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ENHANCED METEOROID AND ORBITAL DEBRIS SHIELDING

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Summary—An innovative, low-weight shield system has been developed by NASA Johnson Space Center (JSC) and Marshall Space Flight Center (MSFC) engineers to enhance the protection of conventional Whipple shields. This shield, the "Stuffed Whipple" shield, includes a flexible blanket combining Nextel™ ceramic fabric and Kevlar™ fabric (or "stuffing") between the aluminum bumper and rear wall of a Whipple shield. The Stuffed Whipple (SW) shield is particularly effective if shield standoffs are short (i.e., shield spacing to projectile diameter ratios of 15 or less). Alternative shields using aluminum, Nextel™ or Kevlar™ alone as the intermediate bumper were tested but did not provide the same level of protection performance for the weight as a combination of Nextel™ and Kevlar™. Hypervelocity impact (HVI) testing with greater than 1g aluminum projectiles using Light-Gas Guns (LGG) up to ~7 km/sec and Shaped-Charge Launchers (SCL) up to ~11 km/sec were used in the development program.

NOTATION

d	Projectile diameter (cm)
d_c	Projectile diameter causing failure; i.e., "critical" particle that just results in complete penetration of the shield's rear wall (cm)
ρ	Density (g/cm^3)
m	Areal density (g/cm^2)
S	Overall spacing from the front of outer bumper to the back of rear wall (cm)
σ	Rear wall yield stress (ksi)
t	Thickness (cm)
θ	Impact angle measured from surface normal (deg)
V	Projectile speed (km/sec)

Subscripts:

b	All bumpers (Nextel™, mesh, and aluminum) and intermediate layers (MLI and Kevlar™)
p	projectile
w	rear wall

INTRODUCTION

The Whipple shield, consisting of an exterior bumper spaced at a given standoff distance from the inner wall (or shield rear wall), is a conventional means for providing protection to critical spacecraft systems from meteoroid and orbital debris impacts. However, an unfortunate fact of life is that the spacecraft volume available for shielding is often severely constrained resulting in short, sub-optimum standoff distances that substantially decrease the protection performance and/or increase the weight of the Whipple shield.

Over the past two years, a team of MSFC and JSC personnel with structural design and hypervelocity impact (HVI) shielding expertise has developed the "Stuffed Whipple" shield as a practical and innovative HVI shielding option to enhance the protection performance of existing Whipple shielding with relatively short standoffs. One particular application for this effort is to enhance the protection of the habitable modules on the Space Station. These modules typically have total shield spacings of 11.4cm (measured from outer surface of the bumper to the inside surface of the rear pressure wall). Typical Al6061-T6 bumper thicknesses are 0.127cm to 0.19cm, and Al2219-T87 pressure wall thicknesses are 0.32cm to 0.48cm. To meet protection requirements, the station module shielding must be effective against orbital debris particles as large as 1cm to 1.5cm in diameter (i.e., S/d = 7.5 to 11).

This paper describes the HVI test and analyses supporting development of the "Stuffed Whipple" shield, which significantly improves the protection performance of Whipple shields. This paper compares the shielding thicknesses (weight) required to provide equivalent protection performance for Whipple, Stuffed Whipple, and all-aluminum double-bumper shields, based on HVI data and ballistic limit equations. Design and performance (i.e., ballistic limit) equations have been developed that are applicable for a variety of Stuffed Whipple shielding options.

THE "STUFFED WHIPPLE" SHIELD

The Stuffed Whipple (SW) shield contains an intermediate blanket of ceramic cloth (Nextel™) and high-strength cloth (Kevlar™) between the Whipple bumper and rear wall (Figure 1). The intermediate materials were selected based on advanced shielding research that resulted in development of low-weight shields such as the Multi-Shock (MS) shield [1], Mesh Double-Bumper (MDB) shield [2], and other advanced material shields [3-5]. The MS and MDB shields reduced shielding weights by ~50% compared to Whipple shields for equivalent protection at optimum standoffs [5, 6]; i.e., when $S/d \geq 30$. However, due to the short standoffs available for Space Station module protection (S=~11cm and S/d<11), the MS and MDB are not as effective.

In some SW shield applications, an aluminum mesh is added on the intermediate Nextel™/Kevlar™ blanket materials, or to the first bumper (either directly on top or just behind the first bumper). The mesh has been shown to increase the protection performance with minimal shield weight increase [2], although this adds to the complexity of the shield design.

The Nextel™/Kevlar™ blanket provides a combination of materials with greater HVI protection effectiveness than a solid-aluminum second-bumper of equal mass per unit area. The Nextel™ ceramic cloth in the blanket is more effective than aluminum at shocking and disrupting fragments of projectile and bumper. The Kevlar™, with a greater strength to weight ratio than aluminum, provides superior capability to slow the expansion speed of the debris cloud before impact with the inner wall of the shield. The bumper materials from the Nextel™/Kevlar™ intermediate layer (small size due to small diameter fibers) are less damaging contributors to debris cloud lethality than fragments from a solid metal bumper. The purpose of the mesh (when used) is to create dispersive stresses in the impacting projectile fragments that cause a wider spread of the debris cloud, which is an advantage at short stand-off distances.

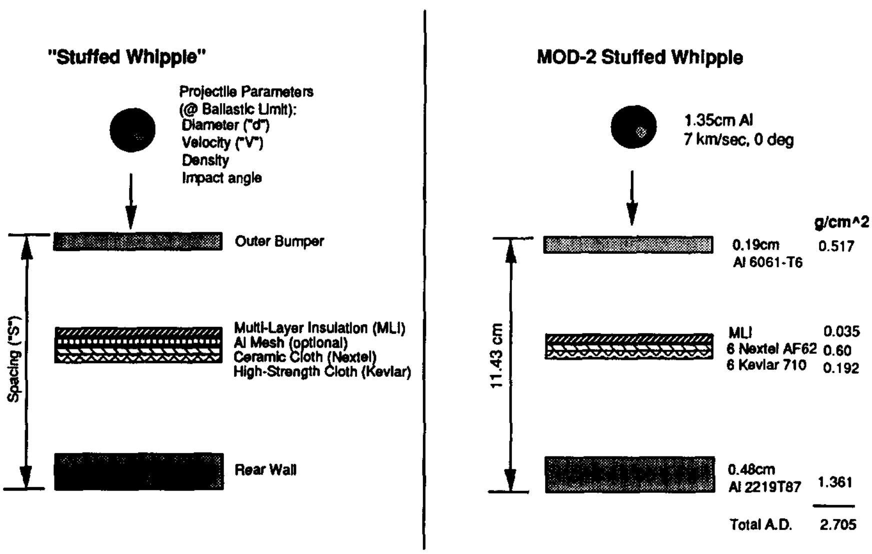


Figure 1. Stuffed Whipple Shield (Generic and MOD-2)

EXPERIMENTAL DESIGN AND RESULTS

Since 1992, HVI tests have been conducted to characterize the protection performance of various stuffed Whipple shield configurations and other enhanced protection alternatives for the Space Station LAB and HAB modules at the Johnson Space Center HIT-F [6] and the Space Debris Impact Facility at Marshall Space Flight Center [7]. In addition, ultra-high speed impact tests (aluminum projectile impact tests at greater than 10 km/sec) were conducted at Southwest Research Institute (SwRI) using the inhibited shaped-charge launcher [8], and at Sandia National Laboratories (SNL) using flyer plate tests with the Hypervelocity Launcher (HVL) [9, 10].

The objectives of the HVI testing were:

(1) Demonstrate the capability of the Nextel™/Kevlar™ material combination, to determine whether they provide a superior combination of material properties compared to other alternatives, such as aluminum, Nextel™ or Kevlar™ alone.
(2) Assess dimensional-scaling characteristics of the Stuffed Whipple shield; i.e., show that subscale testing provides a realistic and/or conservative simulation of full-scale shield performance.
(3) Perform tests to develop ballistic limit (BL) equations for various Stuffed-Whipple shield configurations.
(4) Perform ultra-high speed tests (>10 km/sec) to support verification of shielding performance predicted by the ballistic limit equations.

In some HVI tests, a thin graphite-epoxy panel was added directly behind the Nextel™/Kevlar™ blanket to assess a potential low-weight material candidate for the support structure of the blanket.

Light Gas Gun Testing with Aluminum Projectiles

Test data from the JSC and MSFC light-gas guns (LGG) are shown in Tables 1 and 2. Two primary types of shields are included in Table 1: Stuffed Whipple (SW) and Aluminum Double-Bumper (Al-2B) shields. Full-scale (100%) and subscale tests (75%, 67%, 50%, and 33%) were conducted. The subscale tests reduced the thicknesses of aluminum plates, spacings of the shield elements, and the number of Nextel™/Kevlar™ fabric layers by the same proportion. It was not practical to keep the same number of fabric layers and scale the fabric thickness and diameter of threads as desired for true subscale tests. Typical test configurations (for 67% scale) are shown in Figures 2a and 2b. A summary of damage sustained by the shield rear wall is given in Table 2. Figure 3 illustrates typical results for an impact test on a SW shield.

Table 1. Stuffed Whipple and All-Aluminum Shield Configurations

Shield Type	Size Scale Factor	Bumper	Intermediate Layer*	Rearwall	Areal Density Inter. (g/cm^2)	Areal Density Total (g/cm^2)	Shield Spacing (cm)
Stuffed Whipple Shields							
B2	100%	0.127cm Al6061T6	Mesh/3 Nextel/4 Kevlar	0.32cm Al2219T87	0.458	1.71	11.4
B2-GE	100%	0.127cm Al6061T6	Mesh/3 Nextel/8-GE	0.32cm Al2219T87	0.484	1.73	11.4
MOD-1	100%	0.127cm Al6061T6	Mesh/6 Nextel/6 Kevlar	0.32cm Al2219T87	0.822	2.07	11.4
MOD-1	80%	0.10cm Al6061T6	Mesh/5 Nextel/4 Kevlar	0.25cm Al2024T3	0.658	1.64	9.1
MOD-2	100%	0.19cm Al6061T6	6 Nextel/6 Kevlar	0.48cm Al2219T87	0.792	2.67	11.4
MOD-2	67%	0.127cm Al6061T6	4 Nextel/4 Kevlar	0.32cm Al2219T87	0.528	1.78	7.6
MOD-2/GE	67%	0.127cm Al6061T6	4 Nextel/4 Kevlar/5-GE	0.32cm Al2219T87	0.628	1.88	7.6
MOD-3	100%	0.16cm Al6061T6	3 Nextel/11 Kevlar	0.48cm Al2219T87	0.652	2.45	11.4
MOD-3	67%	0.10cm Al6061T6	2 Nextel/7 Kevlar	0.32cm Al2219T87	0.424	1.60	7.6
MOD-4	100%	0.127cm Al6061T6	Mesh/10 Nextel & 1AF40	0.32cm Al2219T87	1.12	2.37	11.4
MOD-4	75%	0.10cm Al6061T6	Mesh/8 Nextel	0.23cm Al2024T3	0.83	1.74	8.6
MOD-4	67%	0.08cm Al6061T6	Mesh/6 Nextel & 1AF40	0.20cm Al2024T3	0.72	1.50	7.3
MOD-5	100%	0.16cm Al6061T6	Mesh/6 Nextel/6 Kevlar	0.48cm Al2219T87	0.822	2.16	11.4
MOD-5	67%	0.10cm Al6061T6	Mesh/4 Nextel/4 Kevlar	0.32cm Al2219T87	0.566	1.75	7.6
MOD-5	50%	0.08cm Al6061T6	3 Nextel/3 Kevlar	0.25cm Al2219T87	0.396	1.04	5.7
MOD-5	33%	0.05cm Al6061T6	2 Nextel/2 Kevlar	0.16cm Al2024T3	0.268	0.86	3.8
MOD-6	100%	0.16cm Al6061T6	26 Kevlar	0.48cm Al2219T87	0.832	2.65	11.4
All-Aluminum Shields							
Al-1	100%	0.16cm Al6061T6	0.32cm Al6061T6	0.48cm Al2219T87	0.861	2.66	11.4
Al-1	67%	0.10cm Al6061T6	0.20cm Al6061T6	0.32cm Al2219T87	0.551	1.73	7.6
Al-2	100%	0.19cm Al6061T6	0.32cm Al2219T87	0.48cm Al2219T87	0.905	2.78	11.4
Al-2	67%	0.127cm Al6061T6	0.20cm Al2024T3	0.32cm Al2219T87	0.568	1.82	7.6

* Intermediate Materials include:
- Nextel AF62 cloth: 0.1 g/cm^2 per layer and Nextel AF40 (where indicated): 0.085 g/cm^2 per layer
- Kevlar 710 cloth: 0.032 g/cm^2 per layer
- Al Mesh: 20x20 wires per cm^2, 0.023cm diameter wire, 0.03 g/cm^2 per layer
- Graphite-Epoxy (GE) panel: AS4/3501-6, 8 ply=0.154 g/cm^2, 5 ply=0.1 g/cm^2

* Stuffed Whipple intermediate material & Al-1 second-bumper placed midway between bumper and rear wall
* Al-2 aluminum second-bumper located at (2/3*total standoff) behind front bumper

Table 2. Stuffed Whipple and All-Aluminum Shield HVI Data

Shield Type	Size Scale Factor	MLI+	Test Number	Proj. Dia. Actual (cm)	Proj. Dia. Scaled (cm)	Impact Speed (km/s)	Impact Angle (deg)	Rear Wall Damage
Stuffed-Whipple Shields								
B2	100%	None	JSC B229	0.95	0.95	6.71	0	No Perf
B2	100%	20-BI	JSC B290	0.95	0.95	7.24	0	No Perf
B2	100%	None	JSC B264	0.95	0.95	6.90	45	No Perf
B2	100%	20-BI	JSC B291	0.95	0.95	6.69	45	No Perf
B2-GE	100%	None	JSC B433	0.95	0.95	6.75	45	No Perf
MOD-1	100%	20-BI	MSFC 1451	1.27	1.27	5.73	45	Perf: 16mm, 70mm cracks
MOD-1	80%	15-BI	JSC B297	0.95	1.19	6.52	0	No Perf
MOD-2	100%	20-TI	JSC B654	1.00	1.00	6.84	0	No Perf, very slight dish
MOD-2	67%	b14-BB	JSC B552	0.91	1.37	6.73	45	No Perf
MOD-2/GE	67%	14-TI	JSC B568	0.91	1.37	6.80	45	No Perf
MOD-2/GE	67%	14-TI	JSC B570	0.95	1.43	6.62	45	No Perf, 4.7mm deflection
MOD-2/GE	67%	14-TI	JSC B575	0.95	1.43	6.77	45	No Perf
MOD-3	100%	20-BI	MSFC 1458	1.27	1.27	5.81	45	Perf, BL, pinhole ~1mm
MOD-3	67%	15-BI	MSFC 1467	0.95	1.43	6.70	45	Perf, (4)cracks: 40mm-60mm
MOD-3	67%	15-BI	JSC B306	0.95	1.43	6.89	45	Perf: 30mmx20mm; 3cracks:40mm
MOD-4	75%	15-BI	JSC B303	0.95	1.27	6.21	45	No Perf
MOD-4	67%	12-BI	JSC B313	0.87	1.36	6.97	45	Perf: 58mm x 29mm
MOD-5	100%	20-BI	MSFC 1454	1.27	1.27	5.86	45	No Perf, crater ~1mm deep
MOD-5	100%	20-BI	MSFC 1470	1.27	1.27	4.86	45	No Perf, crater ~3mm deep
MOD-5	100%	20-BI	MSFC 1455	1.27	1.27	5.82	0	Perf: ~16mm
MOD-5	100%	None	JSC B398	1.00	1.00	6.70	45	No Perf
MOD-5*#	100%	None	JSC B536	1.00	1.00	6.85	15	No Perf: slight dish
MOD-5*#	100%	None	JSC B537	1.00	1.00	4.86	15	No Perf
MOD-5*#	100%	None	JSC B538	1.00	1.00	4.00	15	No Perf: crater in center
MOD-5	67%	15-BI	JSC B305	0.95	1.43	6.70	45	No Perf: 7mm deflection
MOD-5*	67%	None	JSC B505	0.95	1.43	6.78	60	No Perf: 1.0mm deflection
MOD-5*	67%	None	JSC B549	1.00	1.50	6.60	60	No Perf: 6.3mm deflection
MOD-5	50%	11-BI	MSFC 1466	0.80	1.59	7.06	45	Perf: 20mm x 6mm
MOD-5	33%	None	JSC B316	0.95	2.86	4.88	75	No Perf
MOD-6	100%	20-BI	MSFC 1456	1.27	1.27	5.78	45	Perf, large failure
All-Aluminum Shields								
Al-1#	100%	None	JSC B533	1.00	1.00	6.81	15	Perf: petalled (53mm)
Al-1#	100%	None	JSC B532	0.95	0.95	6.78	15	No Perf: 10.8mm deflection
Al-1#	100%	None	JSC B535	0.95	0.95	6.64	15	Perf: 32mm thru-crack
Al-1	67%	None	JSC B503	0.95	1.42	6.81	60	Perf: petalled (23mm)
Al-1	67%	None	JSC B520	0.75	1.13	6.99	60	Perf: 5.8x4.5mm
Al-1	67%	None	JSC B519	0.71	1.07	6.95	60	No Perf
Al-2	67%	14BB@1"	JSC B560	0.71	1.07	6.94	45	Perf: 3 thru-cracks ~15mm ea.
Al-2	67%	14BB@1"	JSC B562	0.71	1.07	6.42	45	Perf: 4.2x2.8mm with cracks
Al-2	67%	14BB@1"	JSC B557	0.67	1.01	6.64	45	No Perf, near BL
Al-2	67%	14BB@1"	JSC B563	0.67	1.01	6.96	45	No Perf, near BL, large defl.

* No Al mesh present in test
+MLI (Multi-Layer Insulation) "##-XX" = Number of Layers, MLI Location. MLI Location: BB = behind bumper, TI = top of intermediate layer, BI = behind intermediate layer. Number of Layers of double-aluminumized mylar: 20 layer=0.035 g/cm^2, 14 layer=0.025 g/cm^2, "b"=beta cloth present at front of MLI adding 0.025g/cm^2.
Al2024-T3 rear wall used instead of Al2219-T87

Shaped-Charge Testing

Inhibited shaped charge launcher (SCL) tests were performed at SwRI on two-thirds (67%) scale Stuffed Whipple (Figure 2a) and Al-2B (Figure 2b) shields. The SCL launches an aluminum (6061) projectile at 11.0 to 11.5 km/sec [8]. The projectile is in the shape of a hollow cylinder (or thick-walled pipe) with length to outside diameter ratio (L/D) of from 1 to 3. Two sets of orthogonal flash X-rays are used to record projectile size, shape, and orientation prior to impact. Projectile mass is determined by SwRI from digitized X-ray images. An example of an X-ray image of the projectile from one of the tests is given in Figure 4.

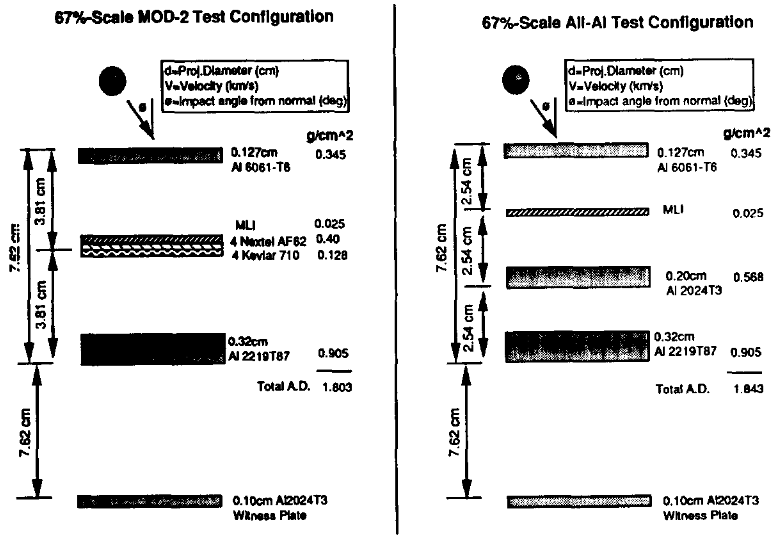
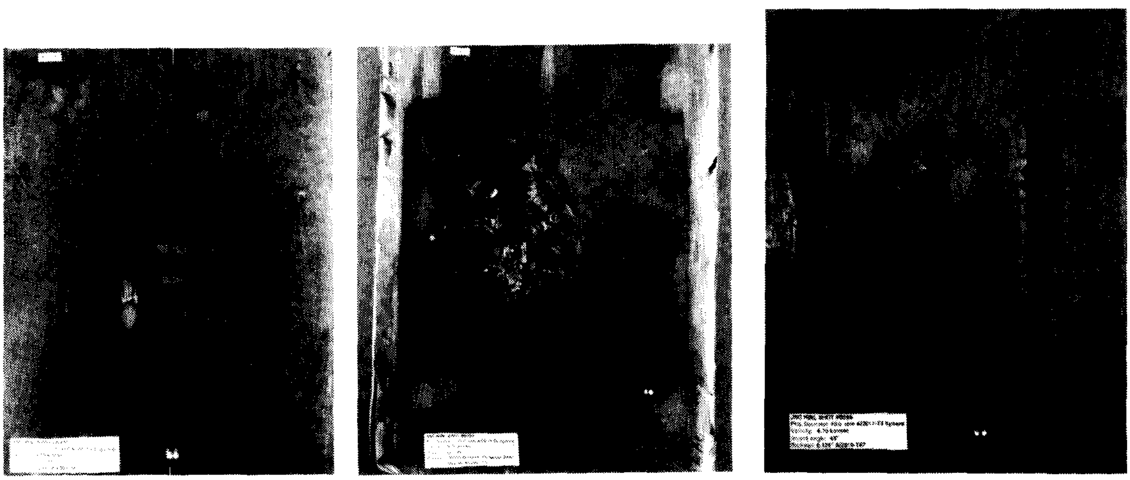
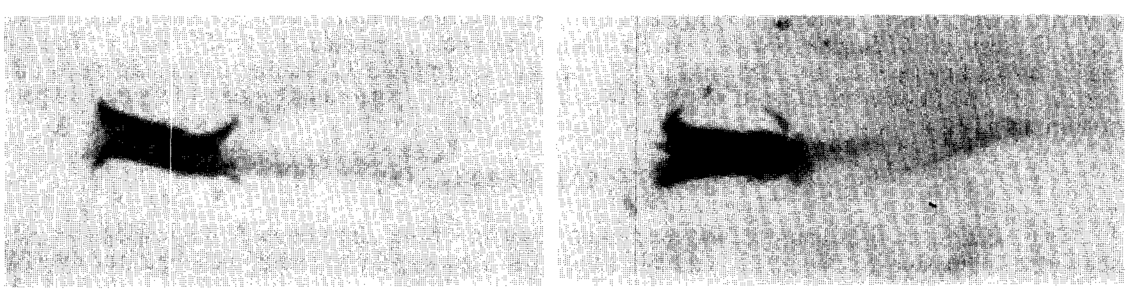


Figure 2. (a) 67%-scale Stuffed Whipple (MOD-2) Shield Test Configuration
(b) 67%-scale All-Aluminum Shield (Al-2) Test Configuration



front bumper 10 cm *intermediate blanket* 10 cm *rear wall* 10 cm

Figure 3. JSC HIT-F Shot B398 (front view)



Flight Direction

Figure 4. X-Ray orthogonal views of Inhibited Shaped-Charge Projectile from SwRI Test No.5993-3.

The SCL test data in Table 3 indicates impact conditions and whether the shield's rear wall is perforated (shield failure) or not. Tests were performed at both normal (0°) and oblique (45°) angles to the shield's bumper. The equivalent diameter for a solid spherical projectile with the same mass as the SCL projectile is given in Table 3. Hydrocode simulations have indicated that an equivalent mass sphere (at the same velocity) is less damaging than a heated shaped-charge projectile. Therefore, the no-failure tests with the shaped-charge are thought to be conservative relative to HVI testing using spherical projectiles. The hydrocode studies are continuing to determine the effect of projectile shape under a wide range of impact orientation and velocity conditions.

Table 3. Inhibited Shaped Charge Tests

NOTE: All shields 2/3rds (67%) scale Al-2 and MOD-2

SwRI No.	Shield	Shield Angle (deg)	PROJECTILE PARAMETERS L/D	Length (mm)	OD (mm)	ID (mm)	Mass (g)	Equiv. Dia. (cm)	Velocity (km/s)	Rear Wall Damage Results
5993-2 12.8cm	Al-2B	0	1.44	9.53	6.60	1.83	0.84	0.84	11.03	Perf: 4.3cm petalled hole w/ cracks
5993-3	Al-2B	45	2.39	14.55	6.10	2.11	1.04	0.90	11.33	Perf: 7.8x4.1cm petalled
5993-12	Al-2B	45	2.6	18.16	6.99	3.07	1.56	1.03	11.42	Perf: 5.6x4.3cm petalled
5993-13	Al-2B	45	1.96	13.21	6.73	2.51	1.12	0.92	11.32	Perf: large petalled hole
5993-10	SW	0	1.26	9.46	7.49	3.39	0.87	0.85	11.18	No Perf: deep bulge
5993-6	SW	45	1.57	10.26	6.55	2.08	0.86	0.85	11.21	No Perf: slight bulge
5993-8	SW	45	1.29	8.42	6.74	3.16	0.63	0.76	11.20	No Perf: slight bulge
5993-9	SW	45	1.51	11.27	7.49	3.45	1.02	0.90	11.14	No Perf: slight bulge
5993-14	SW	45	2.07	15.32	7.42	3.10	1.52	1.01	11.42	No Perf: bulge

(Chamber Pressure < 4 torr)

Table 4. HVL Tests

SNL No.	Shield	Impact Angle (deg)	Impact Vel. (km/s)	Flyer Dia. x thk. (mm)	Flyer Mass (g)	Equiv. Sph. Dia. (mm)	Flyer Integrity	Rear Wall Damage
SWBS-3	Al-2B	0	10.2	18.9 x 1.003	0.746	0.807	Bowed, tilted	Perforated
SWBS-5	SW	0	10.0	17.4 x 0.899	0.565	0.735	Minimal rotation	Survived
SWBS-6	SW	45	10.1	17.3 x 0.897	0.560	0.733	Minimal rotation	Survived

Flyer Plate Tests

Flyer plate tests are being performed with the SNL HVL [9,10] on 67% scale SW and Al-2B shields (Figures 2a and 2b). The flyer is a thin aluminum (6061-T6) disk. These tests are continuing, but preliminary data resulting from tests conducted to-date are given in Table 4. An equivalent spherical projectile diameter is given in Table 4 with mass equal to the flyer used in the tests. Based on the velocity and equivalent spherical diameter, the results obtained from the HVL are consistent with predicted ballistic limits for the 67% scale SW and Al-2B shields.

Simulated High Velocity Testing Using Cadmium

A 3.1 velocity-scaling factor has been proposed recently [11] to simulate the effects of high velocity aluminum projectiles (>8 km/sec) using low-speed Cadmium (Cd) projectile tests in standard LGG ranges. A relative comparison between Stuffed Whipple and All-Aluminum shields using Cd tests on 67% scale SW and Al-2B shields has been conducted at the JSC HIT-F. The Cd testing at 4.5 km/sec (i.e., a scaled velocity of ~14 km/sec using the 3.1 scaling factor) indicated that the Al-2B shield was perforated while SW shield was not perforated under the same impact conditions [12].

ANALYSIS AND DISCUSSION

This section on data analysis and discussion focusses on the objectives of the testing; i.e., (1) show that dimensional scaling (i.e, subscale shields) is a conservative testing technique for the SW shield, (2) develop ballistic limit equations from the LGG and ultra-high velocity data, and (3) demonstrate the Nextel™/Kevlar™ material combination for the second bumper provides better capability than the equivalent weight of aluminum.

Dimensional Scaling

In dimensional scaling, all shield and projectile dimensions are reduced by the same factor. This technique provides data for assessing the ballistic performance of full-scale shields by testing subscale shields. Subscale testing will minimize tests of more expensive, full-scale hardware. The subscale shields would ideally use the same scale factor for the thicknesses of all bumpers, the rear wall, the standoff distance. Practically, some deviation from a uniform scale factor across all shield elements becomes necessary due to constraints on the availability of certain materials in the desired thicknesses. For example, the intermediate blanket material in the Stuffed Whipple shield is scaled as closely as possible to the desired scaled areal density (mass per unit area) by removing layers of intermediate fabric materials. Using the same number of thinner fabric layers has been impractical because the materials are generally unavailable.

Table 5 lists JSC HIT-F shots A2036 (33%) and B398 (67%), and MSFC shot 1454 (100%) which shows that the 33% scale SW shield (MOD-5 shield from Table 1) has sustained somewhat more rear wall damage than either the two-thirds or the full-scale SW shield, even though the scaled projectile diameter is the smallest. Therefore, dimensional scaling (with the deviations noted from true dimensional scaling) appears to be a conservative technique for the SW shield.

Table 5. Dimensionally Scaled HVI Tests

Shot No.	SW MOD-5 Target Scale Factor	Actual Proj. Dia. (cm)	Full-Scale Dia. (cm)	Proj. Velocity (km/sec)	Impact Angle (deg)	Rear Wall Damage
JSC-A2036	33%	0.32	0.95	6.49	45	No Failure, Bulge, 0.28cm high
JSC-B398	67%	1.0	1.50	6.70	45	No Failure, Slight Bulge, 0.23cm high
MSFC-1454	100%	1.27	1.27	5.86	45	No Failure, Bulge, Slight Cratering, 0.1cm deep

Ballistic Limit Equations (LGG, SCL, and HVL)

The HVI test data and analysis provided the basis for formulating ballistic limit equations that define the maximum particle size that a Stuffed Whipple shield is capable of protecting against as a function of projectile velocity, impact angle, density, etc. These equations are used for assessments of meteoroid/orbital debris penetration probability for spacecraft protected by the Stuffed Whipple shield. Equations 1-3 are applicable for the five specific types of Stuffed Whipple shields listed in Table 1 (MOD-1 through MOD-5) with coefficients (C_H, C_{hi}, C_{li}, C_L) defined in Table 6. These equations relate the critical particle size, d_c (cm), which would cause complete penetration of the shield rear wall, to projectile speed, V (km/sec), and impact angle from surface normal, θ (deg) for the five specific types of full-scale Stuffed Whipple shields. These equations and coefficients were developed from more general formulas (Eqn.4-6), which can be used to size shields for any given and/or desired protection level, as discussed in more detail later in this paper. These equations were derived using the same methodologies as developed for previous advanced shielding ballistic limit equations [5] and the HVI test data for the specific shields given in this paper. For sub-scale SW shields, the critical particle size, d_c (cm), calculated by Eqns. 1-3 can be multiplied by the size scaling factor of the shield to determine the ballistic limit particle size for the sub-scale shield.

<u>High-Velocity</u>: for $V \geq 6.5 / (\cos\theta)^{1/3}$,

$$d_c = C_H V^{-1/3} (\cos\theta)^{-0.5} \tag{1}$$

<u>Intermediate-Velocity</u>: for $2.7 / (\cos\theta)^{0.5} < V < 6.5 / (\cos\theta)^{1/3}$,

$$\begin{aligned} d_c &= C_{li} (\cos\theta)^{-4/3} [(6.5 / (\cos\theta)^{1/3} - V) / (6.5 / (\cos\theta)^{1/3} - 2.7 / (\cos\theta)^{0.5})] \\ &+ c_{hi} (\cos\theta)^{-7/18} [(V - 2.7 / (\cos\theta)^{0.5}) / (6.5 / (\cos\theta)^{1/3} - 2.7 / (\cos\theta)^{0.5})] \end{aligned} \tag{2}$$

<u>Low-Velocity</u>: for $V \leq 2.7 / (\cos)^{0.5}$,

$$d_c = C_L V^{-2/3} (\cos\theta)^{-5/3} \tag{3}$$

HVI data in the 6-8 km/sec range was used to determine the coefficient used in the high-velocity ballistic limit equation. Scaling to higher velocities is made based on the assumption that the SW shield ballistic limit (failure threshold) occurs at a constant projectile momentum at velocities above the testable velocity. HVI data at the ballistic limits of the SW shields indicated an impulsive loading condition of the shield rear wall at high-velocities (V>~6.5 km/sec for normal impacts). The predominate characteristic of impulsive loading of the rear wall is bulging with little or no cratering damage from cohesive projectile particles or bumper material. The bulging becomes progressively larger and deeper (distended) as the ballistic limit of the shield is approached until, with sufficient projectile momentum, the shield fails and the rear wall cracks or petals. Impulsive loads were the

Table 6. Ballistic Limit Equation Coefficients for Equations 1-3

SET 1: To be used for projectiles of 2.8 g/cc density impacting on shields with a 11.4 cm (4.5") overall spacing:

	SHIELD TYPE				
	MOD-1	MOD-2	MOD-3	MOD-4	MOD-5
C_H	2.219	2.584	2.368	2.274	2.584
C_{li}	0.503	0.636	0.597	0.570	0.636
C_{hi}	1.189	1.385	1.269	1.218	1.385
C_L	0.975	1.233	1.158	1.105	1.233

SET 2 To be used for particles of 2.8 g/cc density impacting shields with a 24 cm (9.5") overall spacing:

	SHIELD TYPE				
	MOD-1	MOD-2	MOD-3	MOD-4	MOD-5
C_H	3.652	4.253	3.896	3.742	4.253
C_{li}	0.503	0.636	0.597	0.570	0.636
C_{hi}	1.957	2.279	2.088	2.005	2.279
C_L	0.975	1.233	1.158	1.105	1.233

SET 3: To be used for 0.5 g/cc density particles impacting shields with a 11.4 cm (4.5") overall spacing:

	SHIELD TYPE				
	MOD-1	MOD-2	MOD-3	MOD-4	MOD-5
c_H	3.941	4.589	4.205	4.038	4.589
c_{li}	1.190	1.505	1.413	1.348	1.505
c_{hi}	2.112	2.459	2.253	2.164	2.459
c_L	2.308	2.917	2.739	2.614	2.917

SET 4: To be used for particles with a 0.5 g/cc density on shields with a 24 cm (9.5") overall spacing:

	SHIELD TYPE				
	MOD-1	MOD-2	MOD-3	MOD-4	MOD-5
c_H	6.486	7.553	6.919	6.645	7.553
c_{li}	1.190	1.505	1.413	1.348	1.505
c_{hi}	3.475	4.047	3.707	3.561	4.047
c_L	2.308	2.917	2.739	2.614	2.917

SET 5: For predicting laboratory experiments using low-density plastic projectiles (assuming projectile density = 1 g/cc) on shields with a 11.4 cm (4.5") overall spacing:

	SHIELD TYPE				
	MOD-1	MOD-2	MOD-3	MOD-4	MOD-5
c_H	3.128	3.643	3.337	3.205	3.643
c_{li}	0.842	1.064	0.999	0.953	1.064
c_{hi}	1.676	1.952	1.788	1.717	1.952
c_L	1.632	2.063	1.937	1.848	2.063

predominate damage mode for the SW shield above 6.5 km/sec (for normal impacts) because projectile fragments were defeated by the Nextel™/Kevlar™ fabric layer. In addition, the fibrous nature of the Nextel™/Kevlar™ second bumper did not contribute damaging fragments to the debris cloud that impacted the rear wall. When impulsive loading of the rear wall is the primary damage mode at the ballistic limit, velocity scaling as a function of constant projectile momentum has been applied in previous scaling efforts for advanced, multilayer, fabric bumper shields [1,2,5]. Oblique impacts result in greater expansion of the debris cloud momentum ellipse on the rear wall as impact obliquity increases. Thus, the high-velocity equation scales with constant impact momentum (that results in threshold shield failure) for each particular impact angle. It should be noted that these equations are subject to change, based on further HVI tests and analysis.

Separate sets of coefficients (C_H, C_{hi}, C_{li}, C_L) for Eqn.(1-3) given in Table 6 are applicable for the following situations:

(1) For use with orbital debris analyses with a 2.8 g/cc constant density option; i.e., valid for aluminum spherical projectiles only:
  (a) Shields with a 11.4 cm (4.5") overall spacing between outside of bumper and inside of rear wall (Set 1).
  (b)Shields with a 24 cm (9.5") overall spacing between outside of bumper and inside of rear wall (Set 2).
(2) For use with meteoroid analyses and valid for particles with a 0.5 g/cc density:
  (a) Shields with a 11.4 cm (4.5") overall spacing (Set 3).
  (b) Shields with a 24 cm (9.5") overall spacing (Set 4).
(3) For use in planning laboratory experiments with low-density plastic projectiles (assuming projectile density = 1 g/cc) given shields with a 11.4 cm (4.5") overall spacing (Set 5).

A comparison between HVI test data using aluminum projectiles at near normal impact angles (0° -15°) and the predicted ballistic limit curve from Eqns.(1-3) for the MOD-5 shield is shown in Figure 5. Failure of the shield is predicted to occur above the curve, no-failure below the curve.

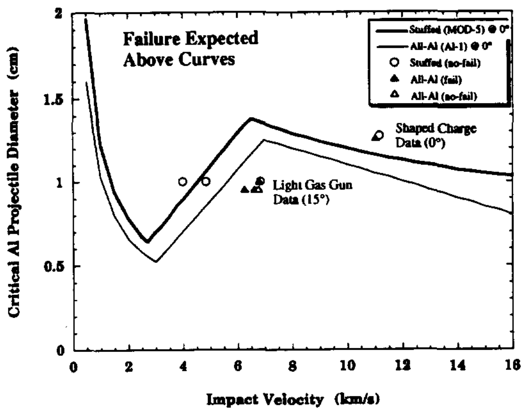


Figure 5. Stuffed Whipple (MOD-5) and All-Aluminum (Al-1) Ballistic Limits for Near Normal Impacts (0° and 15°).

A set of generalized equations (Equations 4-6) have been derived to allow a preliminary scaling of shield parameters for satisfying a wide range of impact protection requirement levels. These equations were derived using the HVI data from this paper and the same techniques from development of previous ballistic limit equations [5]. Additional HVI data is recommended however, to verify shield performance for shields (and subscale models) beyond those listed in Table 4. The generalized equations are:

High-Velocity: for $V \geq 6.5 / (\cos\theta)^{1/3}$,

$$d_c = 0.6\,(t_w \rho_w)^{1/3}\,\rho_p^{-1/3}\,V^{-1/3}\,(\cos\theta)^{-1/2}\,S^{2/3}\,(\sigma/40)^{1/6} \qquad (4)$$

Intermediate-Velocity: for $2.7 / (\cos\theta)^{0.5} < V < 6.5 / (\cos\theta)^{1/3}$,

$$d_c = 1.031\,\rho_p^{-0.5}\,[t_w\,(\sigma / 40)^{0.5} + 0.37 m_b]\,(\cos\theta)^{-4/3}\,[(6.5 / (\cos\theta)^{1/3} - V) / (6.5 / (\cos\theta)^{1/3} - 2.7 / (\cos\theta)^{0.5})] + 0.321\,(t_w \rho_w)^{1/3}\,\rho_p^{-1/3}\,(\cos\theta)^{-7/18}\,S^{2/3}\,(\sigma / 40)^{1/6}\,[(V - 2.7 / (\cos\theta)^{0.5}) / (6.5 / (\cos\theta)^{1/3} - 2.7 / (\cos\theta)^{0.5})] \qquad (5)$$

Low-Velocity: for $V \leq 2.7 / (\cos\theta)^{0.5}$,

$$d_c = 2[t_w\,(\sigma / 40)^{0.5} + 0.37 m_b] / [(\cos\theta)^{5/3}\,\rho_p^{0.5}\,V^{2/3}] \qquad (6)$$

Comparison to Double-Aluminum Bumper Shields

The HVI tests from the light-gas guns (LGG), shaped-charge launcher (SCL), and SNL hypervelocity launcher (HVL), all indicate that the Stuffed Whipple shield provides better protection than an aluminum double-bumper shield of equivalent weight. Figures 5-7 show the comparison between the MOD-2 Stuffed Whipple and comparable weight aluminum shield using light-gas gun and shaped-charge test results (adjusted to full-scale) at different (0°, 45°, and 60°) impact obliquity angles. Tests on subscale targets have been scaled to full-scale (i.e., full-scale projectile diameter = test diameter/scale factor).

A comparison of the ballistic limit curves for full-scale shields is given in Figure 8. For instance, the LGG data indicates that the full-scale aluminum double-bumper shield protects against a 0.98cm projectile at 7km/sec and 45°, while the Stuffed Whipple can protect against a 1.54cm aluminum projectile at the same impact conditions (indicating the SW stops projectiles with ~3 times greater mass than the Al-2B shield at these impact conditions). The SCL data shows that the Al-2B shield was completely perforated by a 1g SCL projectile at 11 km/sec and 45° while the SW was not penetrated by a 1.5g SCL projectile (50% heavier). Equations 1-3 with the MOD-2 coefficients were used to plot the Stuffed Whipple ballistic limits, which are higher (i.e., indicating superior performance) for the Stuffed Whipple shield compared to the all-aluminum.

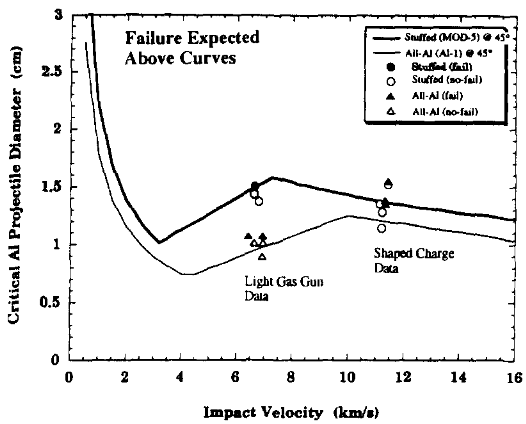


Figure 6. Stuffed Whipple (MOD-2) and All-Aluminum (Al-2) Ballistic Limits for 45° Impacts.

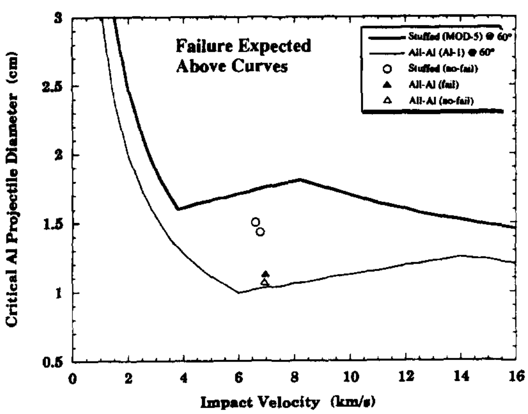


Figure 7. Stuffed Whipple (MOD-5) and All-Aluminum (Al-1) Ballistic Limits for 60° Impacts.

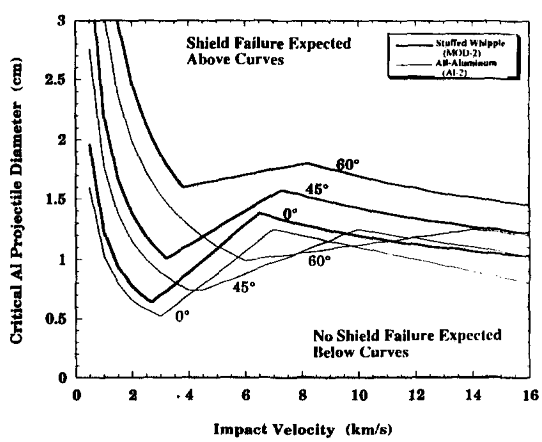


Figure 8. Ballistic Limits of Stuffed Whipple (MOD-2) and All-Aluminum (Al-2) Shields.

The shaped-charge data provides support for concluding the Stuffed Whipple ballistic limit curves are conservative at high velocities (Figs. 5 and 6). However, additional SCL data (at other impact angles) and further analysis of projectile shape effects is required to quantify the degree of conservatism and to modify the SW high-velocity ballistic limit equations. However, a simple comparison can be made of ballistic protection performance between the Stuffed Whipple and all-aluminum shield using the SCL data in Table 3: for 0° impacts compare Test 2 (All-Al) to Test 10 (SW), for 45° impacts compare Test 3 & 13 (All-Al) to Test 9 (SW) for ~1g projectiles, and Test 12 (All-Al) to Test 14 (SW) for ~1.5g projectiles. The performance advantage for Nextel™/Kevlar™ SW shields compared to an all-aluminum shield is indicated in these tests which failed the all-aluminum shield's rear wall while similar impacts on the Stuffed Whipple shield did not fail the rear wall. However, because the impact attitude of the projectile varied in the shaped-charge tests, further shaped-charge data is needed to confirm that this comparison is valid at other projectile impact orientations.

Comparison to Whipple Shields

Using previously published ballistic limit equations for Whipple shields [5] and supporting HVI data, a Whipple shield would weigh ~2.5X more than the MOD-2 Stuffed-Whipple shield for protecting from 1.35cm diameter aluminum projectile at 7 km/sec (normal) with a 11 cm standoff.

HYDROCODE SIMULATION RESULTS

CTH hydrocode simulations show the shaped charge projectile (hollow cylinder at elevated temperatures) is more damaging than a solid sphere of equal weight and ambient temperature as indicated in Figures 9-10 for an all-aluminum shield [13]. The same result was found for a Stuffed Whipple shield using Nextel™/Kevlar™ intermediate bumper [13]. Therefore, converting the shaped-charge mass into a diameter assuming an equal weight sphere and comparing to the predicted ballistic limit curves is conservative.

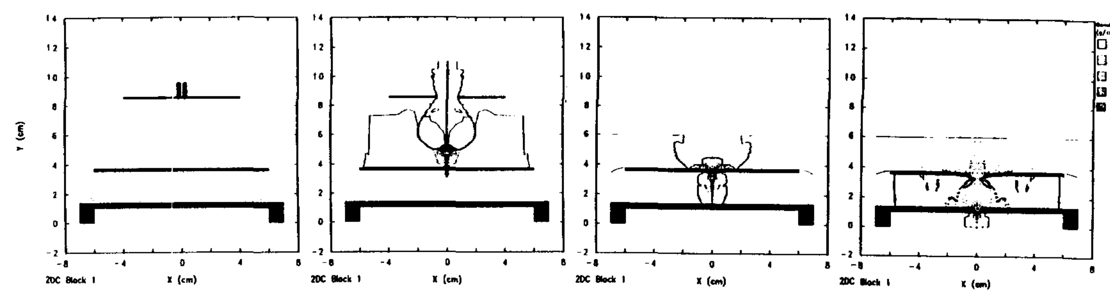


Figure 9. CTH simulation of 500°K, 0.84g, L/D=1.44 hollow cylinder impact at 11.03 km/sec on all-aluminum shield (time = 0, 4μs, 5.5 μs, and 7.81μs).

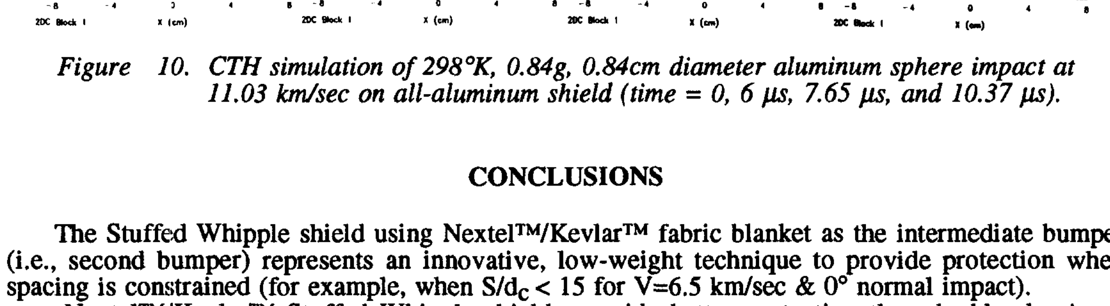


Figure 10. CTH simulation of 298°K, 0.84g, 0.84cm diameter aluminum sphere impact at 11.03 km/sec on all-aluminum shield (time = 0, 6 μs, 7.65 μs, and 10.37 μs).

CONCLUSIONS

The Stuffed Whipple shield using Nextel™/Kevlar™ fabric blanket as the intermediate bumper (i.e., second bumper) represents an innovative, low-weight technique to provide protection when spacing is constrained (for example, when $S/d_c < 15$ for V=6.5 km/sec & 0° normal impact).

Nextel™/Kevlar™ Stuffed Whipple shields provide better protection than double-aluminum bumper shields of equal weight (by stopping 50% to 300% more massive projectiles). Shield performance is improved (compared to aluminum) because Nextel™ ceramic fabric is better at shocking projectile fragments than aluminum, and Kevlar™ is better at slowing debris cloud expansion than aluminum. In addition, the particle size of bumper materials within the debris cloud ("secondaries" fragment size) is smaller for Nextel™/Kevlar™ bumpers than aluminum, which results in less rear wall damage compared to the larger fragments produced by aluminum bumpers.

Ballistic limit equations have been developed for determining protection performance (critical diameter) as function of velocity and impact angle for specific Nextel™/Kevlar™ stuffed shields (for first bumper thickness from 0.127cm to 0.19cm aluminum, shield spacing from 11cm to 24cm, wall thicknesses from 0.32cm to 0.48cm aluminum, and Nextel™/Kevlar™ stuffing areal density from 0.71g/cm^2 to 1.18g/cm^2). Generalized ballistic limit equations have been given to be used for preliminary performance estimates of alternative Stuffed Whipple shield configurations. These were developed based on extensive HVI test and analysis results. However, additional HVI testing is needed to verify performance estimates if the equation application extends beyond the test database.

Dimensional scaling (reducing all shield and projectile dimensions by same factor) can be used to determine protection capability for large-scale Stuffed Whipple shields. Tests show the technique to be slightly conservative when scaling up in size.

The Stuffed Whipple shield provides superior protection than any available alternatives for relatively short shield standoffs (i.e., when the ratio of standoff to projectile diameter, S/d, is less than ~15). For greater standoffs the Multi-Shock [1] and Mesh Double-Bumper [2] shields provide superior protection.

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