

Predicted and Observed Directional Dependence of Meteoroid/Debris Impacts on LDEF Thermal Blankets

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SUMMARY

The number of impacts from meteoroids and space debris particles to the various LDEF rows is calculated using ESABASE/DEBRIS, a 3-D numerical analysis tool. It is based on recent reference environment flux models and includes geometrical and directional effects.

A comparison of model predictions and actual observations is made for penetrations of the thermal blankets which covered the UHCR experiment.

The thermal blankets were located on all LDEF rows, except 3, 9 and 12. Because of their uniform composition and thickness these blankets allow a direct analysis of the directional dependence of impacts and provide a test case for the latest meteoroid and debris flux models.

Introduction

In this paper the observed number of holes from particle impacts in the thermal blankets covering the Ultra High Cosmic Rays (UHCR) experiment on LDEF is compared to model predictions.

Trays of the UHCR experiment (AO178) were present on all LDEF rows except 3, 9 and 12. No trays were on the space and Earth pointing ends. The distribution of the thermal blankets on most of the 12 LDEF rows allows a detailed study of the directional dependence of impacts from meteoroids and space debris particles.

The LDEF was deployed in space on April 7, 1984 in an almost circular orbit with mean altitude 477 km and inclination of 28.5°. After a total exposure time in space of 5.76 years, it was retrieved on January 12, 1990. By that time the orbit had decayed to about 335 km.

LDEF was gravity-gradient stabilized with the longitudinal axis pointing towards the center of the Earth. After retrieval it was noticed that the flight attitude had been such that row 9 was facing about 8° off its nominal ram direction.

The thermal blankets covering the UHCR experiment were made of a compound of FEP Teflon ($\approx 125 \mu$) followed by thin layers of Silver and Inconel (combined less than 0.5μ) and Chemglaze Z306 black paint ($60 - 100 \mu$). The thermal blankets covered a total area of about 18 m^2 .

In the next section the procedure is presented which is used to calculate the number of impacts and penetrations on the thermal blankets and the results are given. The predicted and observed number of holes is then compared.

Numerical Analysis Procedure

Flux models have been developed for both micrometeoroids and space debris to predict the number of impacts for given mission parameters. The resulting damage can be assessed through empirically derived design equations which give penetration capabilities, crater sizes, etc. as function of the particle parameters.

For a detailed impact risk assessment a fully three dimensional numerical analysis tool was developed which includes directional and geometrical effects and spacecraft shielding considerations. It is based on the latest environment and particle/wall interaction models [1].

This tool is a new application of the ESABASE framework of system level analysis and engineering tools and is supported by enhanced 3-D graphics.

The user specifies the mission parameters, spacecraft geometry, attitude and shielding as well as the particle type, size and velocity range to be analysed. The computed output includes:

- the number of impacts,
- the number of failures, taking into account the spacecraft shielding and damage assessment equations,
- the probability of no failure,
- the mean particle velocity (amplitude and direction),
- the percentage of cratered area.

The new tool was applied to an ESABASE model of the LDEF.

Flux Model for Micrometeoroids

The total average meteoroid flux can be given in terms of the integral flux $F_{M,0}$ which is the number of particles with mass m or larger per m^2 per year impacting a randomly-oriented flat plate under a viewing angle of 2π . The unshielded interplanetary flux at 1 AU distance from the sun can be described analytically [2] as

$$F_{M,0}(m) = 3.15576 \cdot 10^7 (F_1(m) + F_2(m) + F_3(m))$$

where:

$$F_1(m) = (2.2 \cdot 10^3 m^{0.306} + 15)^{-4.38}$$

$$F_2(m) = 1.3 \cdot 10^{-9} (m + 10^{11} m^2 + 10^{27} m^4)^{-0.36}$$

$$F_3(m) = 1.3 \cdot 10^{-16} (m + 10^6 m^2)^{-0.85}$$

with m in grams.

It should be emphasized that the meteoroid flux model gives a yearly average. At times of peak activity of a major meteor stream fluxes can be up to 5 times higher for a 1-2 day period.

Relative collision velocities for meteoroids can range from 11 to 72 km/s.

The following velocity distribution is used in the present reference flux model [3]:

$$g(v) = \begin{array}{ll} 0.112 & \text{if } 11.1 \leq v < 16.3 \text{ km/s} \\ 3.328 \cdot 10^5 v^{-5.34} & \text{if } 16.3 \leq v < 55.0 \text{ km/s} \\ 1.695 \cdot 10^{-4} & \text{if } 55.0 \leq v < 72.2 \text{ km/s} \end{array}$$

The average impact velocity is about 17 km/s.

The unshielded flux $F_{M,0}$ has to be modified to account for the gravitational attraction (which enhances the meteoroid flux in the Earth proximity) and the geometrical shielding of the Earth (which reduces the flux). The gravitational enhancement factor G_e for the velocity distribution given above is defined as [3]:

$$G_e = 1 + \frac{R_e}{r}$$

where R_e is the mean earth radius and r is the orbit radius.

The meteoroid flux to an earth orbiting spacecraft is then given by: $F_M = F_{M,0}G_e$.

The Earth shielding factor for a given surface depends on the spacecraft altitude above the Earth surface and on the relative orientation of the surface normal with respect to the Earth direction. It is calculated numerically and applied for every surface element of the model.

For a surface with normal pointing towards Earth the flux is reduced by a factor $F = \cos^2\Theta$ relative to a surface pointing exactly away from Earth

(with: $\sin\Theta = (R_e + 100)/(R_e + h)$; R_e = Earth radius, h = spacecraft altitude).

The Earth shielding factor for a surface with normal perpendicular to the Earth direction (like the 12 LDEF rows) is given by:

$$F = 1 - 1/\pi (\Theta + 0.5 \sin 2\Theta).$$

According to ref. 3 the average density of micrometeoroids larger than 0.01 g is assumed to be 0.5 g/cm³. Smaller particles are thought to have a higher density; however, there is still a considerable uncertainty about these densities. In this study a constant value of 1.0 g/cm³ is used for the penetration analysis of the thermal blankets.

The assumption of spherical shape is made for converting particle diameters to masses.

According to the reference model used [3] the annual averaged meteoroid flux is omnidirectional with respect to the Earth surface. Relative to an orbiting spacecraft with fixed orientation w.r.t. the flight direction the meteoroid flux has a directional dependence.

When performing an impact analysis with the ESABASE/DEBRIS tool the impact flux and the directional dependence is obtained by a Monte Carlo procedure. For each surface element of the spacecraft model a user specified number of rays (typically several hundred) is analysed. Directions and velocities of the rays are selected at random but account for the flux distribution as given by the models (e.g. for meteoroids, isotropic impact direction with the exclusion of the Earth cone and the velocity distribution given above). To account for the spacecraft velocity each ray with given direction and velocity is then weighted by a factor:

$$k = v^3 / (v_m^2 v^*)$$

$$\text{with : } v^* = (v_m^2 - v_s^2 \sin^2 \alpha)^{0.5}$$

where v is the impact velocity, v_m is the meteoroid velocity, v_s is the spacecraft

velocity and α is the impact angle measured w.r.t. the flight direction.

A surface constantly facing into the flight direction will encounter about 7 times higher fluxes than a trailing surface. In addition, the average impact velocity for leading surfaces is higher as well.

The Earth shielding introduces a directional dependence as well. At an altitude of 470 km (and assuming an atmosphere thickness of 100 km) a surface with normal pointing directly towards Earth will receive about 9 times less impacts from meteoroids than a surface facing in the opposite direction towards space.

Flux Model for Space Debris

A new flux-diameter model, predicting the average space debris environment for low earth orbits, was recently published [3].

According to this model the cumulative flux of orbital debris of size d and larger on spacecraft orbiting at altitude h , inclination i , in the year t , when the solar activity for the previous year was S , is given by the following equation:

$$F = H(d) \cdot k_D \cdot \Phi(h, s) \cdot \Psi(i) \cdot [F_1(d) \cdot g_1(t) + F_2(d) \cdot g_2(t)]$$

where

F = flux in impacts per square meter of surface area per year

k_D = directional factor; = 1 for randomly tumbling surface

d = orbital debris diameter in cm

t = time expressed in years

h = altitude in km ($h \leq 2000$ km)

S = 10.7 cm-wavelength solar flux in year $t - 1$

i = inclination in degrees

and $H(d) = \sqrt{10^{\exp(-(\log_{10} d - 0.78)^2 / 0.637^2)}}$

$$\Phi(h, S) = \Phi_1(h, S) / (\Phi_1(h, S) + 1)$$

$$\Phi_1(h, S) = 10^{(h/200 - S/140 - 1.5)}$$

$$F_1(d) = 1.22 \times 10^{-5} \cdot d^{-2.5}$$

$$F_2(d) = 8.1 \times 10^{10} \cdot (d + 700)^{-6}$$

$$g_1(t) = (1 + q)^{(t-1988)}$$

$$g_2(t) = 1 + p(t - 1988)$$

q = the assumed annual growth rate of fragments in orbit.
 p = the assumed annual growth rate of mass in orbit.
 $q = 0.02$; $p = 0.05$, the values recommended by NASA are used in this study.

$\Psi(i)$ = inclination dependence of flux; $\Psi(28.5^\circ) = 0.931$

Impact velocities can range from 0 to about 15.5 km/s with an average velocity of 10 km/s.

For an oriented spacecraft surface the debris fluxes will be different for the various surfaces.

The present debris flux models are based on the approximation that all debris is moving in circular orbits. Relative to a moving spacecraft this implies that all space debris arrival directions are confined to a plane parallel to the surface of the Earth. The model excludes impacts from below (Earth direction) or above (space direction). Furthermore, for a spacecraft in circular orbit, a simple addition of velocity vectors shows that impacts can only occur under angles between 0° and 90° w.r.t. the flight direction and that every impact direction is associated with a unique impact velocity:

$$v = 2 v_o \cos \alpha.$$

The velocity distribution for a given orbit is specified as well in ref. 3 and included in the present study. For the LDEF orbit the model gives the following relative impact velocity distribution:

$$g(v) = v(2v_o - v) \left[18.7 e^{-((v-2.5v_o)/0.5v_o)^2} + 0.67 e^{-((v-1.3v_o)/0.56v_o)^2} \right] + 0.01156 v (4v_o - v)$$

with $v_o = 7.27$.

According to the reference model used, for $I = 28.5^\circ$, most impacts are expected from the sides, between 30° and 80° from the flight direction.

This distribution of space debris fluxes leads to a considerable directional dependence. For the LDEF orbit forward facing surfaces will receive about 2.6 times higher fluxes than randomly oriented surfaces while exactly backwards facing surfaces should encounter no impacts at all.

The average density of particles larger than 0.62 cm in diameter is assumed to be $\rho = 2.8d^{-0.74}$ g/cm³. The average density of smaller space debris particles is thought to be 4.0 g/cm³.

These densities were used for the present analysis.

Mission Parameters

For the calculation of meteoroid fluxes a constant altitude of 470 km was assumed. Given the weak dependence of meteoroid fluxes on the altitude that implies only a minor approximation. Average annual fluxes are used for this long duration mission.

For the space debris analysis the changing LDEF orbit and solar activity were considered. The mission was split into 8 different time periods. For each one of these periods the altitude and the value for the solar activity were kept constant.

The periods, altitudes and solar activity parameters chosen are given in Table 1 together with the relative contributions (last column) of each period to the total number of impacts from space debris. This relative weight is the same for any debris size.

Penetration Analysis

To calculate the number of holes in the blankets a design or damage equation has to be used which gives the ballistic limit for given target thickness and impact parameters. For the specific material compound of the thermal blankets a specific damage equation is not available.

In this study, the number of holes (punctures) is calculated by using the following equation which was derived for single metal plates (thin plate formula) [4]:

$$t = 0.57m^{0.352}\rho^{0.167}v^{0.875}$$

where:

- t : threshold thickness for penetration
- m : mass of projectile [g]
- ρ : density of projectile [g/cm³]
- v : impact velocity of projectile [km/s]

A puncture occurs whenever the threshold thickness for an impacting particle with given mass, density and velocity exceeds the shielding thickness of the surface under consideration.

Use of this equation for thermal blankets implies several approximations and uncertainties.

This equation was derived for normal impact directions. Impacts from both meteoroids and space debris particles, however, will generally not occur under normal direction. In that case the velocity entering into the equation can either be taken as the total impact velocity, assuming that over a wide range of angles the penetration capability is independent of the impact angle, or the normal component of the velocity can be used. In this study the total impact velocity was used.

The given equation is strictly valid only for Aluminium. Different procedures have been suggested to modify the equation or to derive an equivalent thickness for materials other than metals and for compounds (see e.g. ref.5). However, to avoid the introduction of another uncertainty in this study the equation was used as given above and applied to different effective thicknesses of the blankets: 200 μ , 225 μ and 250 μ .

Using a different equivalent thickness does change the absolute number of penetrations but has only a minor effect on their relative distribution on the various rows.

3-D Results

Predicted Number of Impacts

The predicted number of impacts from meteoroids and space debris particles on the 12 LDEF rows and the space and Earth ends as obtained by the ESABASE/DEBRIS analysis tool is given in Table 2. These results are for particles with a diameter of 100 μ or larger (assuming $\rho = 1 \text{ g/cm}^3$ and spherical shape for meteoroids). The results are given / m^2 and for the total mission duration of 5.76 years.

According to present models the directional distribution is the same for all particle sizes.

In this size regime the meteoroids are clearly dominating.

The directional dependence is noticeably different for meteoroids and space debris. Meteoroid impacts are predicted on all faces. The flux ratio front/rear is about 7 and the ratio space end/Earth end is about 9. (Note that this result is for constant impacting particle sizes. The ratio for constant crater dimensions will be different.)

Debris impacts are more concentrated on forward and side faces. As a direct consequence of the model assumption of circular orbits no impacts are predicted for the two ends and the very small number on row 3 is a result of the 8° attitude offset.

Observed Number of Holes

After an initial inspection at KSC 2/3 of each thermal blanket from the UHCR experiment was transported to ESTEC while the remaining 1/3 remained with NASA.

In total ESA received about 12 m² of thermal blankets from 16 different sections which were located on 9 different rows.

For a preliminary analysis at ESTEC each of the 16 sections was split into 6 subsections and the number of complete penetrations of the blankets was counted [*]. All subsections had roughly the same area of 0.11 m². The results for the total number of holes, independent of their size, are presented in Table 3. Given is the absolute count for each subsection and section and then for each section again the average number /m². In several cases there is a surprisingly large variation over the different samples from the same row. This is especially evident for the sections on rows 2, 7 and 10. Possible explanations for these differences are the encounter of localised clusters of particles or an uneven thickness of the thermal blankets (mainly the paint could vary in thickness). A final conclusion on these findings has not been reached.

Comparison of Predictions and Measurements

The predicted number of penetrations and the actually observed number of holes in the thermal blankets is presented in Table 4. Compared are the values /m². For the observations the average value is given if several sections were on the same row.

The calculated values in Table 4 are for an effective blanket thickness of 250 μ which gave the best overall agreement with the observations.

The clear majority of holes is predicted to result from meteoroid impacts.

The predicted number of holes is larger than the predicted number of impacts with $D > 100 \mu$ (Table 2) showing that smaller particles can penetrate the 250 μ blankets.

The relevance of the predicted absolute numbers should not be overstressed. Some of the main uncertainties in the numerical penetration analysis were mentioned before. For some parameters a sensitivity analysis was performed:

If the effective thickness of the blankets is reduced to 225 μ , the number of holes increases by 20 - 25 %. It increases by 70 - 80 % for a thickness of 200 μ .

For the assumed blanket thickness the predicted number of penetrations from meteoroids increases by 20 - 30 % if the density of meteoroids is increased from 1 g/cm³ to 2 g/cm³. For a lower density the number is reduced correspondingly.

In all these cases the directional distribution of the holes is relatively little changed.

The measurements indicate some systematic deviation from the predicted directional dependence. The front/rear ratio of observed holes is larger than predicted. Such a discrepancy could have several reasons. It is possible that the directional dependence (especially for meteoroids) is not treated accurately enough in the numerical tool.

* F.Levadou, private communication, ESA/ESTEC, 1991.

Another possible explanation is that the fluxes of Earth orbiting particles which would heavily favor impacts on forward pointing faces are underestimated by the models. The man made debris population could be larger than assumed or a belt of Earth orbiting meteoroids could exist, as was suggested before (see e.g. ref. 5).

In addition there clearly is a North/South asymmetry with more penetrations having occurred on the North side (centered around row 12). Such a North/South asymmetry was reported before, and in the microabrasion package experiment MAP AO 023, it was found to be reversed for crater diameters smaller than 20 μ .

Conclusion

Predicted and observed numbers of holes on LDEF AO178 thermal blankets were compared. The predictions are based on reference flux models which are presently used as standards for spacecraft shielding design and analysis purposes. A recently developed 3-D numerical analysis tool was used for the actual calculations.

The overall agreement is quite good but some systematic differences in the directional dependence are found.

In this study only the number of complete penetrations is compared. A more detailed study of the observed impact features including analysis of crater dimensions, geometries and morphologies is in progress. The measured size distribution of penetration holes in these blankets with diameters $> 300 \mu$ has been reported before [6].

It would be highly desirable to distinguish between impacts from meteoroids and man made debris. That would require a chemical analysis of particle residues in the craters. Such an element analysis has been successfully performed for impacts on other LDEF surfaces and structural parts. For most impact features on these thermal blankets, however, such an analysis seems not feasible. As the blankets are very thin few residues are found. In addition the blanket material compound contains a large range of elements which makes it very difficult to distinguish material from the blankets and the impactor.

Despite these shortcomings the blankets (which were not designed for impact analyses) have already provided much new information on the meteoroid and debris environment and more can be expected as results of more detailed analyses become available.

References

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6. T.H.See, F.Hörz, M.E.Zolensky, M.K.Allbrooks, D.R.Atkinson and C.G.Simon, 'Meteoroid and Debris Special Investigation Group Preliminary Results: Size-Frequency Distribution and Spatial Density of Large Impact Features on LDEF', Proceed. of First LDEF Post-retrieval Symp., NASA CR 3134, Part 1, P.477, 1991.

Table 1: Parameters used for LDEF space debris analysis. The last column gives the relative contribution of each period.

Period	S_{t-1}	h [km]	Δt [years]	$\Phi_{g_1} \Delta t$
7/4/84 - 31/12/84	120	475	0.73	0.344
1/1/85 - 31/12/85	100	475	1.0	0.557
1/1/86 - 31/12/86	75	470	1.0	0.647
1/1/87 - 31/12/87	75	465	1.0	0.648
1/1/88 - 31/12/88	85	455	1.0	0.595
1/1/89 - 30/6/89	120	415	0.5	0.175
1/7/89 - 31/12/89	160	370	0.5	0.071
1/1/90 - 12/1/90	200	340	0.033	0.002

Table 2: Predicted number of impacts, N_I , from meteoroids ($\rho=1.0 \text{ g/cm}^3$) and space debris with particle diameters $D > 100 \mu$ on the various LDEF faces. The values given are per m^2 and for the total LDEF mission duration of 5.76 years.

Row	$N_{I,met}$	$N_{I,deb}$	$N_{I,tot}$
	[impacts / m^2 / 5.76 years]		
1	20.8	2.75	23.6
2	11.3	0.417	11.7
3	7.26	4.40 E-4	7.26
4	8.46	3.90 E-2	8.50
5	15.0	1.26	16.3
6	26.6	4.11	30.7
7	39.2	6.10	45.3
8	47.7	7.46	55.2
9	51.4	8.86	60.3
10	50.4	8.35	58.8
11	44.3	6.75	51.1
12	33.3	5.35	38.7
Space end	42.7	0	42.7
Earth end	4.49	0	4.49

Table 3: Observed number of holes on LDEF thermal blankets.

Location	Number of holes counted		Holes /m ²
	count on 6 subsections	sum	
D1	14,9,9,6,10,8	56	85
A2	0,2,0,6,1,3	12	18
E2	6,6,7,4,7,1	31	47
A4	2,4,4,5,6,1	22	34
F4	1,4,2,2,4,3	16	24
B5	1,5,3,2,5,2	18	27
C5	4,3,2,4,5,3	21	32
D5	5,3,4,2,7,2	23	35
C6	8,7,9,10,4,8	47	70
B7	15,29,25,28,34,23	154	235
D7	17,13,8,20,22,22	102	156
C8	28,23,27,26,26,22	152	232
A10	51,49,53,35,34,45	267	408
E10	28,32,40,30,33,29	192	293
C11	26,25,24,26,23,25	149	227
D11	23,27,24,27,28,33	162	247

Table 4: Comparison of predicted and observed number of holes, N_h , /m² on LDEF thermal blankets.

Row	Predicted			Observed
	$N_{h,met}$	$N_{h,deb}$	$N_{h,tot}$	
1	72.1	21.3	93.4	85
2	31.8	1.48	33.3	32.5
4	18.6	0.06	18.7	29
5	41.0	7.17	48.2	31.3
6	92.8	32	125	70
7	156	47.4	203	195.5
8	201	62.8	264	232
10	213	66.6	280	350.7
11	188	58.6	247	237

