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SPACE STATION MMOD SHIELDING

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ABSTRACT

This paper describes International Space Station (ISS) micro-meteoroid orbital debris (MMOD) impact shielding including requirements for protection as well as technical approaches to meeting requirements. Current activities in providing MMOD protection for ISS are described, including efforts to augment MMOD protection by adding shields on-orbit. Another activity is to observe MMOD impact damage on ISS elements and returned hardware, and to compare the observed damage with predicted damage using Bumper code risk assessment software. A conclusion of this paper is that ISS will be protected adequately from MMOD impact after completing augmentation of ISS shielding for Service Module, and after improving MMOD protection for Soyuz and Progress vehicles. Another conclusion is that impact damage observed to the ISS mini-pressurized logistics module matches the distribution of impacts predicted by Bumper code.

Introduction

Providing adequate micro-meteoroid orbital debris (MMOD) protection for the International Space Station (ISS) is essential to ensure crew safety, vehicle survivability and functionality. A number of papers and NASA reports provide a detailed description of the ISS MMOD protection strategy, requirements for protection and means to meet requirements[1-6]. ISS consists of a number of individual elements provided by NASA and international partners in Europe, Russia, Japan, and Canada. Top-level ISS MMOD requirements are allocated to individual elements. The element providers are responsible for meeting allocated MMOD protection requirements, while NASA is responsible for determining compliance to the top-level requirement.

This paper summarizes current status of ISS MMOD protection. The methodology used in assessing MMOD risk and typical shielding techniques implemented to meet requirements are described. On-orbit augmentation of Service Module MMOD shielding is underway. Methods to improve MMOD protection for Soyuz and Progress have been evaluated and will substantially reduce MMOD risks for these vehicles. These changes/modifications are necessary to meet ISS MMOD protection requirements.

ISS MMOD Requirements

MMOD protection exists to ensure crew safety and mission success. MMOD requirements for ISS have the following objectives:

- Protect the crew from meteoroid/debris impact.
- Protect ISS critical hardware from meteoroid/debris impact.
- Minimize damage to all station elements from meteoroid/debris.

Specific requirements for ISS MMOD protection include:

(1) Comply with overall ISS shielding penetration probability requirement of less than 24% over 10 years; i.e., meet/exceed 0.76 Probability of No Penetration (PNP).

(2) Comply with ISS catastrophic penetration probability requirement of less than 5%; i.e., meet/exceed 0.95 Probability of No Catastrophic Failure (PNCF).

By definition, a hole or through-crack in the pressure shell of an ISS module is a "penetration" of MMOD shielding covered by the first requirement; i.e., there should be less than a 24% chance that a shield penetration or depressurization event occurs from MMOD impact to ISS over 10years. A PNP requirement is allocated to each ISS module and external "MMOD critical" element (such as pressure vessels or control moment gyros) based on the surface area (in m^2) and exposed duration (years) of the module/element using the following formula:

$$PNP = 0.99999^{\text{Surface Area * Duration}}$$

PNP is assessed using the *Bumper* code. Pressure shell leaks of any size from MMOD impact would be a serious operational issue. ISS crews are trained to locate, isolate and patch leaks in the pressure shell[7]. However, certain types of penetrations are potentially catastrophic, i.e., a penetration could be of the size or in a location that results in death of one or more crew members. Determining risk of catastrophic impact from MMOD involves calculation of the "R" factor for each ISS module and external critical element, which is the ratio of catastrophic loss to shield penetrating impacts. PNCF for each module and external shielded element is determined from PNP and R as follows:

$$PNCF = PNP^{R}$$

R-factor includes assessment of crew loss due to a number of scenarios including catastrophic rupture of the crew module pressure shell, hypoxia of crew from fast depressurization, loss of crew from internal fragments and other effects of a MMOD penetration, as well other factors[1,8].

MMOD Shielding Development

Development of MMOD shielding for ISS is based on risk assessments using *Bumper* code supported by hypervelocity impact tests and numerical simulations as illustrated in Figure 1.

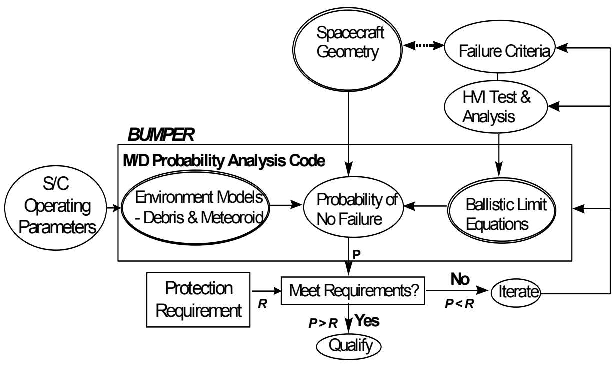

Fig. 1: MMOD risk assessment process showing that failure criteria is defined for each part of the vehicle, hypervelocity impact (HVI) tests and analysis are performed to develop ballistic limit equations (BLE), the BLEs and MMOD environment models are used in Bumper code to assess MMOD risk.

An objective of the assessments is to identify risk drivers (i.e., areas of the vehicle that contribute a majority of the overall MMOD risk), and determine relative effectiveness of changes in vehicle design, shielding or operations to reduce MMOD risk. *Bumper* code results provide the basis for showing compliance of the hardware to MMOD protection requirements. Additional details of the *Bumper* code can be found elsewhere[1,9].

After vehicle shielding has been developed and verified, the risk assessment process is not over. Actual MMOD damage to the vehicle is identified during mission operations, to assess how well actual damage compares to *Bumper* predictions, to trend damage, evaluate design margins, and most importantly to determine if changes should be considered to vehicle design and operations to decrease MMOD damage and vehicle survivability. As an example, based on actual MMOD damage identified in post-flight inspections, changes were made to vehicle design and operations (i.e., via selection of low-risk flight attitudes and on-orbit inspections) to reduce MMOD risks to Shuttle radiator and wing leading-edge systems[10].

Overall Status

Results of MMOD risk assessments indicate ISS MMOD risks are driven by Service Module (SM), Soyuz and Progress as illustrated by Figure 2 showing penetration risk breakdown for each element on ISS assuming 2-Progress operations. The reason for this result is simply that low-weight and relatively low-performance shields protect areas of these elements. As shown in Table 1, the average shield mass per unit area for elements of ISS that are risk drivers (SM, Soyuz, Progress) are a factor of 5 lower than the MMOD shielding mass for the rest of ISS. The lightly shielded elements on ISS constitute only 15% of the total exposed area, but contribute a disproportionate amount of MMOD risk to ISS. The most effective way to reduce MMOD risk to the elements that are risk drivers is to add supplemental MMOD shielding in locations where risks are highest. The effort to improve MMOD shielding on these elements is underway.

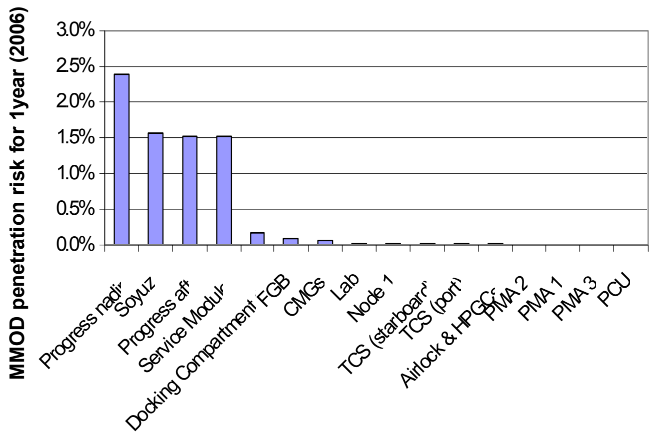

Fig. 2: MMOD penetration risk breakdown for ISS in current configuration (basis: 1 year, 2006).

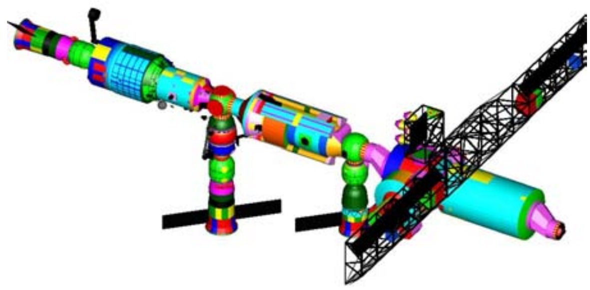

Fig. 3: Current ISS configuration showing 2 Progress vehicles and 1 Soyuz docked to ISS (excluding solar arrays, radiators and truss).

ISS Elements	**MMOD Risk & Shielding Metrics**
Combined for 12 of 16 current elements *(FGB, Node 1, PMA 1, PMA 2, PMA 3, CMG, PCU, US Lab, Airlock & HPGC, TCS-S, TCS-P, MPLM)* and 10 future elements *(Node 2, Columbus, ATV, JEM PM, JEM ELM-PS, HTV, Node 3, MLM/FGB-2, Research Module, Cupola)*	1. 85% of total ISS by area 2. Penetration Risk 14% of total 3. Catastrophic Risk 49% of total 4. Shielding mass 22,700kg 5. Shielding mass/area 10kg/m^2 6. “Average” shielding capability=1cm
Combined for 4 elements: Service Module, Soyuz, Progress & Docking Compartment	1. 15% of total ISS by area 2. Penetration Risk 86% of total 3. Catastrophic Risk 51% of total 4. Shielding mass 700kg 5. Shielding mass/area <2kg/m^2 6. “Average” shielding capability=0.3cm

Table 1: MMOD risk and shielding mass/area for current and future ISS elements.

ISS MMOD Shields

Many hundreds of MMOD shields protect ISS elements, differing by location and in materials of construction, mass, thickness and volume. Figure 4 illustrates typical MMOD shield types used on ISS, which include Whipple and "Stuffed" Whipple (SW) shields. Whipple shields consist of an outer bumper (typically aluminum), multi-layer insulation (MLI) thermal blanket, and an inner rearwall or pressure shell (also aluminum typically). The SW shield includes an intermediate bumper (typically non-metallic) between outer bumper and pressure shell. The SW shields are more capable at providing MMOD protection than Whipple shields, and are used in areas of ISS where higher concentrations of MMOD impacts are expected to occur, generally forward and port/starboard areas of ISS elements. For instance, approximately half of the cylinder section of the US Laboratory module is protected by the SW shield shown in Figure 5 (port and starboard quadrants). MMOD shield performance is improved with greater standoff distance from outer bumper to rearwall or pressure wall, and typically ISS shields have the maximum standoff possible that fits within the launch vehicle shroud/payload bay envelope and to meet other volume requirements and constraints. Generally, ISS shield standoff distances are between 10cm and 30cm. Details of ISS MMOD shields are described in other reports[1,2,9].

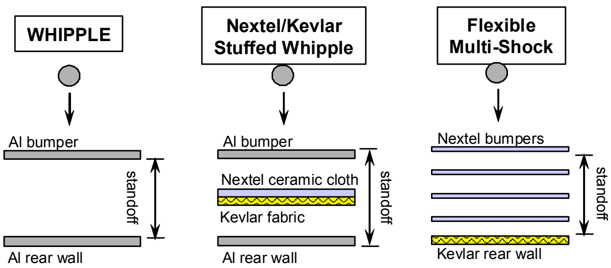

Fig. 4: Typical ISS MMOD Shield Types.

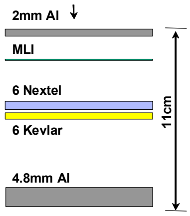

Fig. 5: US Laboratory Nextel/Kevlar Stuffed Whipple (SW) Shield[2]. Nextel™ is a ceramic fabric from 3M Corporation and Kevlar™ is a high-strength fabric made by DuPont.

Ballistic Limit Equations (BLEs)

Ballistic limit equations for all ISS shields are essential for MMOD risk assessments. BLEs define the MMOD particle size that "fails" a shield as a function of impact velocity, angle, density of MMOD particle and shape. Failure is defined for ISS shields as a complete penetration, through-hole or through-crack in the rearwall or pressure shell of the shield. Detached spall (without a through-hole) in the rearwall is also a failure mode, but does not commonly occur in impact tests on realistic shields containing MLI thermal blankets and/or intermediate bumpers. Ballistic limit equations are based on extensive hypervelocity impact (HVI) testing, hydrocode simulations and analytical models. Ballistic limits for typical ISS SW shields protecting the US Laboratory, Columbus and Japanese Experiment Module (JEM) are given in Figure 6 based on equations given elsewhere[9,11]. The difference in the ballistic limits is due to differences in the intermediate layer configuration and in overall standoff distance of the shield. In this particular example, the Columbus SW shield has the higher ballistic limit and MMOD shielding performance, but has a greater shield mass and larger standoff than the other two shield types.

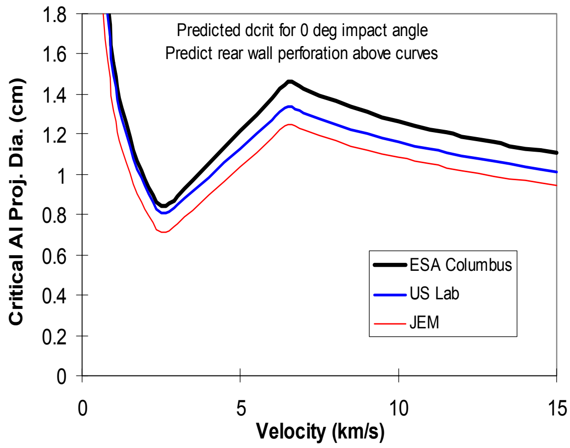

Fig. 6: Typical ISS Stuffed Whipple (SW) Shield ballistic limits for aluminum spherical impactors at normal (0^o) impact angle[9]. ESA Columbus overall shield mass/area is $3.1 g/cm^2$ and shield standoff is 13cm, US Laboratory module shield mass/area is $2.7 g/cm^2$ and shield standoff 11cm, JEM shield mass/area is $2.2 g/cm^2$ and shield standoff is 11cm.

Whipple shield ballistic limits are strongly influenced by the presence, location and mass of MLI thermal blanket, as given in Figure 7. To provide more accurate MMOD risk assessments, ballistic limits for ISS Whipple shields have been developed based on impact tests on targets that include MLI thermal blankets.

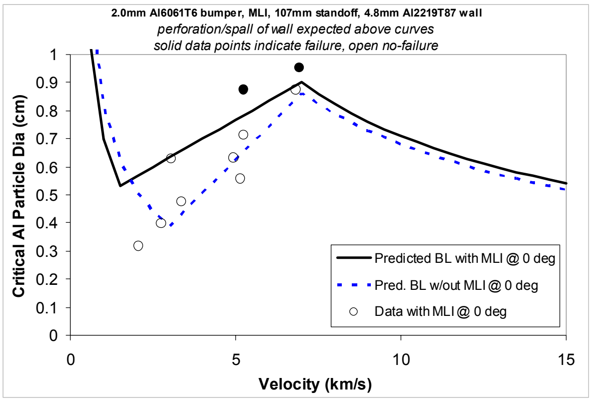

Fig. 7: Typical ISS Whipple Shield ballistic limits[9,11]. MLI thermal blanket improves the shielding performance. Bumper thickness 0.2cm Al, rearwall thickness 0.48cm Al, 10.7cm standoff.

Service Module Augmentation Shields

Service Module (SM) MMOD protection will be improved by adding augmentation shields on-orbit by extravehicular activity (EVA). SM augmentation shields (Figure 8) include 23 conformal shield panels to be attached in the conical region between small and large diameter cylinders, 2 deployable shield "wings", and turning the solar arrays in near-vertical orientation (±22.5 degrees).

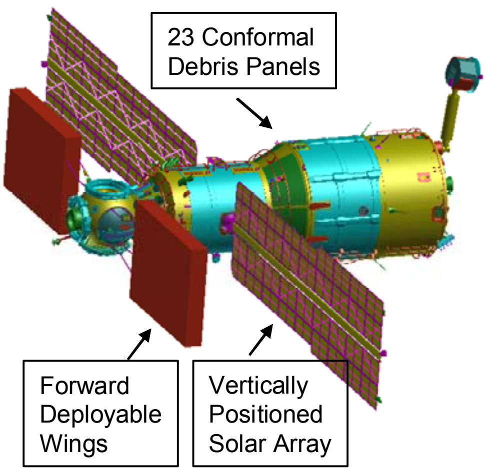

Fig. 8: Augmentation of Service Module MMOD Shielding

Six of the 23 SM conformal shield panels were delivered to ISS on flight UF2 (June 2002) and installed shortly thereafter by EVA (Figure 9). The remaining 17 conformal panels have been manufactured and are awaiting launch on flight 12A.1 planned in 2007. Conformal panels are approximately 10cm thick and consist of an outer aluminum cover, a corrugated aluminum layer behind the cover, a glass-fiber reinforced layer within the panel followed by several layers of technical cloth (Russian "Kevlar" equivalent). The cross-section of a conformal panel on the SM conical region is similar to the stuffed Whipple shields protecting other ISS modules. Hypervelocity impact tests in Russia and at NASA indicate the conformal panels over SM conical region materials provide similar levels of MMOD protection as ISS Stuffed Whipple shields (Figure 10).

Conformal panels cannot be used everywhere on SM to increase MMOD protection, because they would cover body-mounted radiators on the small and large diameter cylinder sections of the Service Module. Shields deployed orthogonal to the SM cylinders were selected as the most effective solution to augment MMOD protection in areas covered by radiators.

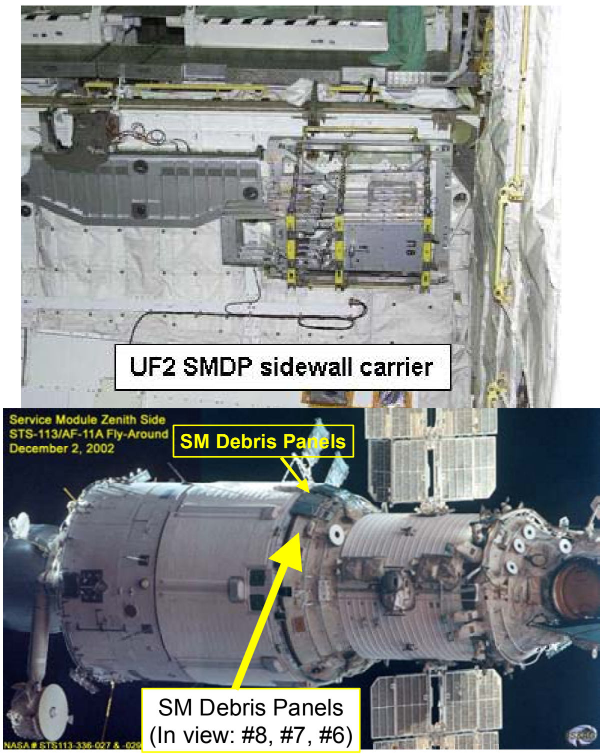

Fig. 9: SM conformal panels mounted on sidewall carrier for UF2 flight to ISS in June 2002. SM conformal panels attached to ISS in on-orbit photo from December 2002.

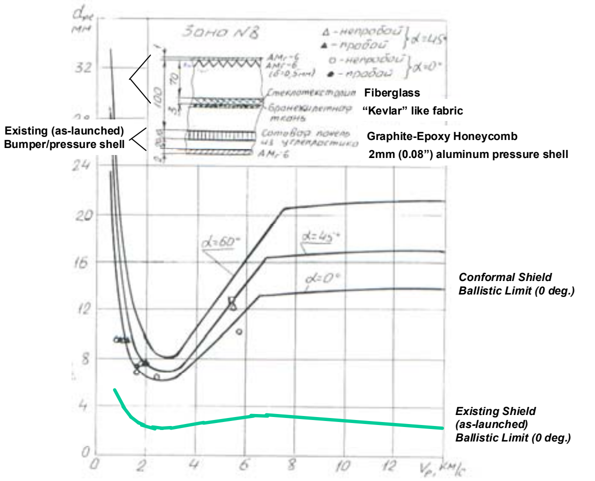

Fig. 10: SM conformal panel ballistic limits determined from hypervelocity impact tests and analysis.

Two SM deployable wings are manifested on Shuttle flight ULF4 (launch planned in 2009-2010) and will be mounted to port and starboard sides of the SM forward node. Each forward deployable wing consists of 3 separate layers of Russian basalt cloth protected by a fiberglass cover (25cm from front to back layer). Impact tests have demonstrated that the deployable multi-shock shield will provide protection equivalent to the best shields on ISS[9,11]. SM vertical solar arrays are required along with the deployable wings to provide complete augmentation. SM solar arrays have lower MMOD shielding capability than the deployable shields, but are larger and have greater coverage than the deployables which helps reduce MMOD risks.

Enhancing Soyuz/Progress MMOD Protection

Russia (RSC-Energia) and NASA have assessed means to improve MMOD protection for the Soyuz/Progress Orbital Module. Options included (1) adding Nextel/Kevlar to the existing thermal blanket or (2) increasing the standoff from the Orbital Module pressure shell to the thermal blanket by installing standoffs and adding an aluminum bumper to attach the thermal blanket. Both options increase the ballistic protection of the orbital module (Figure 11) and substantially decrease MMOD risk (by factor of 4x to 5x), but adds mass to the vehicle (20kg-25kg per vehicle).

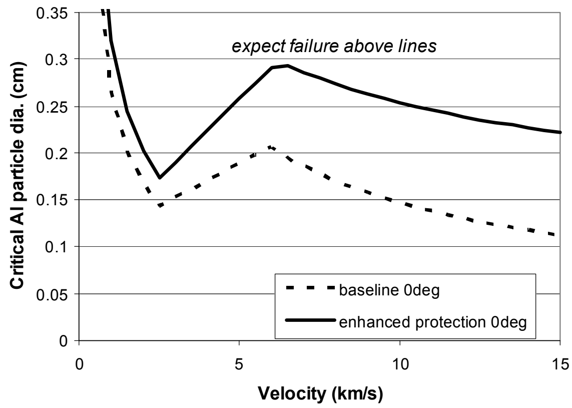

Fig. 11: Change in ballistic limits with improvements in MMOD protection of Soyuz and Progress Orbital Module[9,11].

MMOD shield augmentation/enhancement effect on ISS MMOD Risks

Completing augmentation of Service Module shields and enhancing MMOD protection of the Soyuz and Progress decreases the contribution from risk drivers to overall ISS risks as shown in Figure 12. Based on current projections, SM augmentation and improvement of Soyuz/Progress MMOD protection is necessary to meet overall ISS MMOD requirements (Table 2). Note MMOD risks projections are subject to change based on many variables related to assembly sequence, visiting vehicle mix, shielding capabilities and MMOD environment models.

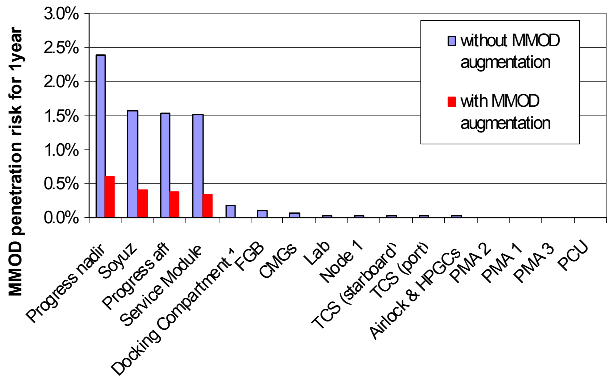

Fig. 12: Change in MMOD penetration risks with augmentation of Service Module protection and improvements in Soyuz and Progress Orbital Module.

ISS MMOD risks for 10-year time period (2007-2016)		
	Penetration Risk	**Catastrophic Risk**
ISS with no SM augmentation & no Soyuz/Progress enhancements	55%	9%
ISS with SM augmentation	49%	8%
ISS with SM augmentation and Soyuz/Progress enhancement	29%	5%
Requirements	≤ 24%	≤ 5%

Table 2: Change in ISS MMOD risk with augmentation of Service Module protection and improvements in Soyuz and Progress Orbital Module (assumes 2-Progress operations)[2]. Assessed risks are subject to change depending on visiting vehicle mix, assembly sequence, environment model changes, and other factors.

On-Orbit MMOD Damage

Monitoring and trending actual MMOD impacts to the ISS and Shuttle vehicles is part of the MMOD risk management process for these vehicles. On ISS, multiple MMOD impacts have been observed to the mini-pressurization logistics module (MPLM)[12,13], ISS windows, ISS radiators, Service Module (SM) impact sensors, and other elements. One of the most significant damages observed to-date on ISS was an impact on the outer pane of SM window #13, which was large enough to reduce the strength of the outer pane to below requirements and resulted in the window being "safed" by placing an opaque cover over the window on the inside, thus effectively eliminating use of this window except for emergencies. Observed MMOD damage to the MPLM has been compared to predictions by *Bumper* code. Observed damage occurs in areas with high predicted impact risk (Figure 14). MMOD perforations in the outer bumper of the Whipple shield protecting MPLM are summarized in Table 3, showing that *Bumper* predictions are in reasonably good agreement with observations of actual damage.

Fig. 13: MMOD impact observed to Service Module window #7; damage measures 3mm to 5mm across.

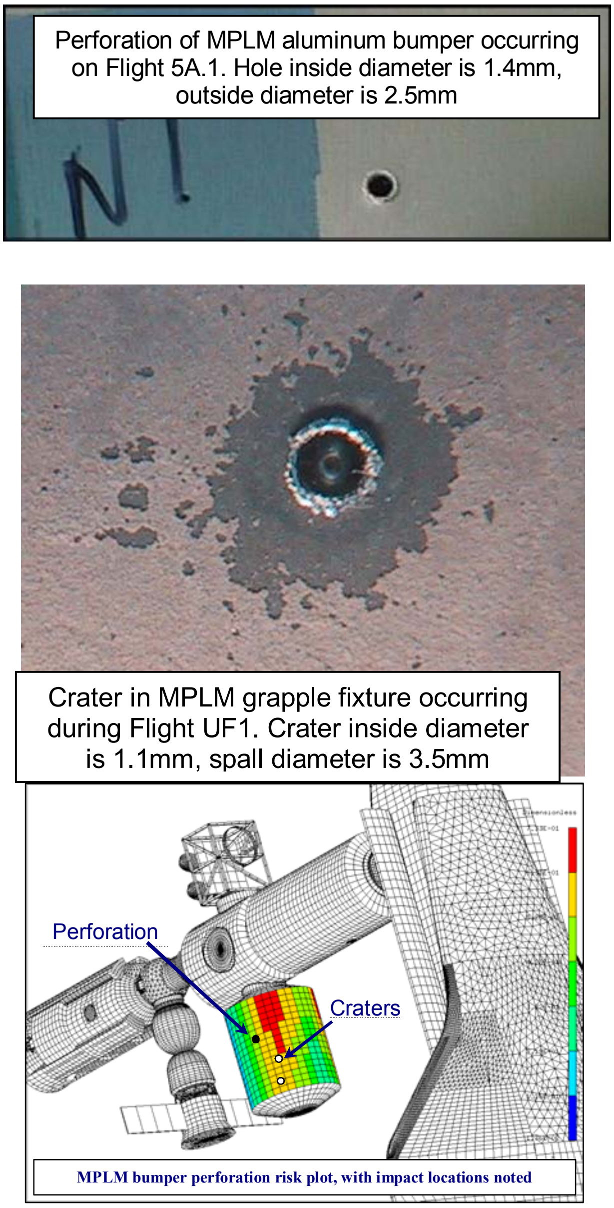

Fig. 14: Damages found on various MPLM flights, and distribution of actual MMOD damages found on the MPLM after STS-102 (ISS flight 5A.1) and *Bumper* code predictions.

	Per flight risk	Frequency of bumper perforations
Predicted	55%	1 every 2 flights
Actual Experience	40%	1 every 2.5 flights

Table 3: Comparison of MPLM actual damage and *Bumper* code predictions for perforations in the outer bumper of the MPLM shield. Data from first five flights of the MPLM.

Concluding Remarks

ISS is protected with the most capable MMOD shields ever flown which cover most of the modules and external critical elements of ISS. However, the majority of MMOD risk to ISS is represented by a few areas of the vehicle that are not as well protected, namely Service Module, Soyuz and Progress. Augmentation of Service Module MMOD protection is currently underway with shielding that is equal in capability with the best shields on ISS. Improving Soyuz and Progress MMOD protection has been shown to be technically feasible by RSC-Energia testing and evaluation. Completing the augmentation of Service Module shielding, as well as improving Soyuz and Progress shielding, is required to meet overall ISS MMOD protection requirements and will improve ISS crew safety and mission success.

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