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Toughened Thermal Blanket for Micrometeoroid and Orbital Debris Protection

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Abstract

Toughened thermal blankets have been developed that greatly improve protection from hypervelocity micrometeoroid and orbital debris (MMOD) impacts. Three types of materials were added to the thermal blanket to enhance its MMOD performance: (1) disrupter layers, near the outside of the blanket to improve breakup of the projectile, (2) standoff layers, in the middle of the blanket to provide an area or gap that the broken-up projectile can expand, and (3) stopper layers, near the back of the blanket where the projectile debris is captured and stopped. Hypervelocity impact tests were performed on candidate toughened thermal blanket configurations at the NASA White Sands Test Facility and at the University of Dayton Research Institute. From these tests the best disrupter materials were found to be beta-cloth and fiberglass fabric. Polyimide open-cell foams provide a light-weight means to increase the blanket thickness and improve MMOD protection. The best stopper material is Spectra™ 1000-952 or Kevlar™ KM2-705. These blankets can be outfitted if so desired with a reliable means to determine the location, depth and extent of MMOD impact damage by incorporating an impact sensitive piezoelectric film.

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Keywords: orbital debris; micrometeoroids; MMOD; thermal blanket

Nomenclature

d	projectile diameter (cm)
d_n	projectile diameter on failure threshold of shield, nth step (cm)
d_{n+1}	projectile diameter on failure threshold of shield, n+1 step (cm)
Δd	change in calculated projectile diameter; Δd = dn+1 - dn
f_{MLI}	MLI effectiveness factor (non-dimensional)
m_b	areal density of bumpers (g/cm^2)
$m_{back\text{-}cover}$	areal density of the blanket's back-cover (g/cm^2)
$m_{disrupter}$	areal density of all beta-cloth or fiberglass disrupter layers (g/cm^2)
m_{foam}	areal density of foam spacer (g/cm^2)
$m_{front\text{-}cover}$	areal density of the blanket's front- or outer-cover (g/cm^2)
m_{MLI}	areal density of MLI (g/cm^2)
$m_{MLI\text{-}foam\_eff}$	Effective areal density of MLI (g/cm^2)
m_{Sh}	areal density of shield (g/cm^2)
m_{Sh_eff}	areal density of shield including effective contribution of MLI (g/cm^2)
m_w	areal density of rear wall (g/cm^2)

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M_p	projectile mass (g)
ρ_p	projectile density (g/cm^3)
θ	impact angle (deg) measured from surface normal (0 deg impact angle is normal to the surface)
$\cos\theta$	cosine of impact angle
S	Total thickness of the MLI and/or the total shield thickness and standoff distance (cm)
V	impact velocity (km/s)
Vn	normal component of impact velocity (km/s) = V $\cos\theta$

1. Introduction

Multilayer thermal blankets are used extensively on spacecraft to provide passive thermal control of spacecraft hardware from temperature extremes encountered in space. On the International Space Station (ISS) and other spacecraft, MLI thermal blankets cover various electronic boxes and other hardware. These blankets are often referred to as multilayer insulation (MLI). Standard MLI blankets consist of multiple (10-20 typically) layers of thin (0.006 mm, typical) aluminized Mylar™ or Kapton™ polymer layers, that are separated by a non-conducting, porous spacer layer that is either added between the polymer layers or built-into each aluminized polymer layer. A thicker exterior layer is used on either side of the blanket to protect from handling damage during manufacture and installation. Because of their light-weight, on the order of 0.03 g/cm^2 to 0.07 g/cm^2, they typically are completely penetrated by small micrometeoroid and orbital debris (MMOD) particles. For instance, a 0.06 g/cm^2 thermal blanket is easily penetrated by a 0.4 mm diameter aluminum spherical projectile impacting normal to the blanket at 7 km/s. This blanket consists of an outer layer of glass-teflon fabric (referred to as beta-cloth) followed by 20 layers of aluminized Mylar and a 0.05 mm thick Mylar back cover.

The purpose of the work reported here is to develop methods to improve MMOD protection of standard thermal blankets. Hypervelocity impact tests were performed on various candidate blanket configurations and compared. Particle sizes resulting in threshold failure for two failure modes of interest were evaluated in these tests, namely (1) threshold perforation of the thermal blanket, and (2) perforation of an aluminum plate following the thermal blanket (which represents the spacecraft system that is covered by the thermal blanket). The best performing thermal blanket candidates were identified from the test results which provided protection from the largest projectile with the least mass.

Although not a major emphasis of this paper, several of the best performing enhanced thermal blankets were evaluated in thermal-vacuum tests spanning several days. The thermal-vacuum tests indicated minimal changes in the effective emittance of the toughened thermal blankets, and it was concluded that the additional materials added to the blanket for MMOD protection resulted in no significant degradation of the blanket's thermal performance.

1.1. Previous work

Previous work in this area includes the MMOD toughened blankets used on the RADARSAT satellite, reported in [1] and [2]. These blankets incorporated a layer of Nextel™ ceramic cloth or aluminum mesh just behind the top of the cover of the thermal blanket. The authors of this paper were responsible for developing and demonstrating the effectiveness of these blankets in MMOD tests. The added materials were primarily effective by enhancing the breakup of impacting hypervelocity impact projectiles. The debris from collisions on the toughened blankets was stopped by the hardware behind the thermal blanket, which were either electronics boxes or wire cable bundles. Another application of toughened thermal blankets was reported in [3] where Kevlar™ was impact tested to determine its ability to improve the MMOD resistance of thermal insulation for ISS visiting vehicles.

2. Enhancement Approach

Improved MMOD protection of thermal blankets has been obtained by adding selective materials at various locations within the thermal blanket. The approach taken in this work is given in Fig. 1, where three types of materials are added to the thermal blanket to enhance its MMOD performance: (1) disrupter layers, near the outside of the blanket to improve breakup of the projectile, (2) spacer layers, in the middle of the blanket to provide an area or gap that the broken-up projectile can expand, and (3) stopper layers, near the back of the blanket where the projectile debris should be captured and stopped. The best suited materials for these different layers vary. Density and thickness is important for the disrupter layer. Higher densities generally result in better projectile breakup for the disrupter layer, and adequate thickness to shock/disrupt the projectile is needed. A high-strength to weight ratio is useful for the stopper layer, to improve the slowing and capture of debris particles. The spacer layer should provide volume with minimum mass. Lightening holes are punched in the spacer layer to reduce mass. A list of materials that were evaluated by impact test is given in Table 1.

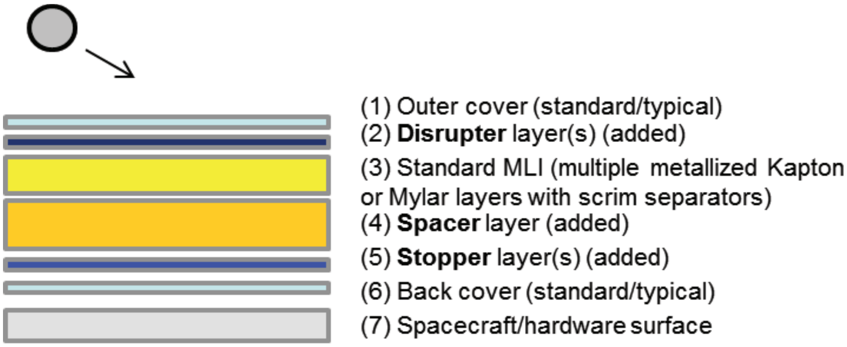

Fig. 1. Illustration of MMOD Toughened Thermal Blanket.

Table 1. Materials Evaluated for Toughened Thermal Blanket.

Element	Material Candidates	Mass per unit area (g/cm^2)
Disrupter Layer	Beta Cloth Fiberglass Cloth Nextel	5mil beta cloth: 0.025 g/cm^2 FG 7781: 0.029 g/cm^2 Nextel AF10: 0.0292 g/cm^2
Spacing Layer	Open Cell Foam (polyimide foam) Polymer Batting	Polyimide AC 550 foam 1.0" thick: 0.018 g/cm^2 AC 530 foam, 1" thick: 0.014 g/cm^2 Polyester 1.0" thick foam: 0.081 g/cm^2
Stopper Layer	Spectra (Polyethylene) Kevlar (Aramid) Beta Cloth	Spectra 1000 style 955 – 0.0112 g/cm^2 Spectra 1000 style 952 – 0.0237 g/cm^2 Kevlar KM2 style 705 – 0.0244 g/cm^2 Kevlar 159 style 779 – 0.0132 g/cm^2 5mil Beta Cloth – 0.025 g/cm^2

2.1. Test configurations

The specific thermal blanket configurations tested are given in Table 2. A standard thermal blanket with no additional MMOD protective materials is represented by configuration 1. No extra materials were added to this blanket. The enhanced thermal blankets are represented by configurations 2-6. Configuration 2 has fiberglass fabric disrupter layer, a 2.5 cm (1") thick low-density polyimide foam spacer, and three (3) layers of Spectra-952 fabric stopper layers added to the thermal blanket. Configuration 3 is similar except with two (2) layers of fiberglass fabric. Configuration 4 has beta-cloth substituting for the fiberglass fabric in the disrupter layer. Configurations 5 and 6 are thicker blankets designed to stop larger projectiles. Each blanket sample was immediately followed by a 0.04" (1.0mm) thick Al 2024-T3 plate (that is, the blanket rested directly on top of the aluminum plate). This aluminum plate or "rear wall" simulated the spacecraft hardware behind the thermal blanket. Additional configurations and materials were also evaluated as reported in [4] and [5]. Two failure modes of interest were evaluated in the hypervelocity test series: (1) threshold perforation of the thermal blanket, and (2) perforation of the aluminum rear wall behind the thermal blanket.

Table 2. Toughened thermal blanket description.

Blanket configuration number	MLI description	Enhancement layers	Blanket mass per unit area (g/cm^2)	Enhancement mass per unit area (g/cm^2)
1 – baseline (not enhanced)	baseline MLI: beta cloth outer cover, 19 layers alternating 0.00025" thick aluminized Kapton & Dacron scrim, 0.002" thick Mylar back cover	none	0.065	0
2	same as 1	Disrupter: (1) FG7781	0.183	0.118

		Spacer: 1” AC550 foam Stopper: (3) Spectra-952		
3	same as 1	Disrupter: (2) FG7781 Spacer: 1” AC550 foam Stopper: (3) Spectra-952	0.212	0.147
4	same as 1	Disrupter: (2) beta-cloth Spacer: 1” AC550 foam Stopper: (3) Spectra-952	0.204	0.139
5	same as 1	Disrupter: (4) FG7781 Spacer: 2” AC550 foam Stopper: (6) Spectra-952	0.359	0.294
6	same as 1	Disrupter: (12) FG7781 Spacer: 6” AC550 foam Stopper: (12) Spectra-952	0.805	0.740

2.2. Hypervelocity impact tests

Over 35 hypervelocity impact tests were performed on the toughened thermal blankets as documented in [4-5]. Table 3 provides the results from several of these tests. The damage assessment column in Table 3 shows if the blanket and rear wall either passes or fails the test, where pass means there was no complete penetration of that particular target element. The tests were conducted at the NASA White Sands Test Facility (WSTF) and at the University of Dayton Research Institute (UDRI). As shown in Fig. 3, the standard thermal blanket used as comparison in this testing is completely penetrated by a 0.4 mm diameter aluminum spherical projectile at 7.1 km/s. In contrast, a toughened thermal blanket with two (2) layers of fiberglass FG-7781 cloth, 1” (2.5cm) thick open-cell polyimide foam and three (3) layers of Spectra 1000-952 (configuration 3) stops a 1.3 mm diameter aluminum spherical projectile at 7.1 km/s. A toughened blanket with 15 cm (6”) of open-cell polyimide foam, 12 layers of FG-7781 and 12 layers of Spectra 1000-952 (0.805 g/cm^2 overall) is able to stop a 6.0 mm diameter aluminum projectile at 6.9 km/s. This factor of 10 increase in particle size stopped translates roughly into a factor of 1000 decrease in MMOD penetration risk. Fig. 4 shows the results for an impact test on a typical toughened thermal blanket.

Table 3. Toughened thermal blanket hypervelocity test results.

Test Number	Target Config. No.	Projectile Diameter (mm)	Projectile Mass (g)	Impact Velocity (km/s)	Impact Angle (deg)	Damage Assessments (mm)
HITF11214	1	0.4	0.00009	7.09	0	blanket fail, rear wall pass Blanket back cover = 0.4mm x 0.2mm perforation Rear wall damage = minor surface damage present
HITF11254	1	0.9	0.00107	6.93	0	blanket fail, rear wall fail Blanket back cover = 6.4mm diameter perforation Rear wall damage = 1.4mm x 2.0mm perforation Witness plate damage = minor cratering
HITF11191	2	1.25	0.00287	7.01	0	blanket pass, rear wall pass Blanket back cover = no perforation, impact residue
HITF11270	3	1.4	0.00395	7.16	0	blanket pass, rear wall pass Blanket back cover = no perforation
HITF11198	3	1.5	0.00510	7.14	0	blanket fail, rear wall pass Blanket back cover = 1.8mm x 1.3mm perforation Rear wall damage = 1.5mm diameter crater
HITF11200	4	1.3	0.00340	7.08	0	blanket pass, rear wall pass Blanket back cover = Impact residue, no perforation
HITF11199	4	1.4	0.00397	6.93	0	blanket fail, rear wall pass Blanket back cover = 0.8mm diameter perforation Rear wall damage = 0.7 x 0.8 crater with a max depth of 0.05
HITF11202	4	2.0	0.01191	6.99	0	blanket fail, rear wall fail Blanket back cover = multiple perforations, 11mm x 6.6mm max Rear wall damage = multiple perforations, 1.7mm x 1.1mm max Witness plate damage = minor cratering

HITF11360	5	2.6	0.02554	7.10	0	blanket pass, rear wall pass Blanket back cover = 28 x 26mm wrinkled area on back cover, no perforation Rear wall damage = 18.3mm diameter x 0.3mm deep shallow bowl
HITF11361	6	6.0	0.31200	6.91	0	blanket pass, rear wall pass Blanket back cover = 24 x 20mm wrinkled area on back cover, no perforation present (light tight) Rear wall damage = 44mm diameter x 6mm deep dish
UDRI8-3371 HITF13110	3	1.52	0.00510	9.63	0	blanket fail, rear wall pass Blanket back cover = 4.6mm x 2.1mm perforation Rear wall damage = slight cratering

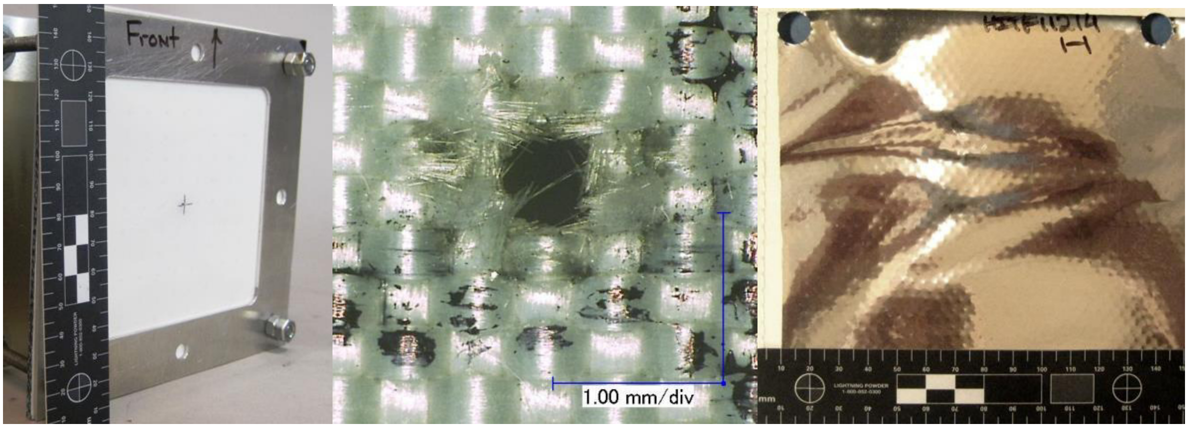

Fig. 3. Standard thermal blanket (config. 1) on left after test HITF-11214. Perforation of outer cover of thermal blanket in center. The 0.4 mm Al 2017-T4 sphere at 7.09 km/s results in a 0.4 x 0.2 mm perforation of thermal blanket back cover (right).

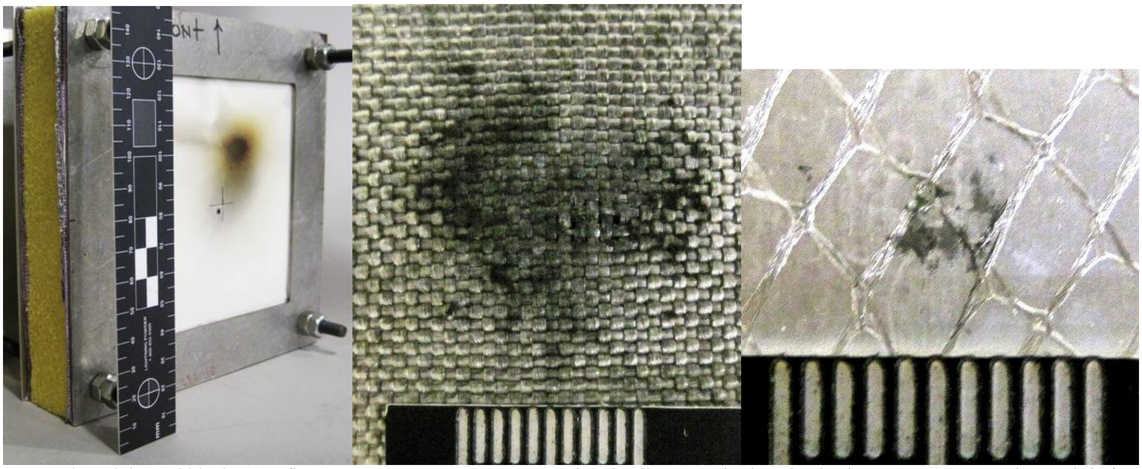

Fig. 4. Toughened thermal blanket (config. 2). Test HITF-11191, 1.25mm Al projectile at 7.01 km/s and 0 deg impact angle. Front view on left, front of Spectra stopper layer in center, front of thermal blanket back cover showing no perforation (right).

3. Analysis

A set of ballistic limit equations (BLEs) was developed to assess the MMOD particle size that will be on the failure threshold of the toughened thermal blanket as a function of impact velocity and impact angle. Failure is defined as a complete penetration of the last layer of the thermal blanket (0.002” thick Mylar in the toughened thermal blankets tested in this work). These equations are modified versions of the multishock shield equations provided in [3] and were initially proposed in 2011 [6]. These BLEs can be used to assess the particle size at the threshold of complete penetration of each layer of the blanket, starting with the second layer of the blanket. These equations were developed by solving two equations previously developed for sizing multishock shields [Ref. 3, Eq.4-22 and Eq.4-24] to determine the areal density of the multishock bumpers and rear wall to protect from a given size/velocity of projectile, namely:

$$m_b = 0.185\, d \cdot \rho_p \tag{1}$$

$$m_w = 29\, M_p \cdot V_n \cdot S^{-2} = \frac{29\pi}{6} \cdot d^3 \cdot \rho_p \cdot V_n \cdot S^{-2} \tag{2}$$

These equations are valid for high-velocity impacts with $V \geq 6.4\cos^{-0.25}\theta$. For the toughened thermal blankets, the MLI and open-cell foam layers are partially effective as a bumper in breaking up the projectile. To include the effectiveness of the MLI and foam in the ballistic limit equations for the toughened thermal blanket, we introduce the effective MLI and foam in Eq. (3) which becomes upon rearranging Eq. (4):

$$m_{sh\_eff} = m_b + m_w + m_{MLI-foam\_eff} = 0.185\, d \cdot \rho_p + \frac{29\pi}{6} \cdot d^3 \cdot \rho_p \cdot V_n \cdot S^{-2} \tag{3}$$

$$\frac{29\pi}{6} \cdot d^3 \cdot \rho_p \cdot V_n \cdot S^{-2} + 0.185\, d \cdot \rho_p - m_{sh\_eff} = 0 \tag{4}$$

For high velocity impacts, where $V \geq 6.4/\cos^{0.25}\theta$, the diameter of the projectile on the ballistic limit of the shield (penetration threshold of last layer in the blanket or the rear wall behind the blanket) is found from:

$$d_{n+1} = d_n - \left[\frac{\left(\frac{29\pi}{6} \cdot (d_n)^3 \cdot \rho_p \cdot V\cos\theta \cdot S^{-2} + 0.185\, d_n \cdot \rho_p - m_{sh\_eff}\right)}{\left(\frac{29\pi}{6} \cdot 3(d_n)^2 \cdot \rho_p \cdot V\cos\theta \cdot S^{-2} + 0.185\, \rho_p\right)}\right] \tag{5}$$

$$\Delta d = d_{n+1} - d_n \tag{6}$$

Equation (6) uses the Newton-Raphson method to solve a cubic equation for the MMOD particle diameter on the failure threshold of the shield. The Newton-Raphson method is a root-finding method for equations of the form: $f(x) = 0$. The roots of the function (x) can be found by an iterative method which starts with an initial guess x_o, and finds better and better approximations to the answer using:

$$x_{n+1} = x_n - f(x_n)/f'(x_n) \tag{7}$$

Where for this application, $d_{n+1} = x_{n+1}$, and $d_n = x_n$. Also, $f(d_n)$ is given in Equation (8), and the derivative $f'(d_n)$ is given in Equation (9):

$$f(d_n) = \left(\frac{29\pi}{6} \cdot (d_n)^3 \cdot \rho_p \cdot V\cos\theta \cdot S^{-2} + 0.185\, d_n \cdot \rho_p - m_{sh\_eff}\right) \tag{8}$$

$$f'(d_n) = \left(\frac{29\pi}{6} \cdot 3(d_n)^2 \cdot \rho_p \cdot V\cos\theta \cdot S^{-2} + 0.185\, \rho_p\right) \tag{9}$$

Solve Equation (5) by initializing d_n and calculating d_{n+1}, and determine the change in diameter from Equation (6). The initial value of d_n can be set to 0.5 cm, although the solution to this iterative technique is not sensitive to the starting value of d_n. Then iteratively solve Equations (5) and (6) using a new value for d_n equal to the previously calculated value for d_{n+1}. Iterate 10 times, or until Δd is a small fraction of d_n (typically, $\Delta d/d_n$ should be less than 1E-6 after 10 iterations).

Table 4 provides the shield parameters to be used in the toughened blanket ballistic limit equations, for the failure criteria of complete penetration of the thermal blanket. The bumper areal density, m_b, is the sum of the mass per unit area of the outer cover (beta cloth) and the disrupter layers (Equation 10). An "equivalent" areal density of the multilayer insulation layers excluding scrim and AC550 foam is derived from the product of the effectiveness factor, f_{MLI}, and the total MLI and foam areal density (Equation 11). A value of $f_{MLI} = 0.25$ was found to best fit the test data.

$$m_b = m_{front-cover} + m_{disrupter} \tag{10}$$

$$m_{MLI-foam} = f_{MLI}\left(m_{MLI} + m_{foam}\right) \tag{11}$$

For all configurations, the multilayer insulation layers consist of 19 layers of 0.00025” thick aluminized Kapton, with a mass per area (excluding the scrim) $m_{\_mli}$ of 0.017 g/cm^2. A one inch thick (2.54cm) AC550 polyimide foam layer (without lightening holes) has a mass per unit area, $m_{\_foam}$ of 0.018 g/cm^2. The rear wall areal density, m_w, is found by summing the areal density for the thermal blanket back cover (i.e., 0.002” thick Mylar in this case, which is 0.0095 g/cm^2) and the stopper layers.

$$m_w = m_{back-cover} + m_{stopper} \tag{12}$$

Note, that if the failure criterion is penetration of an aluminum rear wall or spacecraft structure behind the thermal blanket, then the areal density of the rear wall would include the areal density of the aluminum rear wall (or spacecraft structure) as well as the thermal blanket back cover and stopper layers. In addition, for the structure behind the thermal blanket failure criterion, the total standoff, S (cm), in the above equations would be the total thermal blanket thickness plus the standoff (if any) included between the thermal blanket and spacecraft structure. The effective shield areal density, m_{sh_eff}, is determined by summing the areal density of the MMOD shielding materials (bumpers, rear wall, and effective MLI and foam layers), that is:

$$m_{sh_{eff}} = m_b + m_w + m_{MLI-foam} \tag{13}$$

For low velocity impacts, where $V \leq 2.4/\cos^{0.5}\theta$, the diameter of the projectile at the failure threshold of the blanket or rear wall, d (cm), is found from:

$$d = 2.7\frac{(0.5\, m_W + 0.37\, m_b)}{\left(\cos^{4/3}\theta \cdot (\rho_p)^{0.5} \cdot V^{2/3}\right)} \tag{14}$$

In this equation, we assumed that at low-speeds, the bumpers are not effective at breaking up the projectile, but acts to slow and deform the projectile. For intermediate velocity impacts, where $2.4/\cos^{0.5}\theta < V < 6.4/\cos^{0.25}\theta$, the projectile diameter at the failure threshold of the shield, d (cm), is found by linearly interpolating between the low- and high-velocity projectile diameter predictions, as follows:

$$d = d_{lo} + (d_{hi} - d_{lo}) \cdot \left(V - 2.4\cos^{-0.5}\theta\right) / \left(6.4\cos^{-0.25}\theta - 2.4\cos^{-0.5}\theta\right) \tag{15}$$

Where d_{lo} is found from Equation (14) with $V = 2.4\cos^{-0.5}\theta$, and d_{hi} found from Equation (5) with $V = 6.4\cos^{-0.25}\theta$.

Table 4. Toughened blanket input parameters for ballistic limit equations (for blanket penetration failure criteria).

Thermal blanket configuration number	Areal density bumpers, m_b (g/cm^2)	Overall blanket thickness, S (cm)	Areal density rear wall, m_w (g/cm^2)	Effective shield areal density, m_{sh_eff} (g/cm^2)
2 – beta cloth, 1-FG7781, MLI, 1” AC550 foam, 3-Spectra-952, 2mil Mylar	0.063	3.29	0.0827	0.145
3 – beta cloth, 2-FG7781, MLI, 1” AC550 foam, 3-Spectra-952, 2mil Mylar	0.092	3.32	0.0827	0.174
4 - beta cloth, 2-beta cloth, MLI, 1” AC550 foam, 3-Spectra-952, 2mil Mylar	0.084	3.30	0.0827	0.166
5 - beta cloth, 4-FG7781, MLI, 2” AC550 foam, 6-Spectra-952, 2mil Mylar	0.154	6.03	0.1559	0.310
6 - beta cloth, 12-FG7781, MLI, 6” AC550 foam, 12-Spectra-952, 2mil Mylar	0.382	16.61	0.3023	0.684

Figure 5 shows the predicted ballistic limits using the above equations as a function of impact velocity for aluminum projectiles impacting blanket configuration 3, with fiberglass 7781 cloth disrupter, 1” of open-cell polyimide foam and Spectra 1000-952 stopper. The impact test data is plotted in Fig. 6 versus the predicted ballistic limits at 0 deg impact angle, and shows the data compares well with the predicted ballistic limits predictions.

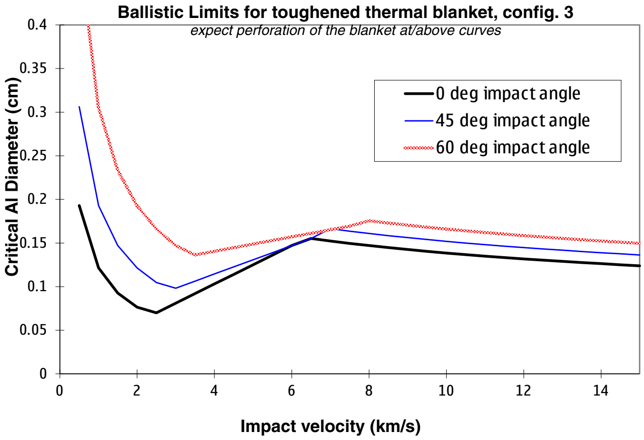

Fig. 5. Ballistic limit predictions for toughened thermal blanket configuration 3, for aluminum projectiles and blanket perforation failure criterion.

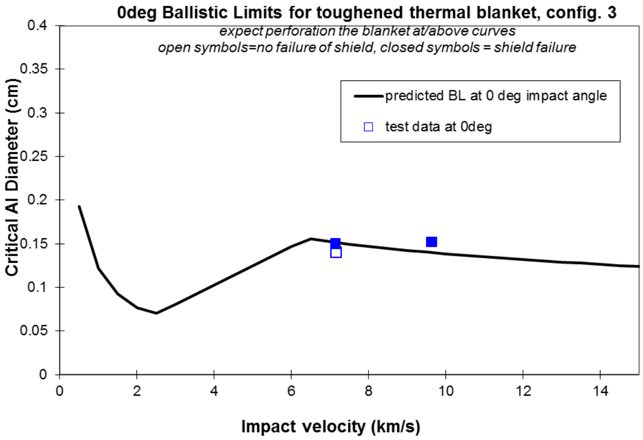

Fig. 6. Ballistic limit predictions and impact test data for 0 deg impacts by aluminum projectiles on toughened thermal blanket configuration 3.

4. Concluding Remarks

MMOD protection performance of thermal blankets can be significantly improved by adding suitable materials. Hypervelocity impact tests were performed to evaluate a range of different materials for this application. From these tests the best disrupter materials were found to be beta-cloth and fiberglass fabric. Polyimide AC550 and AC530 open-cell foams provide a light-weight means to increase the blanket thickness and improve MMOD protection. The best stopper material is Spectra 1000-952. The tests were also used in the development of ballistic limit equations that are used to determine the projectile size at the threshold of failure of the toughened thermal blanket as a function of impact angle, impact velocity and blanket configuration.

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