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SLOW HEATING AND CUSHIONING EVALUATION OF FOAM DUNNAGE MATERIALS FOR AMMUNITION PACKAGING

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14. ABSTRACT

A high temperature drop-in replacement for polyethylene (PE) foam packaging dunnage is desirable to some ammunition items. Various foam materials were tested at small-scale for heat resistance up to 400 °F. Those materials capable of withstanding exposure to high temperature were subjected to three small-scale cushioning tests that only a cross-linked polyamide foam was able to successfully pass. Heating tests proved that the polyamide material is extremely resilient to high temperature exposure. Due to the cross-linked nature of the material, it deforms plastically after compression; however, the overall result was acceptable. Another series of heating tests was conducted using inert ammunition with high fidelity 40-mm M430A1 packaging in a slow cook-off environment. These tests successfully proved that the polyamide dunnage continues to provide cushioning support at the system level. This material may be a suitable alternative to PE foam dunnage currently used for packaging ammunition. Additional work needs to be done to prove that the material has acceptable cushioning properties at all densities, specifically dynamic cushioning.

15. SUBJECT TERMS
Foam Dunnage Cushioning Packaging Polyethylene (PE) Polyethylene foam PE Foam High-density polyethylene (HDPE) HDPE foam Polyamide Polyester polyurethane Silicone Slow cook-off Cook-off Packaging containers Insensitive munitions

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INTRODUCTION

Polyethylene (PE) foams are widely utilized throughout the packaging industry to provide protective cushioning during shipping, storage, and rough handling. The Packaging Division at the U.S. Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC), Picatinny Arsenal, NJ, uses several classes and grades of high-density polyethylene (HDPE) foam with unique properties specific to ammunition packaging. These military grade foams are specified in Commercial Item Description A-A-59136 (ref. 1), which includes requirements for density, temperature stability, electrical resistivity, lower explosive limit, and dynamic cushioning amongst others. The PE foams are highly effective at providing cushioning and protection to ammunition items during rough handling in regular operational use temperatures.

Ammunition items are often exposed to more extreme storage and distribution environments than that experienced in the commercial shipping industry. U.S. Army ammunition packaging is generally tested at temperatures ranging from - 65 up to +160 °F; however, foam cushioning curves are usually generated at ambient conditions only. Cushioning tests conducted at elevated temperatures revealed that PE foams can begin to lose significant mechanical strength above 140 °F (ref. 2). Additionally, the thermoplastic nature of non-cross-linked PE foam results in the material transitioning to an amorphous, viscous fluid at elevated temperatures. This is undesirable in case of accidental fires where the viscous PE can prevent venting of hazardous gases produced by energetic materials. The DEVCOM AC Packaging Division has begun work to identify alternate materials that provide adequate cushioning and maintain their form throughout a greater temperature range when compared to PE foams.

BACKGROUND

The Joint Program Executive Office Armaments and Ammunition (JPEO A&A) has tasked DEVCOM AC to improve the insensitive munitions (IM) reactions of numerous ammunition items within its portfolio. When munitions are exposed to heat, such as in a fire, they generate large amounts of dangerous gases, which can result in a violent burning, deflagration, explosion, or detonation. The DEVCOM AC propulsion, warhead, and packaging groups have designed various venting systems to allow for pressure relief of these dangerous gases. During system level testing of one such venting solution, it was found that PE foam dunnage may melt within the packaging. Testing with the 40-mm M430A1 high velocity grenade system suggests that as the PE foam melts, it may clog venting mechanisms and prevent their proper function (ref. 3). Figure 1 shows the packaging configuration for the M430A1 grenades before and after exposure to high temperature. The right photograph depicts the extent of melting PE foam after exposure to a temperature of 320 °F.

Figure 1
40-mm M430A1 foam packaging

The DEVCOM AC Packaging Division began to research dunnage systems that can withstand elevated temperatures. A material solution effort was initiated to find a foam dunnage capable of operating temperatures up to 400 °F. The alternate material must also provide adequate cushioning and meet the other requirements of A-A-59136 for ammunition packaging. This alternate dunnage material should be a drop-in replacement for PE foam in ammunition packaging systems that are vulnerable to high temperatures.

Material research was conducted to identify various methods of increasing the melting temperature of PE foams; however, no additives were found that would adequately increase operating temperatures. Alternative foam materials were then identified for evaluation. Various materials were incrementally heated in a programmable oven up to 300, 350, and 400 °F. Those materials that were capable of withstanding heat exposure up to 400 °F were subjected to three laboratory-scale cushioning tests in accordance with A-A-59136 and American Society for Testing an Materials (ASTM) D3575 (ref. 4): compression set, load deflection, and constant compression set. The final candidate found to meet all initial criteria was used to conduct a slow cook-off test utilizing inert M430A1 rounds. These results may be compared against the results utilizing PE foam dunnage previously documented in reference 3.

TEST RESULTS AND DISCUSSION

Foam Slow Heating Characterization Tests

Approximately 30 materials were subjected to a small-scale slow heating test. The majority of samples were cut into 2 x 2 x 2-in. cubes with the exception of several materials that were supplied in thicknesses of less than 2 in. Two samples of each material were used per test. One sample was unloaded and the other had a 14-g steel washer placed on top to simulate minor loading (approximately 0.01 psi). Each sample was placed onto a 7-in. diameter aluminum plate to contain any melting materials. Figure 2 shows representative test samples inside a programmable oven. For fire safety reasons, testing was conducted incrementally starting with temperatures up to 300 °F, then 350 °F, and finally 400 °F. Any material that failed due to melting, shrinking, burning, or other reasons was removed from further tests. The heating ramp for each small-scale test was based on STANAG 4382 Edition 2 (ref. 5) with several deviations in procedure. The slow heating test 4 and slow cook-off tests with inert M430A1 rounds were conducted using an increased heating rate from the North Atlantic Treaty Organization (NATO) Allied Ordnance Publication (AOP)-4382, which has been ratified and approved for use as of March 2020 (ref. 6).

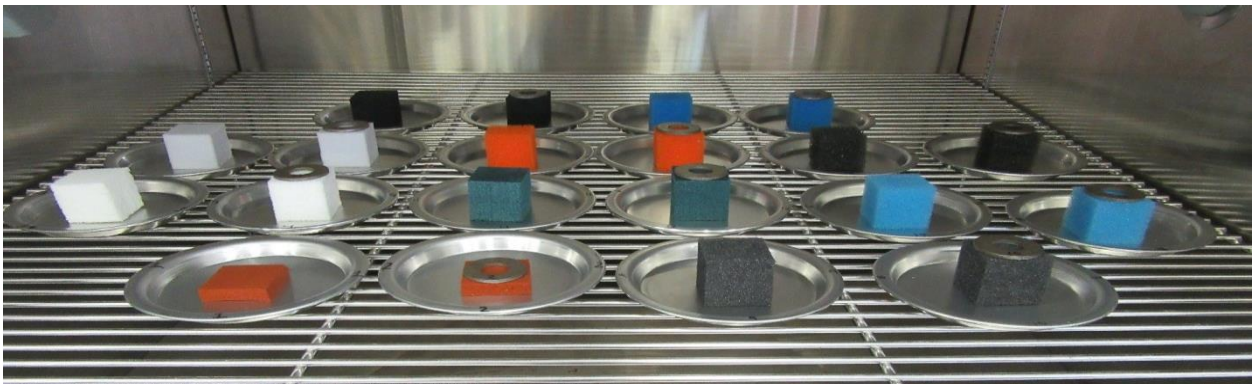


Figure 2
Pretest samples

Tables 1 and 2 summarize the results for each material tested. Table 1 lists those materials that underwent all heating and cushioning tests. Table 2 lists those materials that did not pass the heating tests and hence were not tested for cushioning properties. Table 2 includes three unknown samples that were provided without identification by one supplier. The exact formulation of those materials was never discovered due to staffing changes at the supplier. The same supplier provided the 6 pound per cubic foot (PCF) polyester polyurethane sample in table 1, which was properly identified.

Table 1
Test results - fully tested materials

Material	Heat resistance to 300 °F	Heat resistance to 350 °F	Heat resistance to 400 °F	Compression set under constant deflection	Constant compression creep	Compression deflection (load deflection)
Cross-linked polyamide (4 PCF)	✓	✓	✓	o	✓	o
Silicone sponge rubber (40 PCF)	✓	✓	✓	✓	o	x
Closed cell silicone sponge (40 PCF)	✓	✓	✓	✓	x	x
Open cell silicone sponge (12 PCF)	✓	✓	✓	✓	x	x
Silicone foam (6 PCF)	✓	✓	✓	✓	x	x
Melamine (0.65 PCF)	✓	✓	✓	✓	x	x
Polyester polyurethane (4 PCF)	✓	✓	o	✓	x	x
Polyester polyurethane (2 PCF)	✓	✓	✓	✓	x	x
Reticulated polyether polyurethane; 30 PPI (1.4 PCF)	✓	✓	✓	✓	x	x
Non-reticulated polyester (2 PCF)	✓	✓	o	✓	x	x
Polyester polyurethane/Unknown sample C (6 PCF)	✓	o	o	✓	x	x
Ethylene propylene diene terpolymer (7 PCF)	-	✓	o	✓	x	x
Legend: ✓= Excellent, o = Acceptable, x = Unacceptable, - = Not Tested						

Note: PPI stands for pores per inch.

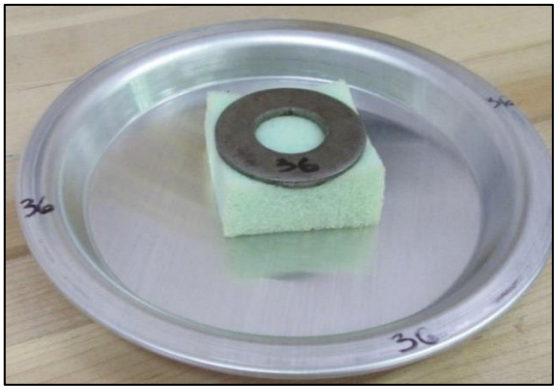
Table 2
Test results - unsuccessful materials

Material	Heat resistance to 300 °F	Heat resistance to 350 °F	Heat resistance to 400 °F	Compression set under constant deflection	Constant compression creep	Compression deflection (load deflection)
Reticulated polyether polyurethane; 15 PPI (1.4 PCF)	✓	✓	x	-	-	-
Reticulated polyether polyurethane; 10 PPI (1.9 PCF)	✓	✓	x	-	-	-
Mycelium (7 PCF)	✓	✓	x	-	-	-
Unknown sample D (7 PCF)	✓	✓	x	-	-	-
Unknown sample B (4 PCF)	✓	o	x	-	-	-
Reticulated polyether polyurethane; 15 PPI (1.3 PCF)	✓	o	x	-	-	-
Reticulated polyether polyurethane; 15 PPI (1.4 PCF)	o	o	x	-	-	-
Reticulated polyether polyurethane; 30 PPI (1.4 PCF)	o	o	x	-	-	-
Unknown sample A (3 PCF)	o	o	x	-	-	-
PE (6 PCF)	x	-	-	-	-	-
Fire retardant PE (9 PCF)	x	-	-	-	-	-
Polyvinylidene flouride (2.5 PCF)	x	-	-	-	-	-
Expanded polypropylene (3.7 PCF)	-	x	-	-	-	-
Expanded polypropylene (1.5 PCF)	-	x	-	-	-	-
Expanded polypropylene (2.3 PCF)	-	x	-	-	-	-
Expanded polypropylene (2.8 PCF)	-	x	-	-	-	-
Expanded polypropylene (4.6 PCF)	-	x	-	-	-	-
Polyvinyl chloride/Acrylonitrile butadiene/Chloroprene (5 PCF)	-	x	-	-	-	-
Cross-linked open cell PE (6 PCF)	-	-	x	-	-	-
Cross-linked closed cell PE (5 PCF)	-	-	x	-	-	-
Legend: ✓= Excellent, o = Acceptable, x = Unacceptable, - = Not Tested						

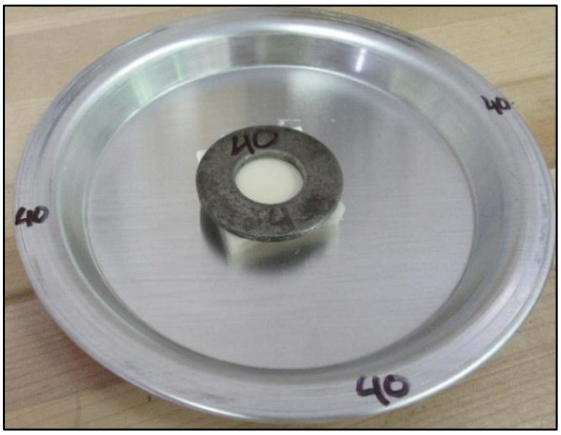
Slow Heating Test 1: 300 °F

For the first test, a total of 40 samples (20 materials, 2 of each) were placed into a large programmable convection oven and conditioned at 165 °F for 8 hr. After the soak, the temperature was ramped at 6 °F/hr for 22 hr, up to 300 °F. The samples included 6 PCF density PE foam and 9 PCF fire-retardant grade PE foam as baseline materials. The two grades of PE foam were the first to show signs of melting at approximately 243 °F. Both were completely melted by the end of the test. All of the other samples appeared unchanged. Sample 36 (unknown sample A) was the only other material to show signs of change during the test at approximately 277 °F. The sample was slightly compressed by the washer; however, no major melting was observed. After the heat chamber cooled down to ambient temperature overnight, each sample was weighed, measured, and any anomalies were noted. Samples 39 and 40, which contained polyvinylidene fluorine, were found to have shrunk by approximately 25% and removed from further testing. Two samples of polyester polyurethane foam, 2 and 6 PCF, were found to have caused significant oxidation of the steel washer; however, the 4 PCF density of the same material did not. The material was kept in the study to see if this would occur again. Other noted changes included minor discoloration or light adhesion to either the steel washer or aluminum test plate for several foams. Photographs of several post-test samples are shown in figure 3.

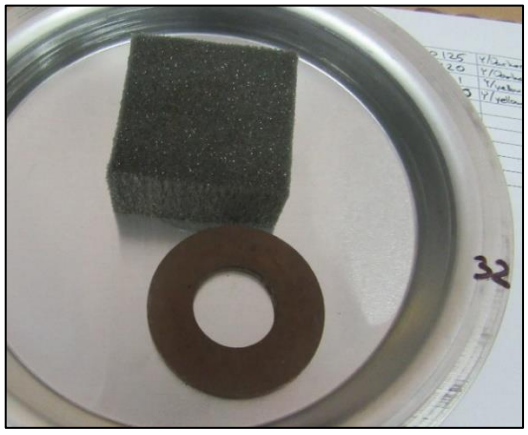
(a)
Melted 6 PCF PE



(b)
Unknown sample A compressed



(c)
Shrunken polyvinylidene fluorine



(d)
PE polyurethane rust

Figure 3
300 °F post-test samples

Slow Heating Test 2: 350 °F

The second test included a total of 44 samples (22 materials, 2 of each). The two PE samples and polyvinylidene fluorine were removed; however, a new expanded polypropylene (EPP) was added in five densities. The samples were conditioned at 122 °F for 8 hr and then the temperature was ramped at 6 °F/hr for 38 hr, up to 350 °F. Four densities of the EPP (1.5, 2.3, 2.8, and 4.6 PCF) all completely melted under 300 °F. The remaining density, 3.7 PCF, was fully melted around 330 °F. The weighted unknown sample A was showing signs of compression similar to the first test at 300 °F and was significantly compressed to approximately a half of its initial height by 330 °F. The weighted unknown sample B was also starting to compress to approximately a half of its initial height. Both weighted unknown samples A and B showed discoloration and heavy adhesion to the test plate and washer. None of the polyester polyurethane samples caused oxidation of the steel washer in this trial. While none of the other materials tested showed signs of melting, many did experience major discoloration. There was some minor adhesion to the test plate and washer by several materials. Post-test photographs of several samples are shown in figure 4.

(a)
Melted EPP

(b)
Unknown sample A

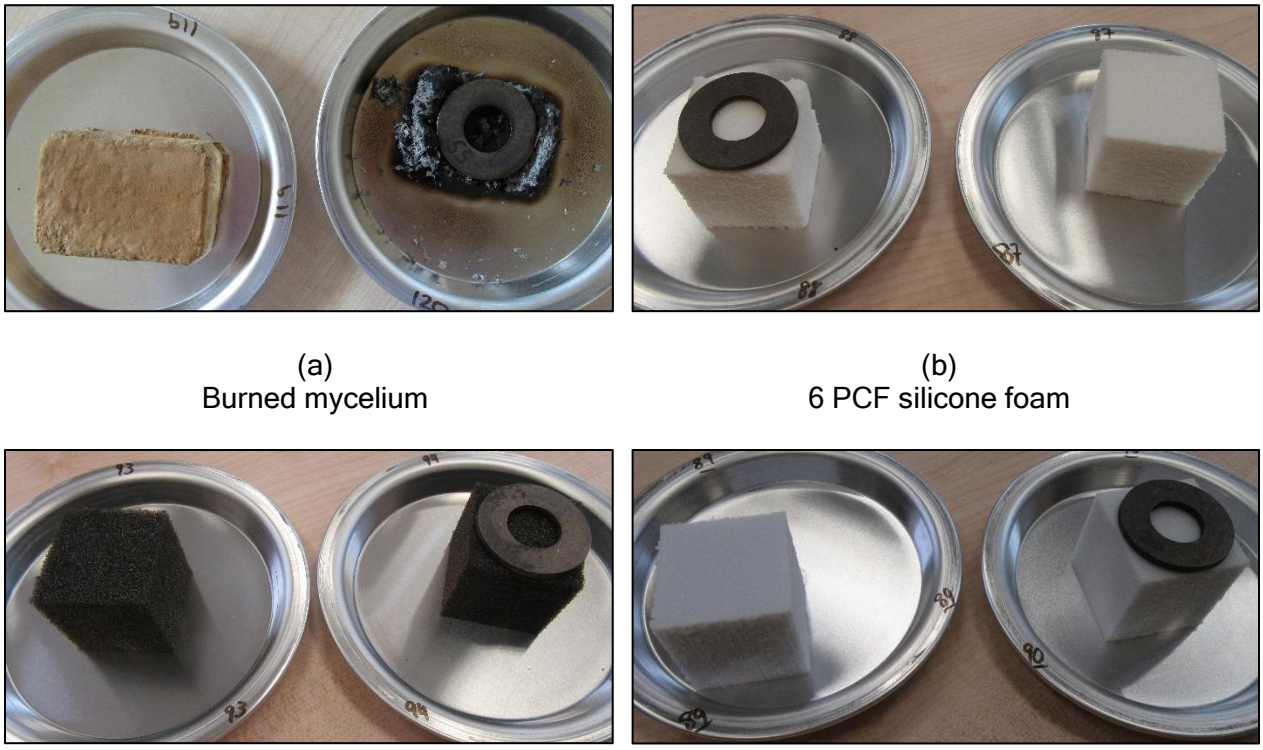
(c)
Unknown sample B

(d)
Discoloration of reticulated polyether polyurethane

Figure 4
350 °F post-test samples

Slow Heating Test 3: 400 °F

The third test included a total of 38 samples (19 materials, 2 of each). All five densities of EPP were removed. New materials added were mycelium and ethylene propylene diene terpolymer. Two smaller ovens were used since the large chamber used for tests 1 and 2 is not capable of reaching 400 °F. The samples were broken up into two separate tests due to smaller oven size; consolidated results are provided. The samples were conditioned at 122 °F for 8 hr and then the temperature was ramped at 6 °F/hr for 47 hr, up to 400 °F. The oven temperature was then held at 400 °F for 1 hr. Much like test 2, many of the samples were significantly discolored by 350 °F, especially the brightly colored reticulated foams. The weighted unknown samples A and B were both significantly compressed by 370 °F, more than half of their original thickness. Several other samples appeared to show physical changes; however, it was very difficult to see inside the test ovens due to condensation and fogging of the view ports. There was also a significant odor during each test suggesting that outgassing was occurring. Each sample was inspected after the test ovens cooled to ambient temperature. Many of the samples exhibited heavy discoloration and signs of burning/charring. The weighted mycelium sample appears to have burned, as only ash remained on the test plate. The unweighted mycelium sample was only discolored. The ethylene propylene diene terpolymer shrank approximately 5 to 10%. The only materials that survived this heating test without physical damage or burning were silicone, melamine, polyester polyurethane, and one grade of reticulated polyether polyurethane. Several post-test photographs are provided in figure 5.



(a)
Burned mycelium

(b)
6 PCF silicone foam

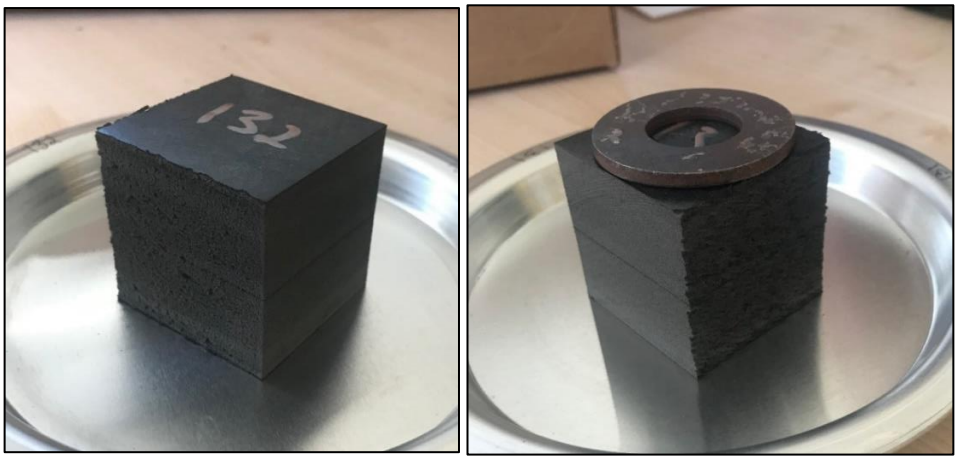
(c)
2 PCF polyester polyurethane

(d)
Melamine

Figure 5
400 °F post-test samples

Additional Slow Heating Test 4: 400 °F

Following slow heating test 3, additional materials were identified for evaluation: open cell cross-linked PE, closed cell cross-linked PE, and cross-linked polyamide. The cross-linking of molecular chains within these materials provides additional rigidity. Formerly free atoms bond to adjacent molecules creating a more rigid molecular structure. This test was conducted using a faster 27 °F/hr heating rate. The samples were conditioned at 122 °F for 8 hr and then temperature ramped at 27 °F/hr for approximately 10 hr, up to 400 °F. The oven temperature was then held at 400 °F for 1 hr. The closed cell PE (similar in appearance to expanded beads) began to melt down around 300 °F. The cross-linking likely didn't help in this material due to the closed cell structure where each individual cell shrank. The open cell PE had a more classic foam structure and the samples did not melt; however, the material did shrink significantly, decreasing over 50% along every dimension. The cross-linked polyamide samples performed very well with no noticeable change to the material other than some minor shrinking and brittleness. Post-test photographs are provided in figure 6.



(a)
Unweighted polyamide

(b)
Weighted polyamide

(c)
Closed cell cross-linked PE

(d)
Open cell cross-linked PE

Figure 6
Additional 400 °F post-test samples

Small-scale Cushioning Tests

The 12 materials that were found to have acceptable high temperature performance were subjected to additional laboratory-scale cushioning tests. While these tests cannot predict dynamic cushioning performance, they are inexpensive and can be conducted without unique test equipment. These tests are specified in A-A-59136 for foam packaging cushioning materials; however, only constant compression creep is a hard requirement. These tests are specified for PE foams with densities of 2, 4, 6, and 9 PCF. Many of the test materials are of different density ranges so several deviations were made for each test. The deviations included different sample sizes than specified and constant compression loading weights. Several materials had to be reused and others had to plied together to meet thickness requirements. Despite the various procedure deviations, these tests are a good discriminator for overall cushioning performance.

Constant Compression Creep Test

The constant compression creep test was conducted in accordance with ASTM D3575 Suffix BB using the loads specified in A-A-59136. Per the test method, a 100 x 100 x 50-mm sample is to be loaded with a static weight of 14, 21, 25, or 37 kg depending on sample density (2, 4, 6, and 9 PCF, respectively). It is noted that the static weights used for 6 and 9 PCF foams should actually be 36 and 72 kg, respectively; however, an error was made while writing A-A-59136, which has yet to be corrected. The proper static loading requirements are included in the previous specification PPP-C-1752, which is no longer active. The author was unaware of this discrepancy during testing and hence the lower loads were used for all tests described herein. The load was applied to the samples and compression measurements taken at specified intervals for 168 hr. In this case, each material was cut into four separate 2 x 2 x 2-in. samples to meet the total 16 in^2 area requirement. Varying metal plates of aluminum and steel were placed on top to apply the desired static load for each material. Measurements were taken using a standard rule. Passing criteria for this test is average creep not greater than 10% of initial thickness. Figure 7 shows the typical test setup used (top plates not shown for clarity).

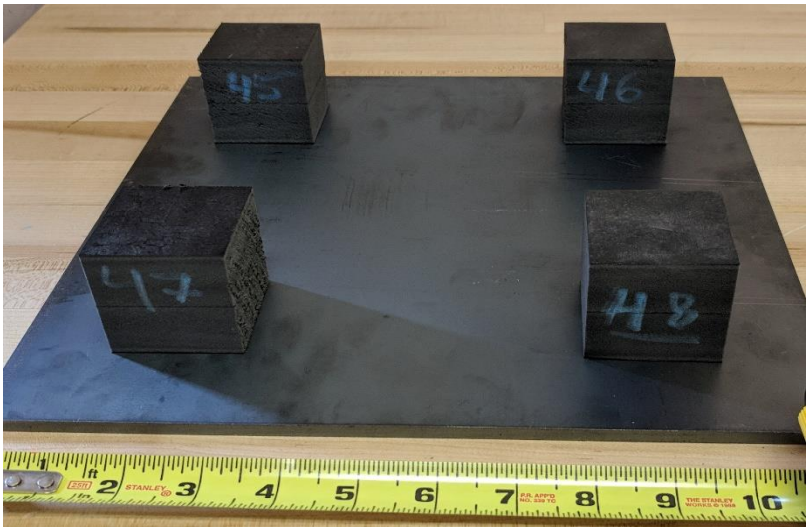


Figure 7
Constant compression creep test setup, polyamide foam shown

The majority of materials that performed acceptably in heat testing failed the constant compression creep test, even while using the less than required loads. Baseline tests with PE foams exhibited less than 1% compression creep for each density. The various open cell silicone foams and sponges immediately compressed by over 60% upon loading. Closed cell silicone sponge compressed about 30%. The various other foam materials exhibited compression creep of 60 to 80%. Only two materials provided acceptable results. The firm silicone sponge rubber remained within the acceptable creep range with an average of about 8% and the cross-linked polyamide foam resulted in 0% creep. The constant compression creep test results are included in table 3.

Table 3
Constant compression creep test results

Material	Static load (kg)	Thickness at start (in.)	Thickness at 168 hr (in.)	Maximum compression (%)	Average compression (%)
Cross-linked polyamide (4 PCF)	21	2	2	0.00	0
		2	2	0.00	
		2	2	0.00	
		2	2	0.00	
Silicone sponge rubber (40 PCF)	37	2	1 7/8	6.25	8
		2	1 3/4	12.50	
		2	1 15/16	3.13	
		2	1 13/16	9.38	
Closed cell silicone sponge (40 PCF)	37	2	1 15/32	26.56	30
		2	1 11/32	32.81	
		2	1 15/32	26.56	
		2	1 5/16	34.38	
Open cell silicone sponge (12 PCF)	37	1 31/32	3/4	61.90	62
		1 31/32	23/32	63.49	
		1 31/32	25/32	60.32	
		1 31/32	23/32	63.49	
Silicone foam (6 PCF)	25	1 15/16	19/32	69.35	70
		1 15/16	21/32	66.13	
		1 15/16	1/2	74.19	
		1 15/16	9/16	70.97	

Table 3
(continued)

Material	Static load (kg)	Thickness at Start (in.)	Thickness at 168 hr (in.)	Maximum compression (%)	Average (%)
Melamine (0.65 PCF)	14	2	31/32	51.56	61
		2	11/16	65.63	
		2	27/32	57.81	
		2	19/32	70.31	
Polyester polyurethane (4 PCF)	21	1 7/8	17/32	71.67	72
		1 7/8	17/32	71.67	
		1 7/8	1/2	73.33	
		1 7/8	9/16	70.00	
Polyester polyurethane (2 PCF)	14	1 15/16	7/16	77.42	76
		1 15/16	1/2	74.19	
		1 15/16	13/32	79.03	
		1 15/16	1/2	74.19	
Reticulated polyether polyurethane; 30 PPI (1.4 PCF)	14	2	17/32	73.44	77
		2	15/32	76.56	
		2	7/16	78.13	
		2	3/8	81.25	
Non-reticulated polyester (2 PCF)	14	2	1/2	75.00	75
		2	13/32	79.69	
		2	5/8	68.75	
		2	1/2	75.00	
Polyester polyurethane/ Unknown sample C (6 PCF)	25	1 25/32	13/16	54.39	60
		1 25/32	11/16	61.40	
		1 25/32	23/32	59.65	
		1 25/32	5/8	64.91	
Ethylene propylene diene terpolymer (7 PCF)	25	2 3/16	15/32	78.57	79
		2 3/16	1/2	77.14	
		2 3/16	7/16	80.00	
		2 3/16	15/32	78.57	

Compression Set under Constant Deflection

The compression set under constant deflection test was conducted in accordance with ASTM D3575 Suffix B. Three 2 x 2 x 2-in. samples of each material were compressed between the platens of a compression device to 50% of their initial thickness. The compressive device used was a Lansmont Squeezer tester. The samples were held in compression for 22 hr ± 30 min. The compression was removed after the 22-hr period and the samples were allowed to recover for 24 hr ± 30 min, at which point the final thickness was measured. Per A-A-59136, the maximum typical

compression set value should not exceed 25% of initial thickness. Figure 8 shows the typical test setup.

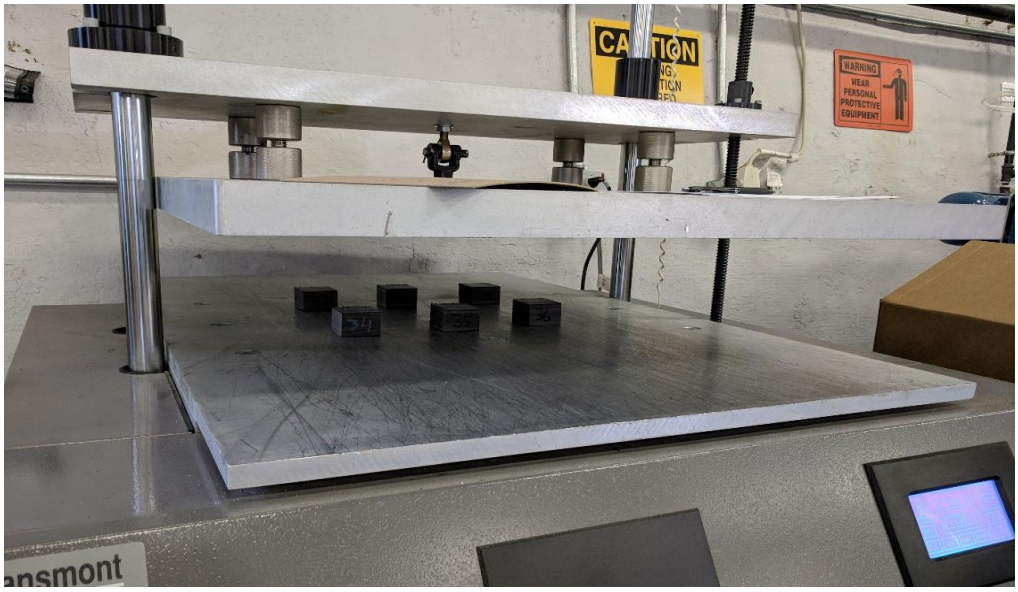


Figure 8
Compression set under constant deflection test setup

The majority of test materials remained within the 25% typical compression set value. Baseline tests with PE foam showed typical values between 6 to 9%. The majority of other materials exhibited less than 4% compression set. The worst performing material in this test was the cross-linked polyamide foam, which resulted in average values of 18 to 20% compression set; however, it was still within the maximum typical value specified in A-A-59136. The cross linking of the polyamide materials likely resulted in plastic deformation, which hinders the materials ability to rebound after a large displacement (ref. 7). The test results are tabulated in table 4.

Table 4
Compression set test results

Material	Thickness at start (in.)	Thickness at end (in.)	Constant deflection compression set (Cd) (%)	Average Cd (%)
Cross-linked polyamide (4 PCF)	2	1 19/32	20.31	20
	2	1 5/8	18.75	
	2	1 19/32	20.31	
Silicone sponge rubber (40 PCF)	1 1/2	1 1/2	0.00	0
	1 1/2	1 1/2	0.00	
	1 1/2	1 1/2	0.00	
Closed cell silicone sponge (40 PCF)	1	1	0.00	0
	1	1	0.00	
	1	1	0.00	
Open cell silicone sponge (12 PCF)	1	1	0.00	0
	1	1	0.00	
	1	1	0.00	
Silicone foam (6 PCF)	1	1	0.00	0
	1	1	0.00	
	1	1	0.00	
Melamine (0.65 PCF)	1	31/32	3.13	1
	1	1	0.00	
	1	1	0.00	
Polyester polyurethane (4 PCF)	1	31/32	3.13	3
	1	31/32	3.13	
	1	31/32	3.13	
Polyester polyurethane (2 PCF)	15/16	15/16	0.00	0
	15/16	15/16	0.00	
	15/16	15/16	0.00	
Reticulated polyether polyurethane; 30 PPI (1.4 PCF)	1	31/32	3.13	2
	1	1	0.00	
	1	31/32	3.13	
Non-reticulated polyester (2 PCF)	1	1	0.00	3
	1	31/32	3.13	
	1	15/16	6.25	
Polyester polyurethane/ Unknown sample C (6 PCF)	7/8	7/8	0.00	0
	7/8	7/8	0.00	
	7/8	7/8	0.00	
Ethylene propylene diene terpolymer (7 PCF)	1 1/8	1 1/8	0.00	0
	1 1/8	1 1/8	0.00	
	1 1/8	1 1/8	0.00	

Compression Deflection Test

The compression deflection test (also known as load deflection and compressive strength) was conducted in accordance with ASTM D3575 Suffix D. Three 2 x 2 x 2-in. samples of each material were placed individually between the platens of a compression device with a force measuring device. The compressive device used was the same Lansmont Squeezer tester shown in figure 8. Each sample was compressed at a rate of 0.5 to 2.0 in. per minute to 75% of its initial thickness. The load required to achieve this compression was recorded at the point of 25% compression. Per A-A-59136, the compressive strength range should be 2 to 12 psi, 13 to 20 psi, 21 to 50 psi, and 51 to 100 psi for 2, 4, 6, and 9 PCF materials, respectively.

Since many of the new materials do not fall within the range of densities of PE foam, this test was conducted for information only. Baseline testing with PE foams returned a wider than expected spread of results; however, each density was within or close to the specified range. The majority of new test materials severely underperformed with values less than 4 psi. The majority of those were less than 2 psi. The 40-PCF closed cell silicone sponge and rubber returned values of only 8 to 10 psi. The only outlier was the 4-PCF cross-linked polyamide foam, which returned values of 44 to 46 psi. The test results are tabulated in table 5.

Table 5
Compression deflection test results

Material	Force required for 25% compression (lb)	Compression deflection force 25% (psi)
Polyamide (4 PCF)	176	44.0
	181	46.7
	184	46.0
Silicone sponge rubber (40 PCF)	40	10.0
	43	10.8
	40	10.0
Closed cell silicone sponge (40 PCF)	31.9	9.1
	33	8.3
	30.1	8.0
Open cell silicone sponge (12 PCF)	13.6	3.4
	13.2	3.3
	13.6	3.4
Silicone foam (6 PCF)	4.7	1.2
	3.9	1.0
	4.5	1.2
Melamine (0.65 PCF)	7.1	1.8
	7.6	1.9
	7.5	1.9
Polyester polyurethane (4 PCF)	4.9	1.3
	4.2	1.1
	4.8	1.3

Table 5
(continued)

Material	Force required for 25% compression (lb)	Compression deflection force 25% (psi)
Polyester polyurethane (2 PCF)	5.5	1.4
	4.8	1.2
	5.2	1.3
Reticulated polyether polyurethane; 30 PPI (1.4 PCF)	4.4	1.1
	4.3	1.1
	3.8	1.0
Non-reticulated polyester (2 PCF)	6.1	1.5
	6.2	1.6
	6.1	1.5
Polyester polyurethane/ Unknown sample C (6 PCF)	4.8	1.4
	6	1.5
	6.4	1.6
Ethylene propylene diene terpolymer (7 PCF)	2.3	0.5
	2.3	0.6
	2.3	0.6

Discussion

A total of 12 materials were found capable of withstanding exposure up to 400 °F in small-scale heating tests. The most promising of these were the various silicones, polyester polyurethane, and polyamide due to their commercial availability in numerous densities and grades. Melamine is only available in extremely low densities and is very reactive to water, as such it would be too unreliable for long-term storage in humid or shipboard environments. Reticulated polyether polyurethane and ethylene propylene diene terpolymer were both too soft and would not be capable of supporting the weight of ammunition items. Silicones are also very soft and by far the most expensive material at 10 to 25 times the cost of PE foam. While firmer grades of silicone could be made to meet the cushioning requirements, those would likely be cost prohibitive. Polyester polyurethane appeared to be a very good candidate at the start of testing, but it was also found to be very soft under constant compression. It is also known that polyester polyurethane reacts poorly to several common chemical compounds used in military logistics. Cross-linked polyamide deforms plastically, cannot be traditionally recycled, and is estimated to cost 4 to 5 times more than PE. It was, however, the best overall material and found to meet the initial requirements. It is commercially available in several densities, produced domestically, and manufacturing capacity is growing, potentially reducing the overall cost in the future. Future work is planned to subject three densities of the polyamide foam (2, 3, and 4 PCF) to dynamic cushioning tests to verify if the material is able to meet cushioning requirements as a drop in replacement for PE foams.

Inert 40-mm M430A1 Slow Cook-off Tests

The only material to show acceptable performance in the small-scale heating and cushioning tests was cross-linked polyamide foam. It was the only material selected for full-scale slow cook-off testing. Three tests were conducted utilizing fully inert 40-mm cartridges. Polyamide foam blocks were machined using a desktop computer numerical control (CNC) lathe to create the unique 40-mm dunnage shapes shown in figure 9. Size-matched containers were assembled using high-

temperature borosilicate glass to allow for visibility of the foam and test items during the test. Prototype foam dunnage and linked inert 40-mm dummy cartridges were packaged in the borosilicate glass containers and subject to modified slow cook-off tests. For all three tests, the samples were conditioned at 122 °F for 19 hr and then the temperature was ramped at 27 °F/hr. Test no. 1 was ramped for 6 hr up to 284 °F, test no. 2 for 9 hr up to 365 °F, and test no. 3 for 11 hr up to 419 °F. Each test was held for 1 hr at the maximum temperature and then allowed to cool overnight before inspection. It should be noted that a single set of polyamide dunnage was used for all three tests. Figure 10 shows the loaded borosilicate glass container with front foam filler removed for clarity.

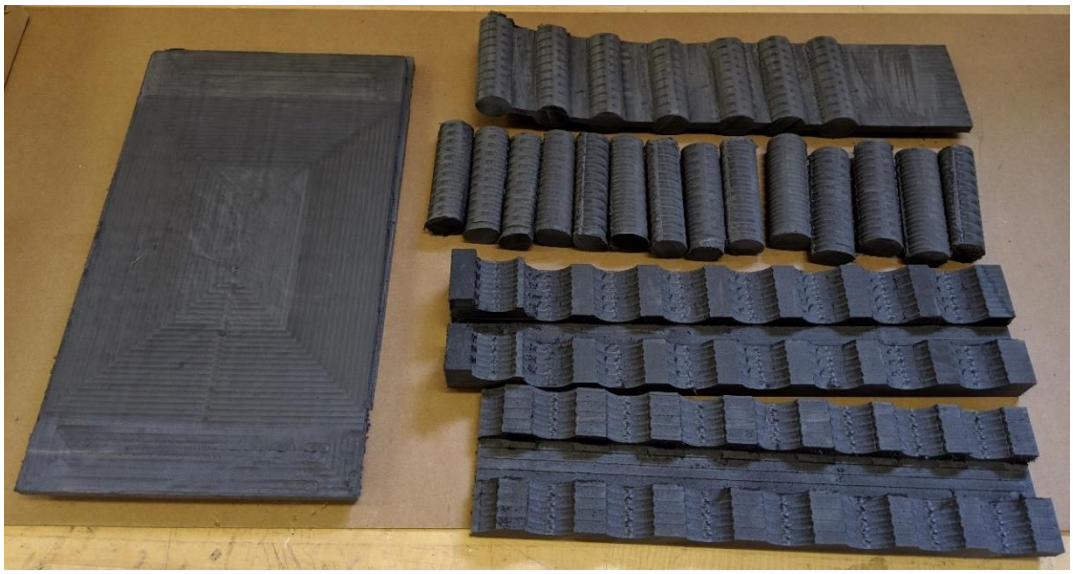


Figure 9
CNC-machined polyamide foam dunnage

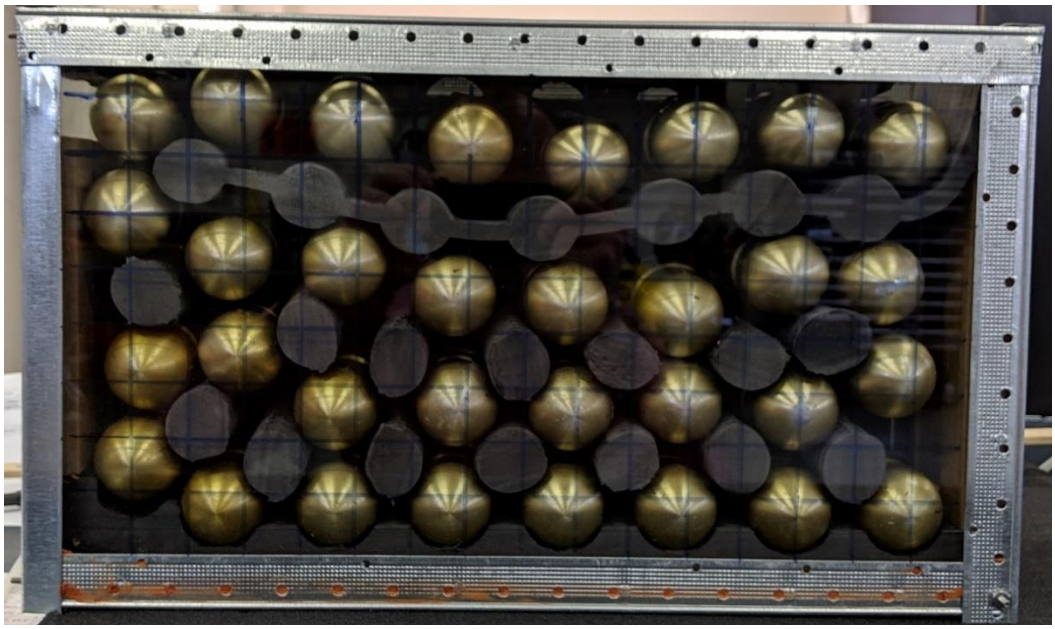


Figure 10
Pre-test-loaded borosilicate glass container

The results of all three tests showed no major change in the polyamide foam material. There were no signs of burning, charring, melting, major shrinkage, or adhesion. The inert rounds remained in their original positions and the polyamide dunnage was easily removed from the container after each test. The second and third tests did result in an increasingly noticeable odor starting around 310 °F. The odor is possibly due to outgassing of the foam cells; however, this is to be expected at such high temperatures. The odor was not noted in the first test up to 284 °F. It was also noted that the material became increasingly brittle to the touch after tests 2 and 3. No additional assessment was conducted on the material as any live item that exceeds 200 ° F in storage would be demilitarized and not used. These results confirm that cross-linked polyamide foam dunnage prevents the melting and slumping seen with PE foam dunnage up to much higher temperatures of over 400 °F. Figures 11 and 12 show the post-test polyamide dunnage following tests 2 and 3, respectively.

Figure 11
Polyamide dunnage post-test 2 (365 °F)

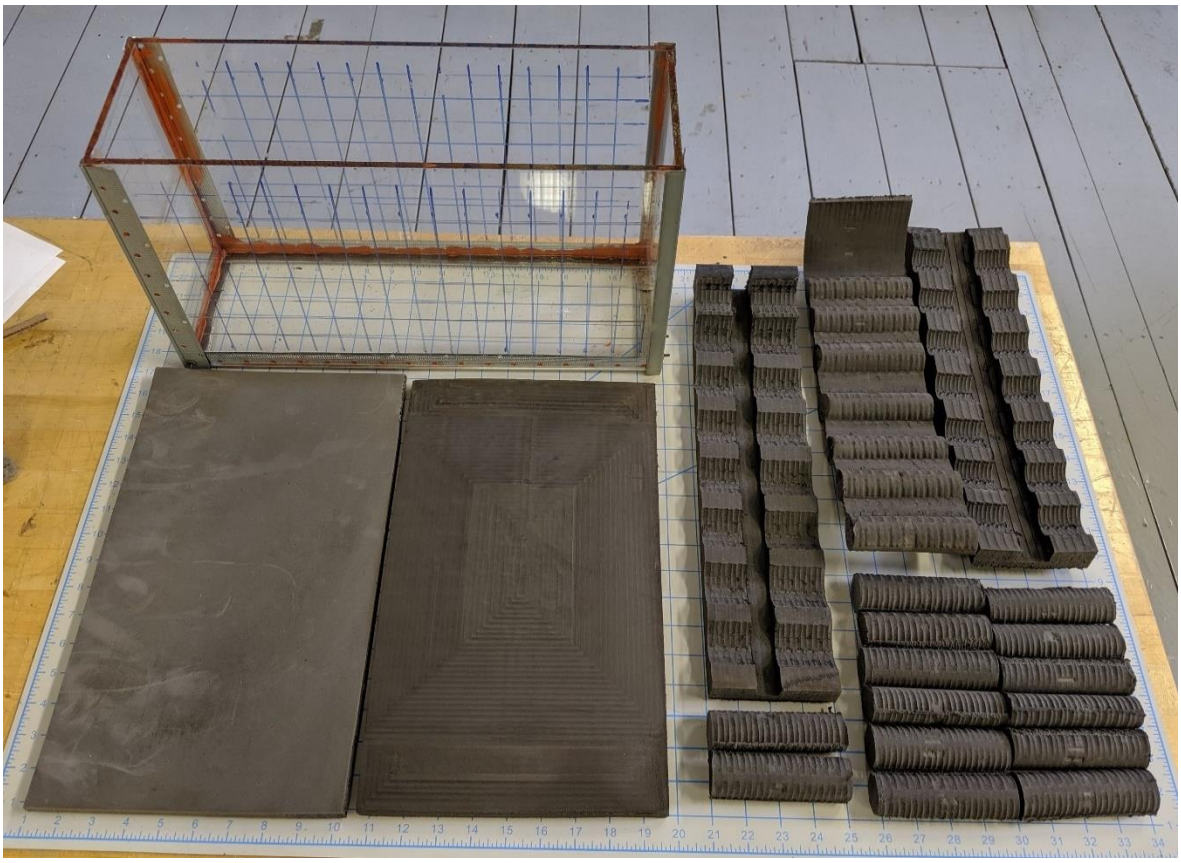


Figure 12
Polyamide dunnage post-test 3 (419 °F)

CONCLUSIONS

Various foam materials were tested at small-scale for heat resistance up to 400 °F of which a dozen were able to withstand exposure to high temperature. Those materials were subjected to three small-scale cushioning tests that only a cross-linked polyamide foam was able to successfully pass. Heating tests proved that the polyamide material is extremely resilient to high temperature exposure. Due to the cross-linked nature of the material, it deforms plastically after compression; however, the overall result was acceptable. Another series of heating tests was conducted using inert ammunition in a highly representative 40-mm M430A1 packaging. These tests successfully proved that the polyamide dunnage will not melt and continues to provide cushioning support at the system level. This material may be a suitable alternative to polyethylene foam dunnage currently used for packaging ammunition. Additional work needs to be done to prove that the material has acceptable cushioning properties for other densities, specifically dynamic cushioning. Work is ongoing to verify the cushioning curves for 2, 3, and 4 per cubic foot (PCF) densities of polyamide foam.

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