DEBRIS SHIELDING DEVELOPMENT FOR THE COLUMBUS ORBITAL FACILITY

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ABSTRACT

The protection of the International Space Station against orbital debris impacts is a key safety issue which commands the development of an innovative, directional shielding system for the European module, Columbus.
The protection shields for the module areas most exposed to the debris threat are made of an aluminium external bumper and an intermediate wall made of a ceramic fiber (Nextel™) mattress and a high resistance fiber (Kevlar™) composite with epoxy resin. The other areas are protected by a simple aluminium Whipple bumper. The directional shielding development and qualification process is based on both experiments and numerical simulations. Hypervelocity tests are performed, using a Light Gas Gun, firing aluminium spheres with a diameter up to 1.7 cm and a velocity up to 6.5 km/s. At higher velocities, Hydrocode simulations are performed with the computer code PAM-SHOCK 3D. Experimental and Hydrocode techniques are used to derive damage describing equations, which are implemented within the ESABASE debris tool, used to simulate the exposure of the Columbus module to the meteoroids and debris environment.

1. ORBITAL DEBRIS RISK FOR THE INTERNATIONAL SPACE STATION

The International Space Station (ISS) program is most affected by the increased man-made debris population in Low Earth Orbit, due to its large dimensions (more than 2000 m^2 surface area), long mission duration (10 years of operations), the highly polluted orbit (400 km altitude, 51.6 degrees of inclination), and with the permanent presence of the astronauts on board. The Columbus Orbital Facility (COF) is the European module attached to the ISS (see Figure 1). COF is developed by an European consortium led by DASA . The European Space Agency (ESA) has participated in the process of formulating verifiable requirements and of identifying a risk management approach, which encompasses the chances to prevent, mitigate and correct a debris collision. Until 1993, this contribution has been described at the First European Conference on Space Debris (Ref. 1). - A debris impact may cause structural failure with potential catastrophic consequences to human life. Fracture control is therefore applied for debris impacts on the COF, and the pressure shell is designed for repairability. Since 1993, NASA focused on two areas:
1) Development of an empirical method to determine the likelihood of a catastrophic debris impact, introducing the Probability of No Catastrophic Failure (PNCF). The main catastrophic modes (as functions of module pressure shell penetration damage) encompass pressure shell unzipping, direct impact and injury to astronauts and module decompression with hypoxia.
2) Determination of the Critical Crack Length (CCL) on the pressure shell under hypervelocity impacts.
Integrating the approximated CCL for unzipping into the PNCF analysis allowed to compare the PNCF and the Probability of No Penetration (PNP) approach and to identify pressure wall thickness increase (from 3.2 to 4.8 for the American manned modules) - together with appropriate shielding - as the most effective preventive solution. ESA is highly convinced of the benefits of the thicker wall and has taken it over to the COF at the beginning of the C/D phase. Then, a new PNP requirement was introduced for the space station manned modules, necessary to design the shields (Ref. 2).
The current strategy to manage the M/OD hazard to the station (Ref. 3) is based on three principles:

(a) Implement state-of-the-art shielding against particles up to about 1 cm diameter
(b) Perform station manoeuvres to avoid collisions with object larger than about 10 cm in diameter detected by ground tracking
(c) Implement operational procedures to mitigate the damaging effects of impacts with objects between about 1 and 10 cm.

2. COF M/OD REQUIREMENTS: PROTECTION, MAINTAINABILITY, VERIFICATION

The ISS PNP requirement is defined as the minimum Probability of No Penetration or detached spall of the pressure shell over a 10-year period of exposure to the M/OD environment. The requirement applies to Critical Items, for which "effects resulting from M/OD impact will endanger the crew or space station survivability".
The PNP for the station was set to 0.9, which was judged a reasonable goal to be met with shielding. The Russian segment added later was also allocated a PNP of 0.9, thus reducing the combined PNP to 0.81. NASA apportioned

the Critical Items their PNP proportional to the exposed surface area. Since 1994, the COF PNP allocation is 0.9885 over 10 years, based on an ISS surface area of 1034 m^2 (before addition of Russian Segment) and a COF surface of about 110 m^2. In view of the increasing debris environment, the COF - like the US and Japanese modules - shall have provisions for M/OD protection augmentation.

The COF pressure shell shall remain functionally operational (i.e., maintain the internal pressure) for 15 years. As such, it shall be accessible, inspectable and repairable in situ for 15 years. The M/OD protection system - for COF called Meteoroids and Debris Protection System (MDPS) - must therefore be designed to allow access, inspection and repair of the pressure shell underneath. In practice, the design has to support External Vehicular Activity and/or remote manipulator operations. The accessibility from the inside is one of the most challenging requirements to the COF design, as tilting of racks does not provide easy access to all areas (for instance, below the stand-offs). The shell itself shall be repairable. The repair methodology and repair scheme development is NASA/ISS system responsibility. ESA requires the COF contractor to provide procedures for inspection, repair and replacement to recover from an impact. The on-orbit equipment for accessibility demonstration is assumed to be available from the ISS. This activity is therefore the subject of NASA and ESA cooperation.

The system requirements for the COF acknowledge the limitations to verify the protection requirements. Analyses have to include Hydrocodes. Testing, as mutually agreed with NASA and consistent with the practice of all the International Partners, is required to validate the ballistic limit of the MDPS. Fracture control of the COF will include Critical Crack Length verification of the pressure shell against an envelope of damage observed during ballistic limit testing of the flight like protection shields.

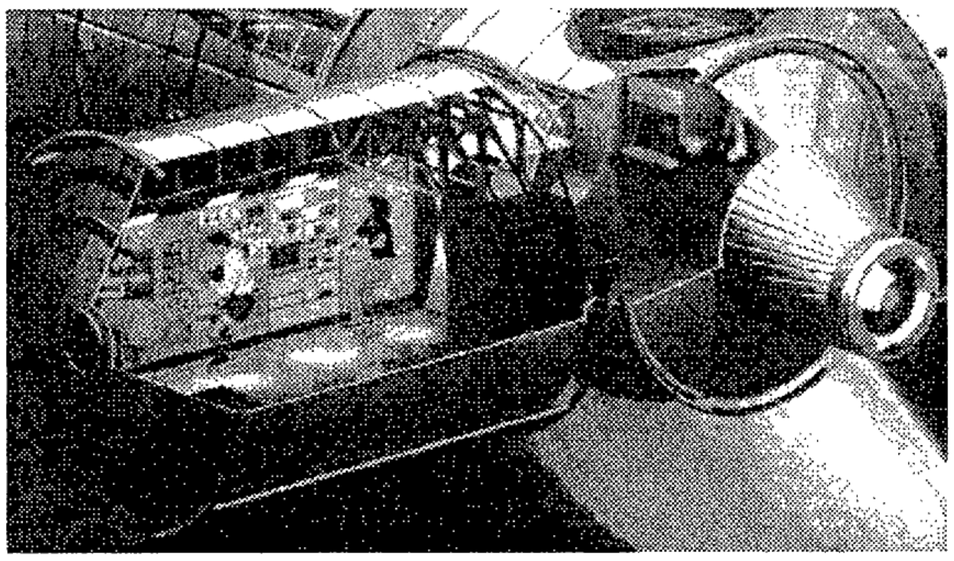

Figure 1: COF attached to the ISS. The European module is composed of a cylindrical section with an aluminium wall 4.8 mm thick and by two conical sections, with an aluminium skin 3.8 mm thick. The Port Cone is attached to Node 2, the Starboard Cone is towards space. The pressure shell is covered by the MDPS.

3. PENETRATION REQUIREMENT ANALYSIS AND PRELIMINARY DESIGN

According to the M/OD environment model (Ref. 4), in the space station orbit the man-made debris environment exceeds the natural meteoroids environment by a factor of 47 for particle masses above 0.1 g and by a factor of 180 for masses above 1 g (Ref. 5). The analysis of the debris impacting on the Columbus module has been performed with the ESABASE debris tool (Ref. 6). The debris environment model is highly directional and hence only some parts of the module are subjected to a high debris flux. The cylindrical 180 degree section facing towards the station velocity (Cylinder Fwd) accounts for about 64% of the impacts, but for only 37% of the surface area. If the central half of this section lying in the orbital plane is considered, it accounts for about 44% of the impacts. The Starboard Cone accounts for 26% of debris impacts and 17% of the area (see Figure 2). In order to meet the 0.9885 PNP requirement, the central forward cylinder has to resist debris as large as 1.1 cm to 1.3 cm in diameter, corresponding to a mass of 2.0 to 3.2 g (with an average velocity of 10-12 km/s and an average impact angle of 40-50 degrees). The meteoroids population in this mass range is negligible, and it may be neglected for the protection of the highly impacted areas. These considerations have led to the design of a directional MDPS: for different zones of the module different shields are implemented according to the M/OD threat and the structural configuration (i.e., pressure shell thickness and stand-off spacing available) as summarized in Table 1. In the areas less exposed to the debris flux, simple Whipple Shields (WS) are envisaged: a thin aluminium bumper (First Bumper Shield, 1st BS) is spaced in front of the rear wall (or back wall, BW) which is the module pressure shell to be protected. For the more impacted areas, high resistance debris shielding - referred to as Advanced Shields (AS) - are investigated, which are able to stop massive projectiles. AS are similar to the Stuffed Whipple system developed by NASA (Ref. 7) and are based on a double bumper structure with the second or inner bumper (2nd BS) made of a combination of blankets of advanced materials, with many layers added up (see Figure 3). The materials used are: Nextel 312 AF62, with an areal density of 0.1 g/cm^2 per layer, Kevlar 129, style 812, with an areal density of 0.028 g/cm^2 per layer, Epoxy resin. Some details on the WS and the AS are reported in Table 2. The design of the reinforced sections is not frozen yet.

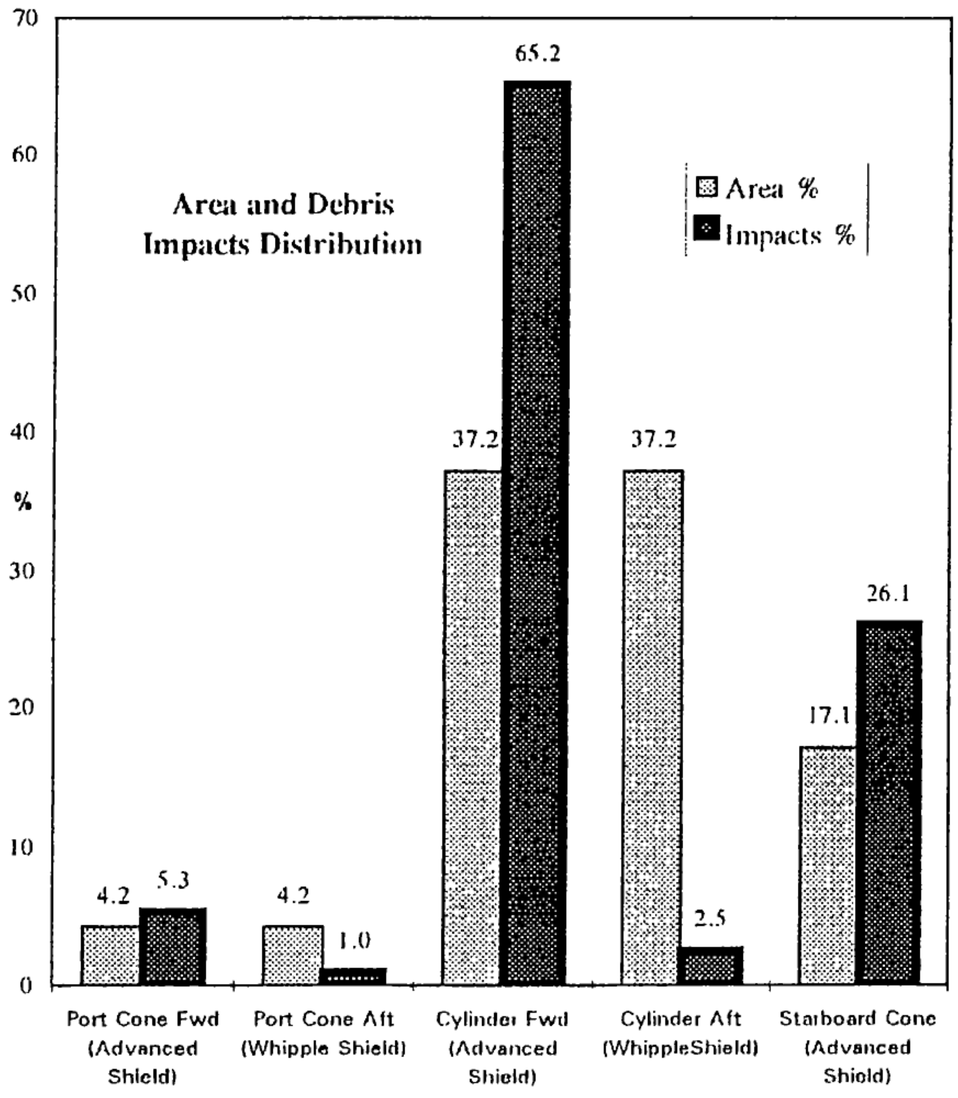

Figure 2: Distribution of the debris impacts on the COF surface (worst case attitude).

4. DEVELOPMENT AND VALIDATION APPROACH

The development and qualification process of the Columbus shielding system is based on both experiments and numerical simulations. As part of the development of the Advanced Shields, hypervelocity tests are performed at the Ernst Mach Institut, in Freiburg, Germany, using the Large Light Gas Gun (LGG- Ref. 8). To simulate debris impacts, aluminium spheres with a diameter from 0.9 to 1.7 cm have been fired at velocities between 3 and 7.0 km/s. The upper limit of 7 km/s is related to the maximum velocity achievable by light gas guns for a projectile with a mass in the range of interest. Since the typical average

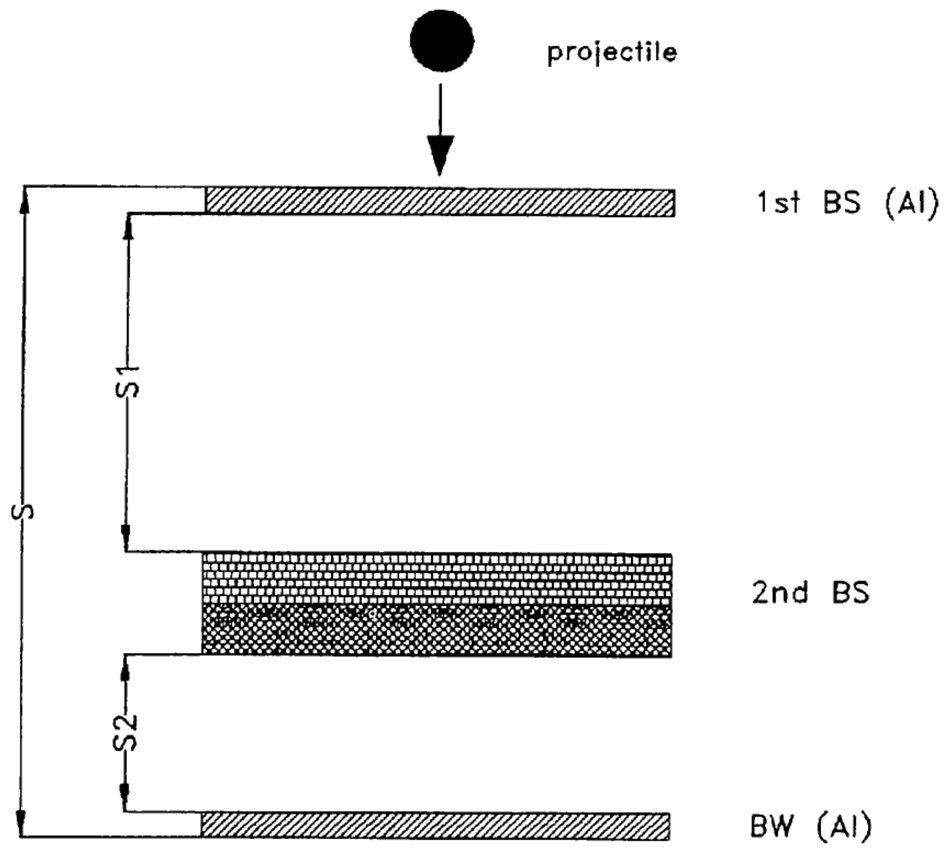

Figure 3: Functional layout of the shielding configurations. S is the overall spacing.

impact velocity of orbital debris on COF is about 10-12 km/s, numerical simulations are necessary in this velocity range, using Hydrocode tools. The finite-elements computer code PAM-SHOCK 3D is being modified by Engineering System International (Ref. 9) to reproduce phenomena where large distortion, fragmentation, phase transitions of both the projectile and the target occur.
The LGG experiments are used to derive damage describing equations for the advanced shields, which give the projectile critical mass (or diameter) which is just able to penetrate the rear wall as a function of the other projectile characteristics (i.e., velocity, density, impact angle). These formulae are based on simple physical laws, which are validated in the high velocity range (above 7 km/s) by Hydrocode simulations. For the aluminium WS, data available in literature and experiments performed at the beginning of the Columbus program are used. The ESABASE debris tool, with the validated damage laws,

Module Zone	M/OD Threat (Density)	Shell Thickness [mm]	Stand-off Spacing [cm]	Shielding Type	Shield Areal Density [g/cm^2]	Total Areal Density [g/cm^2]
Cylinder Fwd (180 degrees section)	High (3.0)	4.8	13.0	Reinforced Advanced Shield (AS2-N4KE6)	1.8	3.2
Cylinder Aft (180 degrees section)	Low (0.1)	4.8	13.0	Aluminium Whipple Shield	0.7	2.1
Port Cone Fwd (180 degrees section)	Medium (2.1)	3.8	17.0	Reinforced Advanced Shield (AS2-N4KE4)	1.6	2.7
Port Cone Aft (180 degrees section)	Low (0.4)	3.8	17.0	Aluminium Whipple Shield	0.7	1.7
Starboard Cone	High (2.6)	3.8	20.0	Reinforced Advanced Shield (AS2-N4KE4)	1.6	2.7

Table 1: Debris threat, structural configuration and directional MDPS for Columbus according to the zone. The threat density is given in arbitrary units.

is used to simulate the exposure of the Columbus module to the M/OD environment, accounting for the detailed design of the exposed structure, the shadowing effect of the other elements of the station, the influence of the space attitude, etc. The development and validation of the shielding system is focused on the advanced shields (and on the relevant damage laws), as reflected in Table 2.

4.1 Whipple and Double Shields Hypervelocity Tests

ESA activity on debris shielding started at the beginning of the space station program participation. Extensive analytical and experimental activities were performed on aluminium, single and double bumper shields (i.e., one or two thin spaced bumpers to protect the rear wall -Ref. 10). Many configurations were tested, converging towards a double bumper made of two aluminium sheets 0.8 mm thick each, evenly spaced, together with a 3.2 mm thick shell and a 12 cm overall spacing. For some shots, the double bumper was replaced by a single wall, 1.6 mm thick. This was the Columbus module configuration before the M/OD requirement was made much more severe and the shell was thickened: the structure overall areal density was about 1.3 g/cm^2, while now it is about 3.2 g/cm^2. On the other hand, the critical mass at 6.5 km/s, normal impact, was about 0.5 g, while now it is about 10 times higher. Figure 4 plots some LGG data, compared with the 3-wall damage formulae implemented in ESABASE (coincident with the New Cour-Palais formula (Ref. 11) above 7 km/s). The formula seems to underpredict slightly the critical diameter. However, the comparison with other single bumper data obtained by ESA and NASA (Ref. 12), demonstrates the formula well suited for the WS structures protecting the COF Cylinder and Port Cone.
In some experiments (Ref. 13), the second aluminium bumper was replaced by a 1.7 mm Kevlar-Epoxy sheet, which had a better efficiency and offered mass saving.

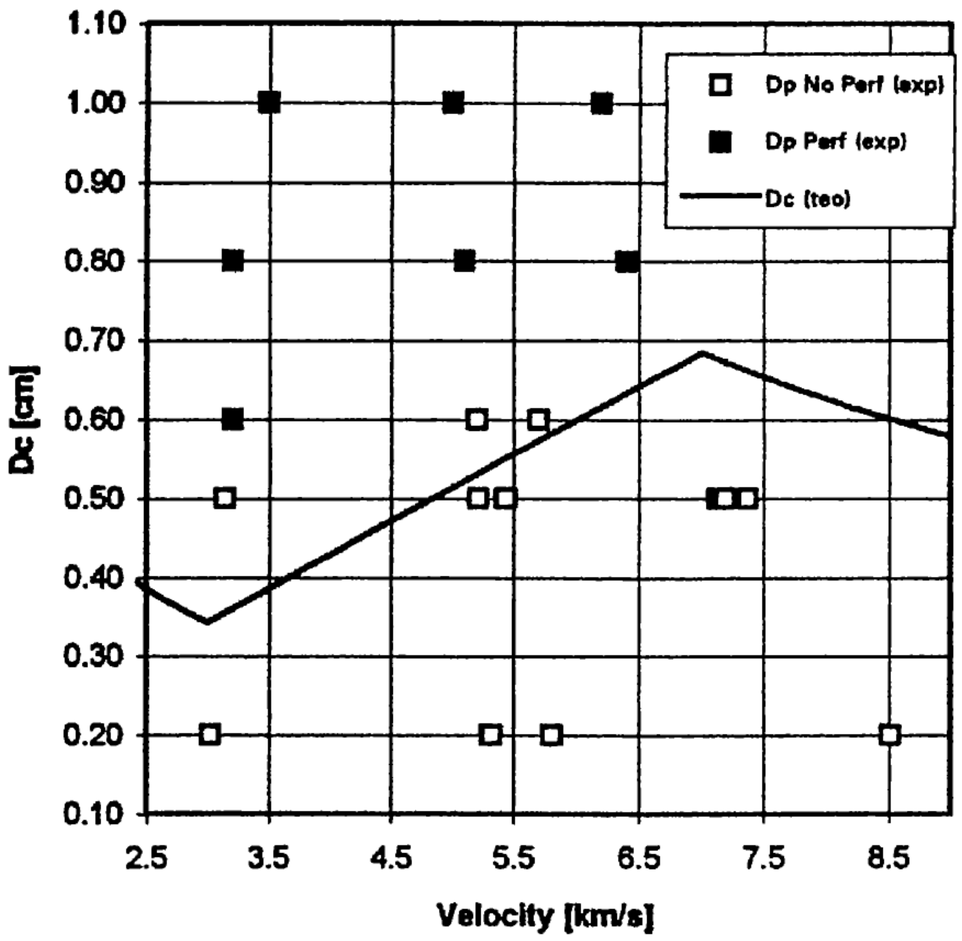

Figure 4: LGG data (Ref. 10) for a single and double bumper protecting a 3.2 aluminium rear wall impacted by aluminium spheres at 0 degree. Critical projectile diameter [cm] (causing on-set of perforation) versus velocity [km/s]. Comparison with the ballistic limit predicted by the ESABASE 3-wall formula.

4.2 Advanced Shields Hypervelocity Tests - Phase 1

The AS LGG experiments started at the Ernst Mach Institut, in the summer of 1995. The first phase of the test campaign was to select a configuration for the Cylinder Fwd, able to meet the PNP requirement. The Columbus pressure shell was not yet increased when the tests started (it was 3.2 mm thick in the cylinder area).
Advanced Shields with an outer aluminium bumper plus an inner wall (2nd BS) were investigated. Several options were tested for the 2nd BS, starting with a thick aluminium wall. This option was named Heavy All Aluminium Shield

		Cylinder Fwd (AS)	Cylinder Aft (WS)	Port Cone Fwd (AS)	Port Cone Aft (WS)	Starboard Cone (AS)
Baseline Configuration						
1st BS	material	Al 6061-T6	Al 6061-T6	Al 6061-T6	Al 6061-T6	Al 6061-T6
	thickness [mm]	2.5	1.6	2.5	1.6	2.5
	areal density [g/cm^2]	0.7	0.4	0.7	0.4	0.7
2nd BS	material	AS2-N4KE6	\	AS2-N4KE4	\	AS2-N4KE4
	areal density [g/cm^2]	1.1		0.9		0.9
BW	material	Al 2219-T851	Al 2219-T851	Al 2219-T851	Al 2219-T851	Al 2219-T851
	thickness [mm]	4.8	4.8	3.8	3.8	3.8
	areal density [g/cm^2]	1.4	1.4	1.1	1.1	1.1
Validation Approach						
Velocities up to 7 km/s		LGG Shots 3, 5, 6.5 km/s 0, 30, 45, degrees	Extrapolation from already available data	LGG Shots 3, 5, 6.5 km/s 0, 30, 45 degrees	Extrapolation from already available data	Extrapolation from Port cone shots
Velocities above 7 km/s		Simple physics laws Hydrocode simulations	Simple physics laws	Simple physics laws Similarity with Cylinder AS section	Simple physics laws	Simple physics laws Similarity with Cylinder AS section

Table 2: MDPS configurations and relevant damage formulae validation approach. N stands for Nextel, followed by the number of fabric layers used. KE stands for Kevlar composed with Epoxy resin, followed by a number giving the KE thickness. The shield data refers to the configurations tested during the AS Hypervelocity Tests Phase 2.

(HAAS) and reported a very poor ballistic behaviour (Ref. 5). For the other options, flexible blankets of Kevlar and/or Nextel have been used. For some configurations, the Kevlar was composite with Epoxy resin (40% by volume) and hence the 2nd BS was a stiff plate, while for the options without resin, it was a flexible mattress. These configurations are referred to as AS1, with the 2nd BS code added to specify the exact configuration. The shielding parameters are reported in Table 3 with the 2nd BS options investigated listed in Table 4. All the advanced targets reported very good ballistic performance, with comparable capabilities against hypervelocity impacts. Typical AS1 critical mass (diameter) is above 4.5 g (1.45 cm) at 6.5 km/s, normal impact and above 5.0 g (1.50 cm) at 6.1 km/s, 30 degrees impact. In some of the experiments a secondary effect induced by the debris cloud impact against the 2nd BS and the subsequent rebound together with 2nd BS material, was reported. This effect was named uprange blast, because the uprange rebound hits the first bumper and its supporting frame with high energy causing a large plastic deformation (up to 40 mm in a 2.5 mm thick steel frame - Ref. 5). This effect was reported for the 2nd BS made of either Kevlar-Epoxy or Kevlar cloth without resin. Only the introduction of the ceramic fiber was able to reduce the effect of the uprange blast. The Nextel cloth alone or a few Nextel layers placed on top (i.e., toward the incoming debris cloud) of the Kevlar or Kevlar-Epoxy, were very effective and no residual plastic deformation in the 1st BS and supporting frame was detected. A total of 28 shots were performed during the Phase 1 (Ref. 14). The AS1 ballistic performance rankings (based on the few data points available) are addressed in Table 4. For the COF program, the configurations without Nextel have been excluded because of the uprange blast effect. The stiff Kevlar-Epoxy plate offers the advantages of supporting the flexible Nextel cloth and easing the 2nd BS edge support within the MDPS panel. Therefore, it was selected for COF design and hence for the second phase of the test campaign.

4.3 Advanced Shields Hypervelocity Tests - Phase 2

The second part of the LGG test campaign started in February 97. In the meantime the Columbus pressurised shell was increased to 4.8 mm in the cylindrical section and to 3.8 mm in the cones areas and the maximum spacing available in the cylinder was reduced to 13 cm. The purpose of the Phase 2 of experiments is:

- to evaluate the shell thickness increase and the minor change in the cylinder spacing
- to define the baseline configuration for the AS Cylinder Fwd and Port Cone Fwd, adjusting the configuration

External Bumper (1st BS)	1st BS Areal Density [g/cm^2]	Rear Wall (BW)	BW Areal Density [g/cm^2]	Overall spacing (S) [cm]	Internal spacing (S2) [cm]
0.25 cm Al 6061-T6	0.7	0.32 cm Al 2219-T851	0.9	14.35	4.20

Table 3: Shielding parameters kept constant for the configurations tested during Phase 1.

Shield Identification	Intermediate Bumper (2nd BS)	2nd BS Areal Density [g/cm^2]	Total Areal Density [g/cm^2]	Remarks	Ballistic performance		Uprange blast
AS1-A6	0.6 cm Al 6061-T6	1.6	3.2	Stiff panel	Very poor	6 (worst)	Low
AS1-KE12	1.2 cm Kevlar™-Epoxy	1.4	3.0	Stiff panel	Very good	4	High
AS1-KE10	1.0 cm Kevlar™-Epoxy	1.2	2.8	Stiff panel	Good	(not ranked)	High
AS1-K50	50 layers Kevlar™	1.4	3.0	Flexible mat	Very good	1 (best)	High
AS1-N7KE6	7 layers Nextel™ + 0.6 cm Kevlar™-Epoxy	1.4	3.0	Stiff panel	Very good	2	Low
AS1-N3KE6	3 layers Nextel™ + 0.6 cm Kevlar™-Epoxy	1.0	2.6	Stiff panel	Good	(not ranked)	Low
AS1-N7K25	7 layers Nextel™ + 25 layers Kevlar™	1.4	3.0	Flexible mat	Very good	3	Low
AS1-N14	14 layers Nextel™	1.4	3.0	Flexible mat	Good	5	Low

Table 4: Phase 1 Advanced Shields tested with ballistic performance and uprange blast ranked. KE is for Kevlar-Epoxy, K is for flexible Kevlar cloth, N is for Nextel cloth. The numbers refer either to the number of layers (for the flexible configurations) or to the thickness (for the aluminium and Kevlar-Epoxy bumpers). The total areal density includes the external bumper and the rear wall.

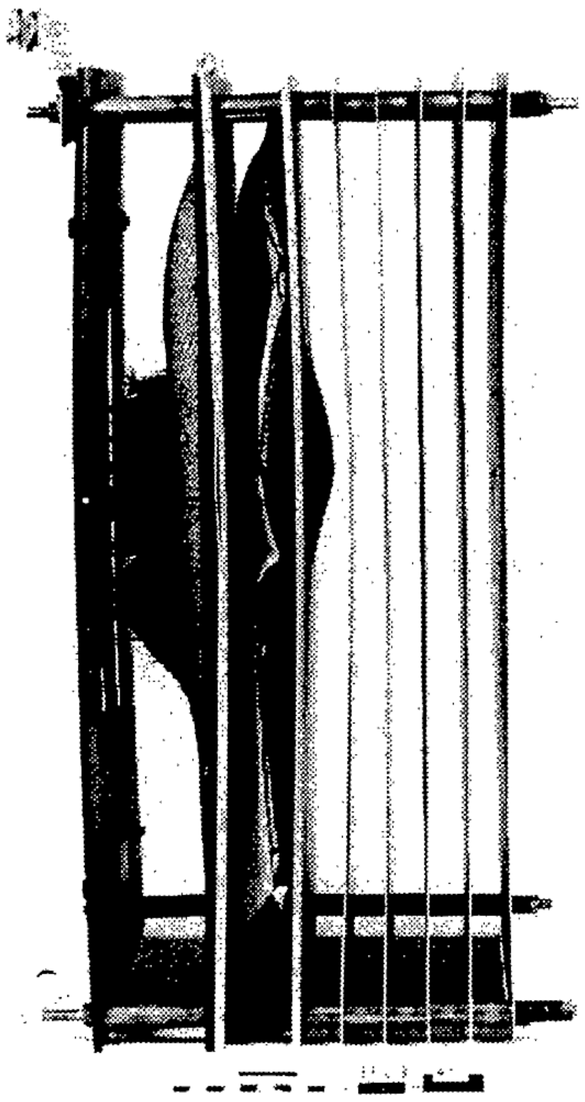

Figure 5: AS2-N4KE6 impacted target with MLI. Projectile was 1.55 cm aluminium sphere (5.5 g), impacting at 6.5 km/s, 45 degrees.

weight to the shielding performance

- to determine the ballistic limit curves for these two configurations (through LGG tests at 3, 5, 6.5 km/s and at 0, 30, 45 degrees)
- to test space qualified epoxy resin (CIBA Brochier 914) for the KE panels.

Only 17 shots on the Cylinder AS have been performed so far. The tested configurations are listed in Table 5. Flat, unpressurized, unstressed plates, 400 x 600 mm, have been used to represent the pressure shell. The Nextel-Kevlar-Epoxy combination confirmed the good ballistic performance, but only broad upper and lower ballistic limits have been established so far (see Table 6). The AS2-N4KE6 shield is in line with the no penetration allocation for the Cylinder Fwd area. During one single shot, a Multi-layer Insulation blanket (MLI) was introduced between the 2nd BS and the BW, which improved the target resistance (see Table 6). This impact target is shown in Figure 5. In Figure 6, some experimental data points are plotted, together with tentative ballistic limit curves for 0, 30 and 45 degrees impact angles. The ballistic limit evolution with the impact angle has to be reassessed when more data are available.

4.4 Hydrocode simulations

The purpose of the hypervelocity impact numerical simulations is to extend the LGG experimental data to higher impact velocities and to quantify kinetic energy/ momentum, spread angle, temperature and mass distribution of the debris cloud against the 2nd BS and BW. All simulations have been performed with the PAM-SHOCK 3D computer code, in which a Smoothed Particle Hydrodynamic solver has been incorporated (Ref. 9).

Shield Identification	Intermediate Bumper (2nd BS)	2nd BS Areal Density [g/cm^2]	Total Areal Density [g/cm^2]	1st BS thickness [mm]	BW thickness [mm]	Stand-off Spacing [cm]
AS2-N7KE6	7 layers Nextel™ + 0.6 cm Kevlar™-Epoxy 914	1.4	3.5	2.5	4.8	13.0
AS2-N4KE6	4 layers Nextel™ + 0.6 cm Kevlar™-Epoxy 914	1.1	3.2	2.5	4.8	13.0

Table 5: Phase 2 targets tested.

Shield Identification	Impact Angle [degrees]	Impact velocity [km/s]	Critical Diameter [cm]	Critical Mass [g]
AS2-N7KE6	0	6.3 - 6.5	$1.55 \leq d_c < 1.70$	$5.5 \leq m_c < 7.3$
	30	6.3 - 6.5	$1.55 < d_c < 1.60$	$5.5 < m_c < 6.7$
	45	6.3 - 6.5	$d_c \approx 1.65$	$m_c \approx 6.7$
AS2-N4KE6	0	3.0 - 3.1	$1.35 \leq d_c \leq 1.50$	$3.6 \leq m_c \leq 5.0$
	0	4.9	$1.40 \leq d_c \leq 1.50$	$4.1 \leq m_c \leq 5.0$
	0	6.5	$d_c \approx 1.50$	$m_c \approx 5.0$
	30	6.4 - 6.5	$1.50 \leq d_c < 1.55$	$5.0 \leq m_c < 5.50$
	45	6.4 - 6.5	$1.55^* \leq d_c \leq 1.55^{**}$	$5.5^* \leq m_c \leq 5.5^{**}$

*=shot without MLI, **=shot with MLI

Table 6: Phase 2 options ballistic performance. *=shot without MLI, **=shot with MLI

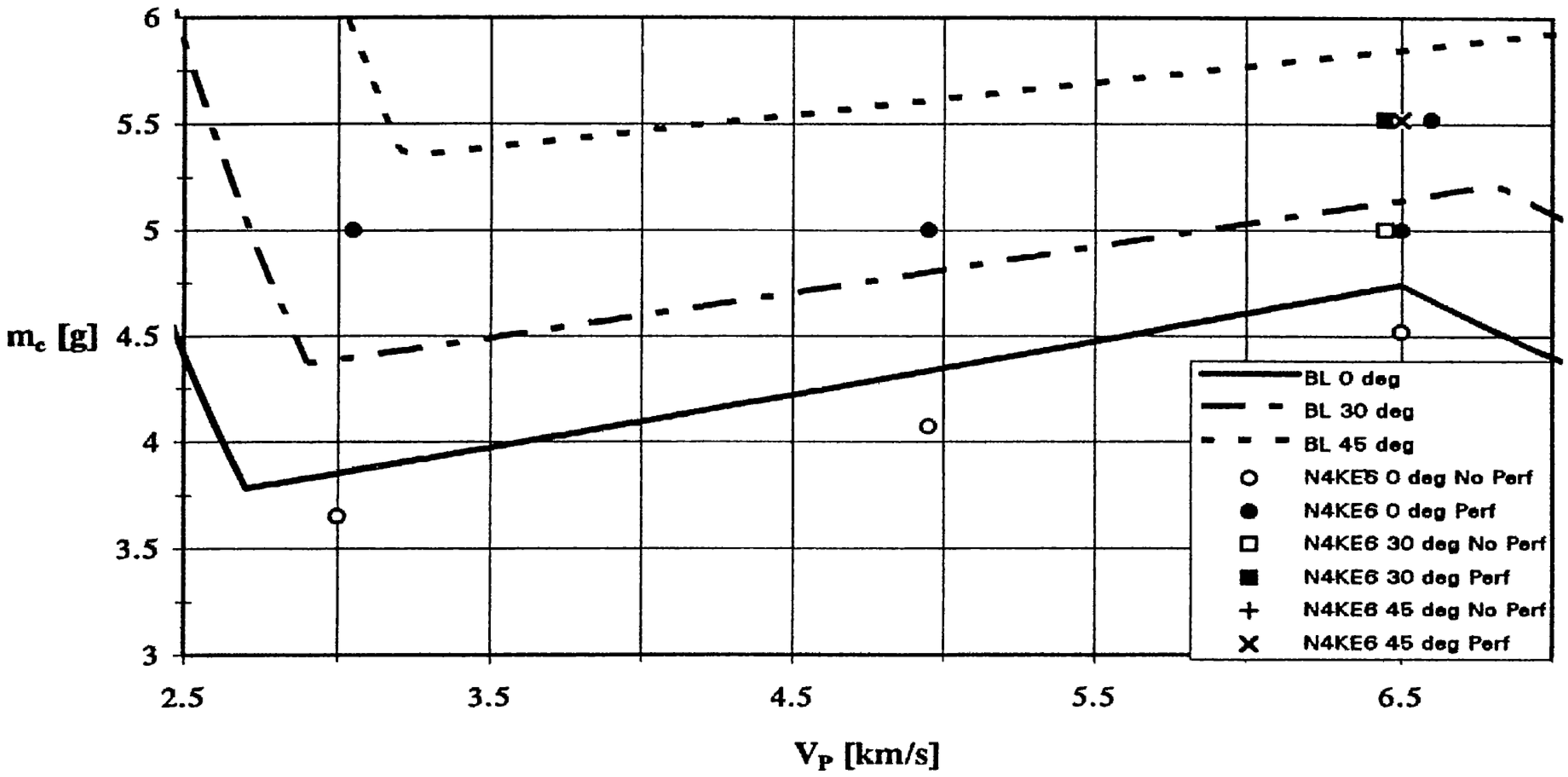

Figure 6: Advanced Shield ballistic limit curves (adapted from Christiansen [Ref. 7] with some modifications of the coefficients). The curves for 0, 30 and 45 degree impacts are compared with AS2-N4KE6 test data.

PAM-SHOCK is originally a non-linear explicit finite-element Lagrangian code that deals well with low impact velocities, but requires a lot of effort like remeshing when large deformations occur. In this case a SPH solver, based on a gridless Lagrangian hydrodynamic technique, becomes more suitable. Finite elements are replaced by interacting particles with variable interconnectivity, representing mathematical interpolation points in which material properties are known. Any function is expressed by an integral interpolant, using a continuous and differentiable function (kernel), whose region of influence is defined by the "smoothing length": when it goes to zero, the kernel is required to approach the delta function. Spatial derivatives of unknown field variables can be expressed as known derivatives of the kernel function. In numerical codes, the integral interpolant is replaced by a summation interpolant over all the particles. However, for computational efficiency, only the particles within the range defined by the smoothing length of the kernel function really contribute. Each particle has its own mass, velocity and density according to the relevant finite element and its evolution is governed by the conservation equations, "modified" by the kernel functions.

The computer code simulations started in the winter of 1996. Many 2D simulations have been performed using the SPH solver to investigate advantages/disadvantages and shortcomings with respect to finite element simulations. In the 200 m/s impact velocity range, the Lagrangian finite-element method gives better results than the SPH solver (which makes the simulation drop into instabilities and not to exactly conserve total energy). Particle motion correction coefficients, to reduce unphysical particle crossing, have sometimes stabilizing effects. Combination between particle motion corrections

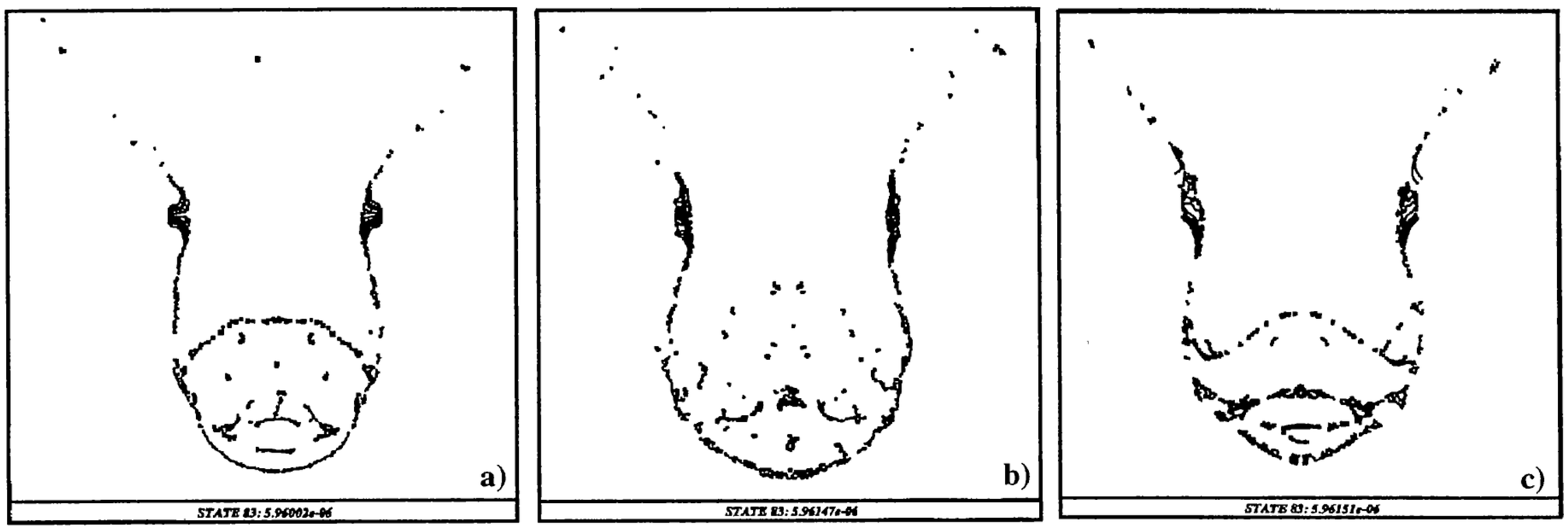

Figure 7: Debris cloud shape as function of smoothing length factor and anticrossing coefficient for a 7 km/s impact.

and Normalized Smoothing Functions (introduced to cut down errors at free boundaries and material interfaces) can improve the system behaviour.
In the 6-7 km/s impact velocity range, the SPH solver seems to work better: less problems of stability have been met and the energy seems to be conserved. The debris cloud shape remains very sensitive to empirical parameters, especially to the anticrossing coefficient and the smoothing length factor. A different and lower dispersion of fragments/particles occur when the smoothing length increases. Only low anticrossing coefficients seem to guarantee the energy conservation.
The pictures of Fig. 7 show a 7 km/s impact of a projectile with a 1.0 cm diameter against an aluminium target 2.5 mm thick. The Johnson-Cook yield model and the polynomial Equation of State (EOS) fitting the Mie-Gruneisen EOS have been selected. In the pictures (a), (b) and (c) the smoothing length factor and the anticrossing coefficients are worth 2.8 and 0.001, 2.0 and 0.001, 2.0 and 0.07, respectively. In all three cases the Normalized Smoothing Function proposed by Johnson (Ref. 15) has been used and all the others parameters have been kept constant. The evolution of the debris cloud is different for the three cases: with a smoothing length factor of 2.8 the projectile particles remain longer close one to another, while with an anticrossing coefficient of 0.001 the projectile tends to fragment completely, already in the very initial instants (~2μs). The evolution of the debris cloud with an anticrossing coefficient of 0.07 is in between the two previous cases, but the energy is not exactly conserved.
A great amount of work has to be still done, in order to assess the influence of the empirical parameters and to evaluate the impact of the debris cloud against the COF Advanced Shield system. In accordance with the LGG test results, the code will be improved, implementing the Nextel and Kevlar-Epoxy Equations of State, constitutive laws and failure models. Besides, 3D oblique impact simulations will be performed.

4.5 Adaptation of Shaped Charges and Multi-Stage Launcher Technology

The Shaped Charges test technique has been tailored to the M/OD application (Ref. 16), and is now ready for use as a standard procedure. Cylindrical projectiles of 1.1 g with an aspect ratio L/D of 3.7 can be accelerated to 11.2 km/s. The reproducibility ranges achieved are 10 % for both the projectile mass and dimensions with a pitch angle less than 10 degrees. An ESA study is in progress on validation of the PAM-SHOCK Hydrocode for normal and oblique hypervelocity impacts created by Shaped Charges.
The explosive Multi-Stage Launcher technique (Ref. 17) accelerates a flat round disk shape at 11 km/s with the potential to fire at velocities above 13 km/s. An ongoing ESA study deals with the optimization of the launcher using various experimental diagnostics and numerical simulations for validation.

5. LIMITATIONS AND UNCERTAINTIES

The PNP evaluation has a limited level of confidence due to both its interrelations with the uncertainties of the M/OD environment and the limited ground verification.
The PNP level is based on assumptions about the future debris environment. If the rate of launches or breakup is different than expected, the predicted PNP will prove to be incorrect. Recent studies also show that the flux of large debris in the ISS orbit is lower than in the adopted model and that debris may strike the ISS at lower velocity and from a wider range of directions than previously thought (Ref. 2).
The PNP is also derived with the uncertainties about the shields effectiveness included in the damage equations.
Direct test for ballistic limit validation is restricted to the LGG velocity range and the Hydrocode is being tuned and validated for COF shields at velocities below 7 km/s.
Uncertainties and limitations are related to the LGG tests for ballistic limit validation: 1) Only spherical aluminium projectiles are fired. Non-spherical debris shapes are by factors 1.2 to 2 more penetrating than equal mass spheres (Ref. 18). 2) Limited size of the test target may introduce edge effects and influence the damage characteristics. 3) Different damage characteristics may also arise from different mounting conditions of the bumpers and rear wall (Ref. 18). 4) The stiffening ribs of the manned modules waffle panel also affect the damage. Additional tests should be performed to quantify the boundary and hit location effects. 5) Scattering of hypervelocity test results are not quantified and would require additional experiments. As a consequence, the critical particle size over velocity is not a line but a distributed function.
The limitations and uncertainties affecting the PNP evaluation are not presently incorporated in the COF shielding and validation approach.

6. CONCLUSIONS

A development and validation approach has been established for the Columbus debris shielding system, leading to two basic shield types: Advanced Shields and Whipple Shields. Light Gas Gun experiments have proved the selected Advanced Shields to resist impacts against aluminium spheres up to 5 g, at 6.5 km/s. These ballistic performances fulfill the Probability of No Penetration allocation for the module. Numerical simulations with a Smoothed Particle Hydrodynamic solver have been started, to validate ballistic limit curves at velocities in excess of 6.5 km/s. Empirical parameters influence the SPH solver stability and the features of the debris cloud formation. Other launching techniques (i.e. Shaped Charges) and additional Light Gas Gun tests would be necessary to improve the validation approach and to reduce the uncertainties. The cooperation with NASA in on-orbit maintenance and repair activities is also in progress.

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