METEOROID/ORBITAL DEBRIS IMPACT DAMAGE PREDICTIONS FOR THE RUSSIAN SPACE STATION *MIR*

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ABSTRACT

Components of the Mir Space Station have been exposed to the meteoroid/orbital debris (M/OD) environment for up to 11 years. Over this period of time, no M/OD impact induced perforation of the pressure shell of the manned modules has been reported. The NASA standard M/OD analysis code BUMPER has been used to predict the probability of M/OD impact damage to various components of the Russian space station Mir. BUMPER analysis indicates a 1 in 2.2 chance from first flight to present (February 1997) that a M/OD impact would have caused a penetration resulting in a pressure leak of the Mir modules. For the next 5 years, the estimated odds become 1 in 3. On an annual basis, penetration risks are approximately 60% higher on average in the next five years as compared to the first 11 years, due to the larger size of the Mir complex and growth in the orbital debris population.

NOMENCLATURE

d_c critical particle diameter at failure (cm)
ρ_p particle density (g/cm^3)
S shield standoff distance (cm)
t_b bumper thickness (cm)
t_w rear wall thickness (cm)
θ impact angle from target normal (deg)
V particle velocity (km/s)
V_n normal velocity component, V cos θ (km/s)

1. INTRODUCTION

The Russian Mir Space Station represents a significant source of information concerning the effects of meteoroid/orbital debris (M/OD) environment due to its large area (now ~1500 m^2 including solar arrays) and long exposure duration (over 11 years for some components). Of particular interest is the use of Mir data to compare to predicted levels of M/OD impact using the NASA standard M/OD analysis code BUMPER. There have been no reported pressure leaks of the crew modules on Mir since the first element of Mir, the Mir core module, was launched February 1986 (Ref.1). A Russian estimate of probability of no penetration (PNP) for 9.5 years of exposure from 1986 through 1995 of the Mir crew modules was 0.84, equivalent to odds of penetration of 1 in 6 (Ref.1). However, this calculation included only orbital debris impact and did not include meteoroids (Refs.1,13). BUMPER has been used to predict crew module leak probability for the time period from first element launch to present (February 1997) to compare to the observed zero leak rate including both meteoroid and orbital debris environments. BUMPER was also used to make a PNP prediction for Mir crew modules over the next five years. A PNP calculation by Russian sources for a 5-year period from 1996 to 2000 was 0.887 or odds of ~1 in 9 for a leak from orbital debris only (Ref.1).

The methodology applied in this paper to determine M/OD risks is illustrated in Figure 1. The Mir risk calculations follow the same approach NASA has used to evaluate hypervelocity impact risks to spacecraft for nearly 30 years (Ref.2). The general approach includes an assessment of impact damage modes and failure criteria for each spacecraft subsystem, identification of critical systems and spacecraft design/operational practices to minimize damage, a hypervelocity impact test and analysis program to determine the "ballistic limit" equations that define impact conditions resulting in threshold failure of the subsystem, and an evaluation of the probability of impact damage and/or failure. The process is iterated as necessary to meet protection requirements by refining the analysis and by reducing impact damage risks through modifications to spacecraft design and operations, such as (1) optimized flight attitudes etc.) to reduce exposure to damage and (2) enhanced, low-weight shielding (Ref.8). The role of BUMPER is to provide a rigorous assessment of M/OD damage probability including shadowing effects. BUMPER combines NASA standard M/OD environment models, spacecraft geometry, and appropriate ballistic limit equations to calculate M/OD penetration and damage probability. It is the NASA standard code for performing M/OD probability calculations (Ref.3,4). The BUMPER Mir calculations provided in this paper represent the beginning of the iterative analysis cycle. More detailed BUMPER calculations are underway to further refine and improve the fidelity of the PNP analysis presented here.

In addition to Mir crew module leak probability, BUMPER predictions have been made to compare relative impact rates on the solar arrays and modules of the current Mir configuration. Numerous localized damage sites have been observed in photographs taken during Shuttle/Mir rendezvous missions on the exterior of the Mir

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modules and solar arrays, many of which could be due to M/OD impact (Ref.5). Damage to Mir solar arrays is more readily observed in Shuttle/Mir photographs compared to damage on modules, perhaps because albedo differences are more distinguishable in damaged and undamaged portions of the solar arrays. BUMPER assessments of damage to the Shuttle found after each mission provides a comparison between observed and predicted damage both as a verification step for the code and as a means to monitor changes in the M/OD environment (Ref.6-7). Extending the assessment of on-orbit damage to Mir will provide a useful independent check on the predictive accuracy of BUMPER and to help monitor changes in the M/OD environment. This process is on-going as quantitative statistics are currently being collected based on the observed Mir exterior damage to compare to BUMPER predictions.

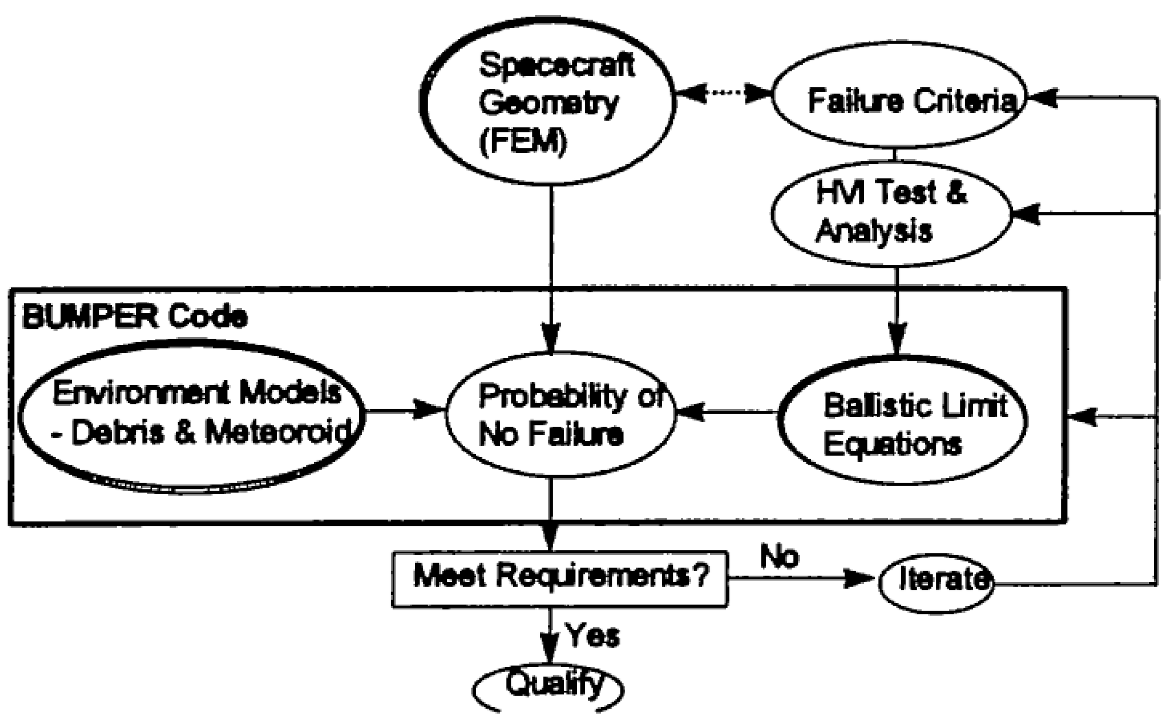

Figure 1. BUMPER M/OD Risk Assessment Code

2. BUMPER CODE

BUMPER has been applied to analyzing M/OD risks for a number of different spacecraft such as the International Space Station (ISS), Space Shuttle, Contingency Return Vehicle (CRV), Space Suits, Iridium satellites, etc. (Refs.7-10). Each assessment requires a finite element model (FEM) describing the spacecraft geometry, location of subsystems and spatial extent of different shielding materials and thicknesses which cover the vehicle (i.e., "property identifiers"). Different levels of damage can be assessed for each vehicle depending on the availability of ballistic limit equations describing the particle size, velocity, angle, and density which are on the "failure" threshold (or damage threshold) for each spacecraft subsystem/structural type (Refs.11-12). BUMPER calculations for Mir have evolved over the last 5 years, and have benefited greatly from Russian inputs and suggestions (Ref.13). However, these calculations will be updated as more detailed information on the configuration of the Mir shielding/structures is modeled, and as additional hypervelocity impact data relevant to the Mir shielding is collected and analyzed to update the ballistic limit equations used in the analysis.

3. MIR FINITE ELEMENT MODEL (FEM)

Several Mir finite element models (FEM) have been created for input to BUMPER. As more modules have been added to Mir over time (Fig.2), separate FEMs are necessary to describe the geometry of the Mir. In addition, the thin solar arrays and other non-critical structures provide some shadowing of the crew modules. Separate FEMs are needed, with and without solar arrays, to assess the effects of solar array semi-shadowing (Fig.3). Figure 4 provides information on some of the shielding thicknesses assumed for the over 50 different regions modeled in the Mir FEM as derived from various sources (Refs.1,13). More details of the shielding assumptions are provided elsewhere, as well as a detailed explanation of the 3-step BUMPER process used to accurately assess effects of semi-shadowing, non-conformal shields such as the Mir solar arrays (Ref.14).

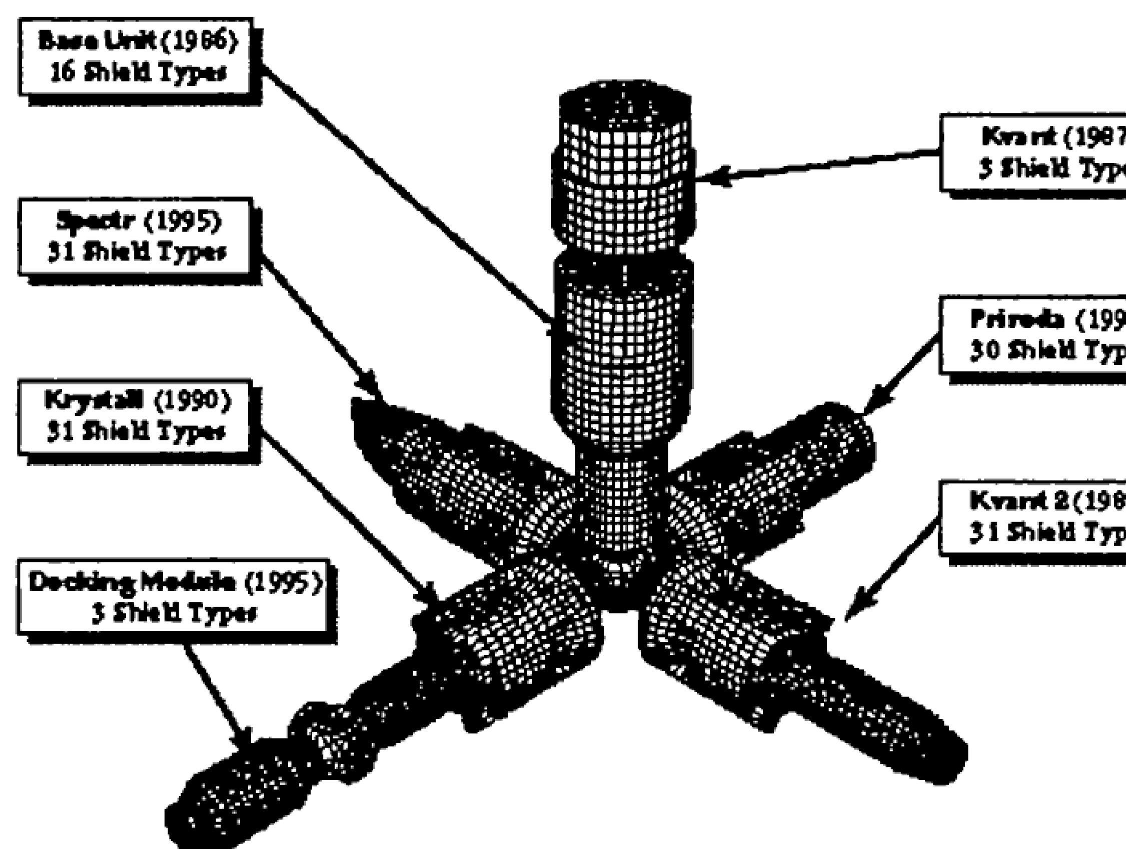

Figure 2. MIR Finite Element Model (FEM) (with launch date and number of shield types indicated for each module)

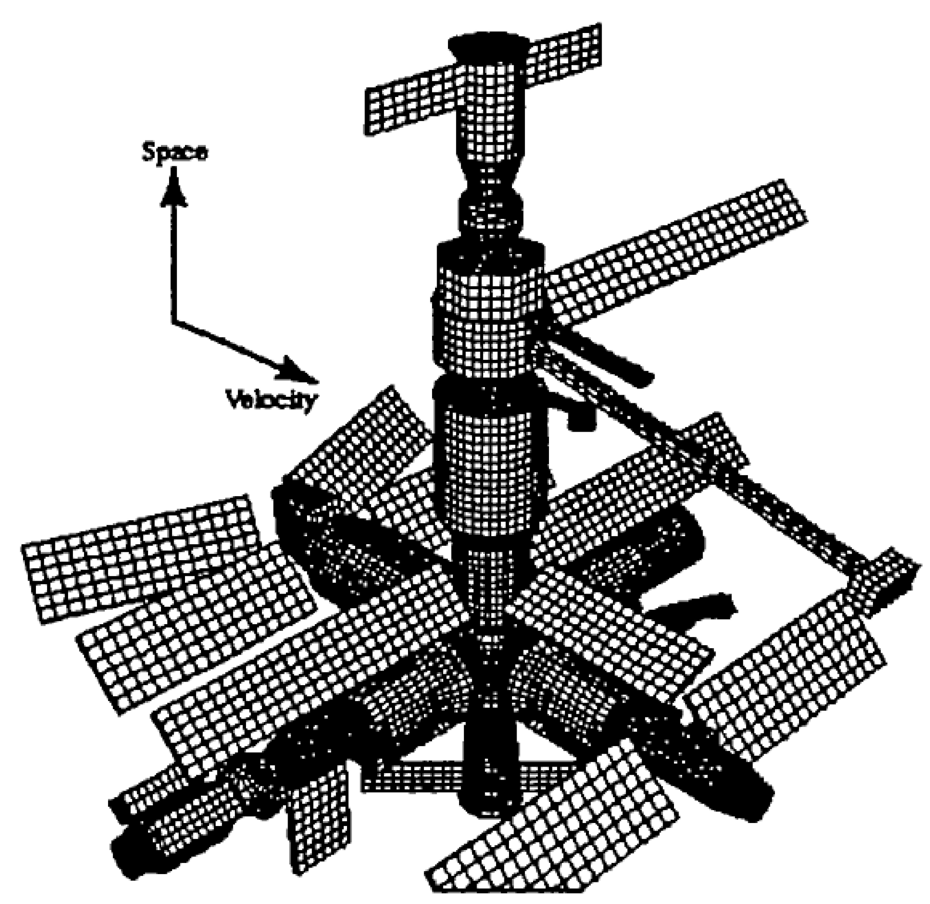

Figure 3. Current configuration MIR FEM with solar arrays and other shadowing elements

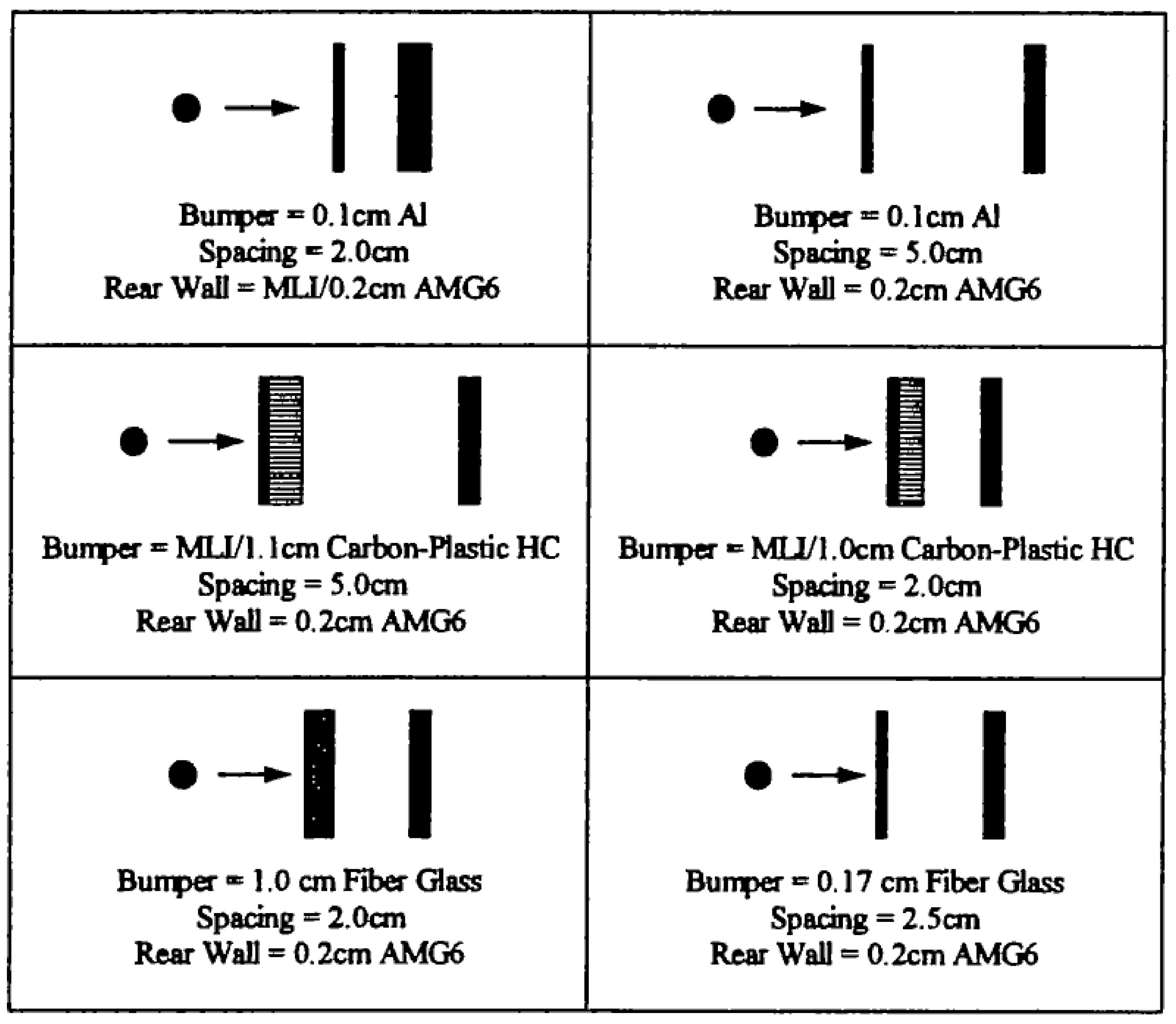

Figure 4. Mir Shielding Examples

4. THRESHOLD PERFORATION BALLISTIC LIMITS

Ballistic limits were derived for the various Mir shields using tests and analysis from the JSC Hypervelocity Impact Test Facility (HIT-F) (Ref.15). Most of these tests were on shields using American materials (Refs.11,12,15). However, some testing of Russian materials, particularly the Russian aluminum AMG-6 alloy used for the pressure shell (Ref.16) indicated that the ballistic limit equations derived from American materials could be applied to Russian AMG-6 using slightly higher yield properties for AMG-6 than the minimum standards supplied by Russian materials properties literature. Eqs.1-3 were used to assess two wall shield ballistic limits on the Russian modules:

for $V_n \geq 7$,

$$d_c = 2.9\, t_w^{2/3}\, S^{1/3}\, \rho_p^{-1/3}\, (V \cos\theta)^{-2/3} \qquad (1)$$

for $3 < V_n < 7$,

$$d_c = 0.79\, t_w^{2/3}\, S^{1/3}\, \rho_p^{-1/3}\, (V \cos\theta/4 - 0.75) + (0.8\, (t_w + t_b)/\cos\theta\, \rho_p^{-0.5})^{(18/19)}\, (1.75 - V\cos\theta/4) \qquad (2)$$

for $V_n \leq 3$,

$$d_c = (1.67\, (t_w + t_b)\, (\cos\theta)^{-5/3}\, \rho_p^{-0.5}\, V^{-2/3})^{(18/19)} \qquad (3)$$

The perforation ballistic limits for particles which first impact the solar arrays or other semi-shadowing elements in the FEM and then impact the shields on the Russian modules are controlled by the ballistic limits for the thinnest shielding on the Mir modules that is impacted by fragments within the debris cloud generated by the particle/solar array impact. For this study, the ballistic limit equations given by Eqs.4-6 are used for solar array shadowed shields. Testing at the JSC HIT-F on similar types of standoff shields indicate Eqs.4-6 are reasonable approximations (Ref.17) although further supporting HVI test/analysis is needed.

for $V \geq 6.4/\cos\theta^{0.25}$,

$$d_c = 2.8\, \rho_p^{-1/3}\, (V \cos\theta)^{-1/3} \qquad (4)$$

for $2.4/\cos\theta^{0.5} < V < 6.4/\cos\theta^{0.25}$,

$$d_c = 1.51\, \rho_p^{-1/3} \cos\theta^{-1/4}\, (V - 2.4/\cos\theta^{0.5}) / (6.4/\cos\theta^{0.25} - 2.4/\cos\theta^{0.5}) + 0.38\, \rho_p^{-0.5}\, (\cos\theta)^{-1}\, (6.4/\cos\theta^{0.25} - V) / (6.4/\cos\theta^{0.25} - 2.4/\cos\theta^{0.5}) \qquad (5)$$

for $V \leq 2.4/\cos\theta^{0.5}$,

$$d_c = 0.68\, (\cos\theta)^{-4/3}\, \rho_p^{-0.5}\, V^{-2/3} \qquad (6)$$

Figure 5 indicates the ballistic limits for 45° oblique impacts of aluminum particles directly on the large cylinder section of the Mir core module using Eqs.1-3 (lower curve in Fig.5), and after breaking up while passing through a solar array and then impacting the Mir core module using Eqs. 4-6 (upper curve).

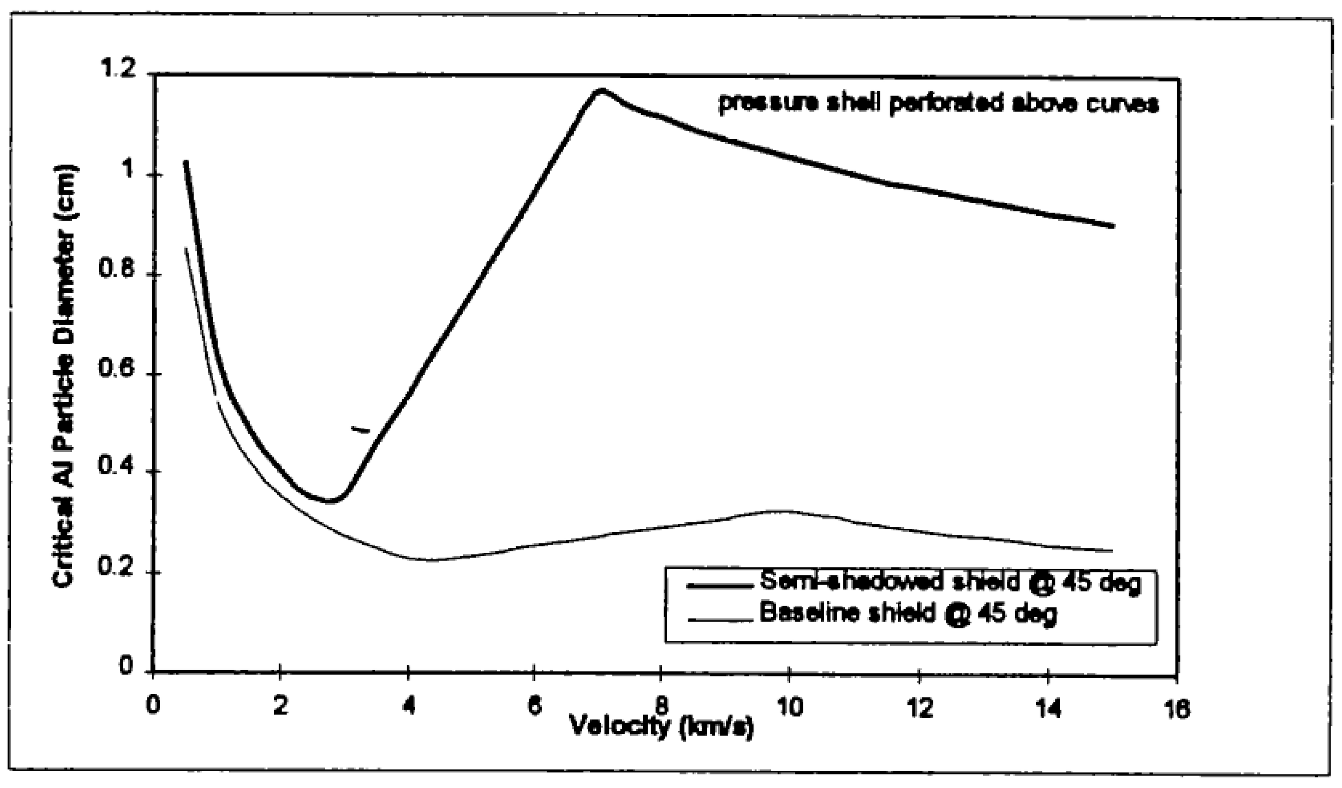

Figure 5. Calculated Ballistic Limits for Aluminum Particles on Core Cylinder Section (0.1cm Al bumper, S=5cm, 0.2cm AMG6 wall)

5. BUMPER PREDICTIONS FOR CREW MODULE SHELL PERFORATION

NASA standard environment models were used in the calculations (Ref.18 for debris and Ref.19 for meteoroids). The results of the calculations are given in Table 1.

Table 1 excludes the U.S. docking module, Soyuz and Progress vehicles. The PNP includes critical penetrations of the pressure vessels (PVs) mounted external to the crew module pressure shell. Pressure vessels represent a potential critical hazard as they could catastrophically rupture from impact causing secondary perforation of the crew module. The critical PV penetration probability was calculated using BUMPER. The probability of catastrophic rupture is one-fourth to one-tenth as likely as a simple perforation of the PV (i.e., causing a leak) based on preliminary HIT-F analysis using published and unpublished data (Ref.20). Table 1 includes overall probabilities of no critical penetration (PNCP) that result in catastrophic rupture of a PV based on a more conservative 4:1 penetration/catastrophic rupture ratio (PVs contribute ~5% to the total crew module penetration risk).

Table 1. Probability of No Penetration (PNP) for Mir Crew Modules
Orbit basis: 350-400 km altitude, 51.6° inclination, variable solar activity (Ref.18)

Module	from Feb.1986-Feb.1997				5 years: 1997-2001				
	duration (yrs)	Meteoroids only	Debris only	Met.& Debris	duration (yrs)	Meteoroids only	Debris only	Met. & Debris	Annual Risk (%/yr)
Core	11	0.8074	0.8467	0.6836	5	0.9073	0.9155	0.8307	3.39%
Kvant	9.8	0.9674	0.9611	0.9298	5	0.9832	0.9763	0.9599	0.80%
Kvant 2	7.3	0.9656	0.9713	0.9378	5	0.9763	0.9758	0.9527	0.95%
Kristall	6	0.9303	0.9879	0.9190	5	0.9416	0.9878	0.9301	1.40%
Spektr	1.6	0.9960	0.9977	0.9937	5	0.9877	0.9925	0.9802	0.40%
Priroda	0.8	0.9952	0.9992	0.9945	5	0.9706	0.9954	0.9661	0.68%
TOTAL	11	0.6955	0.7784	0.5414	5	0.7861	0.8511	0.6691	6.62%

BUMPER results indicate that meteoroids represent the majority of the penetration threat (60% versus 40% for debris). The BUMPER calculations compare reasonably well with the Russian assessment cited previously (Ref.1). The annual risk of penetration from an orbital debris strike averaged 2.0% per year from BUMPER, while the Russian assessment resulted in a 1.7% per year penetration risk from debris (a 15% difference). One reason the Russian risks are lower is that the Spektr and Priroda modules were not included in the 9.5 year Russian calculation since they were delivered later. For a 5 year period, both assessments considered the same number of modules, which should decrease the difference, however the average debris penetration risk from BUMPER was 3.0% per year while the Russian penetration estimate was 2.3% per year (>20% difference). The BUMPER calculations indicate that the most likely areas of penetration over the next five years are ~4 m^2 of unshielded cone section on the Core module (14% of total risk) because it is relatively exposed to M/OD impact and does not have a bumper. Another high risk area is a small region near the base of each auxiliary module where they dock to the common multi-port docking node. This "aft adapter" region, only ~1.2 m^2 per module or ~0.6% of the module area (total), accounts for 16% of the total risk because the region is relatively thin (3mm Al) and exposed to meteoroid impact. A detailed breakdown of predicted M/OD penetration risks for the Mir is given in Ref.14.

The next step in the BUMPER analysis cycle is to verify the analysis, especially concentrating on the major risk drivers. Evaluation and refinement of the analysis proceeds by answering questions such as: (1) Are shielding parameters in high risk areas properly modeled? (2) Can more shadowing be added by including nearby structures to high risk areas of the FEM? (3) Are the ballistic limit assumptions verified? After the analysis is refined and verified, the next step in the general methodology is to assess methods to reduce the M/OD impact risks if necessary to meet protection goals or requirements. For instance, in the case of the "aft adapter" region, a small add-on thermal blanket, possibly "toughened" with Nextel™ ceramic cloth (Refs.12,15), could be assessed as a means to remove the abnormally high penetration risks in this small region. Also, because the regions at most risk of penetration are thin and without a bumper, the likely hole size if a penetration were to occur would be small (~6-10mm in the case of a 3mm thick wall). These size holes could be patched if a patch kit were available.

Table 2. Mir Orientation Effects on PNP
(5-year PNP for all modules)

	Mir Core Gravity-Gradient Orientation			Mir Core parallel to Velocity Vector		
	Met	Debris	Met & Deb	Met	Debris	Met & Deb
Core	0.9073	0.9155	0.8307	0.8812	0.9335	0.8226
Kvant	0.9832	0.9763	0.9599	0.9861	0.9794	0.9657
Kvant 2	0.9763	0.9758	0.9527	0.9183	0.9795	0.8994
Kristall	0.9416	0.9878	0.9301	0.8697	0.8925	0.7753
Spektr	0.9877	0.9925	0.9802	0.9122	0.9814	0.8953
Priroda	0.9706	0.9954	0.9661	0.8814	0.9231	0.8136
TOTAL	0.7861	0.8511	**0.6691**	0.5573	0.7241	**0.4035**

The results in Table 1 are based on a Mir module orientation given in Fig.3 with the core module in a "gravity-gradient" configuration. Table 2 provides a PNP comparison for a module orientation that puts the axis of the core module in-line with the velocity vector. As indicated in Table 2, an in-line module pattern is more likely to be penetrated than the gravity-gradient (by ~80%).

6. MIR SOLAR ARRAY IMPACT PREDICTIONS

The Mir station currently has ~ 700 m^2 of solar array surface area which is roughly equivalent to the area of the modules. Several ~5cm diameter holes have been reported in the solar arrays (Refs.5,21). This size hole was likely due to a particle impact of ~1mm to 1cm in diameter. BUMPER was used to calculate the probability of impact from ≥1mm and ≥1cm meteoroid and orbital debris particles on the solar arrays and modules. The results of the analysis are given in Table 3 which indicates that several (~8) 1 mm class meteoroid and debris impacts are likely on the solar arrays over the next 5 years (expected meteoroid to debris impact ratio = 3:1), but a large 1cm impact is unlikely (0.5% chance of impact). Detailed analysis of the Mir solar array impact damage will be conducted after further data, impact results, and BUMPER assessments are made.

Table 3. Predicted Mir Number of Impacts (N) and Probability of Impact (POI) over next 5 years

	N for ≥1 mm particles			POI for ≥1 cm particles		
	met	debris	M&D	met	debris	M&D
Modules	4.3	2.8	7.1	0.13%	0.40%	0.53%
Solar Arrays	6.5	2.1	8.6	0.20%	0.33%	0.53%
Total	10.8	4.9	15.7	0.33%	0.73%	1.06%

7. CONCLUDING REMARKS

BUMPER assessments of the Mir Space Station indicate that there is a 33% chance that a M/OD impact will cause a leak of the Mir crew module pressure shell over the next five years. On an annual basis, this is higher than the average for the previous 11 years of Mir operations by 1.6X. Risk drivers have been identified from the initial BUMPER calculations. These calculations will be further refined in the near future. The assessments to-date indicate several localized hot spots control a large fraction of the risk. These are thin areas with little chance of a large hole (>1cm) and so could be patched if a penetration occurs or "beefed up" by external application of relatively light-weight protection solutions (i.e., adding a "toughened" insulation blanket to the exterior). From 1986 to 1997, the calculated probability of no penetration is 55%. Thus, BUMPER predictions support historical data that the Mir crew modules have not been penetrated.

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