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METEOROID/DEBRIS IMPACT ANALYSIS APPLICATION TO LDEF, EURECA AND COLUMBUS

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ABSTRACT

Meteoroid/debris impact analyses are performed using ESABASE/DEBRIS, a 3-D numerical analysis tool. It is based on reference flux models and damage equations and includes geometrical and directional effects. The tool is applied to LDEF, EURECA and the Columbus APM. For LDEF, the number of penetrations through 180 μ thick thermal blankets and through a 5 μ foil are calculated and, for the blankets, compared to observations. For EURECA, the number of impacts from meteoroids and space debris particles with diameter > 10 μ is predicted. An assessment of the risk of penetration is performed for the Columbus APM. A probability of no penetration of 0.9981 per year is predicted for the analysed configuration and shielding design.

1. INTRODUCTION

Every spacecraft in low Earth orbit is exposed to a certain flux of micrometeoroids and man made space debris.

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 (Ref. 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.

This tool was applied to ESABASE models of LDEF, EURECA and the Columbus APM.

2. FLUX MODEL FOR METEOROIDS

The total average meteoroid flux is given in terms of the integral flux F_{MI} 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 (Ref. 2) as :

$$F_{MI}(m) = 3.15576\ 10^7(F_1(m) + F_2(m) + F_3(m)) \qquad (1)$$

where:

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

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

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

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.

The unshielded flux F_M 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 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.

Relative collision velocities for meteoroids can range from 11 to 72 km/s. The average impact velocity is about 17 km/s.

According to Ref. 3 the average density of micrometeoroids larger than 0.01 g is assumed to be 0.5 g/cm^3. 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/cm^3 is used. The assumption of spherical shape is made for converting particle diameters to masses.

According to present models 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.

3. FLUX MODEL FOR SPACE DEBRIS

A new flux–diameter model, predicting the average space debris environment for low Earth orbits was recently published (Ref. 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:

$$F_D = H(d) \cdot k_D \cdot \Phi(h, s) \cdot \Psi(i) \cdot [F_1(d) \cdot g_1(t) + F_2(d) \cdot g_2(t)] \qquad (2)$$

where

F_D = 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; $\Psi(28.5°) = 0.91$

Impact velocities can range from 0 to about 15.5 km/s with an average velocity around 10 km/s for low inclination orbits. The velocity distribution for a given orbit is specified as well in Ref. 3 and included in the present study.

The average density of particles larger than 0.62 cm in diameter is assumed to be $\rho = 2.8 d^{-0.74}$ g/cm^3. The average density of smaller space debris particles is thought to be 4.0 g/cm^3. These densities were used for the present analysis.

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 on 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 to a unique impact velocity ($v_{max} = 2\ v_{spacecraft}$ for head on collisions). According to present models, for I = 28.5°, most impacts are expected from angles between 25° and 70° from the flight direction.

For spacecraft with varying orientations with respect to the flight direction, as Eureca, the fluxes from both meteoroids and space debris to given surfaces change constantly along the orbit. This is taken into account in the present analysis.

4. DAMAGE ANALYSIS

To assess the damage resulting from an hypervelocity impact the failure mode (e.g. perforation of a shield or penetration up to a certain depth into a material), the shielding type (e.g. single or multiple wall shield) and the shielding thickness have to be provided. In addition, so called damage or design equations have to be used which define for given shielding and impacting particle parameters (mass, velocity, density, direction) whether a failure will occur or not.

The damage equation corresponding to a single plate shielding was used for the present LDEF failure assessment. The number of failures (penetrations) is calculated by using the following equation for a single Aluminium plate (thin plate formula):

$$t = 0.57 m^{0.352} \rho^{0.167} v_n^{0.875} \quad (3)$$

where:

t : threshold thickness for penetration
m : mass of projectile [g]
ρ : density of projectile [g/cm^3]
v_n : normal component of the impact velocity of the projectile [km/s]

This equation was derived for normal impact velocities.

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.

For the risk analysis of the Columbus APM, which is shielded by a double bumper and a main wall, a more complex damage formula is used to calculate the penetration of the main wall. It is derived by scaling from a more standard single bumper Whipple shield. The full equation (ESA TRIPLE WALL) and required input parameters are given in Ref. 1.

5. APPLICATION TO LDEF

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 8° off its nominal ram direction.

Table 1 compares predicted and observed holes in the thermal blankets which covered the UHCR (AO 178) experiment. The thermal blankets were made of a compound of FEP Teflon ($\approx$ 125 μ) followed by thin layers of Silver and Inconel (combined less than 0.5 μ) and Chemglaze Z306 black paint. The total thickness is about 180 μ with some variation because of uneven paint thickness.

The thermal blankets were present on all LDEF rows except 3, 9 and 12. They covered a total area of about 18 m^2.

The values in Table 1 are given per m^2. For the observations the average value is given if several sections were on the same row. A more detailed description of the distribution of observed holes is given in Ref. 4.

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

The absolute numbers agree quite well for the forward and sideward facing rows while the observed number of holes is underestimated for the more backward facing rows. The latter can, at least partially, be explained by the simplified debris model used which does not include particles in eccentric orbits and therefore predicts no debris impacts on trailing surfaces.

Space debris particles have been identified on trailing surfaces (Refs. 5,6) and the need to improve the space debris model to include elliptical orbits had been noted before (see e.g. Ref. 7).

When assessing the present comparison one has to keep in mind some of the assumptions made in the numerical analysis. The impact damage on a compound as function of particle velocity, impact direction and density is not accurately known. In the present analysis the thermal blanket Teflon/Silver/paint compound was modelled by a single Aluminium plate of 180 μ thickness. The material erosion by atomic oxygen, which effected the various rows to different levels was ignored.

The normal component of the impact velocity was used for the penetration analysis. When the total velocity component is used instead, the present predicted ratio of 30.8 for holes on rows 10 and 4 is reduced to 15 (for a 250 μ foil, see Ref. 4).

Table 2 gives the predicted number of penetrations through a 5 μ thick Aluminium foil for the various LDEF faces. Such a foil thickness will sample particles of about 1 μ size or larger and in this size regime the predicted debris flux is far larger than the micrometeoroid flux, at least for forward and sideward faces.

Experimental measurements (Ref. 8) confirm the dominance of debris particles in this size regime but the present space debris model seems to overestimate the actual flux by as much as 3–10 times , depending on the surface orientation.

Some refinement of the debris model for smaller sizes is certainly needed.

While the present comparison clearly shows that flux models need to be improved in certain aspects it is also evident that overall the present models are validated by the LDEF results.

6. APPLICATION TO EURECA

The ESABASE model used for the 3–D impact analysis of EURECA is shown in Figs. 1 and 2.

EURECA was launched on July 31, 1992 and is presently scheduled to be retrieved in May 1993. The attitude of EURECA is sun–pointing: one face of the spacecraft and the solar arrays, which are rigidly attached to the main body, are always facing to the sun. The y–axis (long axis of main body, see Figs. 1 and 2) is in the orbital plane.

For the actual EURECA impact analysis the following parameters were used in the flux models:

- h = 515 km, I = 28.5°, circular orbit.
- S = 140, corresponding to a mean solar activity.
- q = 0.02; p = 0.05 as growth rates
- t = 1992, as reference year for the debris flux.

The analysis was performed for a total mission duration of 9 months. The sun–pointing attitude of the spacecraft is fully taken into account.

The results are shown in Figs. 1 and 2, superimposed on the ESABASE model of EURECA.

Figure 1 shows the predicted number of impacts from meteoroids with diameter 10 μ or larger per m^2 for the EURECA mission. A meteoroid density of $\rho = 1$ g/cm^3 and spherical shape were assumed to convert diameters to masses. Figure 2 shows the corresponding predicted space debris flux.

For the size range considered the absolute number of impacts from meteoroids and debris are comparable, ranging from 100 to 200 per m^2 for most outer surfaces.

Impact features created by 10 μ particles could be just observable on certain surfaces, like the solar array cover glasses. For other materials, like the MLI which covers most parts of the main body, larger particles will generally be required to leave observable marks.

The sun–pointing attitude of EURECA leads to an averaging out of directional effects. The orientation of a given surface w.r.t. the ram and Earth direction, which are most important for the directional distribution of impacts changes constantly along the orbit. Besides some self shadowing of some spacecraft parts the only more noticeable directional effect predicted is an increased space debris flux on the 'sides' of the main body (with surface normals in +/- X direction).

These surfaces actually never face directly into the ram–direction but they are always exposed to some debris flux.

An EURECA meteoroid/debris post–flight analysis is planned after retrieval to compare model predictions and observations.

7. APPLICATION TO THE COLUMBUS APM

An assessment of the risk of penetration was performed for the Columbus Attached Pressurized Module (APM). The analysis was carried out for the present shielding design which consist of 2 Aluminium bumpers of 0.8 mm thickness each and a main Aluminium wall of 3.2 mm. The spacing between the two bumpers and between the second bumper and the rear wall is 6 cm. The design equation used for the analysis is given in Ref. 1 (ESA TRIPLE WALL).

The following parameters were used in the flux models:

- h = 400 km, I = 28.5°, circular orbit.
- S = 70, corresponding to a worst case solar activity.
- q = 0.02; p = 0.05 as growth rates
- t = 2004, as reference year for the debris flux.

The analysis was performed for a mission duration of 1 year.

The ESABASE model of Fig. 3 shows the Space Station Freedom configuration analysed. Calculations were performed for 2 different attitudes with pitch angles of 17° and 35°. The first case represents the free–flying attitude while the second is the shuttle attached case.

Figure 3 shows the predicted number of penetrations from space debris particles superimposed on the ESABASE model of the Space Station. For the present analysis the same shielding was assumed for all modules.

The results are $/m^2/year$ and for the free–flying attitude. As expected from the flux model forward and sidewards facing surfaces encounter the highest penetration fluxes, reaching a maximum of about 8×10^{-5} $/m^2/year$.

For the Columbus APM, the number of penetrations from meteoroids and space debris and the resulting probability of no penetration is summarized in Table 3. These results were obtained by assuming the free–flying attitude for 90% of the time and the shuttle attached case (which leads to slightly higher impact fluxes) for 10% of the time.

The main results are given in the first row of Table 3 which includes particles of all sizes capable of penetrating the APM shield.

The other 3 rows of Table 3 give the corresponding numbers when considering only particles larger than 1, 2 and 10 cm diameter respectively. The resulting number of penetrations can give an indication about the hypothetical risk that would remain if shielding protection could be provided against all smaller particles. Of course, these numbers are only an indication, as the penetration capability also depends on the impact velocity and direction.

When going back to the first row, which gives the results for all particles, it is seen that for the relatively heavy shielding of the APM the space debris particles, which dominate in LEO for sizes larger than about 1 mm, pose a far larger thread than meteoroids. A total probability of no penetration of 0.99811 per year is predicted for the APM in the baseline environment for the present shielding design.

References

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Row	$N_{F,met}$	$N_{F,deb}$	$N_{F,tot}$	Observed
1	37.9	4.67	42.6	85.0
2	14.3	$5.33\ 10^{-2}$	14.4	32.5
3	8.22	$< 10^{-6}$	8.22	
4	9.47	$4.47\ 10^{-4}$	9.47	29.0
5	22.4	0.671	23.1	31.3
6	58.4	18.0	76.4	70.0
7	119.5	76.0	195.5	195.5
8	182.7	77.4	260.1	232.0
9	215.9	92.6	308.5	
10	206.6	84.8	291.4	350.7
11	158.0	77.3	235.3	237.0
12	87.5	46.8	134.3	
Space end	91.8	0	91.8	
Earth end	1.46	0	1.46	

Table 1: Predicted and observed number of penetrations ($/m^2/$ 5.76 years) of LDEF thermal blankets (180 μ). $\rho_{met} = 1$ g/cm^3, $\rho_{deb} = 4$ g/cm^3, normal component of impact velocity.

Row	$N_{F,met}$	$N_{F,deb}$	$N_{F,tot}$
1	3265	2.26E+4*	2.59E+4
2	1430	258	1688
3	844	$< 10^{-6}$	844
4	994	2.17	996
5	2103	3248	5351
6	4646	8.71E+4	9.17E+4
7	8240	3.68E+5	3.76E+5
8	1.15E+4	3.75E+5	3.87E+5
9	1.30E+4	4.48E+5	4.61E+5
10	1.26E+4	4.10E+5	4.23E+5
11	1.02E+4	3.74E+5	3.84E+5
12	6435	2.26E+5	2.32E+5
Space end	7342	0	7342
Earth end	318	0	318

* **E+4 denotes:** $\times 10^{+4}$

Table 2: Predicted number of penetrations, N_F, ($/m^2/$ 5.76 years) of a 5 μ thick Aluminium foil for the various LDEF faces. $\rho_{met} = 1$ g/cm^3, $\rho_{deb} = 4$ g/cm^3, normal component of impact velocity.

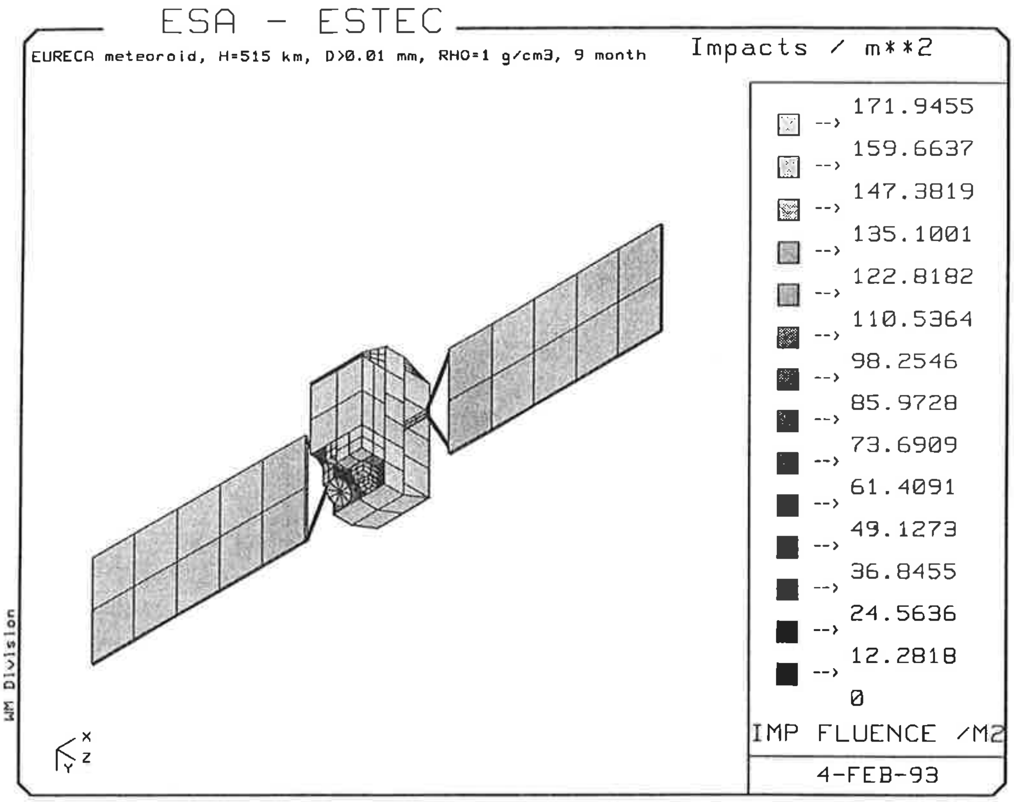

Figure 1: Predicted impact distribution on EURECA for meteoroids with diameter larger than 10 μ.

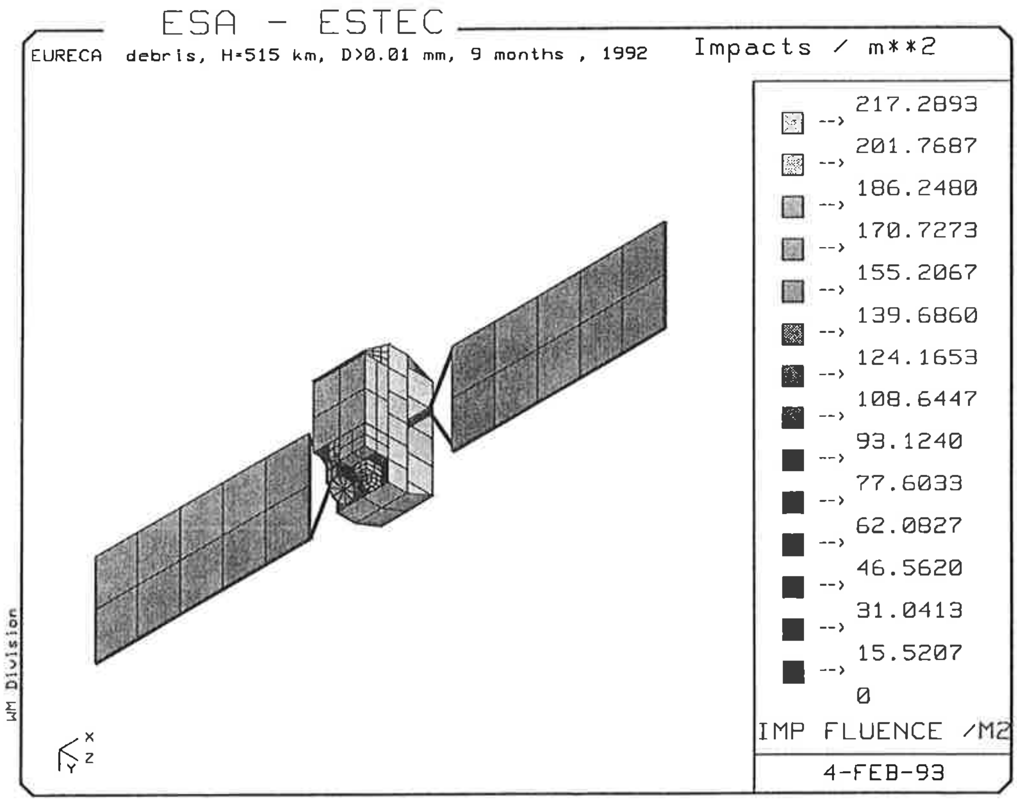

Figure 2: Predicted impact distribution on EURECA for space debris with diameter larger than 10 μ.

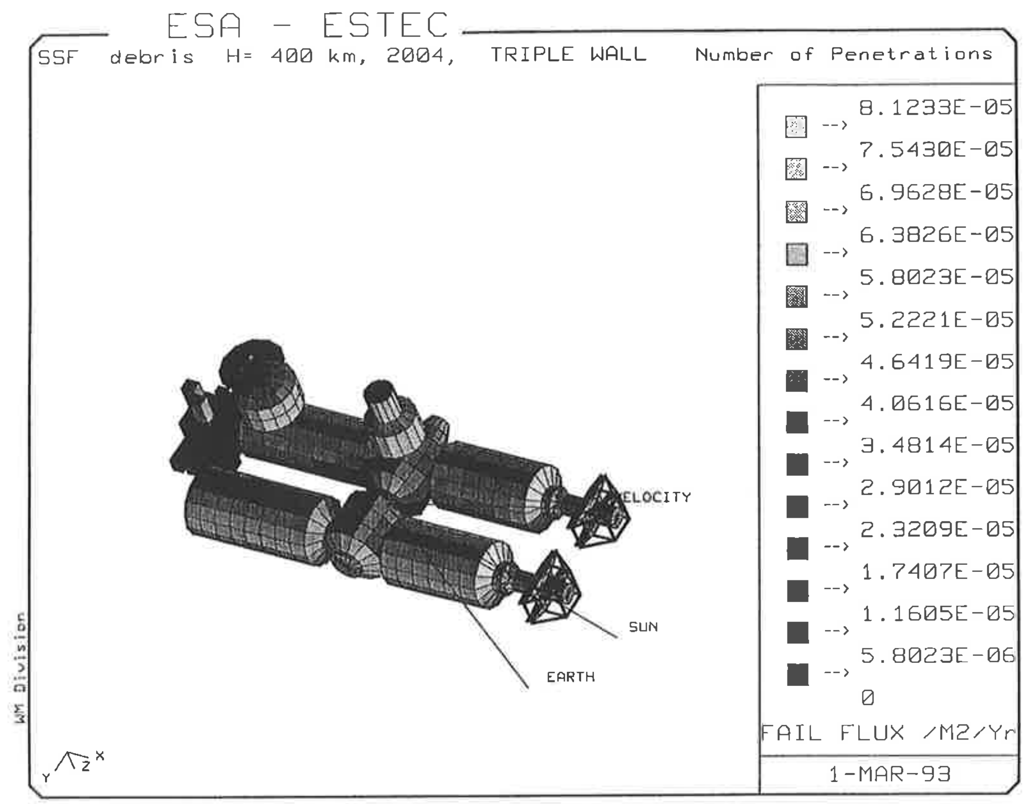

Figure 3: Predicted number of penetrations ($/m^2$/year) for Space Station Freedom. A triple wall Aluminium shielding with two 0.8 mm bumpers, a 3.2 mm main wall and 6 cm spacings is assumed for all modules.

d (cm)	$N_{F,deb}$	$N_{F,met}$	$N_{F,tot}$	$P_{0,deb}$	$P_{0,met}$	$P_{0,tot}$
all	1.729E-03	1.631E-04	1.893E-03	0.99827	0.99984	0.99811
1.0	7.986E-04	5.297E-05	8.516E-04	0.99920	0.99995	0.99915
2.0	2.935E-04	3.967E-06	2.975E-04	0.99971	1.00000	0.99971
10.0	1.220E-04	< 1.0E-10	1.220E-04	0.99988	1.00000	0.99988

Table 3: Number of penetrations, N_F, and probability of no penetration, P_0, (per year) of the APM triple wall shield due to particles with diameter d or larger for the SSF nominal mission (H=400 km, year=2004, 90 % free flying, 10 % shuttle attached).