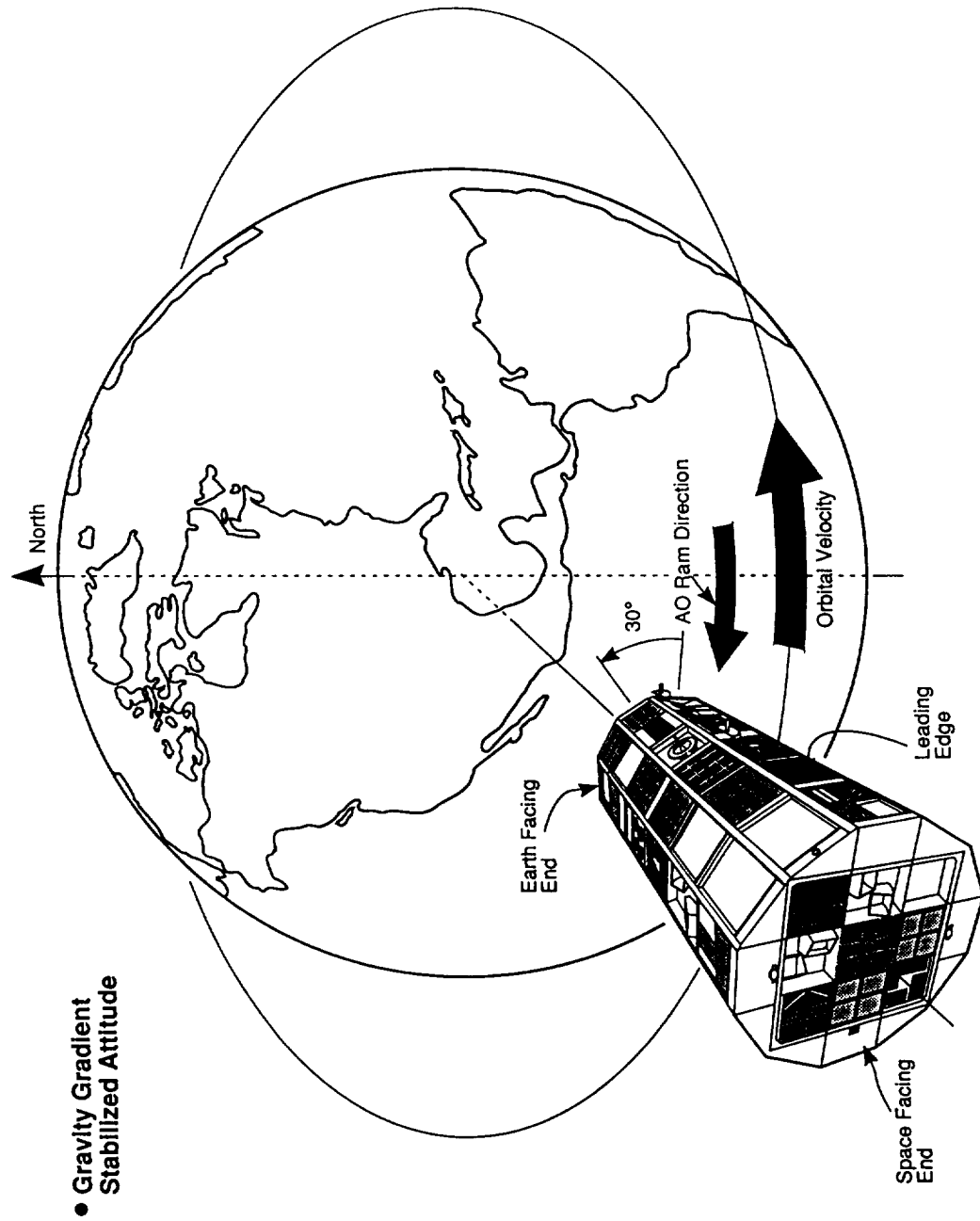


Figure 1. Schematic of LDEF in orbit.

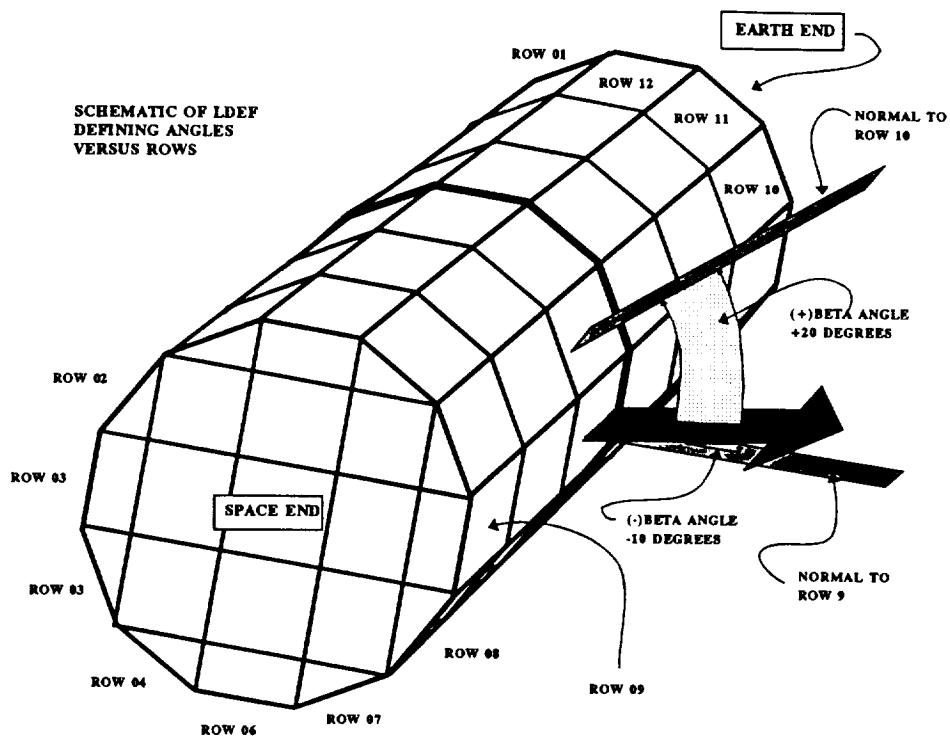


Figure 2. Definition of angle Beta.

FILE:HW/LDEF01

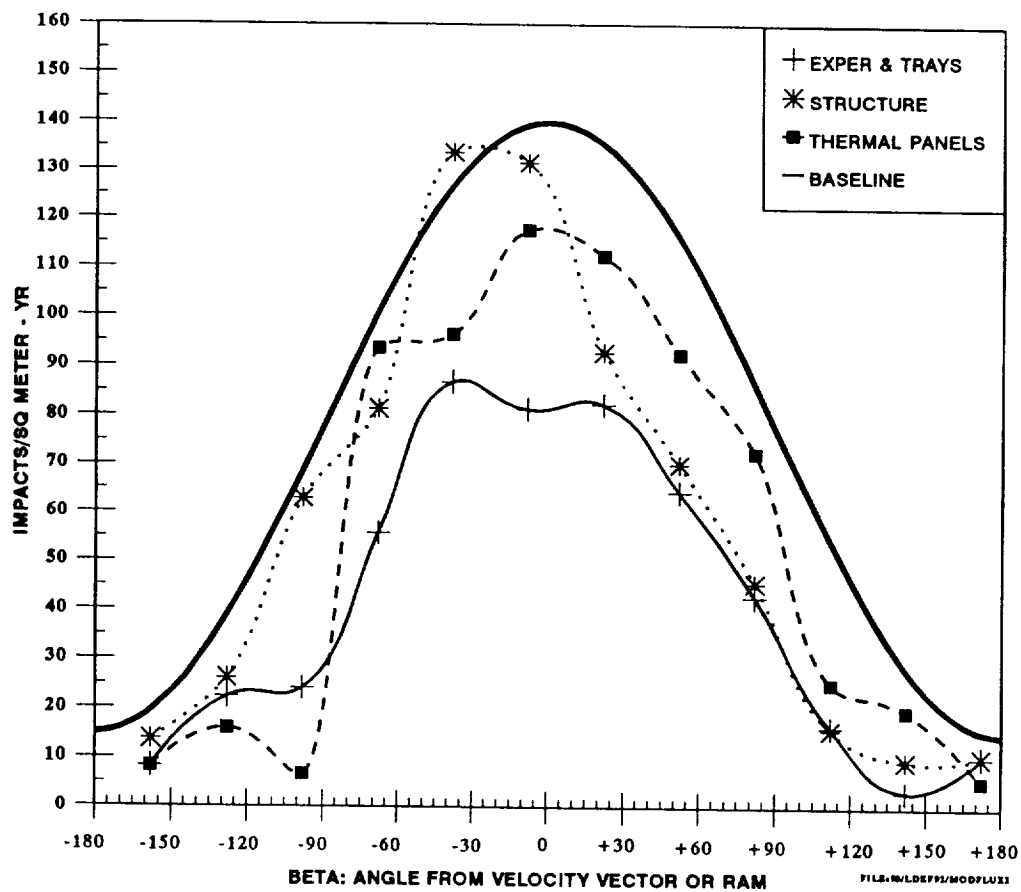


Figure 3. Directional dependence of meteoroid/space debris impact craters.

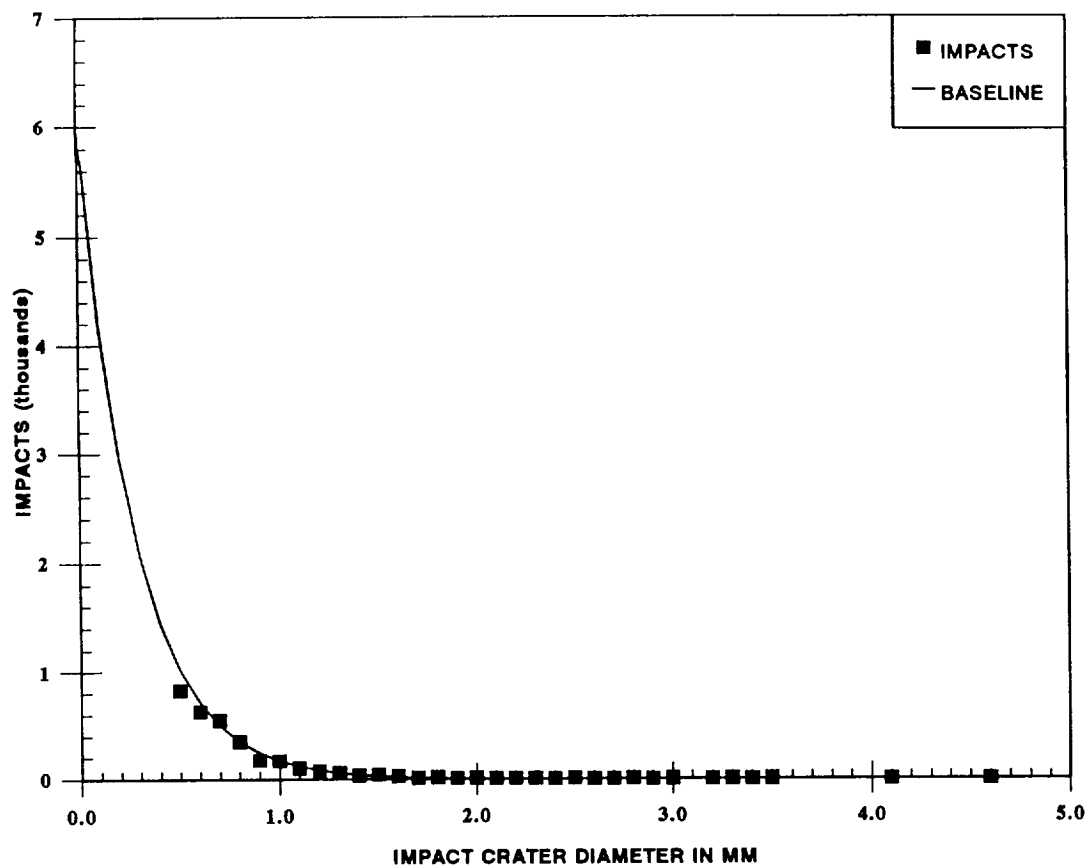


Figure 4. Size dependence of impact craters.

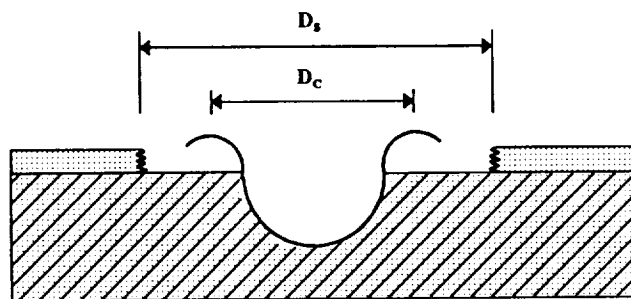


Figure 5. Definition of spall diameter and crater diameter.

COMPARISON OF LDEF FLIGHT  
COATINGS TO GROUND TEST SAMPLES

YB71 FLIGHT SAMPLE

1 mm

Z93 GROUND TEST SAMPLE

1 mm

Figure 6. Impact spall damage to white paints Z93 and YB71 having ceramic type binders.

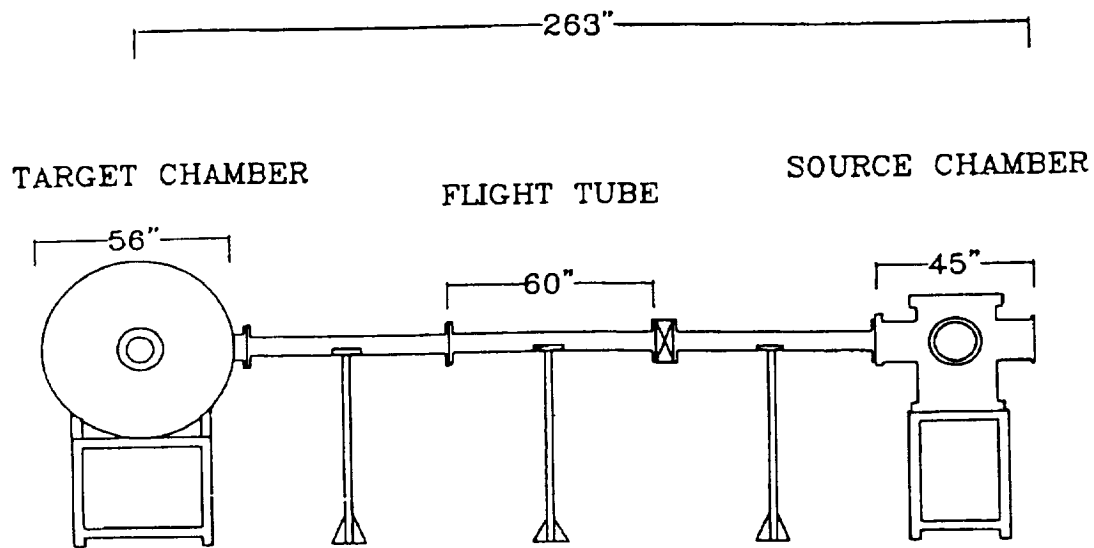


Figure 7. Schematic of AU's hypervelocity accelerator (ref. 6).

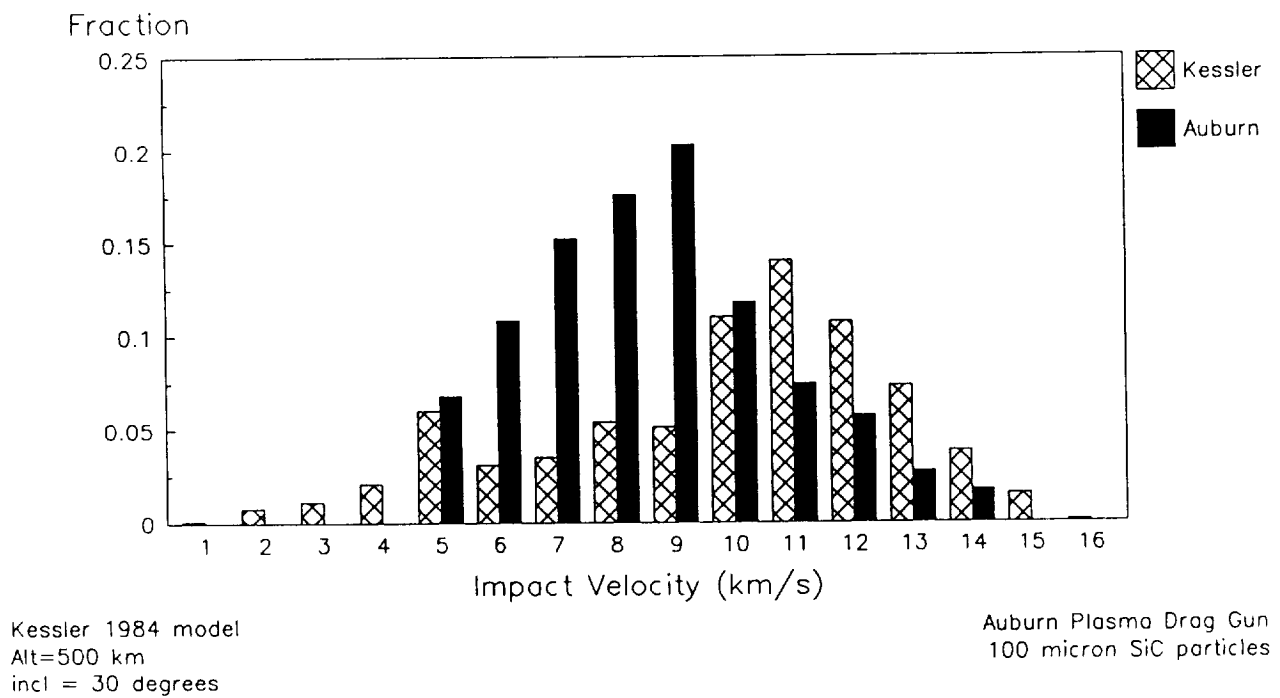


Figure 8. Particle impact velocity comparison between ground testing and flight.

**LDEF FLIGHT  
SAMPLE**



**HVI GROUND TEST  
SAMPLE**



**MSFC STUDY CONTRACT  
AUBURN UNIV.**

Figure 9. Impact spall damage to S13GLO white paint having a silicone type binder.





Figure 10. Impact spall damage to silver Teflon™ on LDEF experiment S0069 (ref. 9).

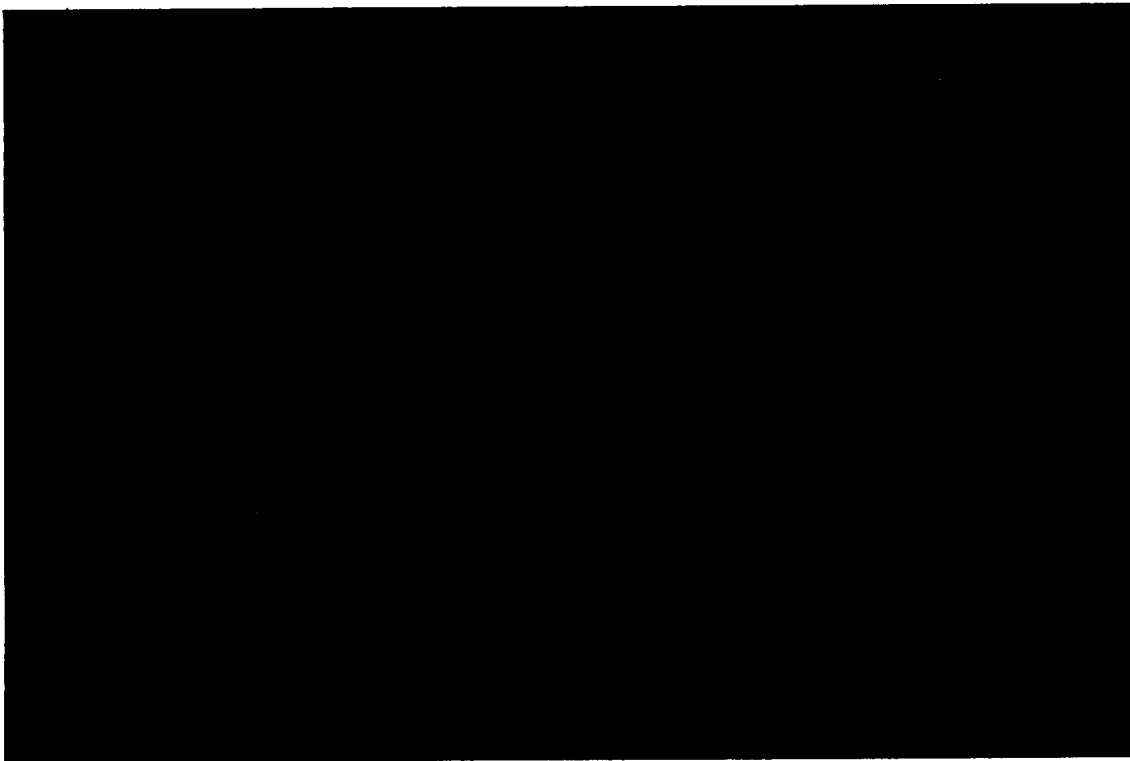


Figure 11. Impact damage to chromic anodized coating on LDEF experiment S0069 (ref. 9).

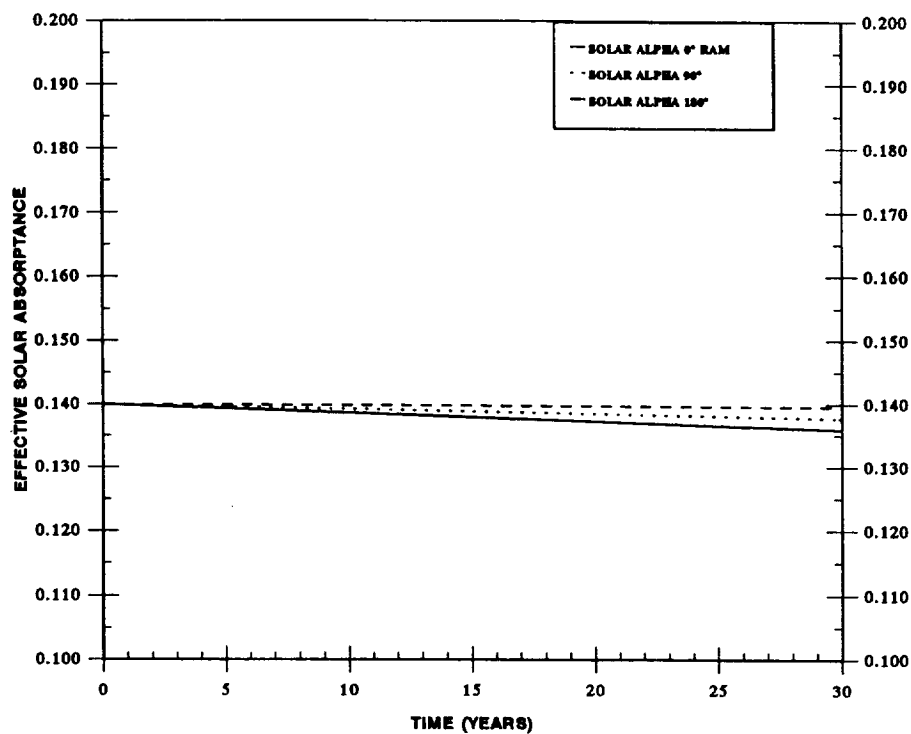


Figure 12. Z93 M/OD effect on solar absorptance versus time.

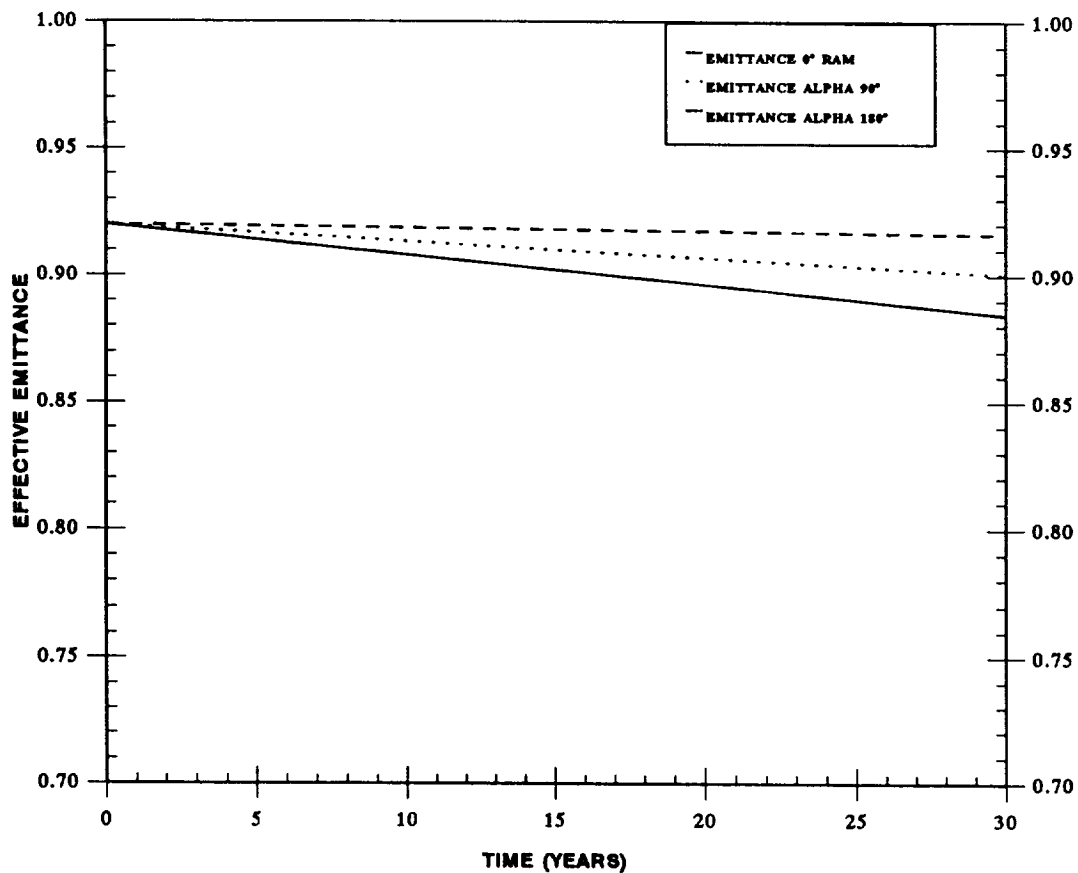


Figure 13. Z93 M/OD effect on emittance versus time.

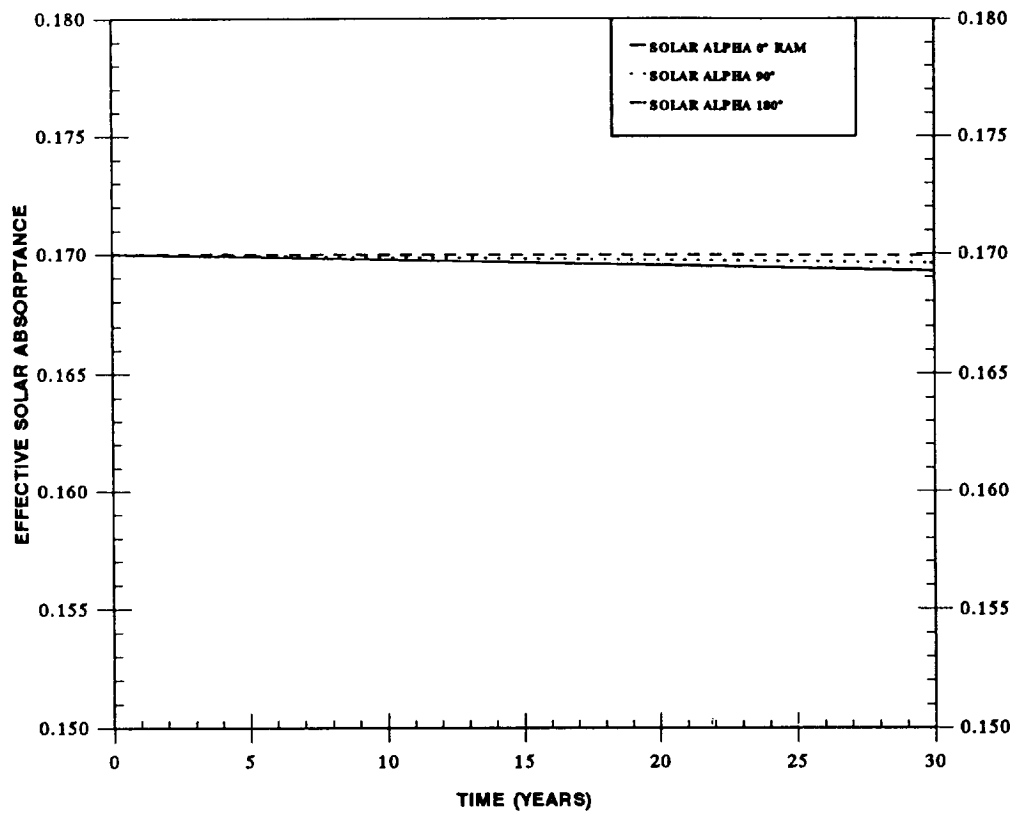


Figure 14. S13G/LO M/OD effect on solar absorptance versus time.

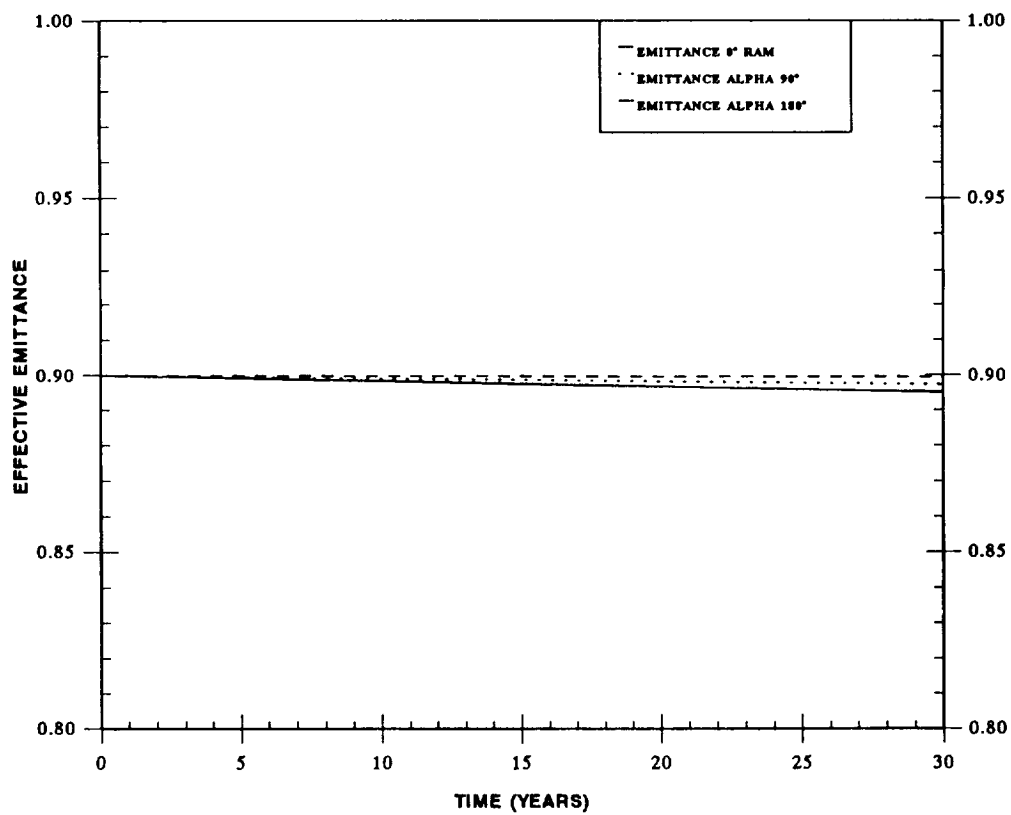


Figure 15. S13G/LO M/OD effect on emittance versus time.

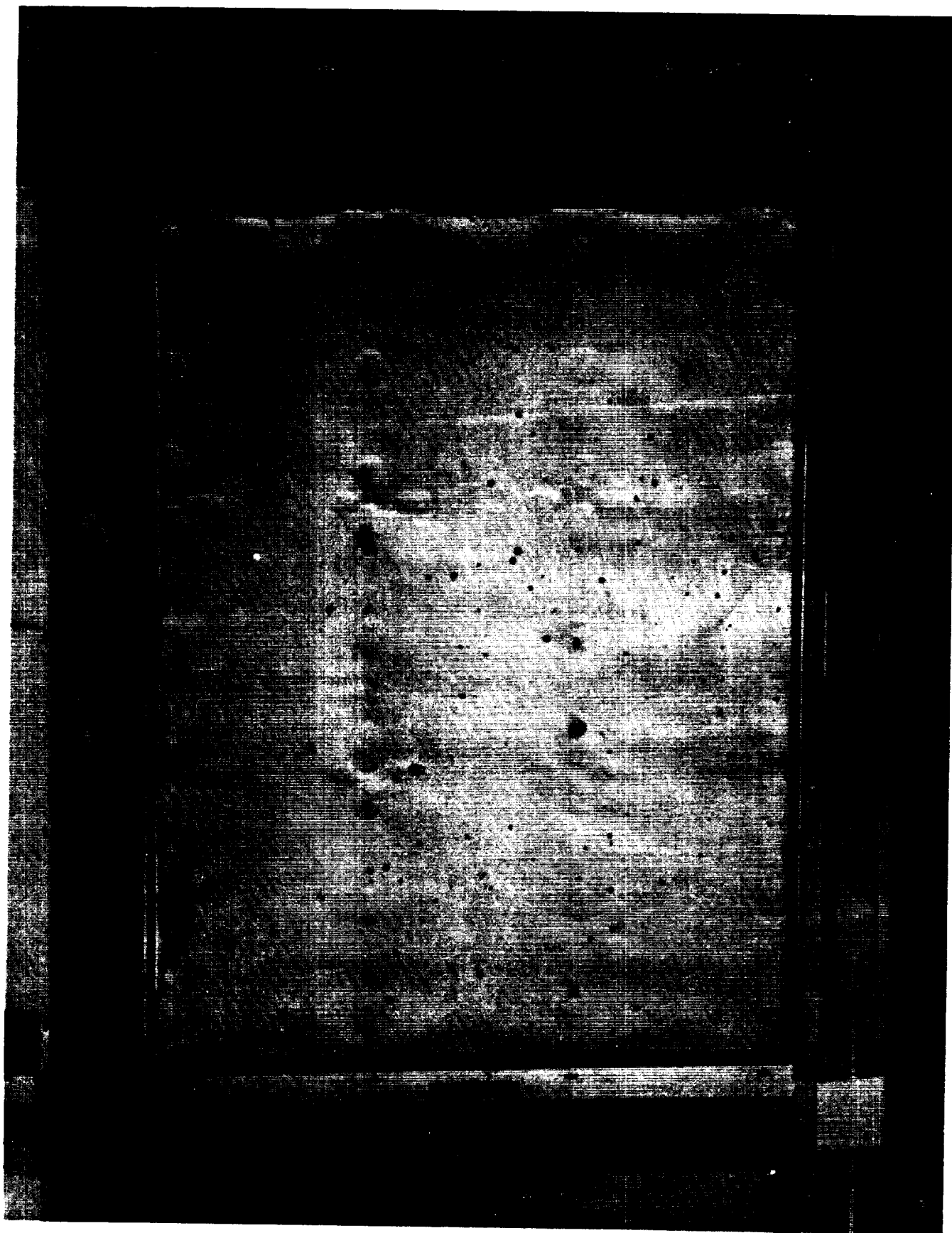


Figure 16. Silver Teflon™ blanket flown on LDEF experiment A0178 row 10E.

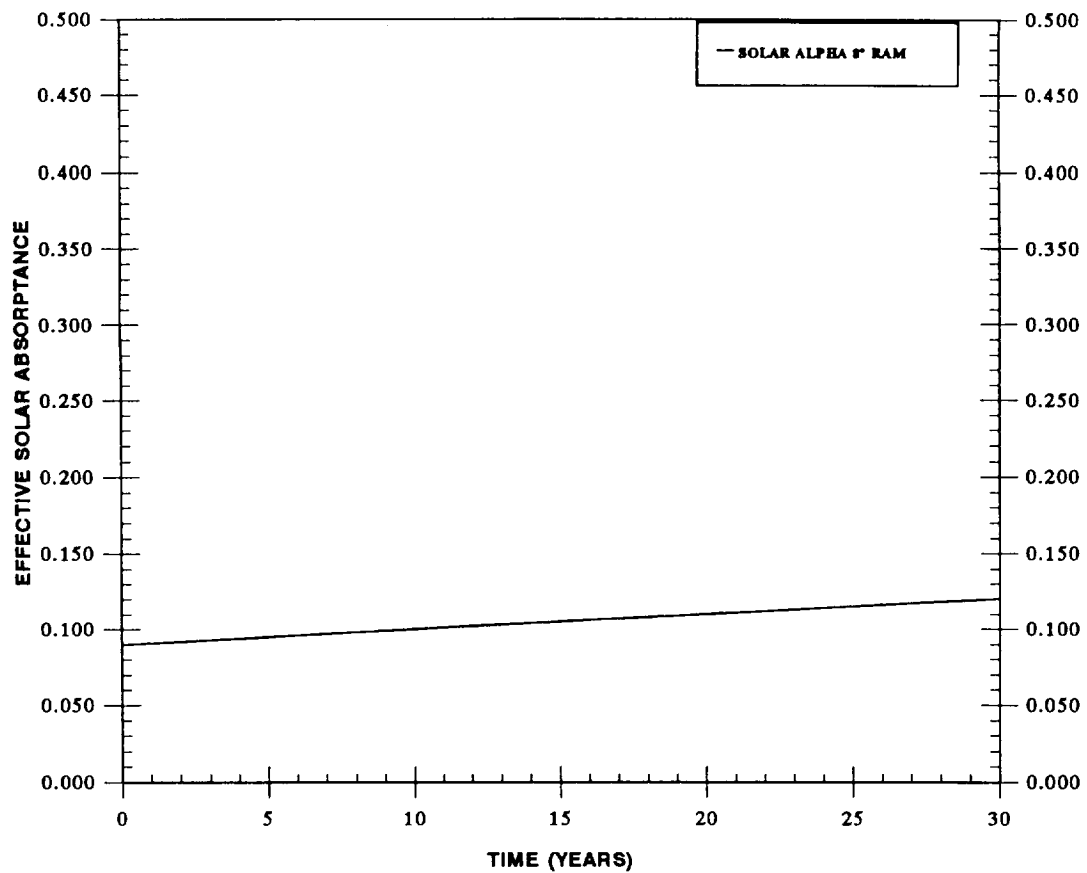


Figure 17. Ag/FEP M/OD effect on solar absorptance versus time.

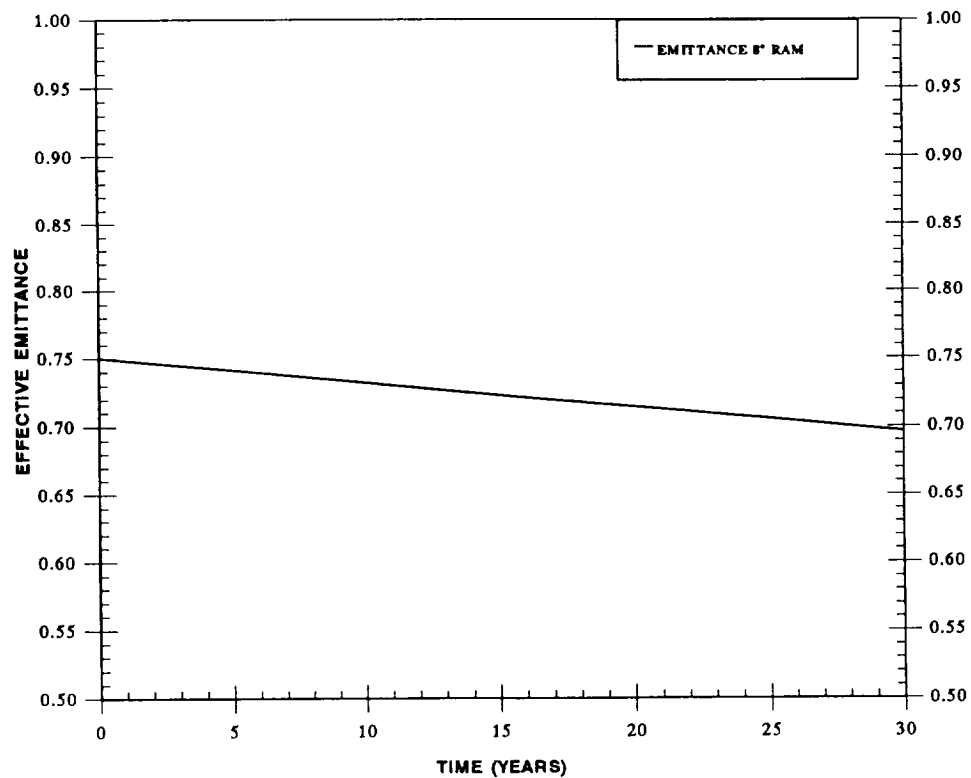


Figure 18. Ag/FEP M/OD effect on emittance versus time.

