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MESH DOUBLE-BUMPER SHIELD: A LOW-WEIGHT ALTERNATIVE FOR SPACECRAFT METEOROID AND ORBITAL DEBRIS PROTECTION

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ABSTRACT

A number of new, innovative, low-weight shielding concepts have resulted from a decade of research at the NASA Johnson Space Center (JSC) Hypervelocity Impact Test Facility (HIT-F). One such concept, the mesh double-bumper (MDB) shield is a highly efficient method to provide protection from meteoroid and orbital debris impacts. Hypervelocity impact (HVI) testing of the MDB shield at the HIT-F and other facilities have demonstrated weight savings of approximately 30% to 50% at light gas gun velocities compared with conventional dual-sheet aluminum Whipple shields at normal impact angles. Even larger weight savings, approximately 70%, have been achieved at 45 degree oblique angles. The MDB shield was developed to demonstrate that a Whipple shield could be "augmented" or modified to substantially improve protection by adding a mesh a short distance in front of the Whipple bumper and inserting a layer of high strength fabric between the second bumper and rear wall. From the test results, formulas have been developed that allow the design engineer to size MDB shield elements for spacecraft applications.

GLOSSARY OF SYMBOLS USED

- C equation coefficient
- d diameter (cm)
- d_c projectile diameter causing failure (cm)
- ρ density (g/cc)
- m areal density (g/cm^2)
- S overall spacing between outer bumper and rear wall (cm)
- σ rear wall allowable yield stress (ksi)
- t thickness (cm)
- θ impact angle measured from surface normal (deg)
- V projectile velocity (km/sec)
- V_n normal component of projectile velocity (km/sec) = $V \cos \theta$

Subscripts:
- b bumpers [first & second bumper in mesh double-bumper shield]
- I intermediate fabric layer in MDB shield
- p projectile
- w rear wall

INTRODUCTION

NASA and other agencies have historically constructed spacecraft with requirements for protection from meteoroid impact (NASA SP-8042, 1970). A relatively recent design consideration has been the growth of the orbital debris environment in low Earth orbit which now exceeds the natural meteoroid environment for the important size regime of particle diameters greater than ~1 mm (NASA, 1991). Due to weight constraints on spacecraft designers, there is a need for higher performance shielding concepts that provide greater protection for less weight than the conventional two-sheet aluminum Whipple shield.

This paper describes work in progress on characterizing the impact protection performance of an innovative new shield concept: the Mesh Double-Bumper (MDB) shield. The MDB shield is one of several advanced shielding concepts that have resulted from research at the NASA JSC Hypervelocity Impact Test Facility (HIT-F). Weight reductions of 30% to 70% for equivalent hypervelocity impact protection are achieved by the MDB compared to conventional dual-sheet Whipple shields. Hypervelocity impact (HVI) tests, supported by numerical and analytical calculations, have been instrumental in developing the optimum MDB shield configuration. Distinguishing features of the MDB are the combination wire mesh and continuous sheet double-bumper, and a high-strength fabric layer that reduces particulate impacts and impulsive loading on the rear wall.

The MDB shield technology indicates that the protection performance of a Whipple shield can be significantly enhanced by adding a mesh a short distance in front of the standard Whipple bumper and by incorporating a fabric layer (of Kevlar®, Spectra®, Nextel® or other fabric) in front of the rear wall. The mesh bumper provides additional benefits as well, such as reduction of damaging secondary ejecta debris (Crews and Christiansen, 1992).

THE MESH DOUBLE-BUMPER SHIELD

The mesh double-bumper (MDB) shield consists of a spaced array of four distinct layers as shown in Figure 1: (1) wire mesh first bumper, (2) continuous second bumper, (3) high-strength fabric intermediate layer, and (4) a back plate or rear wall. Each has a different function as discussed below.

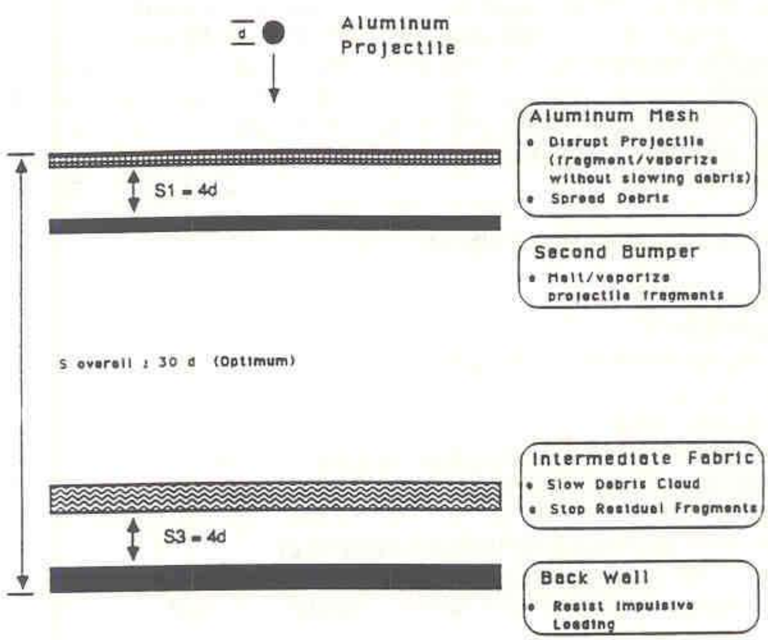


Figure 1. Mesh Double-Bumper Shield (Christiansen, 1990)

Wire Mesh

The wire mesh bumper provides a weight efficient method of breaking up the projectile into smaller fragments which are subsequently shocked by the second bumper. The mesh is composed of overlapping wires in a square pattern. Where the wires overlap, the mesh thickness to projectile diameter ratio is double the wire to projectile diameter ratio. This effectively creates localized mesh areas with greater bumper thickness. These thick areas contribute to the disruptive forces exerted on the projectile by increasing the shock duration in the projectile during the impact event. By removing "excess" bumper material, the mesh bumper is as capable of disrupting a projectile as a heavier continuous bumper.

Based on evidence from high-speed framing camera photography provided in impact tests at the JSC HIT-F, the mesh does not substantially reduce the speed of fragments resulting from the initial impact. Because the velocity of the fragments remains high after the incident particle breaks up on the mesh, the second bumper is more effective in shocking the remaining fragments to a high stress level that will, upon unloading, cause the remnant projectile fragments to release into liquid, vapor or finer solid particles that are less penetrating to the back sheet of the shield.

Less damaging secondary ejecta (external debris) is produced by the MDB shield, with its relatively thin outer mesh bumper, compared to an equivalent performance Whipple shield. Tests have demonstrated that secondary ejecta from mesh bumpers consist of fine, mist-like particles that do not significantly damage witness plates (Christiansen, 1987).

Another observation from the impact tests is that the fragmentation of the projectile on a wire mesh is more dispersive than an impact into the same areal density continuous bumper (Christiansen, 1987, 1990). The debris cloud exiting from a wire mesh bumper spreads laterally to a greater extent than from the same weight per unit area continuous bumper. A recent research study (Horz et al., 1992) substantiates this conclusion. The resulting greater spread in the debris cloud reduces performance degradation at smaller bumper standoffs. This translates into greater weight savings for the MDB shield as overall shield standoff distance is reduced, compared to an equivalent performance Whipple shield.

Second Bumper

The purpose of the second bumper is to produce a second shock in the projectile fragments produced from impact with the initial mesh bumper. The impacting fragments become further pulverized after unloading from the shock on the second bumper, and their thermal state increases which can melt or vaporize them. The second bumper is a continuous sheet that is sized to completely shock the largest particle in the debris cloud from the projectile impact on the mesh. A continuous bumper insures that any small particles passing unhindered through the first mesh are disrupted well before contacting the intermediate layer and rear wall.

Intermediate Fabric Layer and Back Plate

The intermediate fabric layer is used to increase shielding performance by stopping or slowing any remaining solid fragments before they contact the back plate. In addition, the fabric layer slows the expansion of the debris cloud by absorbing energy through stretching and breaking of the fabric fibers, thereby decreasing the momentum loading on the back plate. The purpose of the back plate (or "rear wall") is to resist penetration of any solid fragments and react the impulsive loading from the debris cloud.

EXPERIMENTAL DESIGN AND RESULTS

The concept of using a mesh as a bumper material for shielding has been investigated since the early 1980's by personnel at the NASA JSC Hypervelocity Impact Test Facility (HIT-F). Numerous tests were performed on wire mesh bumper systems before the MDB shield design was perfected (Christiansen, 1987; Crews and Christiansen, 1992). The MDB shield has performance characteristics comparable to the Multi-Shock (MS) Shield described by Cour-Palais and Crews (1990).

Testing of the MDB concept occurred in several distinct phases: (1) research testing to select and optimize the materials, spacings, and weight distribution between the different shield layers, (2) scaling studies to assess thicknesses of the various shield elements as a function of projectile impact conditions (size, velocity, etc.), and (3) development testing to derive equations for predicting overall MDB shield performance as a function of impact velocity, impact angle, and projectile density.

MDB Optimization and Scaling Studies

Results of the MDB optimization studies using 0.32 cm diameter aluminum projectiles have been reported by Christiansen (1987, 1990). This work has been extended to scaling up the MDB shield concept to 0.64 cm, 0.79 cm, and 0.95 cm diameter aluminum projectiles. Scaling equations were developed (reported later in this paper) and verified in the scale-up studies.

Spacing between first and second bumper is a key variable that was evaluated in the impact testing. It is desirable to keep the first and second intra-bumper spacing as small as possible to allow the greatest expansion in the debris cloud that exits the second bumper before impact with the back plate. However, spacing is required between bumpers to allow sufficient material contact with the second bumper to fully shock the debris fragments. The minimum weight MDB configuration was found when first to second bumper spacing was 3 to 4 times the projectile diameter (Christiansen, 1990, 1992).

Hydrocode calculations show residual stresses cause further flattening of the projectile fragments as they travel from first bumper to second bumper (Alme, 1991). The change in aspect ratio of the fragments (to thinner, more disk like shapes) is an advantage upon impact with the second bumper, allowing a thinner second bumper to fully shock the fragments.

The optimization studies investigated the required mesh areal density and mesh geometry parameters. Figure 2 shows some of the aluminum mesh types used in the study. The mesh is composed of overlapping wires in a square pattern with a wire diameter to projectile diameter ratio of from 0.07 to 0.10. Generally, from 4 to 6 wires are "cut" by the diameter of the projectile. Open area of the meshes varies from 20% to 40%. Since a fine mesh is used, small projectiles passing unhindered through the mesh are easily defeated by remaining shield elements.

Aluminum meshes have been extensively tested since they are effective against orbital debris which until 1991 has been defined as having the density of aluminum (NASA, 1991). However, some tests have been performed with steel projectiles on steel meshes and fabrics. Tests with higher density projectiles were conducted since they may be included in future debris environment definitions. It has been found that a higher density mesh bumper is more effective against higher density impacting projectiles.

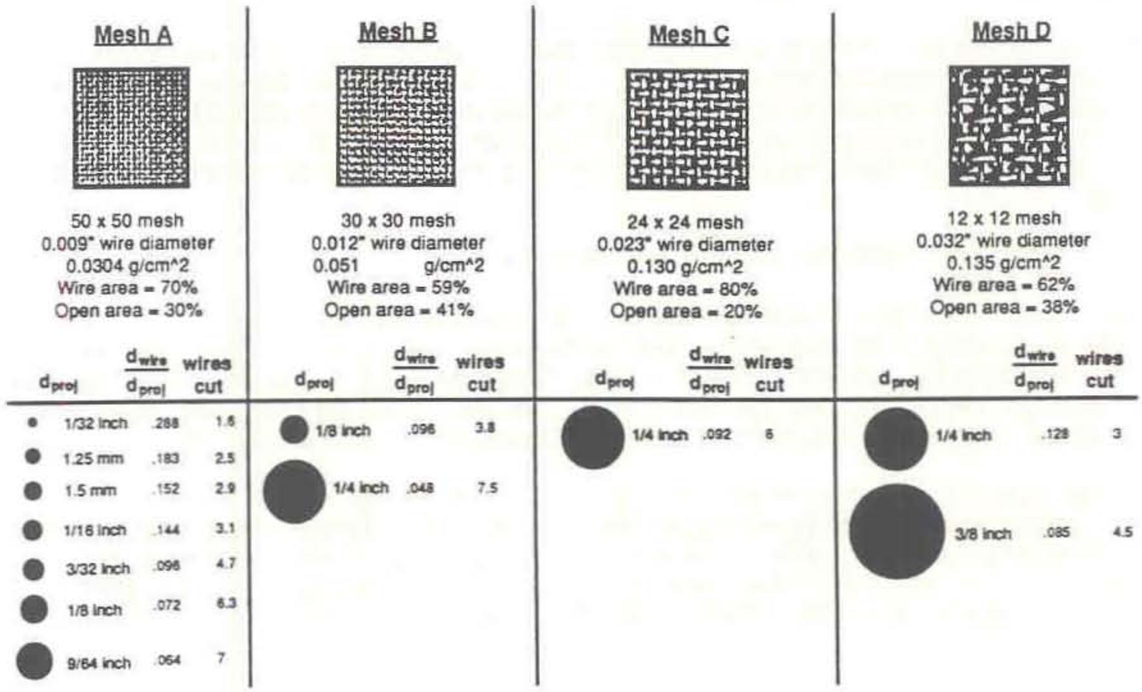


Figure 2. Aluminum Mesh Types Evaluated in HVI Tests

Different materials for the second bumper were evaluated analytically and experimentally (Christiansen, 1990), including various aluminum alloys, graphite-epoxy, and Nextel® ceramic fabric. Although graphite-epoxy and Nextel® performed as well or better than aluminum, aluminum (6061 alloy) was used for the second bumper in the later development testing because the emphasis was on methods to upgrade the protection of typical Whipple shield designs. A series of flash X-ray photographs in Figure 3 from the University of Dayton Research Institute (UDRI) shows a 0.95 cm aluminum impact at 6.8 km/sec on the first two sheets of a mesh double-bumper. After impact with the mesh, the remnant projectile is fractured and flattened. Also of note are precursor "jets" of very fine material that correlate with the gaps between the mesh wires. The projectile fragments are totally broken up into a cloud of very fine particles after impacting the second continuous bumper sheet.

Location of the intermediate fabric layer is a significant parameter influencing the effectiveness of the MDB shield. The optimum fabric layer location is dictated by mounting as far from the bumpers as possible to attain the maximum debris cloud expansion while allowing sufficient clear space to insure the cloth fibers stretch and tear to slow the debris cloud velocity before contacting the rear wall. Testing showed greater impulsive loading damage occurred to the back plate if the fabric layer was mounted directly to the back plate surface (Christiansen, 1990). It was found that the optimum location for the cloth layer was at a short distance, approximately 3 to 4 times the projectile diameter, from the back plate.

A number of different types of fabric materials were considered for the intermediate cloth layer. Impact tests were used to evaluate Kevlar® and Spectra® intermediate layers, primarily because they have high strength to weight ratios giving them excellent ability to absorb energy. Kevlar® is a DuPont product made from aramid fibers while Spectra® is a high modulus polyethylene fabric produced by Allied Signal. Nextel® 312 (made by 3M) ceramic cloth was also tested because it has good high-temperature strength characteristics. Spectra® 900 and Kevlar® 29 fabrics performed somewhat better than Nextel® 312 cloth, although all fabrics increased shielding performance over not having a fabric layer and adding the equivalent mass of the fabric to the back plate.

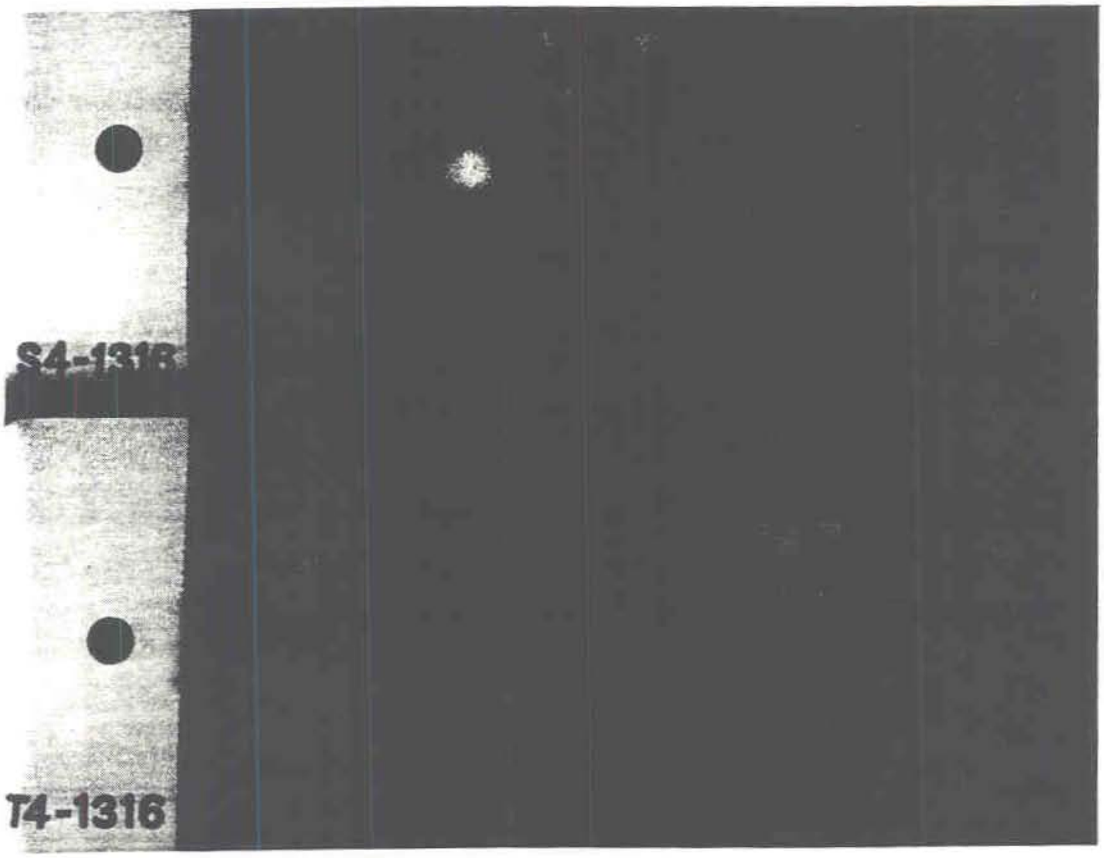
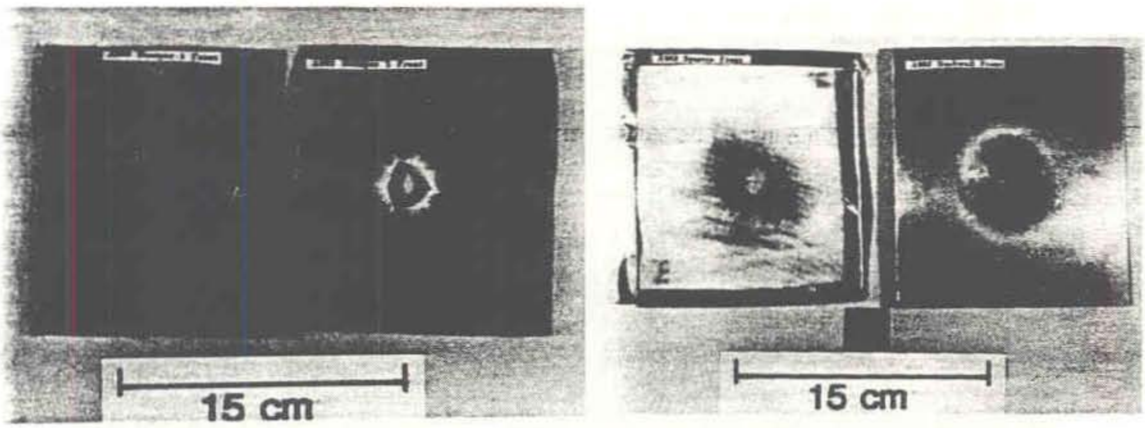


Figure 3. UDRI flash X-ray series of 1 cm, 6.8 km/sec aluminum impact on a mesh double-bumper shield (Mesh Type D)

Alternative back plate materials and configurations, such as laminates, honeycomb, composites and fabrics, have been tested and could potentially provide more protection for less weight than aluminum alloys.

Figure 4 shows typical results of a hypervelocity impact test (JSC Shot No. A963) on an aluminum mesh double-bumper system using a type B mesh (see Figure 2). The projectile was a 3.2 mm aluminum sphere impacting at 6.35 km/sec normal to the shield. This particular test was evaluating small standoffs, with a 5 cm total spacing used in this test (S/d = 16). Spectra® 900 cloth (2 layers of Style 618 fabric) was used in the intermediate layer (0.056 g/cm^2). No perforations or detached spall occurred to the 0.08 cm Al 2024-T3 back plate, which was permanently deformed and bulged by a purely impulsive load. No cratering from solid fragments was evident on the back plate. The total areal density of this MDB shield is 0.41 g/cm^2. This weight is ~60% less than an aluminum Whipple shield providing equivalent protection (no penetration or spall) with the same standoff (1.1 g/cm^2). For this threat case (0.32 cm aluminum with S/d=16), the MDB shield shows a slight improvement over the 0.525 g/cm^2 Nextel® MS shield with a 5 cm total spacing reported by Cour-Palais and Crews (1990). Impact testing at the JSC HIT-F has shown that a double bumper system with a mesh outer bumper exhibits superior performance over the same weight double bumper consisting of two continuous aluminum sheets (Christiansen, 1990).



a) Double-Bumper Front

b) Intermediate Layer and Wall Front

Projectile: 0.32 cm Al 2017T4, 6.35 km/sec, 0°

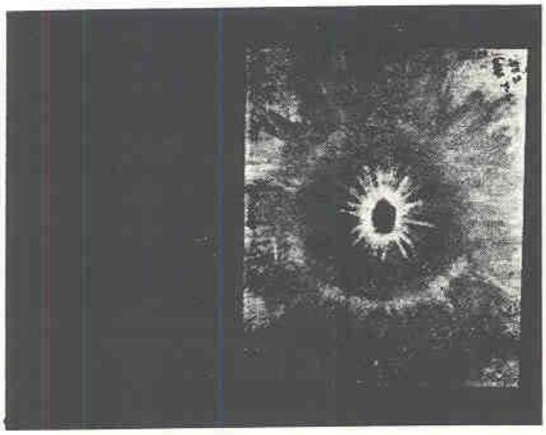
Target: Mesh Type B first bumper (0.03 cm wire diameter), 0.03 cm Al 6061 second bumper, 0.056 g/cm^2 Spectra® 900 Layer (2 Style 618 fabric), 0.08 cm Al 2024T3 rear wall, 5.08 cm overall spacing

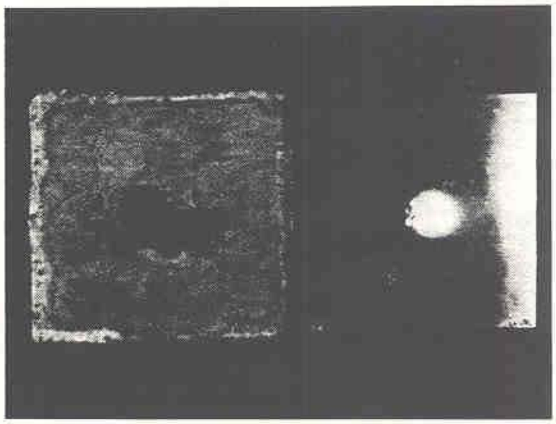
Figure 4. JSC HIT-F Shot No. A963: Performance of MDB Shield with 5 cm overall spacing against 0.32 cm Al projectile.

Figure 5 demonstrates a scaled-up mesh double-bumper that was tested with a 7.9 mm diameter aluminum (2017T4) projectile at 7.43 km/sec (JSC Shot No. B135). For this test, a type A mesh was used (Figure 2) for the first bumper and five sheets of Kevlar® 29 fabric (style 710) with an areal density of 0.16 g/cm^2 was used for the intermediate layer. The Kevlar® was securely mounted to a rigid frame located 3.8 cm in front of the back plate. Overall spacing from first bumper to back plate was 25.4 cm. Total shield areal density for this MDB configuration was 0.766 g/cm^2. In comparison, a Whipple shield with 25.4 cm spacing would weigh 1.3 g/cm^2 to provide similar protection (Christiansen, 1992).

Development Testing

Development testing concentrated on specific MDB configurations to derive MDB shield sizing formulas and performance assessment equations suitable for spacecraft shield design application. In particular, MDB shield performance as a function of projectile size, impact velocity, density, and impact angle was assessed. The basis of the testing was a MDB configuration with an aluminum mesh bumper, Al 6061 second bumper, Kevlar® 49 and Spectra® fabric intermediate layers, and aluminum alloy rear wall.





Mesh Bumper and Second Bumper (front)

Kevlar Intermediate Layer and Back Plate (back)

Projectile: 0.79 cm Al 2024T3, 7.43 km/sec, 0°

Target: Mesh Type A first bumper (0.023 cm wire diameter), 0.08 cm Al 6061T6 second bumper, 0.16 g/cm^2 Kevlar® 29 Layer (5 Style 710 fabric), 0.127 cm Al 2024T3 rear wall, 25.4 cm overall spacing

Figure 5. JSC HIT-F Shot No. B135: Performance of MDB Shield with 25 cm overall spacing against 0.79 cm Al projectile.

Over 100 tests on shields utilizing wire mesh bumpers have been performed. Table 1 lists selected hypervelocity impact data on MDB shields from the research and development testing. The criteria for shielding success in these tests was no perforation or detached spall from the rear wall of the shield protection system. Damage to the rear wall of the MDB was classified with the damage classification system promulgated by Dahl and Cour-Palais (1991) as given by the "Damage Class" column in Table 1. Development tests were performed primarily at the JSC HIT-F using spherical projectiles up to ~8 km/sec, although other facilities were utilized to supplement the required test data (University of Dayton Research Institute and Sandia National Laboratory). Although the test velocities represent only ~25% of the debris threat, the HVI data includes the more damaging low velocity impacts for these particular shields (typically 2-3 km/sec) and therefore represents a higher percentage of the penetrating flux (Christiansen et al., 1992).

ANALYSIS AND DISCUSSION

The equations in this paper are presented in two parts: (1) sizing equations to determine preliminary estimates of shielding thicknesses and weights, and (2) ballistic limit equations that define the impact conditions causing shield failure (perforation or detached spall).

Shield Sizing Equations

The following equations have been modified slightly from those given previously (Christiansen, 1990). These equations have been developed for preliminary shield sizing purposes using a "design" particle method (Christiansen, 1992). A "design" particle (size, average impact velocity and angle) can be determined for each surface of a shielded element from probability of no-failure requirements, meteoroid/debris environment models, surface area, and orientation considerations. The bumper and rear wall thicknesses for each surface can then be calculated from equations (1) through (5). This simplified method is useful for deriving estimates of shielding weights and for performing trade studies. A more detailed approach is used for verifying design adequacy by extending the analysis to include the full distribution of meteoroid and orbital debris impact velocities and angles.

The mesh areal density is given by:

$$m_1 = c_m \, d \, \rho_p \tag{1}$$

Table 1: MDB Hypervelocity Impact Test Data

JSC Shot No.	Projectile Diameter (cm)	Vel. (km/sec)	Impact Angle (deg)	Intermediate Layer Material (# of sheets)	Back-Wall Mat'l	Wall Thick (cm)	Overall Spacing (cm)	Total Ar. Density (g/cm^2)	Damage Class	Wall Damage (P=Perforation, S=Detached Spall)
					Type A Aluminum 5051 Mesh					
A1276	0.318	6.20	0	Kevlar 095(2)	Al2024T3	0.041	10.16	0.283	F3	No P or S, bulge
A1285	0.318	6.42	0	Kevlar 095(2)	A12024T3	0.030	10.16	0.254	F3	No P or S, bulge
A1289	0.318	6.24	0	Spectra 618(2)	A12024T3	0.030	10.16	0.254	F3	No P or S, bulge
A1351	0.239	4.46	45	Kevlar 710(2)	A12024T3	0.051	10.16	0.319	C4	4 Ps, 1.5xlmm max
A1364	0.357	6.00	75	Kevlar 710(2)	A12024T3	0.051	5.08	0.319	C1	No P or S, sm.dmpls
1414	0.079	3.50	0	Spectra 618 (2)	A12024T3	0.030	10.16	0.275	C0	No P or S, No damage
1651	0.149	2.63	0	Kevlar 710(2)	A12024T3	0.051	10.16	0.319	C4	1 P,0.8mm
1652	0.160	3.44	45	Kevlar 710(2)	A12024T3	0.051	10.16	0.319	C2	No P or S, dmpls
1654	0.160	3.41	60	Kevlar 710(2)	A12024T3	0.051	10.16	0.319	C1	No P or S, no dmpls
1660	0.160	4.81	45	Kevlar 710(2)	A12024T3	0.051	10.16	0.319	C2	No P or S, dmpls
1661	0.160	5.74	60	Kevlar 710(2)	A12024T3	0.051	10.16	0.319	C0	No P or S, No damage
					Type B Aluminum 5051 Mesh					
A954	0.318	6.39	0	Spectra 618 (2)	A12024T3	0.079	5.08	0.439	F3	No P or S, some dimples
A963	0.320	6.35	0	Spectra 618 (2)	A12024T3	0.079	5.08	0.412	F3	No P or S, bulge
A971	0.317	6.62	0	Spectra 618 (2)	A13003H12	0.064	10.16	0.364	F3	No P or S, bulge
A978	0.318	6.58	0	Spectra 618 (2)	A16061-0	0.064	10.16	0.362	F3	No P or S, bulge
A1061	0.318	6.11	45	Spectra 618 (2)	A12024T3	0.079	10.16	0.412	C2	No P or S, dmpls
A1068	0.318	5.87	60	Spectra 618 (2)	A13003H12	0.064	10.16	0.364	C4	1 P, 1.3mm
A1069	0.318	6.08	45	Spectra 618 (2)	A13003H12	0.064	10.16	0.364	C2	No P or S, dmpls
A1111	0.318	6.02	60	Spectra 618 (3)	A12024T3	0.064	10.16	0.395	C2	No P or S, dmpls
A1275	0.318	5.90	0	Spectra 618 (2)	A12024T3	0.041	10.16	0.309	F3	No P or S, bulge
B201	0.635	7.46	0	Kevlar 710 (4)	A12024T3	0.102	20.30	0.635	F3	No P or S, bulge
					Type C Aluminum 5051 Mesh					
B27	0.635	6.69	0	Spectra 618(4)	A12024T3	0.079	20.32	0.638	F3	No P or S, bulge
B77	0.635	7.53	0	Kevlar 710(4)	A12024T3	0.180	10.16	0.935	F3	No P or S, bulge
B204	0.635	7.50	0	Kevlar 710 (4)	A12024T3	0.102	20.30	0.714	F3	No P or S, bulge
					Type D Aluminum 5051 Mesh					
B203	0.635	7.25	0	Kevlar 710 (4)	Al2024T3	0.102	20.30	0.719	F3	No P or S,bulge
4-1172(UDRI)	0.953	6.65	0	Kevlar 903 (7)	A12024T3	0.180	30.48	1.084	F3	No P or S, s. bulge

Where c_m can range from 0.035 to 0.057 without changing the accuracy of the following equations. The mesh has wires in a square pattern with a wire diameter to projectile diameter ratio of from 0.07 to 0.10. The first to second bumper spacing is four times the projectile diameter: $S_1 = 4$ d.

The second bumper is a continuous aluminum sheet that is sized by the following equation:

$$m_2 = 0.093 \text{ d } \rho_p \tag{2}$$

A high strength fabric intermediate layer (Spectra®, Kevlar®, Nextel®, etc.) is mounted a distance of $S_3 = 4$ d in front of the rear wall. For Spectra® or Kevlar®, the sizing equation is:

$$m_I = 0.064 \text{ d } \rho_p \tag{3}$$

If Nextel® is used, the sizing equation is:

$$m_I = 0.095 \text{ d } \rho_p \tag{4}$$

The rear wall sizing equation is:

$$m_W = 9 \text{ M } V_n/S^{3/2} \ (40/\sigma)^{0.5} \tag{5}$$

These equations can be applied for a component velocity ($V \times \cos^{1/3}\theta$) of greater than 6.4 km/sec and S/d ratios of more than 15. The wall areal density calculated by (5) is based on the ballistic limit criterion of preventing perforation and detached spall.

The equations are valid for all impact angles. Bumper materials are ejected normal to the bumper in oblique impacts. Bumper particles from oblique impacts on a wire mesh consist of fine mist-like particles that are stopped by the second bumper. Bumper particles from the second bumper are stopped or slowed considerably by the intermediate fabric layer protecting the rear wall. On the other hand, bumper fragments from a Whipple shield are far more damaging to the rear wall for two reasons: (1) an oblique impact on the bumper of the Whipple shield produces bumper fragments that are larger and more penetrating than from the thinner MDB bumpers and (2) these bumper particles can impinge directly on the rear wall of the Whipple shield.

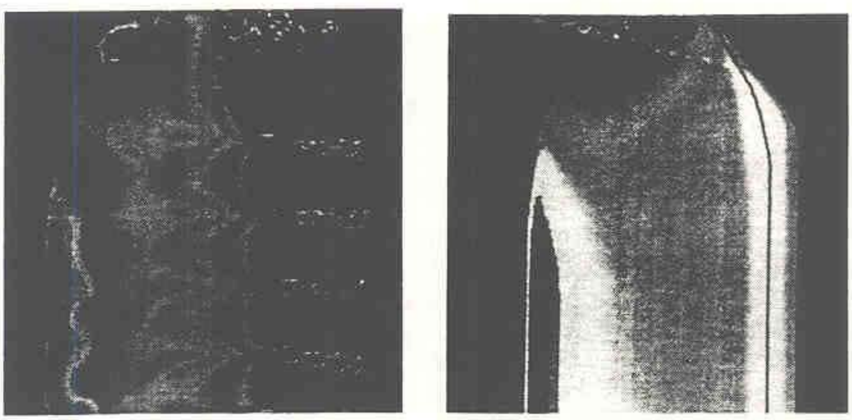


Figure 6. CALE Simulation of impact on discontinuous grid (left) and continuous bumper (right) (Alme, 1991). Impact occurs left to right. Projectile and target boundaries are outlined. Specific energy distribution at 0.4 µs. Scale varies linearly from zero to 0.03 Mb-cc/g on left and to 0.025 Mb-cc/g on right.

For applications to velocities beyond test capabilities, these formulations build on equations originally developed in the 1960's and 1970's for predicting optimum Whipple shield performance against 11-72 km/sec meteoroid threats (Cour-Palais, 1969; Cour-Palais and Crews, 1990). JSC HIT-F applies additional analysis techniques such as hydrodynamic computer codes to evaluate the velocity scaling relations. For example, Figure 6 shows a hydrocode simulation of an impact into equal areal density continuous and discontinuous bumpers. This impact sequence was performed with the CALE hydrocode (Alme, 1991). The discontinuous bumper represents a 50% filled wire grid (a linear pattern of square cross-section wires), with a wire thickness to projectile diameter ratio of 0.08. The pressure contours after 0.35 μsec shows that localized areas of the projectile impacting the grid bumper have been shocked to somewhat higher pressures than the continuous bumper because the duration and extent of the shock wave has been changed by mesh geometry. The code also predicts that areas of the projectile that impacts the grid have a 20% higher thermal energy content than with the impact on the continuous bumper (Figure 6). The simulation shows "jets" of molten material form in the gaps of the grid. The hydrocode evaluations of the MDB are still in progress.

Ballistic Limit Equations

The following ballistic limit equations define MDB shield performance for a configuration using either Kevlar® or Spectra® cloth as an intermediate layer, and aluminum mesh and continuous bumpers and rear wall. The equations are in a form that relates critical particle diameter with impact velocity, impact angle, particle density, and target parameters. Impacts larger than the critical particle size cause shield failure (i.e., perforation or detached spall of the rear wall of the hybrid shield), while those smaller do not. The equations are consistent with the equations given previously, but additional equations are given to cover low and intermediate impact velocities.

These equations predict MDB performance across the full range of impact conditions expected on-orbit and are used in meteoroid/debris probability analyses, such as BUMPER, a computer program that is used by the JSC HIT-F to calculate probabilities of meteoroid and debris impact damage (Christiansen et al., 1992; Crews and Christiansen, 1992).

For $V \geq 6.4/(\cos\theta)^{1/3}$:

$$d_c = 0.6\,(t_w\,\rho_w)^{1/3}\,\rho_p^{-1/3}\,V^{-1/3}\,(\cos\theta)^{-1/3}\,S^{1/2}\,(\sigma/40)^{1/6} \qquad (6)$$

For $2.8/(\cos\theta)^{0.5} < V < 6.4/(\cos\theta)^{1/3}$:

$$\begin{aligned} d_c = {} & 1.11\,\rho_p^{-0.5}\,[t_w\,(\sigma/40)^{0.5} + 0.37\,(m_b+m_I)]\,(\cos\theta)^{-4/3} \\ & [(6.4/(\cos\theta)^{1/3} - V)/(6.4/(\cos\theta)^{1/3} - 2.8/(\cos\theta)^{0.5})] \\ & + 0.323\,(t_w\,\rho_w)^{1/3}\,\rho_p^{-1/3}\,(\cos\theta)^{-2/9}\,S^{1/2}\,(\sigma/40)^{1/6} \\ & [(V - 2.8/(\cos\theta)^{0.5})/(6.4/(\cos\theta)^{1/3} - 2.8/(\cos\theta)^{0.5})] \end{aligned} \qquad (7)$$

For $V \leq 2.8/(\cos\theta)^{0.5}$:

$$d_c = 2.2\,[t_w\,(\sigma/40)^{0.5} + 0.37\,(m_b+m_I)]/[(\cos\theta)^{5/3}\,\rho_p^{0.5}\,V^{2/3}] \qquad (8)$$

An application of these equations to a typical MDB shield configuration is shown in Figure 7. Figure 8 shows a comparison between the HVI test data and predicted shielding performance using (6) through (8) for impact tests on different MDB configurations.

SUMMARY AND CONCLUSIONS

The impact testing and analysis work at the JSC HIT-F has resulted in an alternative low-weight shielding concept: the mesh double- bumper shield. MDB shields offer ~50% weight savings compared to conventional Whipple shields, while reducing the amount of damaging secondary ejecta debris. Impact performance of the MDB has been assessed for the full range of impact conditions assessable in the laboratory (up to 8 km/sec and at normal and oblique impact angles). Equations have been formulated to allow designers to apply the MDB concept to spacecraft meteoroid/debris protection. Aluminum mesh bumpers offer some unique advantages in augmenting conventional Whipple shield meteoroid/debris protection. Work to date indicates that the addition of a mesh to the exterior of equipment items protected by Whipple shields will greatly increase their resistance to penetration.

Ballistic protection can be improved even more if an intermediate fabric layer (of Kevlar®, Spectra®, or Nextel®) is attached near, but not on, the rear wall.

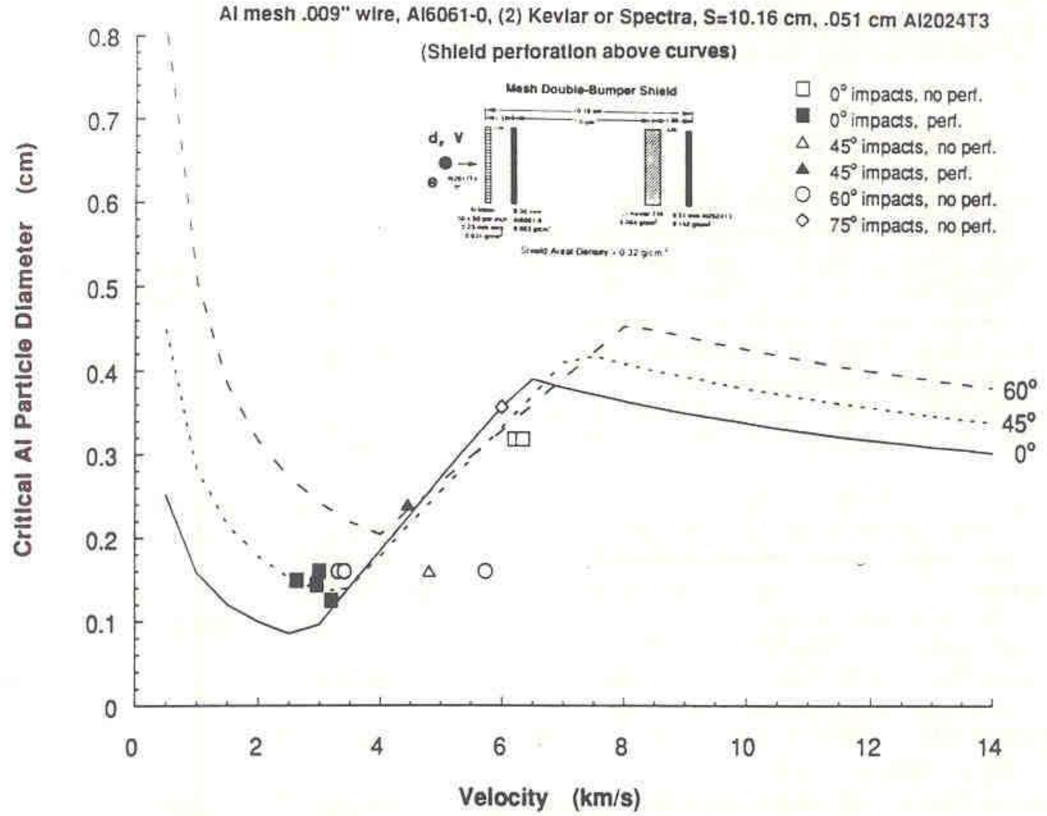


Figure 7. Mesh Double-Bumper Shield Ballistic Limit Curves

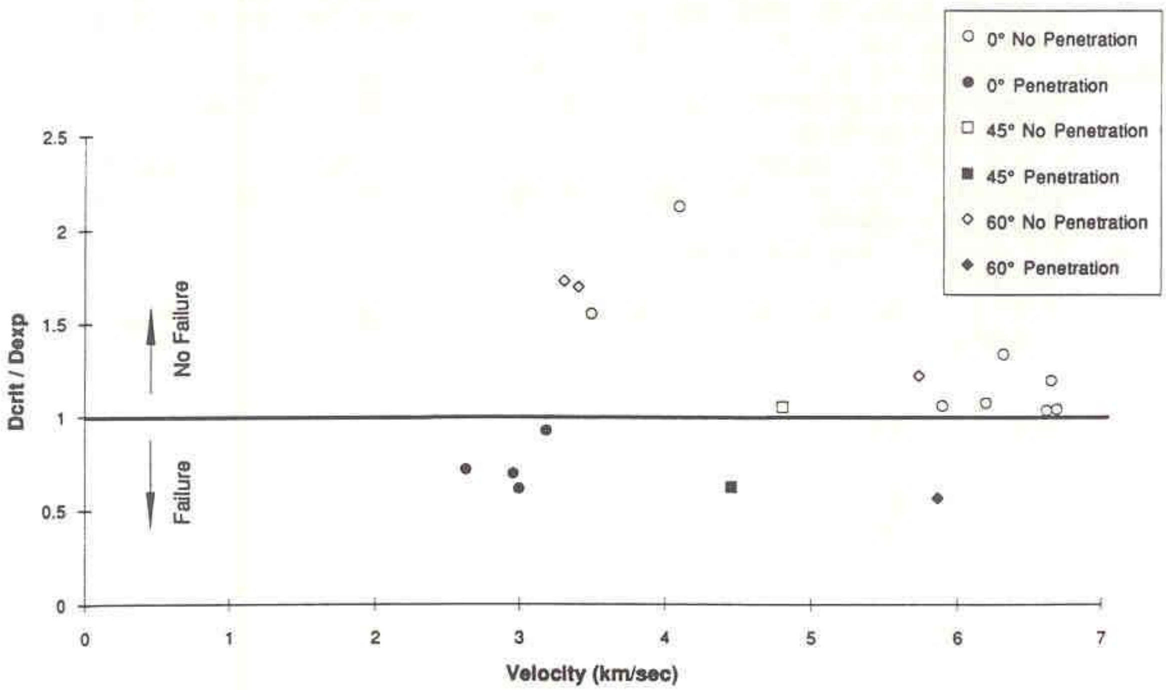


Figure 8. Comparison of MDB Shield Predicted Perfomance with HVI Data

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