

Honeycomb vs. Foam: Evaluating a Potential Upgrade to International Space Station Module Shielding for Micrometeoroids and Orbital Debris

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Glossary of Terms and Abbreviations

Al	aluminum
BUMPER	software application used for spacecraft MMOD risk assessments
Bumper	outermost shield layer used to break up MMOD particles
BLE	ballistic limit equation
CFRP	carbon-fiber reinforced plastic
DL-F	double-layer foam
DL-H	double-layer honeycomb
FGB	functional cargo block (from Russian Funktsionalno-gruzovoy blok)
HC	honeycomb
HITF	Hypervelocity Impact Technology Facility
ISS	International Space Station
JSC	Johnson Space Center
MMOD	micrometeoroid and orbital debris
NASA	National Aeronautics and Space Administration
NO	non-optimum
PPI	pores per linear inch
SP	sandwich panel
WSTF	White Sands Test Facility

Notations

AD	areal density
C	coefficient
d	projectile diameter (cm)
ρ	density (g/cm^3)
K	coefficient
K_{3s}	low-velocity coefficient
K_{3d}	high-velocity coefficient
S	overall spacing between outer bumper and rear wall (cm)
σ	rear wall yield stress (ksi) (Note: 1 ksi = 1,000 lb/in ² = 6.895 MPa)
t	thickness (cm)
θ	impact angle measured from normal to surface (degrees)
V	projectile velocity (km/s)

Subscripts

c	critical
H	high
i	intermediate
L	low
n	normal
p	projectile
w	rear wall

Summary

The presence of a honeycomb core in a multi-wall shielding configuration for protection against micrometeoroid and orbital debris (MMOD) particle impacts at hypervelocity is generally considered to be detrimental as the cell walls act to restrict fragment cloud expansion, creating a more concentrated load on the shield rear wall. However, mission requirements often prevent the inclusion of a dedicated MMOD shield, and as such, structural honeycomb sandwich panels are among the most prevalent shield types. Open-cell metallic foams are a relatively new material with novel mechanical and thermal properties that have shown promising results in preliminary hypervelocity impact shielding evaluations. In this study, an International Space Station-representative MMOD shielding configuration has been modified to evaluate the potential performance enhancement gained by substituting honeycomb for open-cell foam. The baseline shielding configuration consists of a double-mesh outer layer, two honeycomb sandwich panels, and an aluminum rear wall. In the modified configuration, the two honeycomb cores are replaced by open-cell foam. To compensate for the heavier core material, facesheets have been removed from the second sandwich panel in the modified configuration.

A total of 21 tests on the double-layer honeycomb and double-layer foam configurations are reported. For comparable mechanical and thermal performance, the foam modifications were shown to provide a 15% improvement in critical projectile diameter at low velocities (i.e., 3 km/s) and a 3% increase at high velocities (i.e., 7 km/s) for normal impact. With increasing obliquity, the performance enhancement was predicted to increase, up to a 29% improvement at 60° (low velocity). Ballistic limit equations have been developed for the new configuration, and consider the mass of each individual shield component to maintain validity in the event of minor configuration modifications. Previously identified weaknesses of open-cell foams for hypervelocity impact shielding such as large projectile diameters, low velocities, and high degrees of impact obliquity have all been investigated and found to be negligible for the double-layer configuration.

Introduction

The performance of a dual-wall protective spacecraft structure against the impact of micrometeoroid and orbital debris (MMOD) particles is generally considered to be degraded by the presence of a honeycomb core. For impacts that penetrate the shield outer wall (bumper or front facesheet), fragmented projectile and bumper fragments disperse radially as they propagate through the shield interior, distributing the load over an area that is significantly larger than that of the original projectile diameter. The presence of honeycomb cell walls acts to restrict expansion, effectively channeling the fragments within a limited number of honeycomb cells for a more concentrated impact on the rear facesheet. However, mission requirements often prevent the inclusion of a dedicated MMOD shielding structure, and, as such, structural panels (i.e., honeycomb sandwich panels) also commonly serve as the protective system.

Metallic foams are a promising alternative to honeycomb structures as they offer comparable structural and thermal performance without the presence of MMOD shielding-detrimental channeling cells. In this report, modifications to a double-layer honeycomb sandwich panel shielding configuration that is representative of those used on board the International Space Station (ISS) are evaluated. The modifications entail the substitution of aluminum honeycomb for aluminum open-cell foams to provide similar mechanical performance at comparable weight, while improving MMOD shielding capability.

Background

Hypervelocity Impact Performance of Honeycomb Sandwich Panels

Given their common application in space vehicle primary structures, the performance of honeycomb under impact of MMOD particles at hypervelocity has been investigated in many studies. Jex et al. [1] and Sibeaud et al. [2] discuss that the presence of a honeycomb core enhanced the shielding performance of a dual-wall structure at hypervelocity. They conclude that secondary impacts between ejecta fragments and cell walls overcompensated for the detrimental effect of channeling. A more commonly held view is that the presence of a honeycomb core is detrimental to the shielding performance. Taylor et al. [3] quantify the degradation in performance through inclusion of a scaling factor that acts to reduce the effective rear facesheet thickness by 50% in definition of the panel ballistic limit at hypervelocities (i.e., molten and/or vaporized ejecta). Ryan et al. [4] define a degradation in shielding performance due to the presence of a honeycomb core that is equal to a 46% reduction in shielding capability at normal impact, reducing with increasing obliquity (e.g., for impact at 60° , the degradation in performance drops to $\sim 18\%$). Sennett and Lathrop [5] also quantify the effect of the honeycomb core, stating that once the panel thickness increases above two times that of the honeycomb cell size, no increase in shielding capability is achieved with an increase in shield thickness when fragments were either molten or vaporized. For solid fragment ejecta, the effect was not nearly as severe. In Figure 1, a comparison between the failure limits of dual-wall shields with and without a honeycomb core is shown (all other shield parameters and geometry constant).

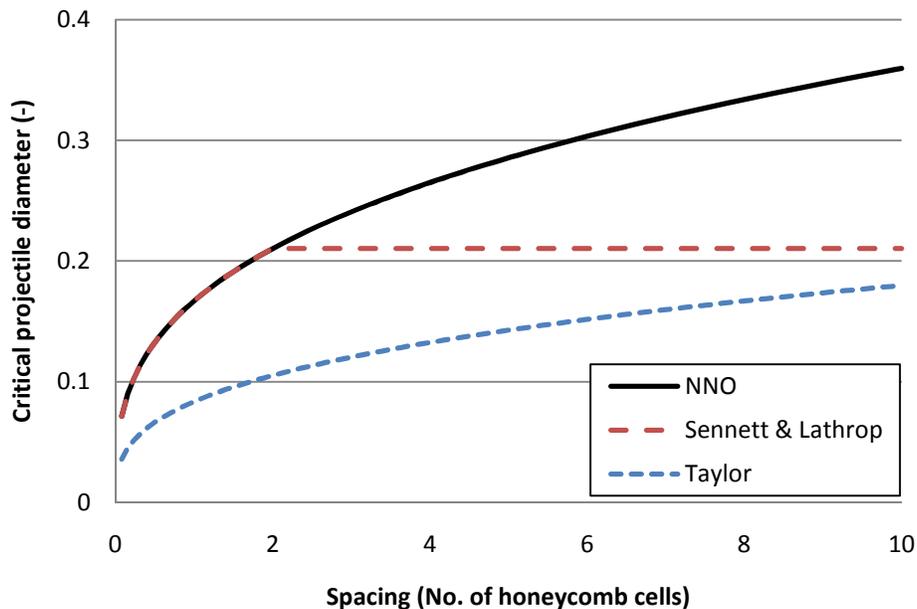


Figure 1: Failure limits for dual-wall shields with (from [5][3]) and without (from [13]) a honeycomb core.

At oblique angles of impact, the presence of honeycomb cell walls increases the amount of shielding material that is “seen” by the impacting projectile. Thus, the dependency of shielding capability on impact angle is greater for honeycomb sandwich panels than for the equivalent Whipple shields (i.e., an increase in impact angle increases the shielding performance of honeycomb sandwich panels more than that of the equivalent Whipple shield). The damage that is induced in the honeycomb cores when subject to oblique hypervelocity impact can be differentiated between that caused by an ejecta cone normal to the structure surface and that along the line of the projectile velocity vector (e.g., see Figure 2). For space-representative sandwich panels, the ballistic limit is nearly always defined by the onset of perforation that is induced by the ejecta cone normal to the facesheet surface. For impact conditions that are marginally

above the ballistic limit, fragments propagating along the projectile velocity vector are defeated within the honeycomb core. As the projectile kinetic energy is increased and the panel is more significantly damaged, the velocity vector fragments travel deeper within the honeycomb core until the impact kinetic energy is sufficiently high that the fragments are able to penetrate the sandwich panel rear facesheet. For some configurations, separate perforation holes can be produced relating to the debris ejected at normal incidence to the front facesheet and the projectile velocity vector, an example of which is shown in Figure 3.

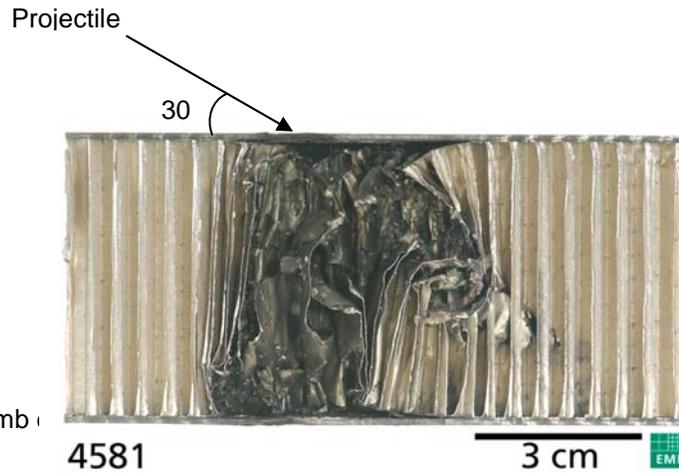


Figure 2: Internal honeycomb core of a sandwich panel impacted by a projectile at 30°.

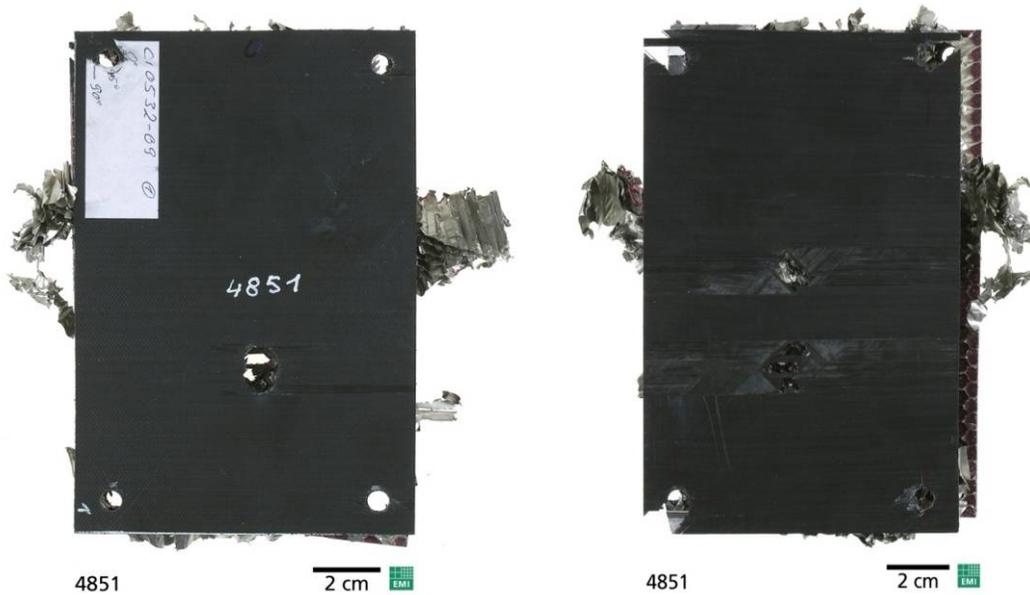


Figure 3: Damage to a sandwich panel with 1.37-mm-thick CFRP facesheets and a 25-mm-thick 3/16-5056-.001 honeycomb core impacted at 60° by a 3.0-mm Al99.9% projectile at 6.29 km/s. Left: front facesheet damage; right: rear facesheet damage showing two perforation holes (1) related to the debris ejected at normal incidence to the front facesheet and (2) along the projectile velocity vector.

Hypervelocity Impact Performance of Metallic Open-cell Foams

Preliminary investigations of the hypervelocity impact performance of metal foam structures have demonstrated their potential, particularly in comparison with traditional structural panels. In [7], alternative configurations for the ISS Columbus module shielding were evaluated. One of the configurations included a panel of open-cell aluminum foam, referred to as AB2Mod. A schematic of the AB2Mod shield is provided in Figure 4.

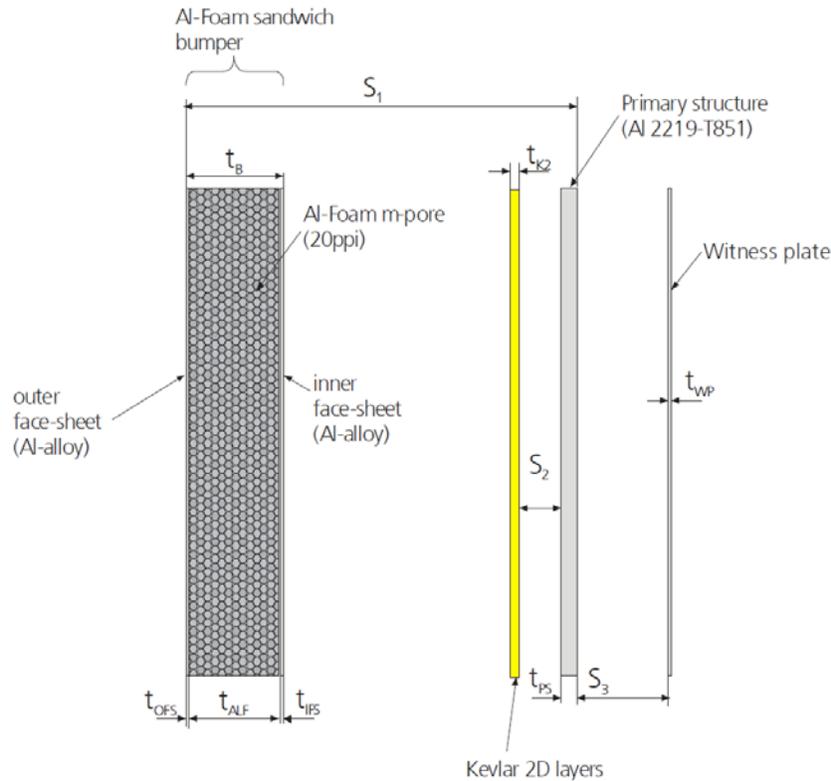


Figure 4: Alternate Columbus MMOD shield configuration incorporating metallic open-cell foam (from [7]).

Testing found that the AB2Mod configuration provided increased protection over the reference Columbus stuffed Whipple shield at high velocities (> 6 km/s) and normal incidence. At oblique incidence, the performance of the reference stuffed Whipple shield and foam-modified configuration were comparable (at high velocity). For low-velocity testing, the performance of the AB2Mod configuration was clearly worse than that of the reference Columbus shield. The authors concluded that the foam configuration was vulnerable to impact of large projectiles (above 1 cm in diameter) at low velocities, as the shield was unable to induce projectile fragmentation. The authors note that while the foam configuration provided a similar level of protection to the reference stuffed Whipple shield overall, the primary advantages of the configuration are related to the extension of the area of the pressure shell that can be protected (due to a concentration of mass in the outer layer), and to other design aspects such as a reduction in non-ballistic mass (stiffeners, local reinforcements, etc.).

The shielding performance of sandwich panel structures with open-cell aluminum foam cores was evaluated in [8] against that of aluminum honeycomb core sandwich panels (Al HC SP). In Figure 5, a comparison between the damage that was induced by the impact of 3.6-mm Al 2017-T4 spheres at normal incidence with velocities of approximately 6.49 ± 0.27 km/s on 5.08-cm-thick sandwich panels is shown. It

should be noted that, to provide comparable areal densities, the facesheet thickness of the honeycomb sandwich panel was significantly thicker than that of the foam sandwich panel (0.127 cm vs. 0.0254 cm).

In Figure 5, the foam core is shown to restrict fragment radial expansion to an equal or greater degree than the honeycomb. However, while fragments are expected to be channeled within the honeycomb cells, the foam homogeneity should ensure that resistance to fragment cloud expansion is equal in all directions, therefore limiting the degree of channeling. Damage to the sandwich panel rear facesheets in this example demonstrates the potential improvements in hypervelocity shielding performance to be gained through the replacement of honeycomb cores with open-cell foams.

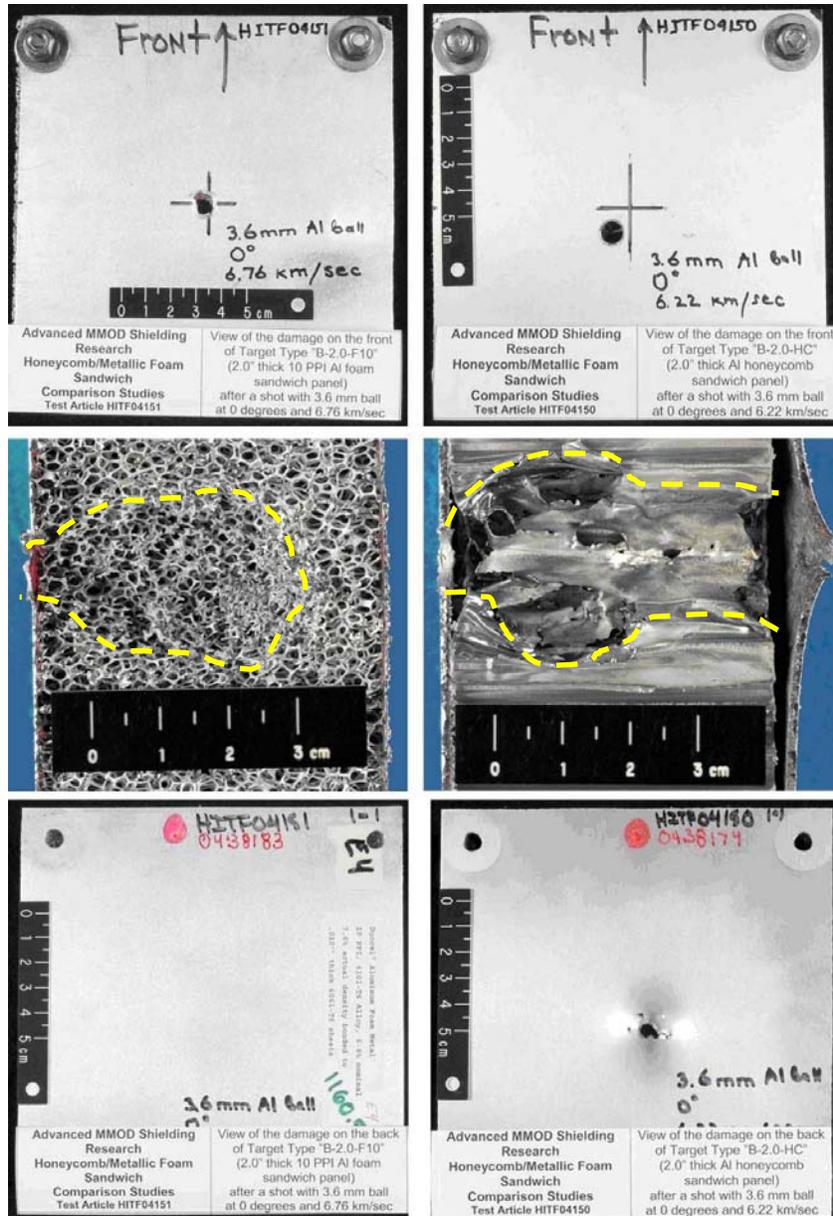


Figure 5: Comparison of damages in open-cell foam core (left) and honeycomb core (right) sandwich panel structures impacted by a 3.6-mm Al-sphere at 6.49 ± 0.27 km/s (0°). Upper: front facesheet damage; middle: core damage (sectioned); bottom: rear facesheet damage (from [8]).

Definition and Properties of Aluminum Open-cell Foam

Open-cell foam is specified in terms of core density relative to the base material (%) and pore density in terms of pores per linear inch (PPI). In Figure 6, foam cells and pores are defined. Foam cells are typically 14-faceted polyhedral or solid tetrakaidecahedrons, while pores are the individual windows between the interconnected foam ligaments.

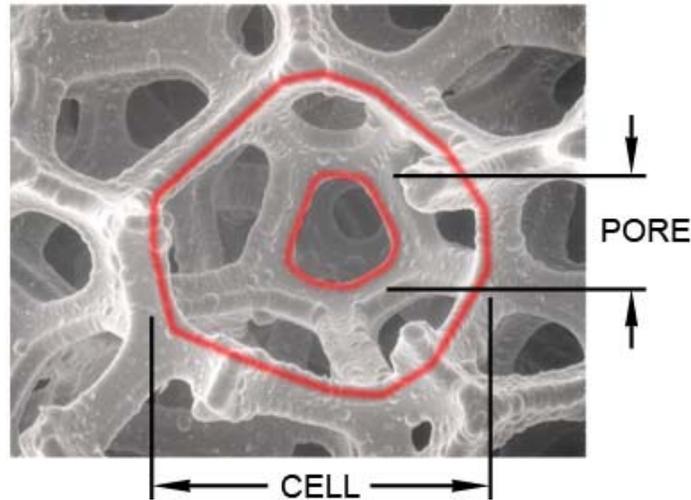


Figure 6: Definition of open-cell foam pore and cell size (© ERG Aerospace).

While pore density controls the number and nominal size of foam ligaments, the relative density controls their cross-sectional form and actual size (see Figure 7).

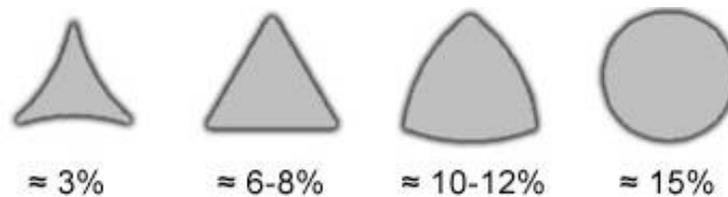


Figure 7: Ligament cross-section shape variation with relative density (© ERG Aerospace).

Depending on manufacturing technique, the mechanical performance of metallic open-cell foams can vary widely. For foams that are formed through use of a solid negative-image ceramic mould (e.g., the Duocel[®] foam that is manufactured by ERG Aerospace), the mechanical properties of the final product can be approximated by the base material properties and the foam relative density (ρ_{rel}); i.e., for Young's modulus (E) and crush strength (σ):

$$E_{foam} = E_{mat} \cdot \rho_{rel}^2 \quad (1)$$

$$\sigma_{foam} = C_1 \cdot \sigma_{mat} \cdot \rho_{rel}^{3/2} \quad (2)$$

where $C_1 = 0.3$ for a wide variety of foams [9].

Target Description

Double-layer Honeycomb (DL-H)

The baseline target consists of two 12.7-mm-thick aluminum honeycomb sandwich panels with 0.4064-cm-thick Al6061-T6 facesheets. The sandwich panels are separated by a 2.0-cm void. There are two layers of SS304 mesh on the front facesheet of the outer sandwich panel, and a 1.016-cm-thick Al2024-T3 rear wall located 6.0 cm from the inner sandwich panel rear facesheet. A schematic of the double-layer honeycomb (DL-H) target is shown in Figure 8.

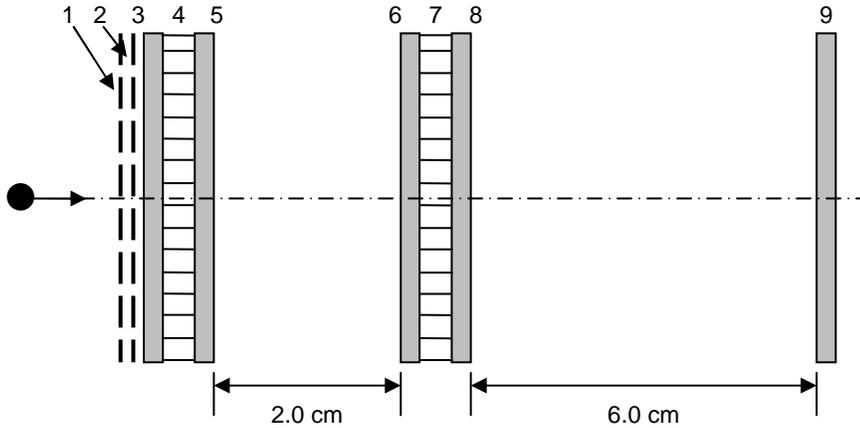


Figure 8: Schematic of the double-layer honeycomb target configuration.

A description of the target components is given in Table 1. The total areal density of the double-layer honeycomb configuration is 1.57 g/cm^3 .

Table 1: Description of Double-layer Honeycomb Target Components

Description	Designation	Thickness (mm)	Areal density (g/cm^2)
1 Mesh outer layer	30x30 [*] SS304 mesh ($\varnothing = 0.016''$)	0.457	0.20
2 Mesh inner layer	30x30 [*] SS304 mesh ($\varnothing = 0.016''$)	0.457	0.20
3 SP1 front facesheet	Al6061-T6	0.4064	
4 SP1 honeycomb core	1.8-5052-.002	12.7	0.37
5 SP1 rear facesheet	Al6061-T6	0.4064	
6 SP2 front facesheet	Al6061-T6	0.4064	
7 SP2 honeycomb core	1.8-5052-.002	12.7	0.37
8 SP2 rear facesheet	Al6061-T6	0.4064	
9 Real wall	Al2024-T3	1.016	0.43

^{*}30 indicates the number of openings per linear inch in the mesh.

Double-layer Foam (DL-F)

The double-layer foam target replaces the two honeycomb sandwich panels of the baseline target with 12.7-mm-thick open-cell Al6101-T6 foam sandwich panels that were manufactured by ERG Aerospace. As the areal weight of the foam core (6%–8% relative density) is greater than that of the honeycomb (~4.8%), facesheets are only installed on the front foam panel. The foam has a pore density of 10 PPI, details of which are given in Figure 9.

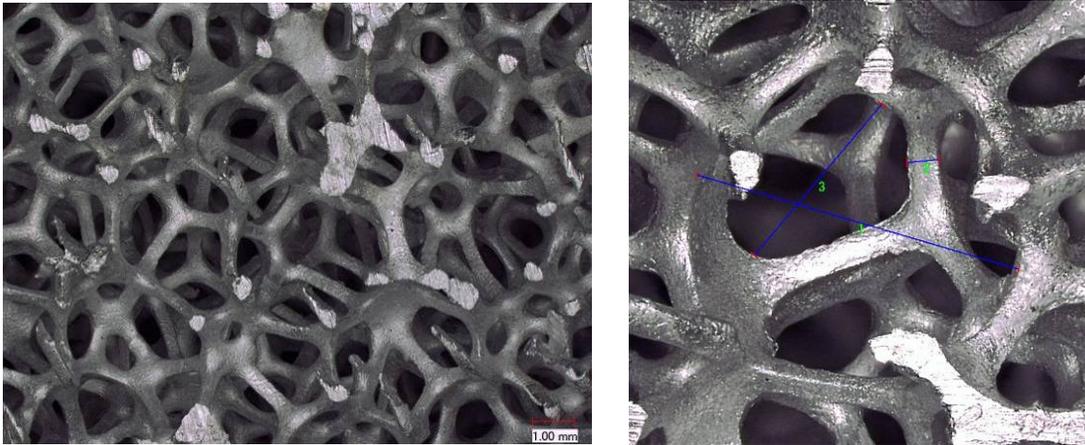


Figure 9: Characterization of the 10-PPI foam structure. Cell size (1) = 3.95 mm, pore size (3) = 2.33 mm, and ligament width (2) = 382 μm .

A schematic of the double-layer foam target is shown in Figure 10.

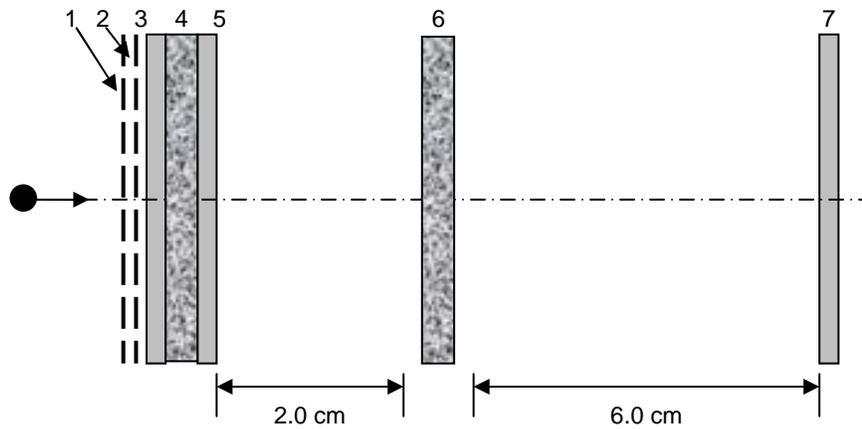


Figure 10: Schematic of the double-layer foam target configuration.

A description of the target components is given in Table 2. The total areal density of the double-layer foam configuration is 1.68 g/cm^2 .

Table 2: Description of Double-layer Foam Target Components

Description	Designation	Thickness	Areal density	
1	Mesh outer layer	30x30 SS304 mesh	0.457 mm	0.20 g/cm^2
2	Mesh inner layer	30x30 SS304 mesh	0.457 mm	0.20 g/cm^2
3	SP1 front facesheet	Al6061-T6	0.4064 mm	
4	SP1 foam core	10 PPI Al6101-T6 foam	12.7 mm	0.56 g/cm^2
5	SP1 rear facesheet	Al6061-T6	0.4064 mm	
6	SP1 foam panel	10 PPI Al6101-T6 foam	12.7 mm	0.29 g/cm^2
7	Rear wall	Al2024-T3	1.016 mm	0.43 g/cm^2

*30 indicates the number of openings per linear inch in the mesh.

Test Results

Nineteen hypervelocity impact tests were performed on the double-layer targets, 13 on the foam configuration and six on the honeycomb configuration. A summary of the test conditions and results is presented in Table 3.

Table 3: Hypervelocity Impact Test Results

	Reference	Target	Angle (deg)	Projectile Material	Projectile Diameter (mm)	Impact Velocity (km/s)	Result (P/SP/NP)
1	HITF08592	DL-F	0	Al2017-T4	0.877	6.76	NP
2	HITF08593	DL-F	45	Al2017-T4	0.837	6.87	NP
3	HITF08594	DL-F	60	Al2017-T4	1.114	6.69	P
4	HITF08595	DL-F	0	Al2017-T4	0.717	3.29	P
5	HITF08599	DL-F	60	Al2017-T4	1.005	7.03	P
6	HITF08596	DL-F	0	Al2017-T4	0.637	3.67	P
7	HITF08597	DL-F	45	Al2017-T4	0.662	3.68	NP
8	HITF08598	DL-F	45	Al2017-T4	0.837	3.62	NP
9	HITF09024	DL-F	60	Al2017-T4	1.005	6.80	NP
10	HITF09038	DL-F	60	Al2017-T4	1.115	6.69	NP
11	HITF09064	DL-F	60	Al2017-T4	1.276	7.00	SP
12	HITF07460	DL-F	0	Al2017-T4	0.833	6.74	NP
13	HITF07461	DL-F	45	Al2017-T4	0.873	6.89	P
14	HITF07458	DL-H	45	Al2017-T4	7.54	6.94	NP
15	HITF07459	DL-H	45	Al2017-T4	6.50	6.88	NP
16	HITF07504	DL-H	0	Al2017-T4	7.30	6.86	NP
17	HITF07509	DL-H	0	Al2017-T4	7.54	6.93	NP
18	HITF07510	DL-H	45	Al2017-T4	8.73	6.74	P
19	HITF07629	DL-H	0	Al2017-T4	8.33	6.91	P

Evaluation of Shield Modification

To evaluate the effect of interchanging aluminum honeycomb for open-cell aluminum foam in the double-layer shielding configuration, a direct comparison can be made between impact damages that are induced on both configurations at nominally identical impact conditions. In Figure 11, damages in the DL-H and DL-F targets induced by the impact of 0.833-cm-diameter projectiles at approximately 6.9 km/s with normal incidence are compared. Damage in the two mesh layers and the entry hole on the first sandwich panel are similar for both configurations. The diameter of the rear facesheet material peeled back from the first sandwich panel exit hole is also similar; however, the extension of core damage is noticeably less in the foam sandwich panel. The through hole in the second panels is shown to be significantly larger for the DL-H configuration than for the DL-F shield (88×90 mm vs. 70×62 mm), indicating that the debris cloud is more finely concentrated by the foam sandwich panel bumper than the honeycomb sandwich panel. The rear wall of the DL-H configuration is perforated, showing a large through crack (80 mm long and 5 mm wide) and multiple individual craters (multiple small bulges observable on the rear side of the panel). Given the appearance of the through crack, it is expected that failure of the rear wall occurred as a result of the penetration of individual solid fragments that acted as crack initiation sites that were propagated during the impulsive load of the fragment cloud. The rear wall of the DL-F configuration is significantly deformed, yet there is no perforation or detachment of spalled material from the rear surface. The majority of deposits on the rear wall are from molten aluminum, resulting in the bright silver coating that can be observed in the target photograph. The rear wall shows some cratering from impact of individual solid fragments, which are also visible as small dimples on the rear side of the panel. Under these impact conditions, the performance of the DL-F shield is clearly superior to that of the baseline DL-H shield.

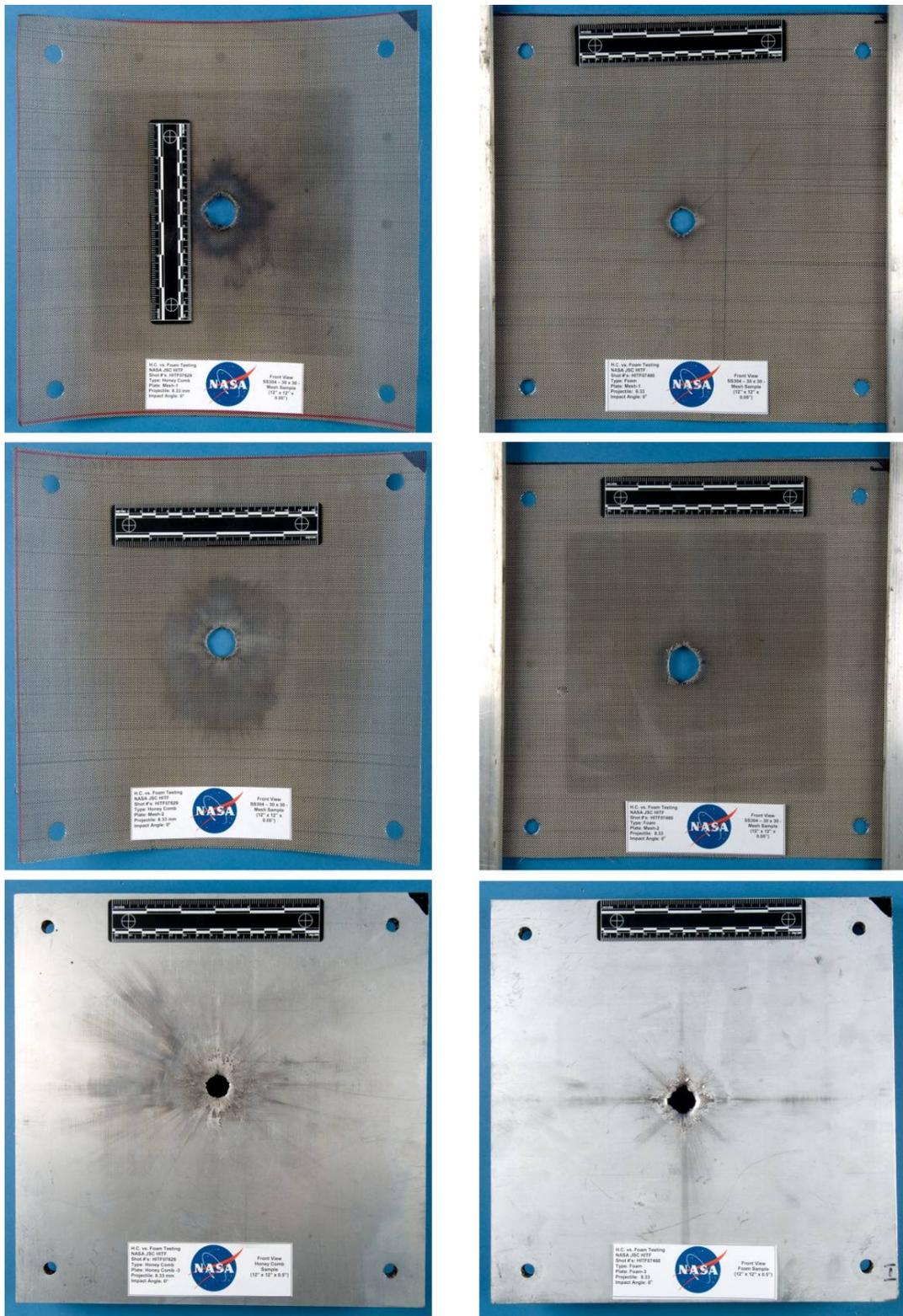


Figure 11: Comparison of impact damages in the DL-H (left) and DL-F (right) targets impacted by a 0.833-cm-diameter Al 2017-T4 sphere at approximately 6.9 km/s and 0°. From top to bottom: first mesh layer (front view), second mesh layer (front view), and first sandwich panel (front view).

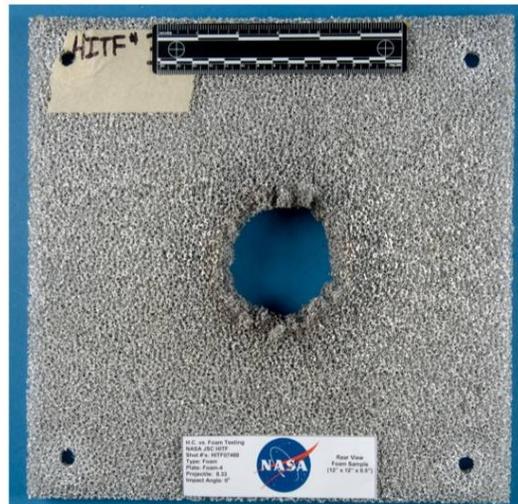
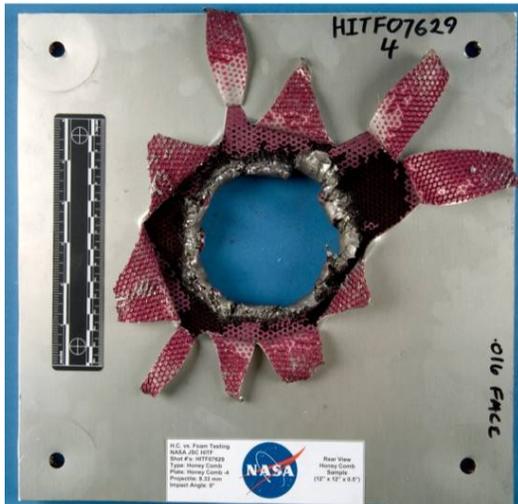
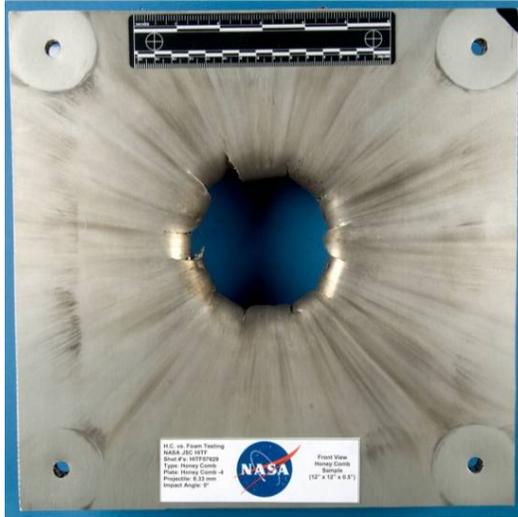
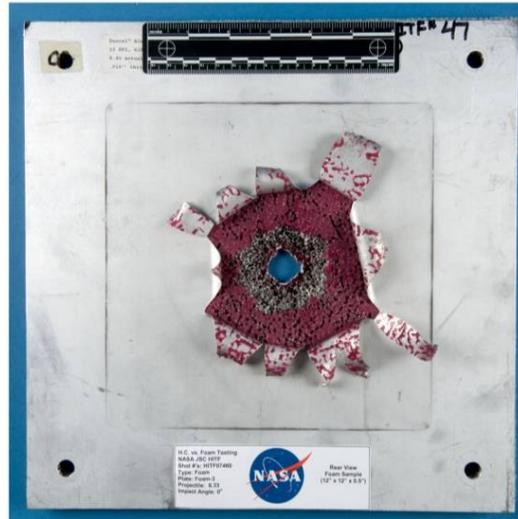
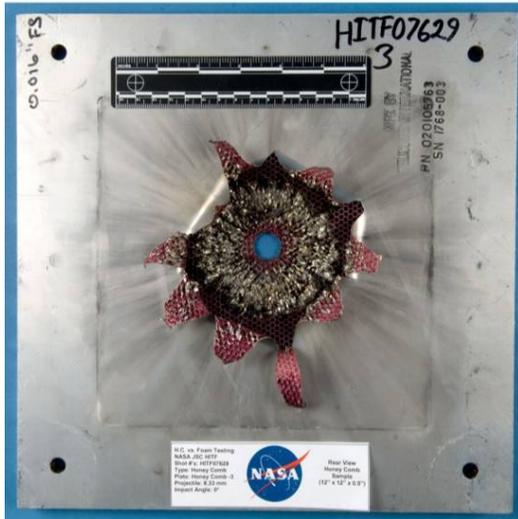


Figure 11 (cont): Comparison of impact damages in the DL-H (left) and DL-F (right) targets impacted by a 0.833-cm-diameter Al 2017-T4 sphere at approximately 6.9 km/s and 0°. From top to bottom: first sandwich panel (rear view), second sandwich panel (front view), and second sandwich panel (rear view).

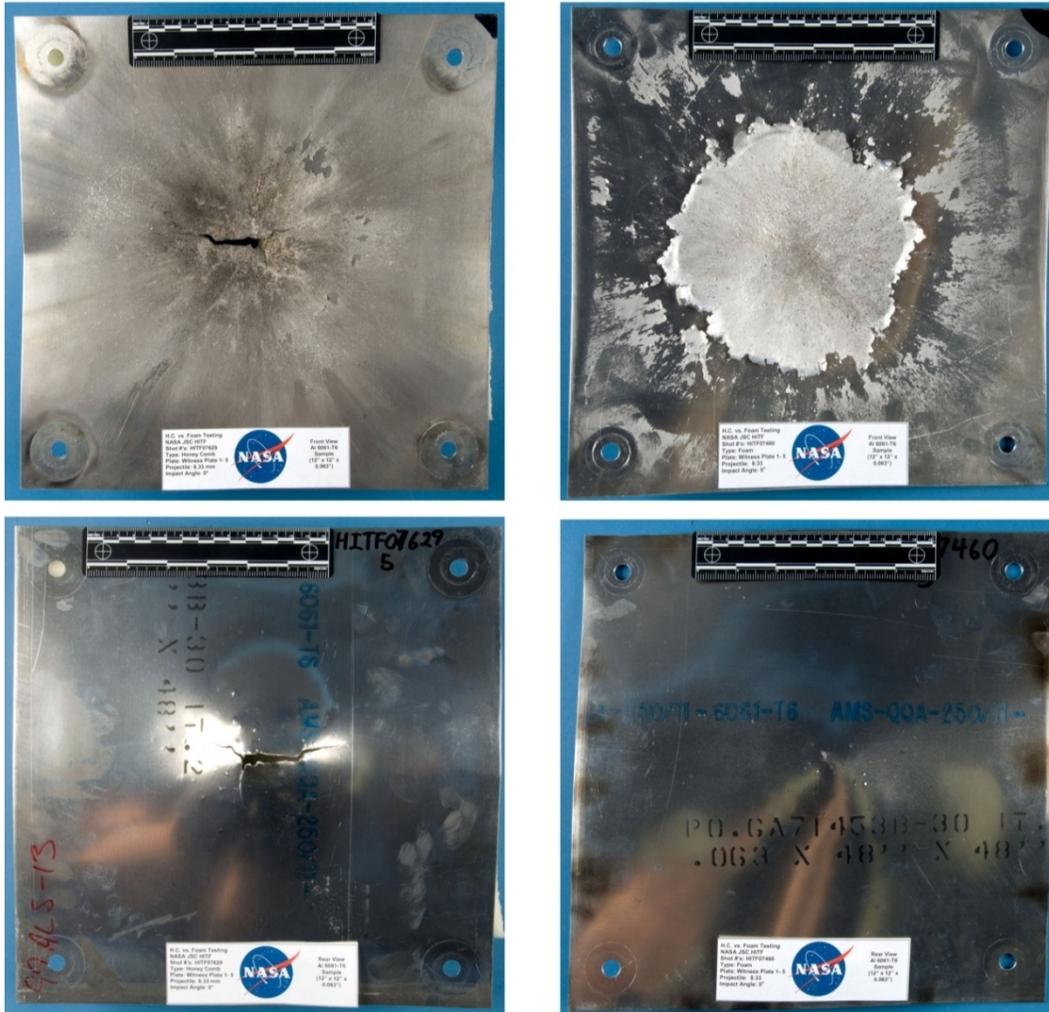


Figure 11 (cont): Comparison of impact damages in the DL-H (left) and DL-F (right) targets impacted by a 0.833-cm-diameter Al 2017-T4 sphere at approximately 6.9 km/s and 0°. From top to bottom: rear wall (front view) and rear wall (rear view).

In Figure 12, damages that were induced in the two configurations under the oblique (45°) impact of 0.873-cm-diameter projectiles at approximately 6.6 km/s are compared. In the two outer mesh layers, the damage is similar. The entry hole in the first foam sandwich panel is slightly larger than that of the HC SP (28×29 mm vs. 23×26 mm); however, the profiles of the entry holes are similar in appearance. The exit hole in the first foam sandwich panel is round, and is offset from the entry hole in the direction of the projectile flight vector. The damage to the panel rear facesheet is significantly larger than that in the foam core (due to delamination), similar to the 0° test. For the honeycomb sandwich panel, the exit hole is circular in shape; however, the petals to the upper left of the exit hole are not fully folded back, giving the hole an unusual shape. The honeycomb core damage limits, which correspond to the rear facesheet damage extension, are again significantly larger than that in the foam core. The through holes in the second panels are more similar in size than the 0° test, however the HC SP hole diameter is still larger than the foam panel. For the HC SP, the rear facesheet petals are peeled back beyond the extension of honeycomb core damage. Both shield rear walls are perforated, with multiple small perforation and spallation sites most likely from individual solid fragments. The DL-F rear wall is more significantly deformed than the DL-H panel, and shows clear deposits of melted aluminum.

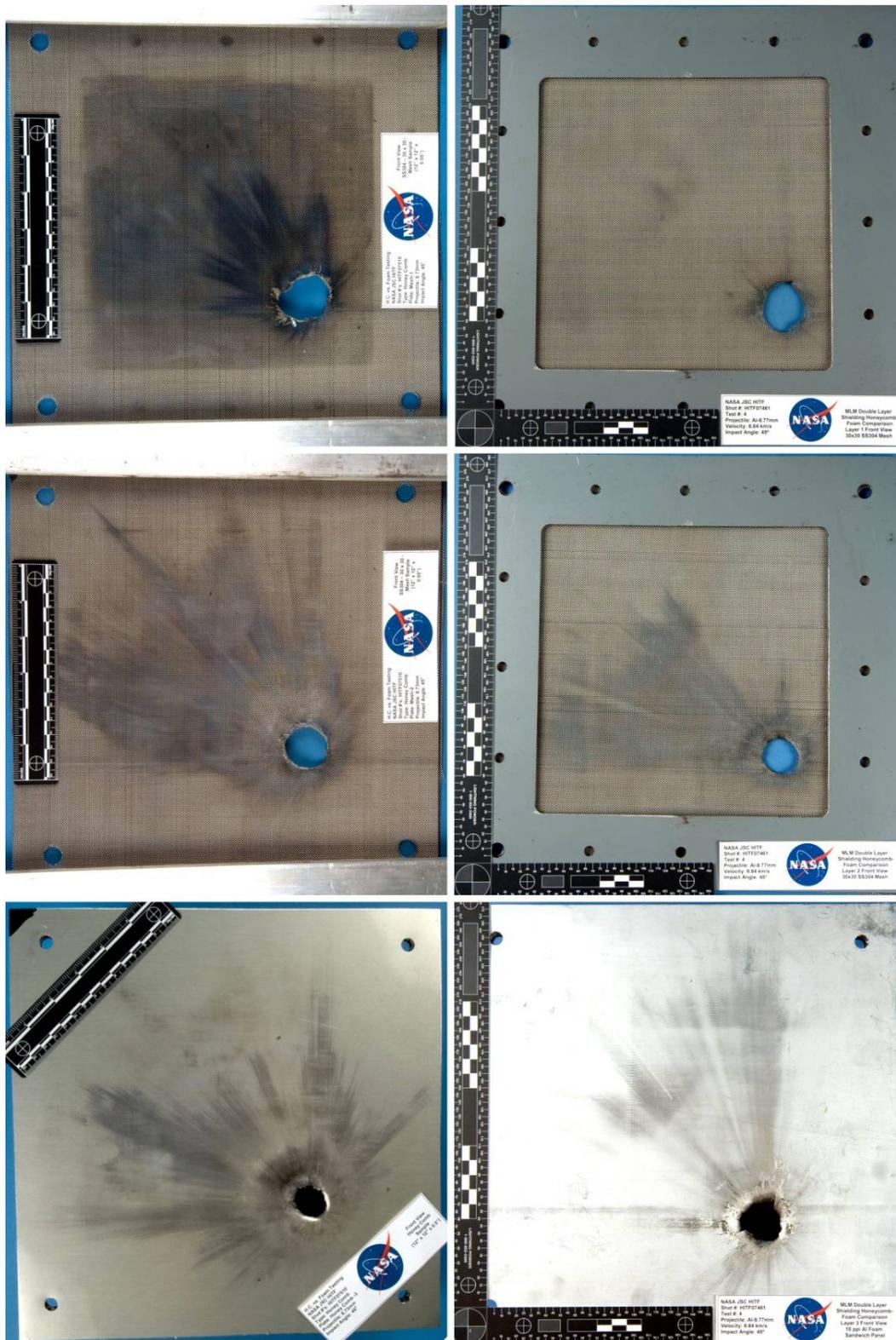


Figure 12: Comparison of impact damages in the DL-H (left) and DL-F (right) targets impacted by a 0.873-cm-diameter Al 2017-T4 sphere at approximately 6.6 km/s and 45°. From top to bottom: first mesh layer (front view), second mesh layer (front view), and first sandwich panel (front view).

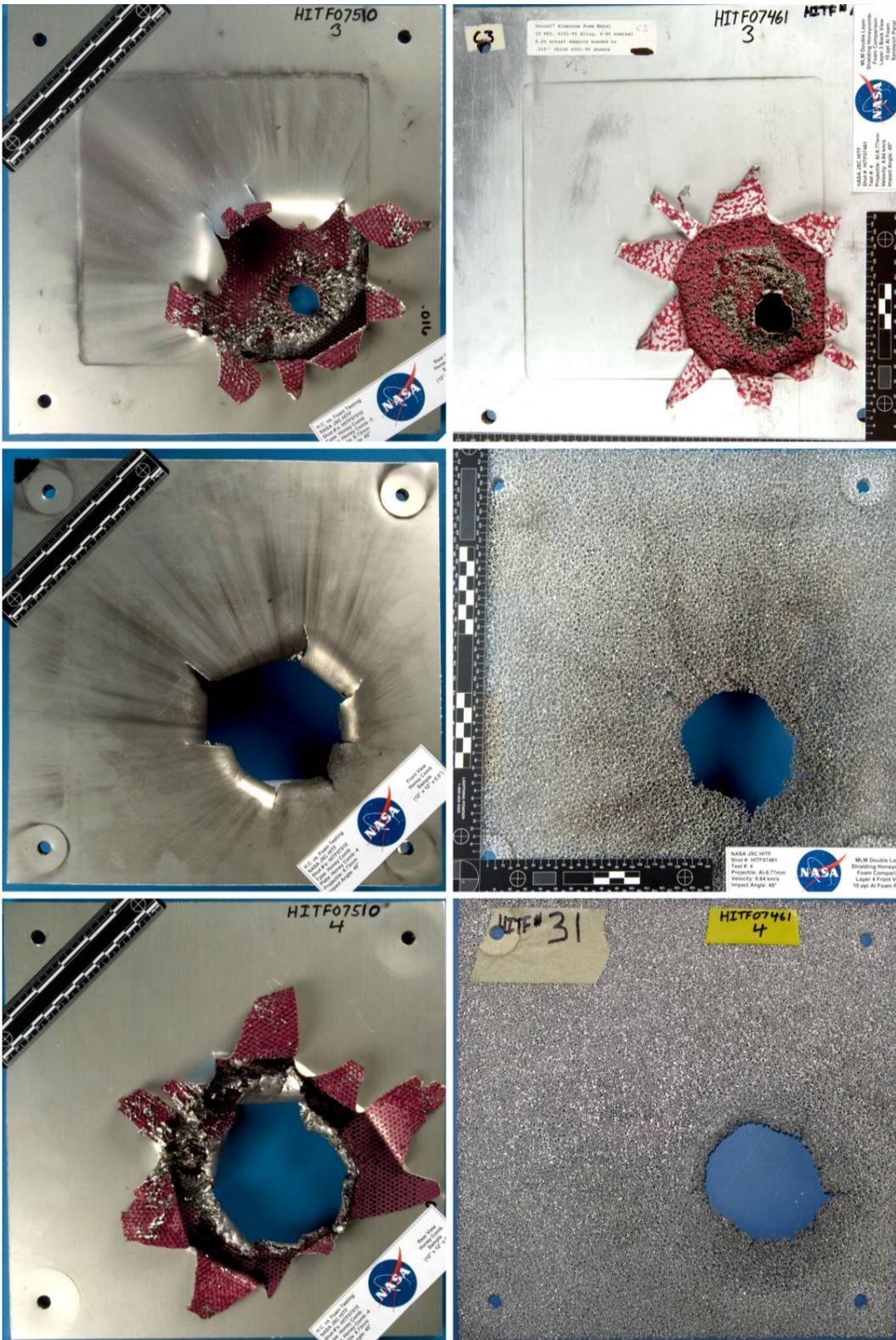


Figure 12 (cont.): Comparison of impact damages in the DL-H (left) and DL-F (right) targets impacted by a 0.873-cm-diameter Al 2017-T4 sphere at approximately 6.6 km/s and 45°. From top to bottom: first sandwich panel (rear view), second sandwich panel (front view), and second sandwich panel (rear view).

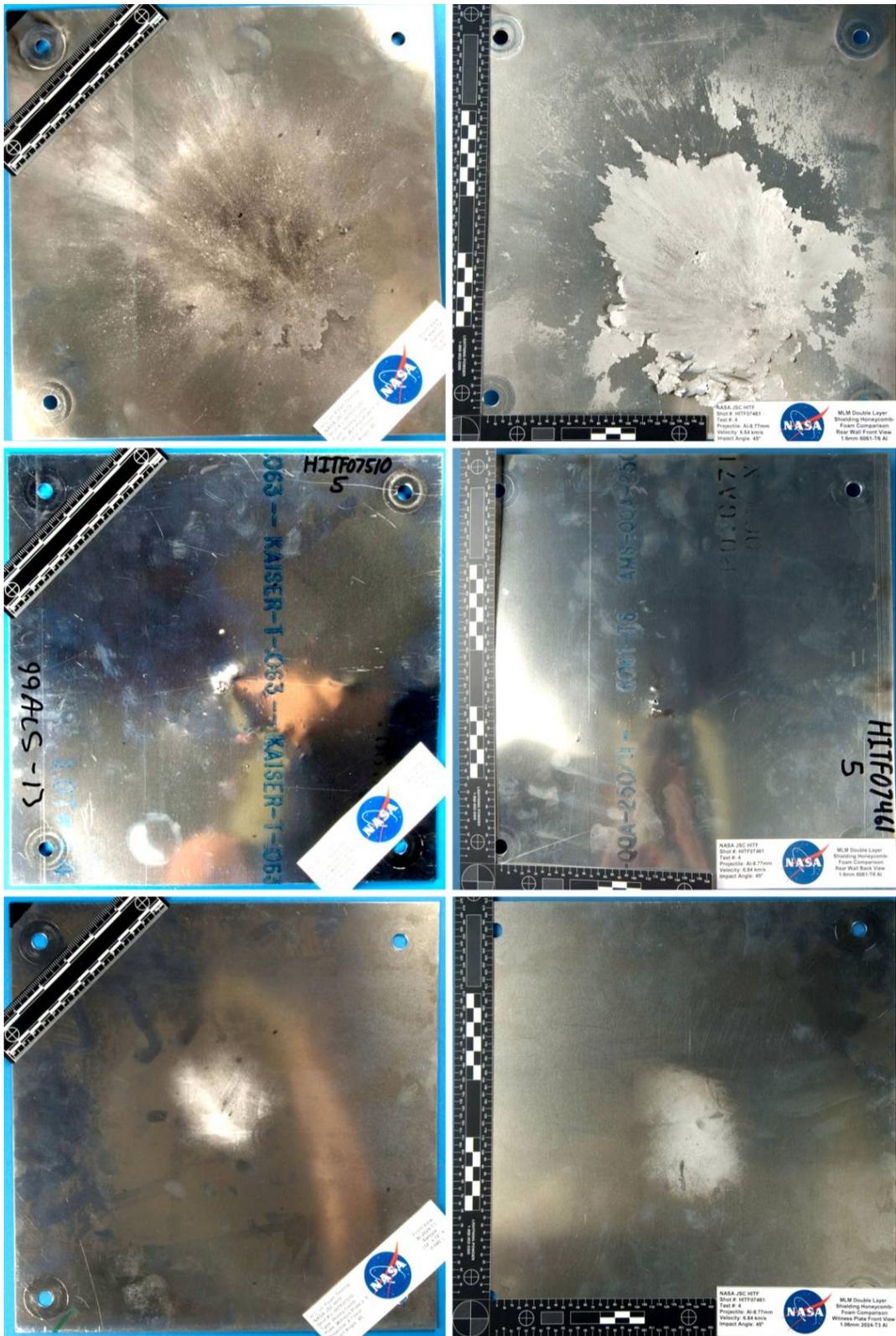


Figure 12 (cont.): Comparison of impact damages in the DL-H (left) and DL-F (right) targets impacted by a 0.873-cm-diameter Al 2017-T4 sphere at approximately 6.6 km/s and 45°. From top to bottom: rear wall (front view), rear wall (rear view), and witness plate (front view).

The Effect of Impact Angle on Shield Performance

In Figure 13, a comparison is shown between rear wall damage for the DL-H target impacted by 0.754-cm-diameter projectiles at approximately 6.9 km/s with normal (0° , HITF07509) and oblique (45° , HITF07458) incidence. The shield rear wall was not perforated in either test; however, the degree of damage to the 45° test is noticeably less than that of the normal incidence test. At 0° , the front side of the rear wall shows more deposits and a number of craters in the central damage zone. The plate is also significantly deformed, while the rear wall from the 45° test has minimal bulging/deformation. It is considered that the 0° target is very close to the limit of perforation.



Figure 13: Comparison of impact damages in the DL-H target rear wall impacted by 0.754-cm-diameter Al 2017-T4 spheres at approximately 6.9 km/s with normal (left) and oblique (45° , right) incidence.

In Figure 14, a comparison between rear wall damage for the DL-F target that was impacted by 1.005-cm-diameter projectiles at approximately 6.9 km/s is shown. For impact at 30° (HITF08599), the rear wall is severely perforated, showing a large petalled perforation hole and extensive cracking. The front of the panel shows extensive deposits of melted aluminum and some cratering about the jagged hole edges. From the appearance of the petalled edges, scientists considered that the rapid hole growth was initiated by perforation of solid individual fragments. The subsequent deformation of the petals and the entire panel resulted from impulsive loading of the predominantly molten fragment cloud. For impact at 60° (HITF09024), the rear wall is not perforated and is significantly less deformed than the structure that was impacted at 30° . The front side of the rear wall shows considerable deposits of melted aluminum and a small degree of cratering spread throughout the damage zone. Normal to the impact site are deposits of solid foam fragments on the rear wall, most likely from the slower moving outer edges of the fragment cloud. The target is well below the ballistic limit for this impactor at 60° , indicating a clear enhancement in shielding performance with increasing obliquity.

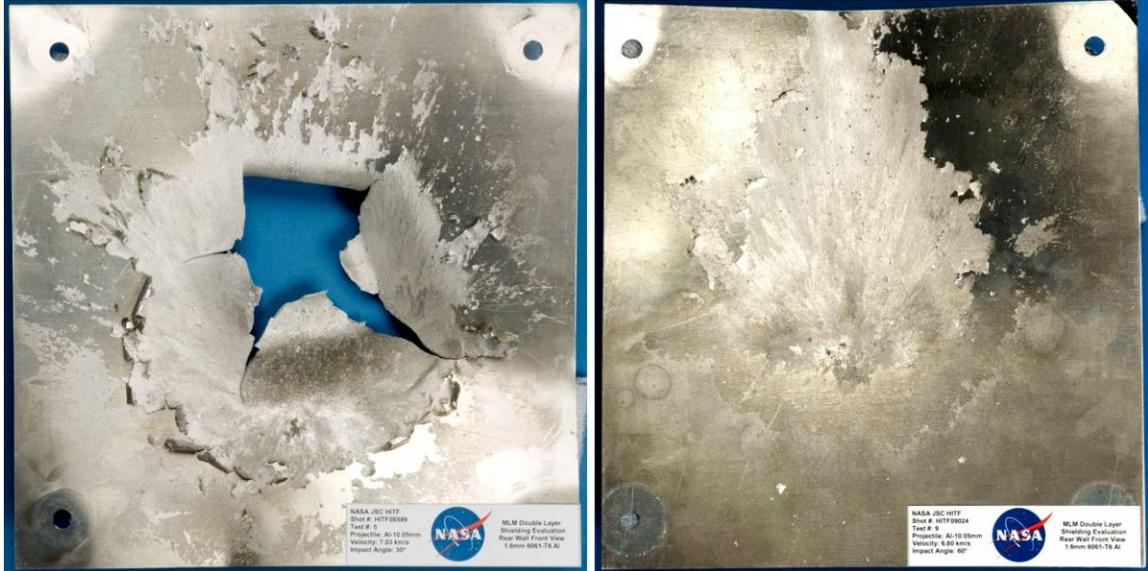


Figure 14: Comparison of impact damages in the DL-F target rear wall impacted by 1.005-cm-diameter Al 2017-T4 spheres at approximately 6.9 km/s with oblique incidence (left: 30°, right: 60°).

Low-velocity Shield Performance

A promising mechanism of open-cell metallic foams for MMOD shielding is the effect of secondary impacts by projectile and bumper fragments on individual foam cell ligaments. By repeatedly shocking these fragments, we expect that increased fragmentation and melting can be achieved at lower velocities than for conventional shielding configurations (e.g., Whipple shield, honeycomb sandwich panel). In Figure 15, the rear wall of a DL-F configuration that was impacted at 3.29 km/s is shown with clear deposits of melted aluminum.



Figure 15: Melted aluminum deposits and solid fragment damage of the DL-F rear wall impacted by a 0.717-cm-diameter projectile at 3.29 km/s with normal incidence (HITF08595).

Although there is no impact data for the DL-H configuration at impact speeds below 6.74 km/s, it is still possible to identify the effect of secondary impacts on the foam structure, compared to that resulting from impacts on the target intermediate layers. The multi-shock shield [10] used repeated shocking of projectile fragments to increase the degree of projectile fragmentation and melting. If the core structures are neglected, the configurations that were evaluated in this study are basically inefficiently spaced metallic multi-shock shields with a double-mesh outer layer. All-metal, multi-shock shields were shown in [10] to increase impact-induced pressures in projectiles such that, for normal impact at 6.3 km/s, pressures representative of impact at 10 km/s on a single bumper shield configuration were generated.

Figure 16 shows rear wall damage for the DL-H and DL-F configurations that were impacted at 6.91 and 6.74 km/s, respectively. The DL-F target shows a degree of melted aluminum deposits, although the predominant damage feature is cratering about the central damage zone. Alternatively, the DL-H target shows significant deposits of melted aluminum over a large central area with only a small number of finite craters. Clearly, therefore, secondary impacts on the foam ligaments act to increase shock heating/entropy, leading to projectile fragmentation, melting, and vaporization at lower impacts velocities than for the DL-H configuration.

Cour-Palais and Crews [10] base their calculation of effective impact velocity on the one-dimensional impact pressures that are required to induce melting and incipient vaporization. Limit values for aluminum-on-aluminum impacts are defined in [11], calculated based on the concept of entropy trapping – in which the entropy that is injected into projectile and target materials can be calculated from the Hugoniot and release isentrope. The increase in entropy acts to raise the material internal energy (or temperature), eventually reaching and exceeding the material fusion energy (melting) and vaporization energy. As noted previously, there is clear evidence of projectile melting below 3.29 km/s for the DL-F configuration.

A Ballistic Limit for the Double-layer Foam Shield Configuration

The baseline double-layer honeycomb shield is representative of the enhanced zone 11 shield on board the FGB module of the ISS [12]. For FGB shielding, a generic ballistic limit equation was defined that is based on the new non-optimum Whipple Shield equation [13]. To adjust the equation for the double-layer honeycomb configuration, the bumper thickness was estimated using the areal density of the first honeycomb layer and half the density of the second honeycomb layer. The remaining 50% of the second honeycomb layer was added to the thickness of the shield rear wall. Impact testing was then performed to provide an empirical basis for adjusting the equation constants.

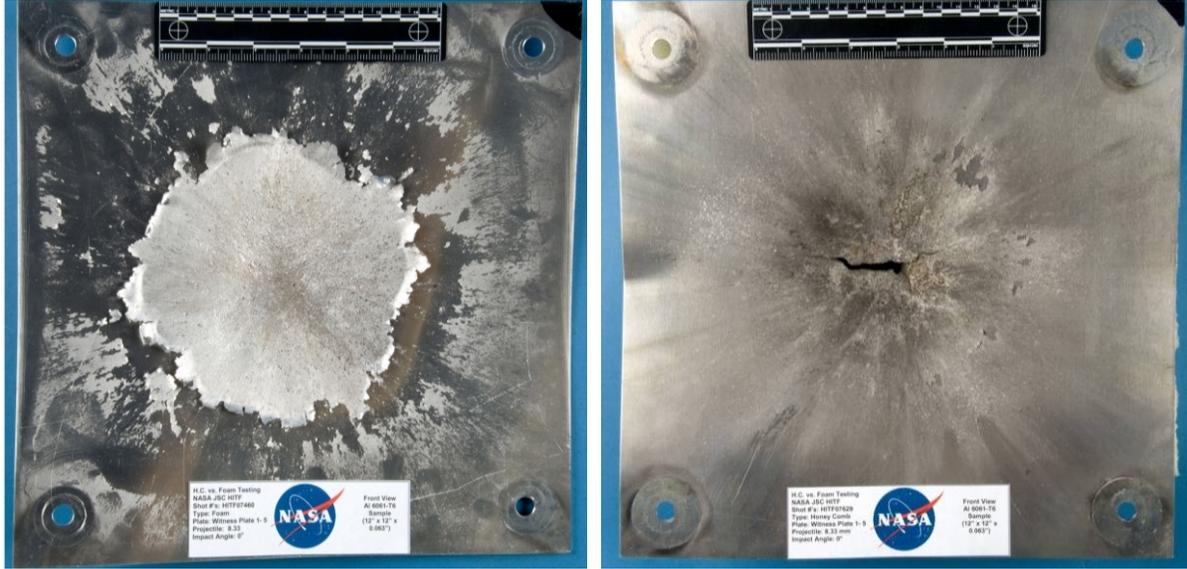


Figure 16: The effect of the foam microstructure on projectile fragmentation and melt is demonstrated by rear wall damage for the DL-H (upper) and DL-F (lower) shields impacted by 0.833-cm-diameter projectiles at approximately 6.9 km/s and 0°.

The general FGB [functional cargo block] ballistic limit equation (repeated from [12]) is defined as:

High velocity: when $V \geq V_H/\cos \theta$,

$$d_c = C_H (V \cos \theta)^{-2/3} \rho_p^{-1/3} \quad (3)$$

where V = projectile velocity (km/s).
 V_L = low-velocity regime upper limit (km/s).
 d_c = critical projectile diameter (cm).
 C_H = high-velocity fit coefficient (-).
 θ = impact angle (deg).
 ρ_p = projectile density (g/cm³).

Intermediate velocity: when $V_L/\cos \theta > V > V_H/\cos \theta$,

$$d_c = C_{hi} \rho_p^{-1/3} (V \cos \theta - V_L) + C_{li} \rho_p^{-9/19} (\cos \theta)^{-18/19} (V_H - V \cos \theta) \quad (4)$$

where V_H = high-velocity regime lower limit (km/s).
 C_{hi} = intermediate- to high-velocity fit coefficient (-).
 C_{li} = intermediate- to low-velocity fit coefficient (-).

Low velocity: when $V \leq V_L/\cos \theta$,

$$d_c = C_L (\cos \theta)^{-30/19} V^{-12/19} \rho_p^{-9/19} \quad (5)$$

where C_L = low-velocity fit coefficient (-).

For the enhanced zone 11 shield, the equation constants are given in Table 4.

Table 4: Constants of the FGB Ballistic Limit Equation for the Enhanced Zone 11 Shield

V_L (km/s)	V_H (km/s)	C_L (-)	C_{li} (-)	C_{hi} (-)	C_H (-)
3	7	1.629	0.203	0.318	4.651

The diameter of the steel wire that was used in the enhanced zone 11 shield was approximately 0.011 in., or less than that of the DL-H configuration tested in this study (0.016 in.). As such, the ballistic limit equation constants must be adjusted to fit the test data. In Figure 17, the modified enhanced zone 11 ballistic limit equation is plotted along with the test results reported in Table 3 using the original equation constants that are defined in Table 4 and the adjusted equation constants in Table 5. The low- and high-velocity coefficients, C_L and C_H , respectively, are calculated using the following relationships:

$$C_L = 3.11(t_w + (2AD_{mesh} + AD_{SP1} + AD_{SP2})/2.8) \quad (6)$$

$$C_H = 3.52 + 3.0AD_{mesh} \quad (7)$$

Table 5: Modified Constants of the FGB Ballistic Limit Equation for the Enhanced Zone 11 Shield

V_L (km/s)	V_H (km/s)	C_L (-)	C_{li} (-)	C_{hi} (-)	C_H (-)
3	7	1.671	0.209	0.290	4.25

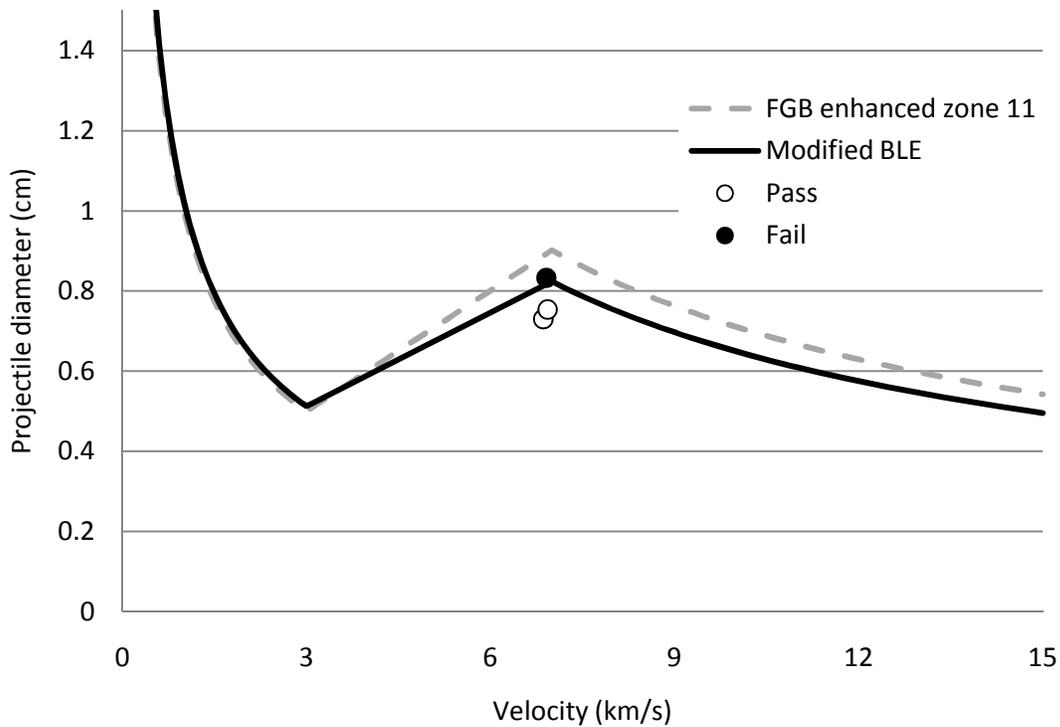


Figure 17: Ballistic limit curve (original and modified) of the DL-H configuration for normal impact.

The original ballistic limit equation constants are shown to over-predict shielding performance at 7 km/s (with normal incidence). Given that the original configuration used lower-gauge wire in the mesh layers (0.011 in. diameter instead of 0.016 in.), this was expected. The original equation constants are therefore considered non-conservative for normal impact at approximately 7 km/s.

For the DL-F configuration, the ballistic limit equation is modified to specify the areal densities of the specific shield components. For honeycomb sandwich panels, the mass of the honeycomb core is generally not used to determine effective shield thicknesses (i.e., the cores are treated as non-ballistic mass). For foam core sandwich panels, however, the foam is an active shielding component. The ballistic limit equation for the double-layer foam configuration is defined as:

High velocity: when $V \geq V_H/\cos \theta$,

$$d_c = C_H (V \cos \theta)^{-\beta} \rho_p^{-1/3} \quad (8)$$

where β = high-velocity angle dependence constant (-) = 0.55.

$$C_H = 3.0 + 2.4 \times AD_{mesh}$$

Intermediate velocity: when $V_L/\cos \theta > V > V_H/\cos \theta$,

$$d_c = d_c(V_L) + \frac{d_c(V_H) - d_c(V_L)}{V_H - V_L} \cdot (V - V_L) \quad (9)$$

Low velocity: when $V \leq V_L/\cos \theta$,

$$d_c = C_L (\cos \theta)^{-\alpha} V^{-12/19} \rho_p^{-9/19} \quad (10)$$

where α = low-velocity angle dependence coefficient (-) = 1.75.

$$C_L = 3(t_w + (2AD_{mesh} + AD_{SP1} + AD_{SP2})/2.8)$$

In Figure 18 through Figure 20, the ballistic limit curve calculated using Eq. (8)–(10) is shown together with the test results (from Table 3). At normal incidence, the curve shows a clear increase in performance in the intermediate (shatter) regime, indicating behavior similar to a multiple-wall shield. The curve is slightly conservative at 7 km/s, predicting failure for a 0.877-cm-diameter projectile – conditions at which the target rear wall was heavily deformed yet not perforated or spalled in the test. At 45°, the performance gain with increasing velocity in the shatter regime is significantly reduced. The curve is shown to fit the test data well, accurately predicting the failure limits at 7 km/s (between 0.837 and 0.873 cm). At higher incidence (i.e., 60°) the equation correctly predicts failure limits at the onset of the transition regime. There are no test data for higher velocities.

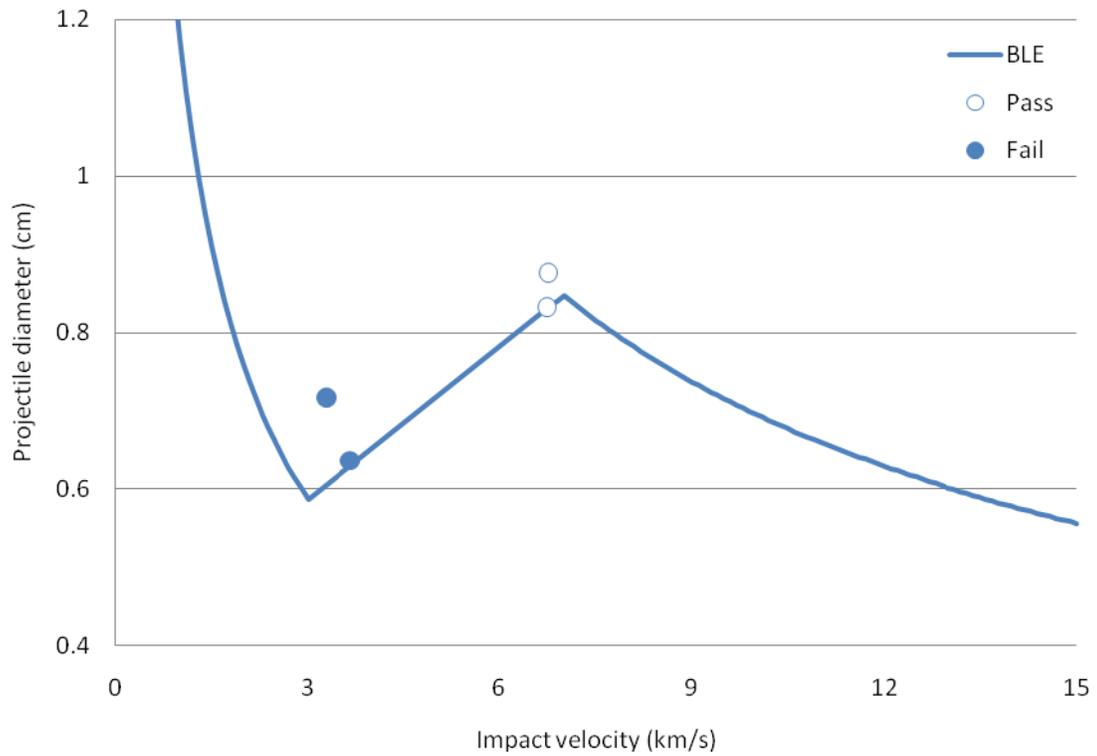


Figure 18: Ballistic limit curves of the double-layer foam shielding configuration at 0°.

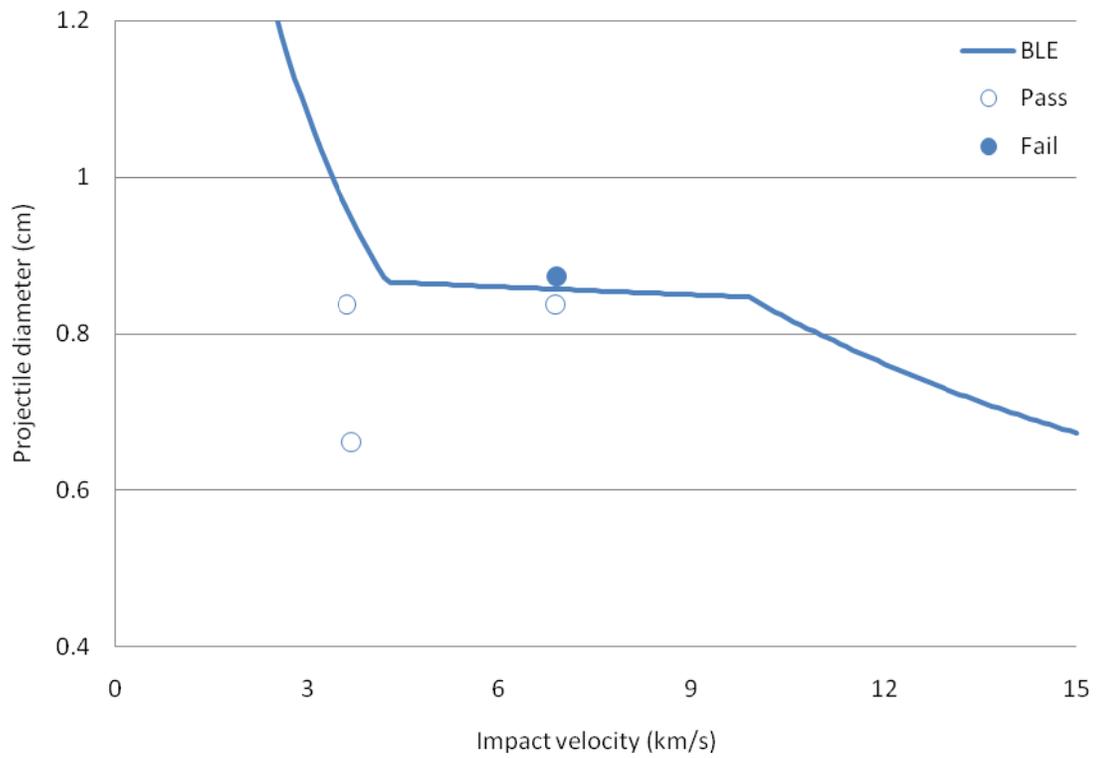


Figure 19: Ballistic limit curves of the double-layer foam shielding configuration at 45°.

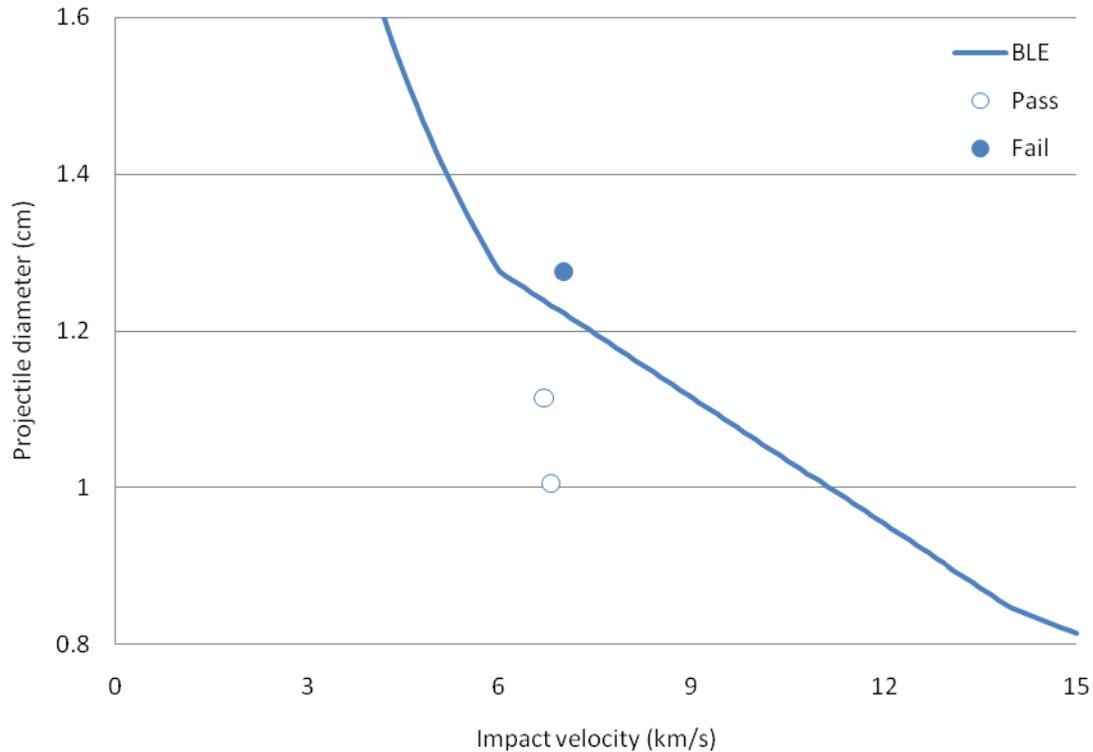


Figure 20: Ballistic limit curves of the double-layer foam shielding configuration at 60°.

Additional Test Data

Additional testing performed prior to this study was conducted on double-layer foam and double-layer honeycomb configurations with lower-gauge steel mesh layers. In these tests, the wire diameter was 0.009 in. (instead of the 0.016 in. diameter that was used in this study); however, the rest of the target components were nominally identical. The areal density of the 30×30 SS304 mesh ($\varnothing = 0.009$ in.) is equal to 0.078 g/cm². A summary of the impact test data is given in Table 6.

Table 6: Additional Hypervelocity Impact Test Results

Reference	Target	Angle (deg)	Projectile Material	Projectile Diameter (mm)	Impact Velocity (km/s)	Result (P/SP/NP)	
1	HITF03141	DL-H	0	Al2017-T4	0.794	6.82	NP
2	HITF03142	DL-H	0	Al2017-T4	0.913	6.86	P
3	HITF04165	DL-H	0	Al2017-T4	0.635	6.67	NP
4	HITF03143	DL-F	0	Al2017-T4	0.794	6.74	P
5	HITF03144	DL-F	0	Al2017-T4	0.794	6.71	P

A comparison between HITF03143 and HITF07460 shows that the mesh diameter can significantly affect shielding performance. The ballistic limit curve of the 0.016-in.-diameter wire mesh and 0.009-in.-diameter wire mesh DL-F and DL-H targets is shown in Figure 22. At 7 km/s, the heavier mesh provides an 8.2% and 13.3% increase in perforation limit for the DL-F and DL-H targets, respectively.

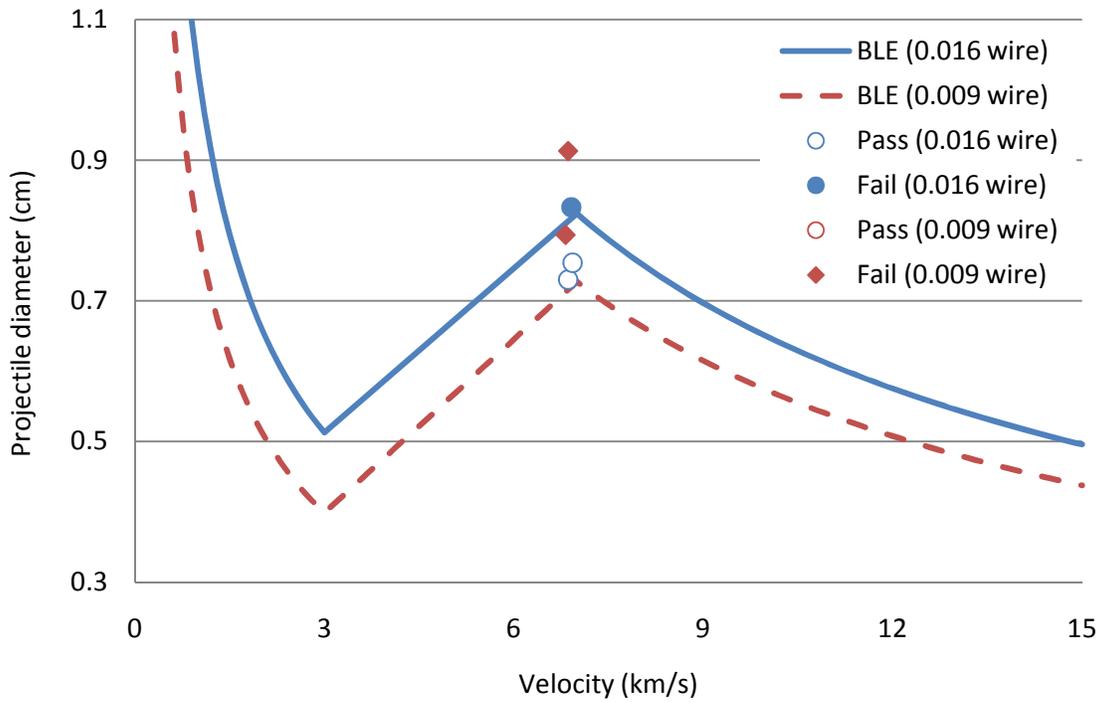


Figure 21: Ballistic limit curve of the DL-H shield with 0.009-in.- and 0.016-in.-diameter wire mesh layers.

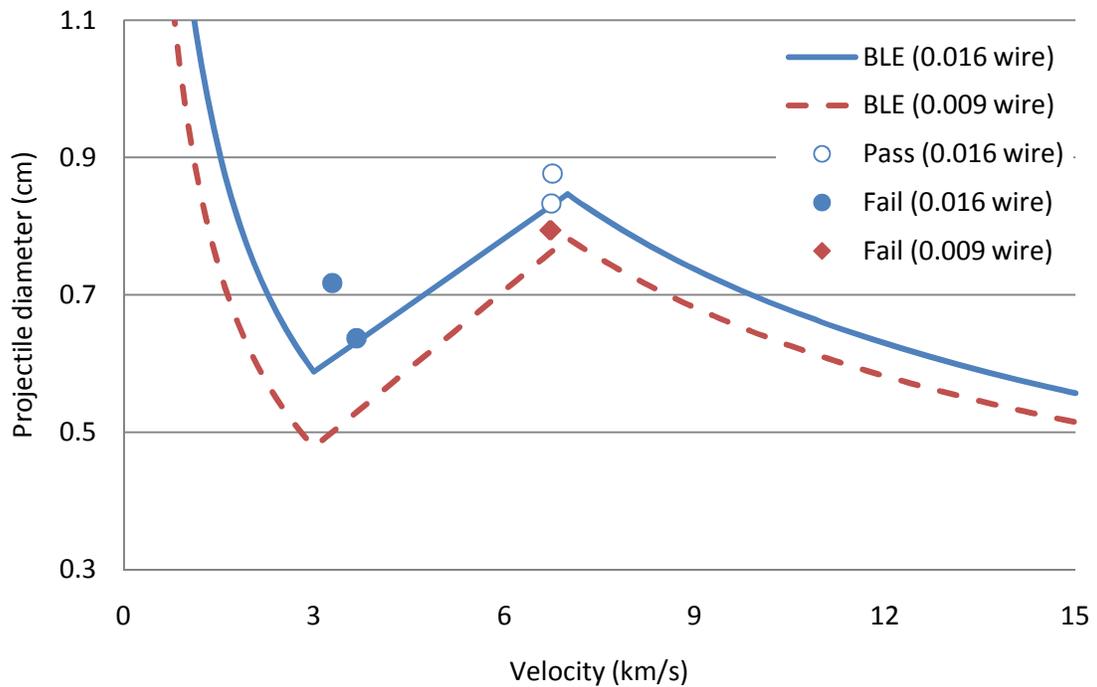


Figure 22: Ballistic limit curve of the DL-F shield with 0.009-in.- and 0.016-in.-diameter wire mesh layers.

Comparison of DL-H and DL-F Ballistic Limit Predictions

The modifications to the double-layer honeycomb sandwich panel configuration can be further assessed through comparison of the ballistic limit curves for the two configurations. In the event of a mission risk analysis, these equations would be used to assess the probability of penetration and catastrophic failure of the applicable vehicle which would then be used to evaluate mission compliance with allowable risk figures. In Figure 23 through Figure 25, the modified enhanced zone 11 FGB ballistic limit equation is plotted against the equation that was derived for the DL-F configuration (in both cases 0.016-in.-diameter wire meshes are considered). For normal impact, the modifications result in a small predicted improvement over the range of applicable impact velocities. At 3 km/s, the shield modifications provide a 15% increase in critical projectile diameter; at 7 km/s, a 3% increase is predicted. The larger low-velocity sizing constant C_L also leads to increasing performance gain with increasing impact velocity, although there is a lack of test data to support or disprove this extrapolation. At oblique impact, the increase in low-velocity performance enhancement increases as a result of the difference in defined angle dependence ($2/3$ vs. 0.55 for the DL-H and DL-F shields, respectively). At 45° , the predicted performance enhancement of the DL-F shield is 22% over that of the baseline DL-H shield, which increases to 29% at 60° . For the DL-H configuration, no test data were generated at low velocities in this study. The low-velocity fit coefficient (C_L) was defined to provide consistency with the original enhanced zone 11 coefficient.

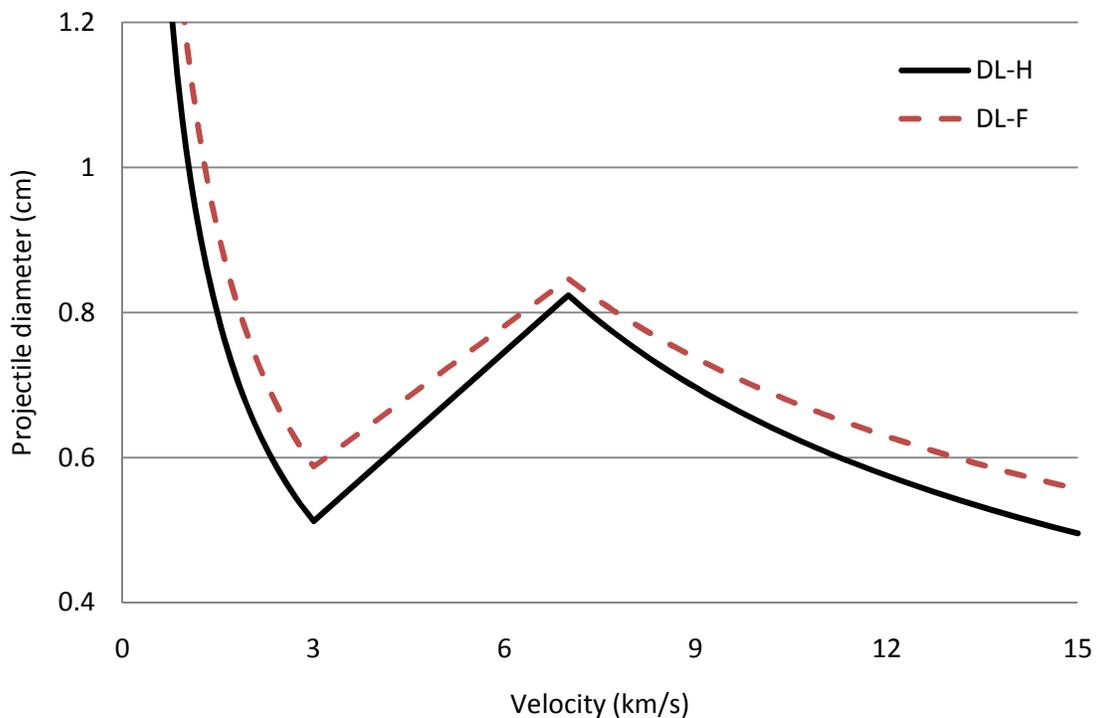


Figure 23: Comparison between the DL-H and DL-F ballistic limit curves at 0° .

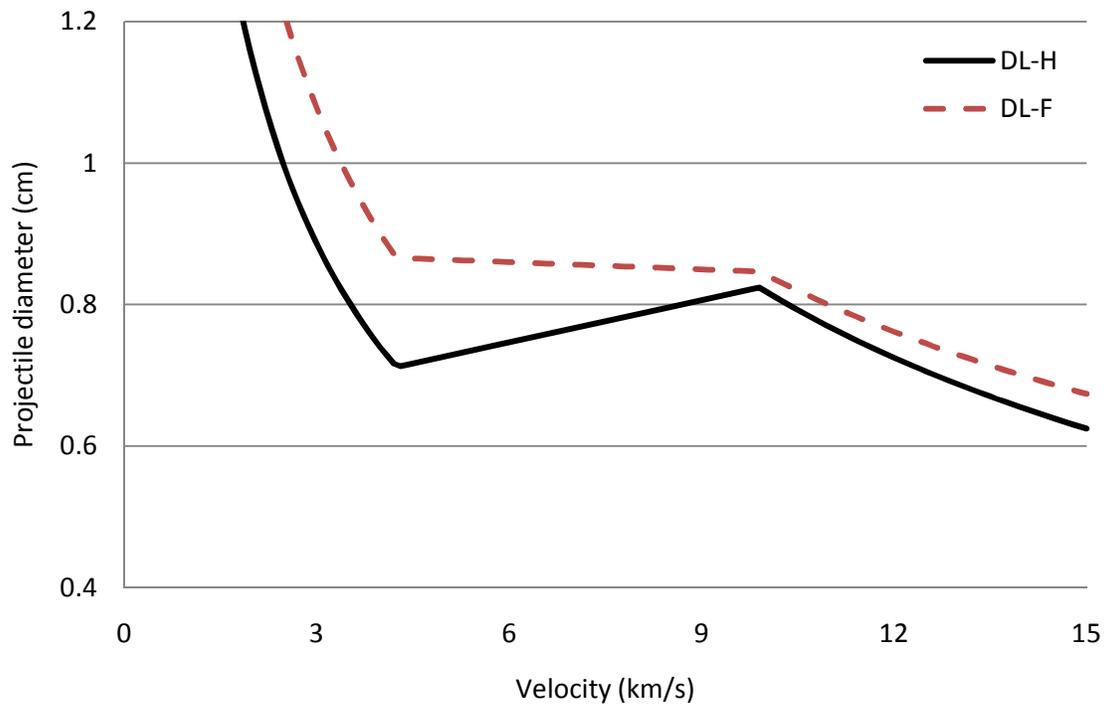


Figure 24: Comparison between the DL-H and DL-F ballistic limit curves at 45°.

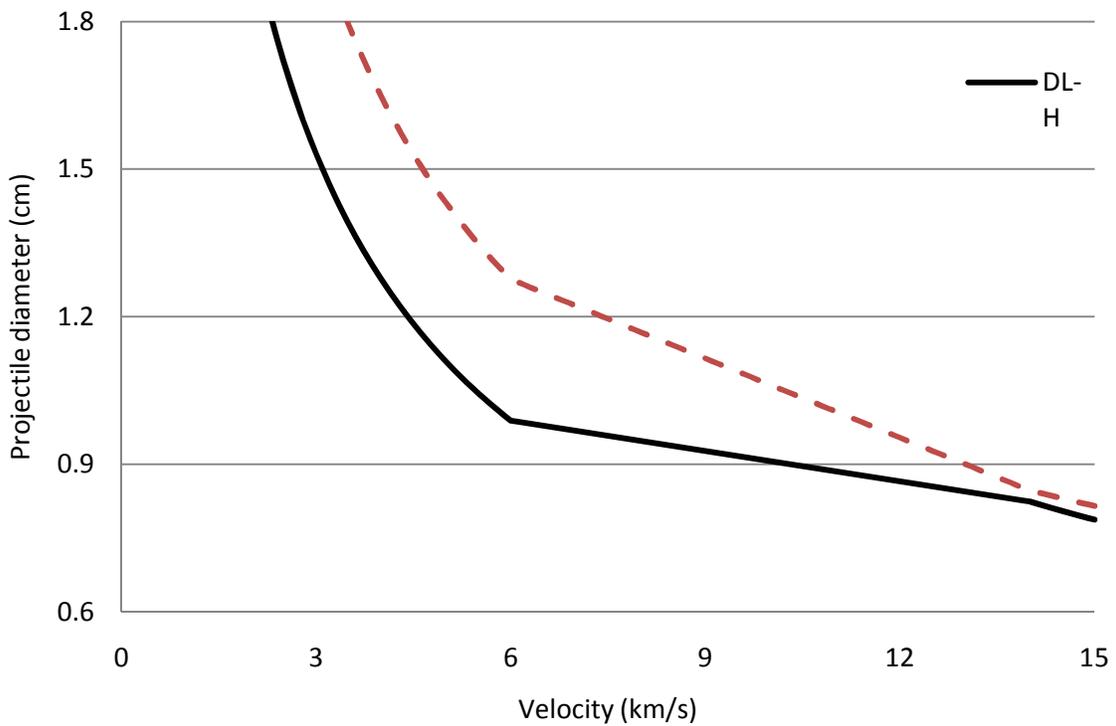


Figure 25: Comparison between the DL-H and DL-F ballistic limit curves at 60°.

Discussion

The ballistic limit equations that are defined for the DL-F and DL-H configurations are based on the JSC Whipple shield equation [13], which separates performance into the three velocity regimes: low, intermediate (or shatter), and hypervelocity. At low velocities, pressures that are generated during impact on the bumper plate are insufficient to cause projectile fragmentation, leading to the impact of an intact (albeit deformed) particle on the shield rear wall. Transition to the shatter regime occurs once pressures are large enough to induce projectile fragmentation via tensile release waves reflected from the bumper (or projectile) free surfaces (depending on impact geometry). Increasing impact velocity within the shatter regime leads to increased projectile fragmentation, resulting in a more finely dispersed debris cloud of smaller and more uniform particles. Incipient melting of projectile and bumper fragments also occurs in the shatter regime, the degree of which increases with increasing impact velocities. Until this point, the failure of the Whipple shield rear wall results from the penetration of individual projectile or bumper fragments through cratering and spallation mechanisms. The transition from shatter to hypervelocity impact regime occurs once the rear wall failure mechanism switches from a cratering-type failure to that of an impulsive blast wave. Increasing impact velocity in the hypervelocity regime increases the kinetic energy of the impulsive load, resulting in a decrease in performance that scales (according to NASA practice) with kinetic energy.

Previous studies (e.g., [14]) have defined the onset of projectile melt to occur at approximately 5.6 km/s (for aluminum-on-aluminum impact), based on planar shock wave theory. For metallic foams, we consider that secondary impacts of projectile and bumper fragments lead to an increase in shock heating (entropy), effectively decreasing material failure strength and leading to increased fragmentation, melting, and vaporization at lower impact velocities. Destefanis et al. [15] reported on tests against a dual-wall configuration with a bumper of open-cell aluminum foam. In these tests, a good deal of melting was observed at velocities as low as 2 km/s, with complete melting reported at velocities as low as 4 km/s. Similar enhanced fragmentation was reported in [16] for millimeter-sized projectiles at normal impact. However, this mechanism was not effective against projectiles in the centimeter-sized range, nor was it effective for oblique impacts. In this study, clear evidence of melted deposits was observed on the target rear wall for test #4 (HITF08595), which was performed at 3.29 km/s. For low-velocity impacts at oblique impact (e.g., test #6 (HITF08596)), there are also clearly observable deposits of melted aluminum on the shield rear wall. Although the onset and degree of projectile and bumper melt are clearly increased by the open-cell foam bumpers, in all of the impact tests that were performed there is evidence of solid fragment impacts on the target rear walls. For oblique impacts, these solid fragment craters are generally in line with the projectile velocity vector, indicating that they are most likely projectile remnants (see Figure 26).

Destefanis et al. [16] define the transition limits of the low- and hypervelocity-impact regimes at 2.7 and 6.5 km/s, respectively, in recognition of the increased fragmentation and melting that are induced by the open-cell foam bumper (compared to a traditional Whipple shield). Although (as discussed) increased fragmentation and melting were also observed for the double-layer foam configuration that was evaluated in this study, evidence of individual solid fragment cratering was found for impacts up to 6.76 km/s at normal incidence. In the absence of additional test data providing clear experimental justification, the transition velocities that were defined in [13] for aluminum Whipple shields and in [12] for the DL-H configuration are maintained in the ballistic limit equation that was derived in this report.



Figure 26: Solid fragment craters on the DL-F rear wall at high-impact velocities (0.877-cm-diameter Al2017-T4 sphere at normal incidence with 6.76 km/s).

The performance of aluminum, open-cell foam bumpers was found to decrease for impact of centimeter-sized projectiles at normal incidence and for millimeter-sized projectiles at oblique incidence in [15]. The authors of this study concluded that secondary impacts were no longer able to induce fragmentation and melting of the entire projectile at these impact conditions. In this study, however, there was no noticeable decrease in performance at obliquity, even for projectiles that were considerably larger than 1 cm in diameter (e.g., test #11 (HITF09064)). The double layer of mesh on top of the first sandwich panel of the DL-F configuration is expected to break up the projectile before impact on the sandwich panel facesheet. Therefore, smaller projectile fragments are propagated to impact within the sandwich panel foam core, and the size limitations of secondary fragmentation and melting that were discussed by Destefanis et al. are not valid.

Conclusions

The purpose of this study was to evaluate the effect on shielding performance achieved by replacing metallic honeycomb cores with metallic open-cell foam cores in a double-sandwich panel MMOD shielding configuration representative of those used onboard the ISS. Toward this goal, 19 hypervelocity impact tests were performed on double-layer honeycomb and foam configurations, from which ballistic limit equations were defined based on the JSC Whipple shield equation [13] and the FGB generic ballistic limit equation [12]. The double-layer honeycomb configuration was similar to the enhanced zone 11 shield on the FGB, which is reported on in [12]. However, the ballistic limit equation constants that were implemented in BUMPER were found to be non-conservative at velocities around 6 to 7 km/s. As such, modified parameters were defined for the double-layer honeycomb (also known as the enhanced zone 11) configuration. For the double-layer foam configuration, new constants for the FGB ballistic limit equation

were empirically derived from the test data. The low-velocity fit coefficients are derived from the areal densities of the individual shield components, enabling their application on modifications to the original shield. Test data on the double-layer foam configuration, which incorporated mesh layers that were constructed with smaller-diameter wires than those used in the baseline configuration, were used to evaluate the accuracy of the low-velocity constant calculation, and good agreement with the test data was shown.

At normal incidence, the foam-modified shield was found to provide a 15% improvement in critical projectile diameter at low velocity (3 km/s) and a 3% increase at high velocity (7 km/s). With increasing impact obliquity, the foam shield performance enhancement increases at the low-shatter regime transition velocity, up to a 29% improvement in critical diameter at 60°. It should be noted that the double-layer honeycomb equation constants are defined for consistency with the enhanced zone 11 shield that is described in [12], for which there are no low-velocity test data.

The presence of honeycomb cells is considered to be detrimental to the shielding performance of a dual-wall configuration due to the cell walls acting to restrict the expansion of projectile and bumper (or front facesheet) fragments referred to as channeling. However, the thickness of the honeycomb sandwich panels in the double-layer configuration are less than twice the diameter of even the smallest projectile used in the tests. Thus, dispersion of the projectile and bumper fragments is expected to be uninterrupted before impact on the sandwich panel rear facesheet. As such, the performance enhancement gained by replacing the honeycomb core with open-cell foams is not expected to result as a simple absence of through-thickness channeling cells. Rather, secondary impacts of projectile and bumper fragments on individual foam cell ligaments induced repeated shocks, increasing fragment entropy and subsequently reducing failure strengths. Evidence of increased projectile fragmentation and melting was shown for the double-layer foam configuration (compared to the double-layer honeycomb configuration). Previous investigations on metallic open-cell foam bumpers have noted a decrease in performance for oblique impact, and normal impact of large centimeter-sized projectile due to the inability of the repeated shocking procedure to fragment the entire projectile at these conditions. However, the presence of the double-mesh outer layers breaks up the projectile before impact on the first sandwich panel front facesheet, thus ensuring the propagation of smaller, more manageable impactors within the foam core.

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