The Next Generation of Kevlar® Fiber for Improved Micrometeoroid and Orbital Debris Protection

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Abstract

The next generation of Kevlar® fiber for Micrometeoroid and Orbital Debris (MMOD) protection demonstrates the potential to increase orbital debris protection while optimizing the overall weight of the MMOD system and reducing damage to the rear wall of the shield. The DuPont™ CoreMatrix™ Technology process combines numerous woven layers by infusing staple fiber to strengthen the fabric and enables lightweight and flexible protective solutions compared to traditional woven structures. DuPont™ CoreMatrix™ Technology is a step-change in debris protection that allows for the improvement of system-level performance while removing heavier portions of the system. This paper introduces this new technology that will be available from DuPont starting in early 2024 and compares the performance of CoreMatrix™ Technology to legacy solutions. NASA's Hypervelocity Impact Technology team has conducted hypervelocity impact tests on a subset of DuPont supplied samples that incorporate this latest Kevlar® material. The paper will describe the hypervelocity impact testing parameters, results, and path forward.

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1 HISTORY FOR USE OF KEVLAR® IN SPACECRAFT METEOROID AND ORBITAL DEBRIS (MMOD) SHIELDING APPLICATIONS

From its earliest days, NASA has provided micrometeoroid and orbital debris (MMOD) protection to its spacecraft to meet crew safety and mission success requirements [1]. Up through the Skylab and Shuttle Programs in the 1970s and 1980s, conventional MMOD protection was provided by all-aluminum Whipple shields (2-wall shielding). With development of the International Space Station (ISS) in the 1990s, higher performance MMOD protection than offered by conventional all-aluminum shielding became a necessity to meet safety requirements due to the large size of the ISS (> 2000 m^2 of critical surface area that required MMOD protection), long duration in orbit (> 15 years) and continued growth of the orbital debris environment. NASA's Hypervelocity Impact Technology (HVIT) team has been involved for many years in developing MMOD shielding for NASA spacecraft that provide higher protection with less mass than conventional all-aluminum shields [2]. The HVIT team was instrumental in developing the Nextel™/Kevlar® "Stuffed Whipple" MMOD shield that is used extensively on ISS and which provides the highest level of MMOD protection ever flown on a spacecraft in terms of the MMOD particle size that can be stopped by the shield [3]. Derivatives of the Stuffed Whipple shield flown on NASA modules on ISS are also used to protect the European, Japanese, and Russian modules on ISS.

Changes to the stuffing layers, in particular the number of layers and type of Kevlar®, were made for later ISS modules as will be explained in the following sections. Further shielding modifications have been made to spacecraft developed and flown since ISS was developed, and those shielding modifications and applications will also be discussed in the following sections of this paper.

1.1 Use of Kevlar® in MMOD shielding

MMOD shields are generally composed of: (A) one or more outer layers or “bumpers”, whose purpose is the breakup the impacting MMOD particle into a cloud of solid, liquid and gas particulates that are much smaller than the original MMOD particle (referred to as a “debris cloud”), (B) a rear wall with enough strength and thickness to prevent perforation or detached spall from the debris cloud, and (C) a space, gap or standoff between the outer bumper and rear wall that allows the debris cloud to expand and distribute the debris cloud particulates and impulsive load across a wide area of the rear wall. Multi-layer spaced shields are far more mass-efficient in stopping hypervelocity MMOD impacts than a single, monolithic shield layer [4, 5]. The density and thickness of the outer most layer(s) of the shield are important parameters that govern the effectiveness of MMOD particle breakup. Material strength is more important for lower layers of the shield (inner bumper layers and the rear wall) than it is for the outer bumper layer(s), where the function of the lower shield layers is to slow and finally stop the debris cloud from further penetration. Kevlar® is typically used in lower layers of the MMOD shield, given Kevlar’s high strength to mass ratio.

Figure 1 illustrates a range of different MMOD shields used to protect NASA spacecraft where Kevlar® fabrics have been applied. These shield types include: (1) Stuffed Whipple shield, (2) High-strength fabrics as the rear wall or near the rear wall, (3) Flexible multi-shock shields that commonly protect inflatable modules, (4) Enhanced multi-layer insulation (MLI) blankets used to provide thermal as well as MMOD protection, (5) Improved thermal protection systems (TPS) used on spacecraft transporting crew and cargo. Each of these shield types is described in the following paragraphs.

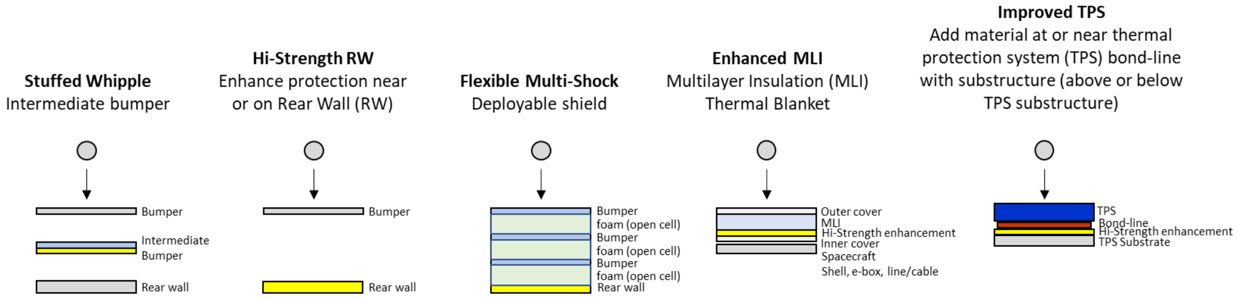

Fig. 1. MMOD shields using Kevlar® (yellow element indicates location of Kevlar® or other high-strength fabric layer)

The Stuffed Whipple shield is used extensively on ISS, protecting US/NASA modules as well as international elements from MMOD impacts. Kevlar® is used as the backing of the intermediate “stuffing” MMOD blanket which is positioned half-way between the outer bumper and interior rear wall. For the ISS US Laboratory module, the intermediate bumper is composed of several ceramic fabric layers with total mass per unit area of 0.6 g/cm^2 and 6 layers of Kevlar® 29 style 710 with total mass per unit area of 0.132 g/cm^2 (Kevlar® is 24% by mass of the US Lab module intermediate layer). The US Stuffed Whipple shield stops a 13mm diameter aluminum sphere at 7 km/s impact velocity. Similar shields provide protection to forward shields on ISS Japanese modules and on the European Space Agency (ESA) Columbus module, although the intermediate blanket configuration differs for each, and total shield standoff can be slightly larger than the US design. A rigid Kevlar-epoxy panel (instead of Kevlar® fabric) is used on the ESA Columbus module, to help support the intermediate bumper. These shields are described in more detail in [4, section 5.2]. A lower mass stuffing option was implemented for the ISS Permanent Multipurpose Module (PMM) and for the European Automated Transfer Vehicle (ATV) where 3 layers of Kevlar® KM2 style 705 with total mass per unit area of 0.073 g/cm^2 was used along with ceramic fabric having a total areal density of 0.058 g/cm^2 (Kevlar® is 56% by mass of the PMM intermediate layer). The light-weight Stuffed Whipple shield on PMM and ATV can provide protection from a 9mm diameter aluminum spherical projectile at 7 km/s impact velocity.

High-strength materials such as Kevlar® have been applied as the rear wall of MMOD shields, or near the rear wall of shields (either in front or behind the rear wall). For instance, the Landsat 9 satellite incorporated Kevlar® on top of the rear wall for electronic boxes critical for mission success and for performing post-mission disposal maneuvers [6, 7]. Another example is the shield for the comet rendezvous spacecraft called CONTOUR [4, section 5.4]. The mesh double-bumper shield also incorporates a high-strength materials near the rear wall [5, section 4.7]. Material strength is an important shield parameter for layers at or near the rear wall and placing Kevlar® in these locations at the back of an MMOD shield will enhance MMOD protection performance as it takes advantage of the high strength to mass characteristic of Kevlar®.

Flexible multi-shock shields with Kevlar® have been used to protect the bladder restraint and bladder layers of inflatable modules [8]. Low-density open-cell foam is used between the bumper layers to allow these shields to be tightly packed prior to launch. The foam will act as a spring to expand the bumpers when the shield restraint straps are released after launch. These shields can be used to protect rigid modules as well.

Kevlar® can be used to enhance the MMOD protection capability of multi-layer insulation (MLI) thermal blankets [9]. Kevlar® has also been used to improve the protection of crew and cargo transfer vehicles by incorporating the Kevlar® at or near the bond-line of the high-temperature thermal protection system (TPS) and the TPS substrate. This application of Kevlar® helps to mitigate burn-throughs of the TPS during atmospheric entry if MMOD penetrates deeply into the TPS. This application has been successfully flown on operational spacecraft.

1.2 Specific types of Kevlar® in MMOD shielding

The Kevlar® used in spacecraft MMOD shielding has typically also been applied in ground-based ballistic protection applications, such as bullet-proof vests and helmets. Initially, the Kevlar® in ISS Stuffed Whipple shielding was Kevlar® 29 style 710 fabric which is a 24 x 24 square plain weave fabric with a mass per unit area of 0.032 g/cm^2. After Kevlar® KM2 and KM2+ fibers were developed with higher strength than Kevlar® 29, later spacecraft MMOD shield applications were based on Kevlar® KM2 style 705 fabric which is a 31 x 31 plain weave fabric with a mass per unit area of 0.0244 g/cm^2. Currently, NASA MMOD shielding uses Kevlar® KM2+ style 775 fabric which is a 31 x 31 plain weave fabric with a mass per unit area of 0.0231 g/cm^2. Other plain weave styles using Kevlar KM2+ fibers are also applicable to MMOD shielding.

A tight, plain weave fabric was found to work well in slowing and stopping solid particulates and liquid/gas in the debris cloud behind the outer bumper due to its superior tensile strength to weight compared to metals and ceramics. The much tighter Kevlar® weave fabrics used for stab protection have not been found to offer any benefits for MMOD protection. Due to its low-density (1.44 g/cm^3), Kevlar® will not shock an impacting medium or high-density MMOD particle (density > 2.5 g/cm^3) to as high a pressure as metals and ceramic materials, which reduces the breakup of incident MMOD particles for Kevlar® relative to metals and ceramics. Therefore Kevlar® is not used as an outer bumper (unless the threat environment contains mainly low-density particles (< 2.5 g/cm^3). A low-temperature vacuum-bake process is applied to degas Kevlar® prior to flight.

2 KEVLAR® EXO™

2.1 The difference between Kevlar® EXO™ and traditional Kevlar® types

Built on the chemistry of our traditional Kevlar® fibers, Kevlar® EXO™ is a new technology platform for applications that require demanding performance beyond our legacy fibers. Kevlar® EXO™ is an entirely new technology platform developed for applications where performance and protection are required in the midst of intense and demanding conditions. The innovation behind Kevlar® EXO™ enables an unprecedented combination of weight reduction, protection and even flexibility not previously seen from any aramid fiber and offers the highest levels of debris protection among all aramid fibers.

Similar to traditional Kevlar® fibers, Kevlar® EXO™ is inherently flame- and temperature-resistant and does not melt, with a decomposition temperature greater than 500°C (932°F). Additional properties such as tenacity and elongation are significantly improved over legacy versions of Kevlar®. Additionally, Kevlar® EXO™ can be used in a traditional plain weave, similar to legacy Kevlar® products, or it can be incorporated into our CoreMatrix™ process for additional performance and ease of system layup.

2.2 An explanation of CoreMatrix™ Technology

DuPont™ CoreMatrix™ Technology is a process that combines numerous woven layers by infusing staple fiber in the z direction (Fig. 2). This hybrid structure creates a solution that allows for easier overall system design and layup while remaining flexible for design challenges or soft goods structures without comprising on the overall impact protection of the system. With the combination of Kevlar® EXO™ and CoreMatrix™ Technology, orbital debris protection systems can be optimized for weight savings or optimized for protection of life, or a combination of both. The incorporation of CoreMatrix™ Technology reduces solution build times and mitigates complex stitching and layup requirements.

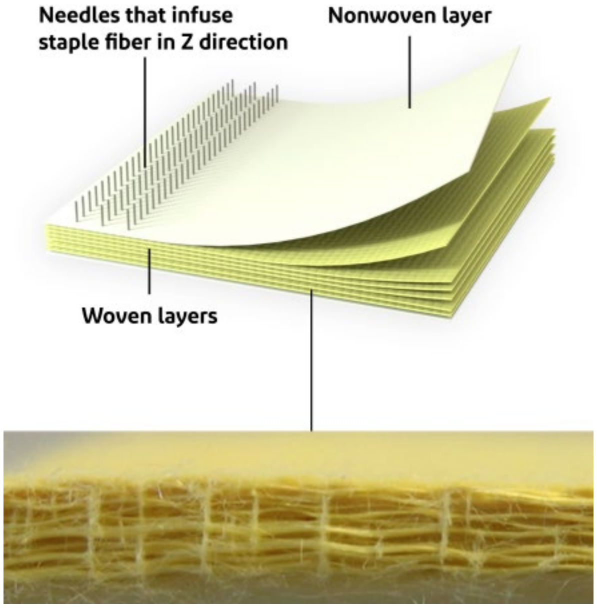

Fig. 2. DuPont™ CoreMatrix™ Technology

3 HYPERVELOCITY IMPACT TESTING

3.1 Test facility

Ten (10) hypervelocity impact tests were performed on shielding containing Kevlar® EXO™ with the 0.50cal two-stage light-gas gun launcher at the NASA White Sands Test Facility (WSTF) (Fig. 3). The tests were all performed using a 10.3mm diameter aluminum (Al 2017-T4) sphere with a mass of 1.61 g in the velocity range of 6.35 to 6.50 km/s. Projectiles are carried through the launch tube with a split sabot, which is aerodynamically separated and arrested in the sabot stripper tank before the projectile enters the target tank. Projectile velocity is determined using laser stations located along the flight range, with an upper bound on the uncertainty in measured velocity of ±1%. The flight range and target tank are evacuated and backfilled with nitrogen gas to between 14 and 16 torr prior to each test. High-speed cameras are used to verify projectile integrity immediately before impact on the target.

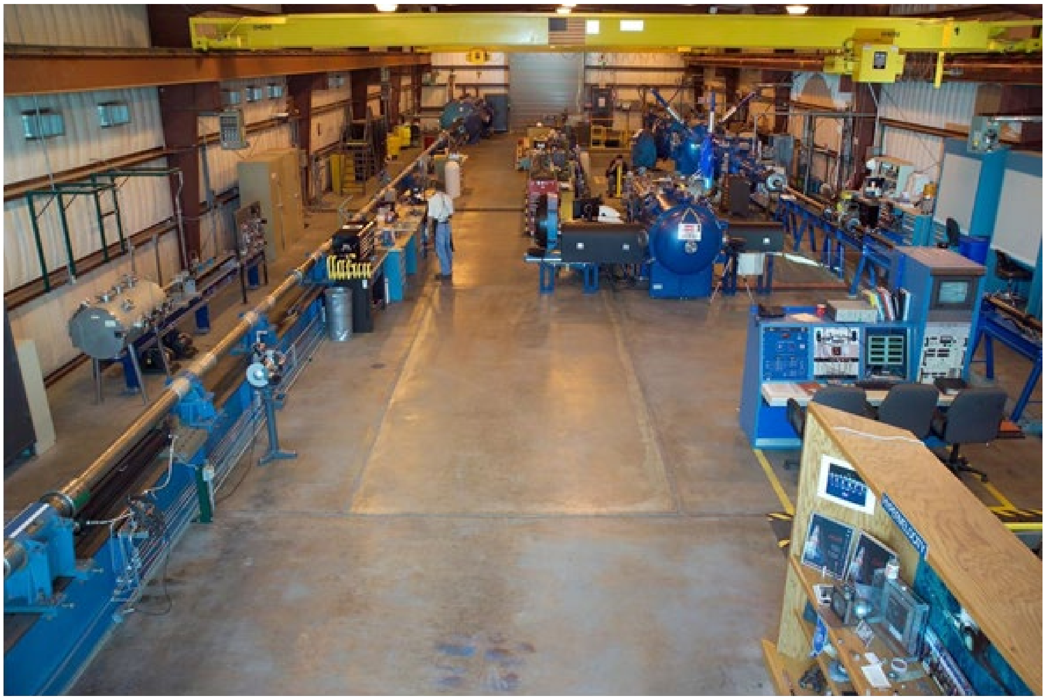

Fig. 3. WSTF Hypervelocity Test Facility (0.50cal range used in this testing is on the far right)

3.2 Test plan

Target Description

The cross-sectional diagram of the target used in these tests is provided in Fig. 4. This target is representative of a typical ISS Nextel™/Kevlar® Stuffed Whipple MMOD shield. The overall target configuration was kept consistent throughout the trials except for the combination used for the stuffing. The distance from the front of the bumper to the back of the rear wall was maintained at 114mm for all tests. Table 1 indicates the number of layers of Nextel™ and the type and number of Kevlar® materials used in the stuffing for each test configuration. Each layer of the target was 305mm by 305mm (square), held in position with nuts, washers, and all-thread at the corners. The stuffing layers were sandwiched between two aluminum picture-frames having a 200mm square hole in center (exposing the Nextel™/Kevlar®). The stuffing was located half-way between the bumper and rear wall (midpoint of the stuffing was equal distance from the bumper and rear wall). Figure 5 provides a side-view of a typical test article. Nextel™ AF62 fabric was used in these tests (areal density of Nextel™ AF62 is 0.1 g/cm^2 per layer), although the number of Nextel™ layers varied from none (0) to six (6) depending on the test. The Nextel™ was not heat cleaned and still retained sizing. The Kevlar® was likewise not scrubbed or heat cleaned. The areal density of each layer of Kevlar® EXO™ CME1100H is 0.115 g/cm^2, Kevlar® EXO™ CM16 0.271 g/cm^2, Kevlar® EXO™ 25x25 PW 0.016 g/cm^2, and Kevlar® KM2+ style 775 0.0231 g/cm^2. Stuffing mass savings provided in the last column of Table 1 is computed relative to the "baseline" ISS Stuffed Whipple shield represented by test number 1.

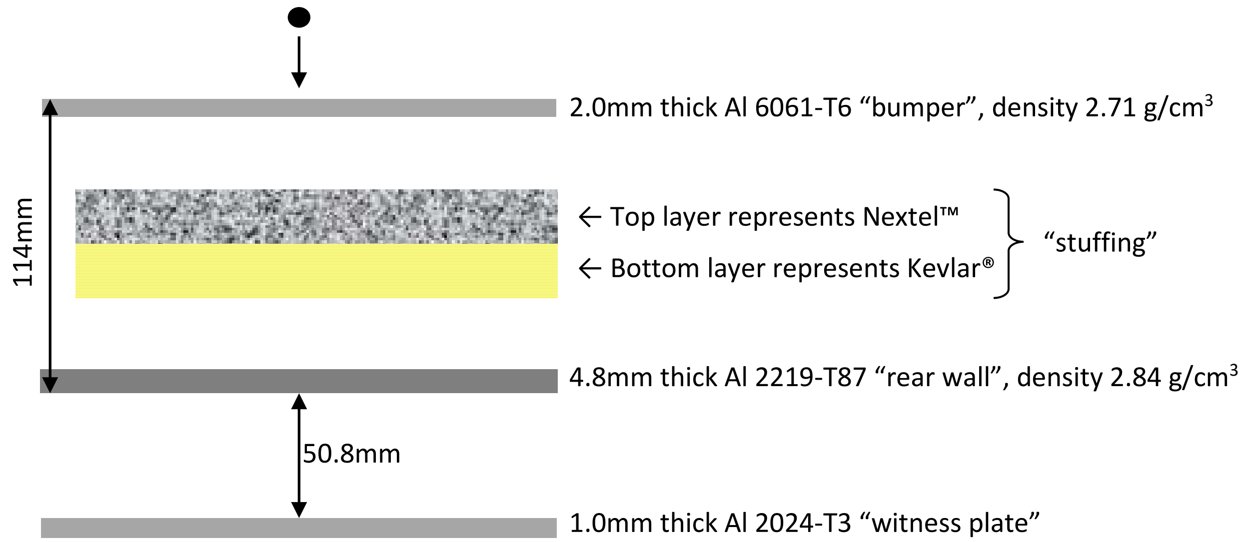

Fig. 4. Cross-sectional diagram of test sample configuration (not to scale).

Table 1. Hypervelocity Test Plan (sorted by stuffing areal density: lowest to highest)

Test #	# Nextel™ layers	Kevlar® Type	# Kevlar® layers	Stuffing Areal Density (g/cm^2)	% Kevlar in Stuffing by mass	Stuffing system mass savings (%)
10	1	Kevlar® EXO™ CME1100H	3	0.445	78%	40%
9	2	Kevlar® EXO™ CME1100H	3	0.545	63%	26%
8	0	Kevlar® EXO™ CME1100H	5	0.575	100%	22%
2	1	Kevlar® EXO™ CM16	2	0.642	84%	13%
7	3	Kevlar® EXO™ CME1100H	3	0.645	53%	13%
4	4	Kevlar® EXO™ CM16	1	0.671	40%	9%
5	6	Kevlar® EXO™ 25x25 PW	6	0.696	34%	6%
6	6	Kevlar® EXO™ CME1100H	1	0.715	16%	3%
1	6	Kevlar® KM2+ 775	6	0.738	19%	0%
3	5	Kevlar® EXO™ CM16	1	0.771	35%	-4%

3.3 Test results

The rear wall did not fail in any of the tests; i.e., the rear wall was intact, with no perforation or detached spall present. Each test resulted in a slight bulge in the rear wall, and the bulge height was measured via a Keyence microscope from the back of the rear wall, where the maximum height of the bulge is reported from the original surface of the rear wall. The results of the tests (bulge height and Kevlar® damage) are provided in Table 2. The Kevlar® hole diameter was measured at the back of the last layer of Kevlar®. The bumper inside hole diameter was 18.9 mm for each test indicating a good clean test (no projectile breakup prior to impact). Figure 5 provides a front view of the bumper and side of the target after test #10. Figure 6 shows the back of the Kevlar® and front of the rear wall after test #10. Figure 7 gives two views of the bulge on the back of the rear wall for test #10.

The graphic in Fig. 8 shows how the rear wall bulge height varies for each test as a function of stuffing areal density. The lower the areal density, and the smaller the bulge, the better the performance of the shield. As indicated by the blue circles, the results of tests on Kevlar® EXO™ CME1100H generally produced the smallest bulges with the least areal density, although the other Kevlar® EXO™ types also generated small bulges although typically higher stuffing masses were used in these tests. Figure 9 shows the percent of Kevlar® by mass in the stuffing for each test, and it appears that Kevlar® mass fractions of 50% to 70% result in the least damage to the rear wall.

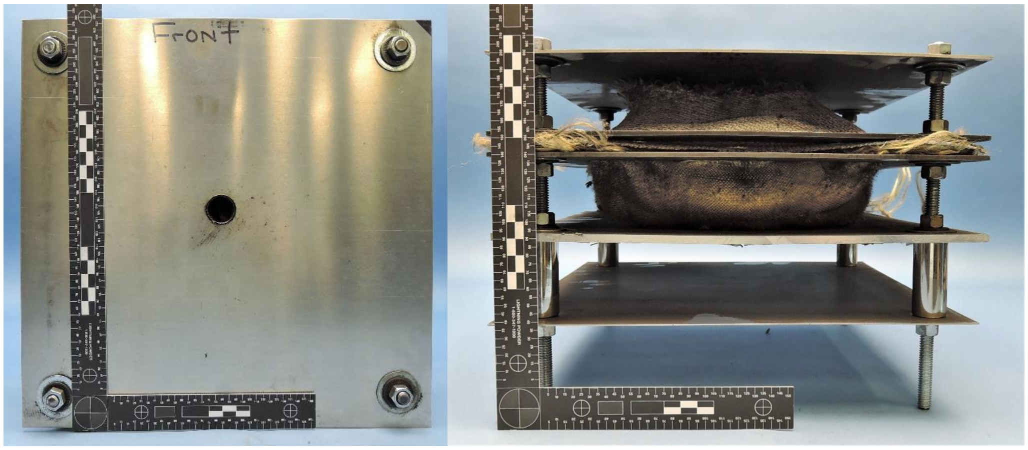

Fig. 5. Front view of the bumper (left) and side view of target (right) after Test #10.

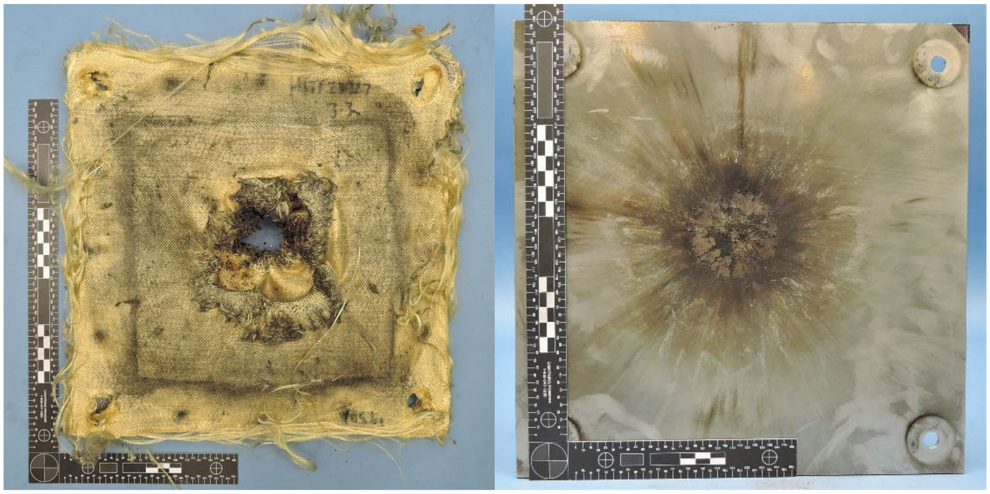

Fig. 6. Back view of the Kevlar® (left) and front view of rear wall (right) after Test #10.

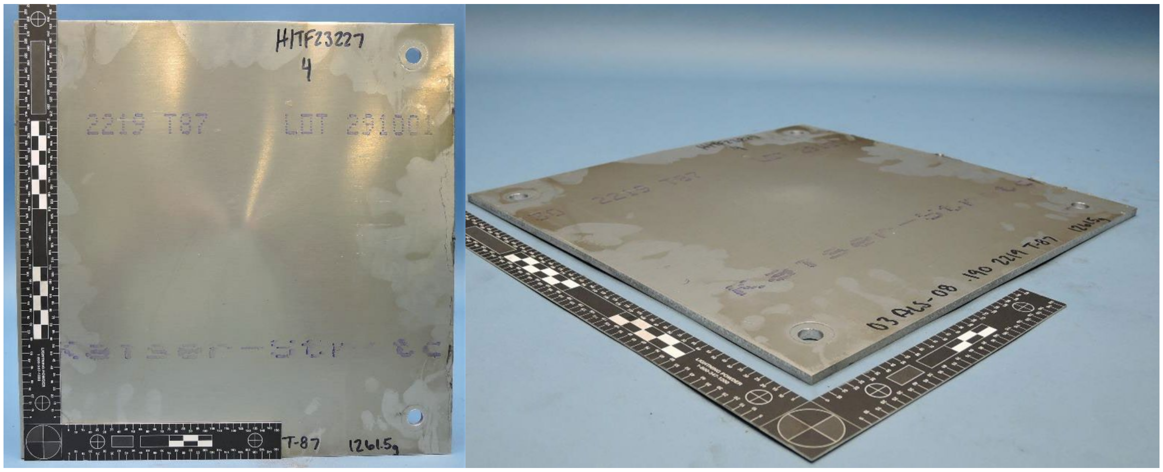

Fig. 7. Back view of the rear wall (left) and oblique view of rear wall bulge (right) after Test #10.

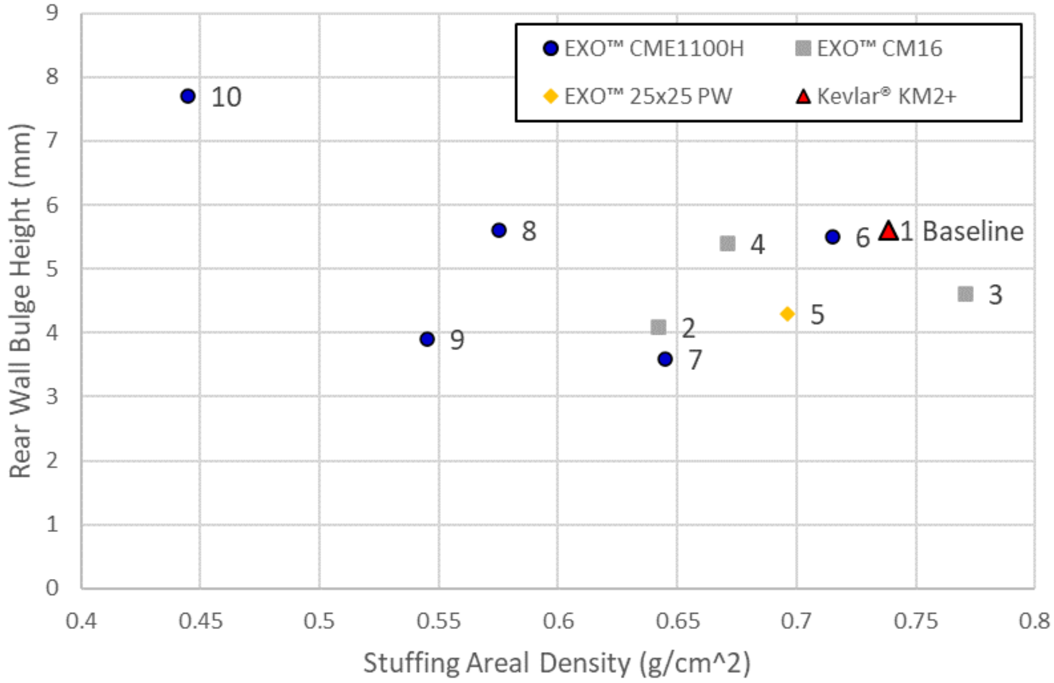

Fig. 8. Rear wall bulge height as a function of stuffing mass per unit area for each test.

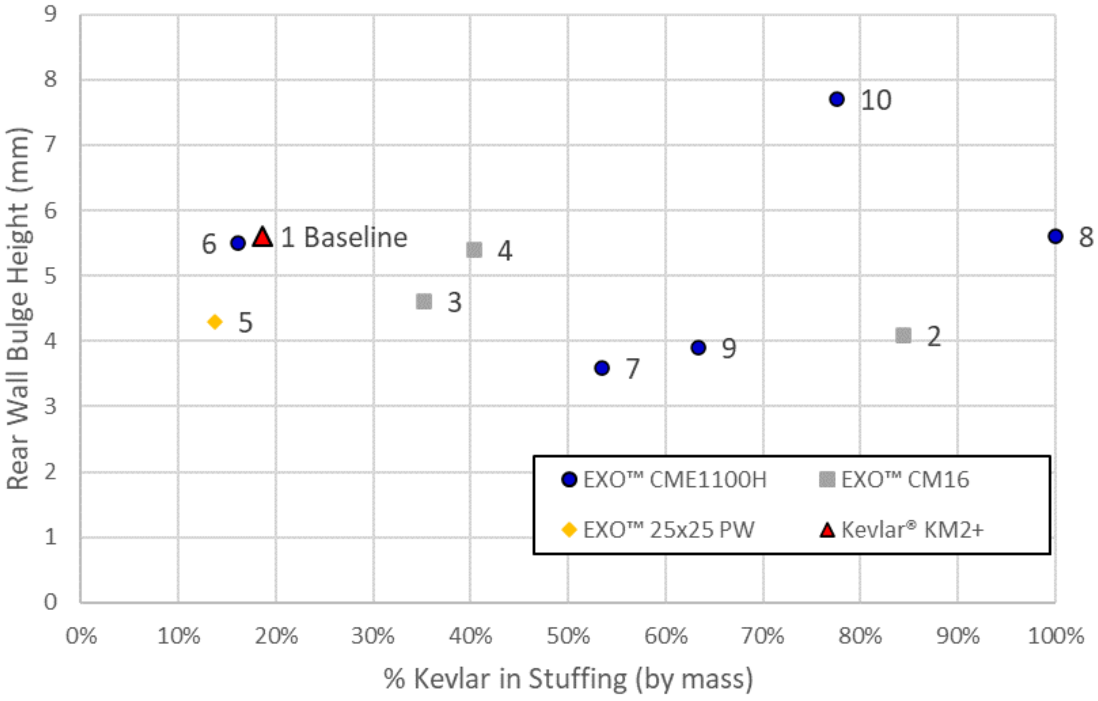

Fig. 9. Rear wall bulge height as a function of percent Kevlar® by mass in the stuffing for each test.

Table 2. HVI Test Results (sorted by system areal density: lowest to highest)

Test #	JSC HVIT Shot Number	Rear wall bulge height (mm)	Kevlar® layer hole diameter (mm)
10	HITF23227	7.7	83 x 76
9	HITF23226	3.9	83 x 65
8	HITF23136	5.6	103 x 89
2	HITF22464	4.1	40 x 29
7	HITF23135	3.6	79 x 53
4	HITF22466	5.4	25 x 20
5	HITF22467	4.3	76 x 73
6	HITF22468	5.5	63 x 54
1	HITF22463	5.6	54
3	HITF22465	4.6	28 x 24

4 CONCLUSIONS

Hypervelocity impact tests have shown that the Kevlar® EXO™ technology offers mass saving benefits to MMOD shielding compared to the current preferred Kevlar® KM2+ fabric. DuPont is in the process of commercializing the Kevlar® EXO™ and additional hypervelocity impact testing will be performed to obtain data for ballistic limit equations used in NASA MMOD risk assessments, and to quantify the mass savings potential for various spacecraft MMOD shield applications.

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