

Foam Composite Specifications and Qualification in Support of NIJ 0115.00

Aaron M. Forster¹, Anthony Chan-Ou-Teung², Emilien Guigues², Amanda L. Forster², Jeff Davis², Kirk Rice²

¹*Engineering Laboratory
aaron.forster@nist.gov*

²*Materials Measurement Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899*

Abstract. A laminate foam composite is recommended in the National Institute of Justice (NIJ) 0115.00 standard as the backing material for testing stab resistant body armor. The foam specification originated from early work to match force-displacement profiles from human stab motion to force-displacement profiles of gravity-driven drop tests. Anecdotal evidence from test labs and qualitative comparisons of foam from different suppliers suggests not all currently specified foams are created equal. NIST has developed a suite of measurements to quantify the differences between non-linear foam composites as a function of impact energy and strain rate. These measurements include standardized (ASTM) quasi-static tests for stress-strain properties, density, and hardness in conjunction with dynamic measurements using an instrumented drop mass to validate performance at realistic velocities and impact energies. Earlier PASS presentations have shown quasi-static and dynamic methods capable of identifying slight differences between foam materials, but they have not been applied to commercially relevant systems used for stab testing. NIST solicited stab pack samples from multiple U.S. and International foam stab pack suppliers in order to compare foam performance. The performance of these stab packs is compared to an accepted legacy foam material. The results show that proper specification of the foam can significantly reduce variability within the current materials supplied to test laboratories. These results have led to suggested changes for the current specification and qualification testing. In order to verify performance, several ASTM qualification methods are recommended as revisions to the standard. It will be shown that these additional tests will identify non-compliant materials before use within a stab test. The impact of the foam composite properties on the penetration of a spike into a model stab resistant armor will be presented.

Keywords. foam, stab testing, NIJ standard, foam specification, body armor

1. INTRODUCTION

A foam laminate is used to support stab resistant body armor for testing in the NIJ 0115.00 standard [1]. The purpose of the foam is to mitigate the force and impact duration during the drop test to better mimic the dynamic response experienced by soft body armor during a realistic stab event. The early research to identify the foam specification arose from Strathclyde University. Gray utilized an instrumented knife to record the biomechanics of male volunteers simulating stab attacks that led to the identification of the foam composite that is used as a tissue simulant [2, 3]. This work recorded the impact energy, axial force, cutting force, lateral force, and torque of volunteer stab measurements attacking a soft body armor covering a Plastilina target. These measurements were conducted on thrust, sweep, and overhand stab motions. The overhand motion provided the highest energy and the thrust motion the lowest energy. The statistics for overhand motion showed a maximum energy 103 J, a 95th percentile of 68 J, and a mean of 36 J. The axial force maximum was 2261 N, with a 95th percentile of 1885 N, and a median of 1091 N. Research at Cranfield University on instrumented stab tests carried out using both male and female volunteers showed that an underarm stab has a 95th percentile energy of 54 J, while an overarm stab has a 95th percentile energy of 77 J [4]. The mean energies for female and male volunteers were 26 J and 46 J, respectively. The maximum force was approximately 800 N. The armor backing for volunteer tests was Plastilina similar to the work of Gray [2]. This research laid the groundwork for the design of the NIJ stab test. The energy levels for stab testing are 24 J, 33 J, and 43 J with over-test energies of 36 J, 50 J, and 65 J.

An impact of the previous research was the development of viscoelastic materials to support armor during testing. Roma plastilina exhibits a plastic response that does not represent the viscoelastic response of tissue. The characteristic force and impact energy measured in volunteer stab tests were used to select an appropriate behind-the-armor tissue surrogate. A hemi-spherical (50 mm radius of curvature) drop mass was instrumented to measure force-displacement profiles for drops into porcine (pig) tissue impacted at energy levels of 19 J, 37 J, and 54 J. It should be noted that the drop tests were conducted with a single-mass hemispherical punch, rather than the two-mass system currently employed in the NIJ standard. Roma Plastilina and several synthetic rubber, foam, and gel combinations were measured using the same impact conditions. Roma Plastilina was determined to be unsuitable as a backing material due to plastic deformation, while the viscoelastic nature of the foam composite better replicated the force-displacement curves measured on porcine tissue in drop tests. The key impact parameters that were matched against the hemispherical drop tests into tissue models were initial dynamic stiffness, linearity, maximum force, and energy absorption (hysteresis) [2]. Research at Cranfield later showed that a foam support combined with a two-mass sabot provided a better representation for the stab test [4]. The principle components of the NIJ stab standard are shown in Figure 1.

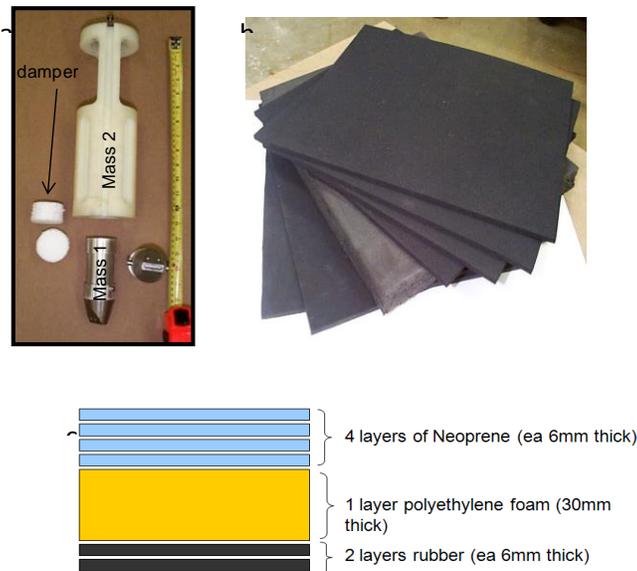


Figure 1. a) Picture of the two-mass drop system with a viscoelastic foam damper that is placed between the two masses (top left), b) picture of actual foam and rubber materials (top right), and c) outline of construction of pack underneath armor (bottom).

The foam specification adopted in both the U.K. and U.S. versions [1] is given in Table 1. There are differences between the two specifications. The neoprene sponge provides two different thicknesses with no tolerance and the listing of firm density (U.K.) and a Shore A hardness (U.S.) can lead to differences in source materials. The polyethylene specification also shows differences in density, thickness, and a Shore A hardness specification.

These differences have the potential to lead to inconsistency in sourcing materials from foam suppliers and lead to a range of foams used in testing across the world. NIST has supported a research program to understand energy absorption in foam layers and in the foam laminate to identify how material properties affect quasi-static and dynamic response. There have been two goals for this program: 1) Determine the variability of foam used in the NIJ 0115.00 standard; 2) Identify a specification that reduces variability during stab testing. In prior PASS proceedings, NIST has demonstrated metrologies for characterizing energy absorption at both quasi-static and dynamic strain rates. In this proceeding, NIJ 0115.00 compliant stab packs were obtained from multiple sources according to the current standard. The physical and

mechanical properties of these materials were measured using quasi-static and dynamic methods. The individual foams and the constructed stab packs are compared to each other, but a single polyethylene and neoprene foam pair, sourced from the United Kingdom, is used as the standard material. From this comparison, a specification for the neoprene and polyethylene foam is identified.

Table 1. Material specification for foam backing materials provided in NIJ 0115.00.

Component Materials	U.S. Specification	UK Specification	UK Reference Part Number
Neoprene sponge	5.8 mm (0.23 in) thick, SCE45, Shore A20-30	6 mm thick, firm density	PSDB/BM/1/99
Polyethylene foam (Plastizote®)3	closed cell, 31 mm (1.22 in) thick, LD45, Shore A14	expanded closed cell to density of 33 kg/m ³ , 30 mm (1.18 in) thick	PSDB/BM/2/99
Rubber	6.4 mm (0.25 in) thick, Shore A45-50	BS2494D, 6 mm thick	PSDB/BM/3/99

2. Experimental¹

2.1 Foam Properties

Foams were obtained from 12 different suppliers. 19 mm diameter cylinders were cut from the foam using a smooth bore cutting tool on a drill press. Deionized water was used as a lubricant and the foams were allowed to dry overnight at standard conditions. The physical and mechanical characteristics were obtained using the relevant American Society for Testing Materials International (ASTM) standards. ASTM D3575-08 was used to measure the density. ASTM D1056-07 was used to measure the compression deflection. ASTM D2240-05 was used to measure the Shore hardness on the 00 scale. Several measurements were conducted over different batches of material in order to characterize the variability in the data.

2.2 Quasi-static Testing

The stress vs. strain behavior of the individual neoprene and polyethylene materials was measured using compression between 150 mm diameter flat platens. Compression data was obtained at a 5 mm/min test rate up to 70 % compression. The sample geometry used for testing was a single polyethylene cylinder with a diameter of 19 mm. The 19 mm diameter neoprene cylinders were stacked into four layers.

2.3 Dynamic Testing

An instrumented drop mass was developed to measure deceleration as a function of time during impact into foam composites with a 19 mm diameter aluminum flat punch indenter. In all cases, the viscoelastic damper within the drop mass was an LD 45 polyethylene specified by the U.S. specifications in NIJ 0115.00. The damper was replaced after 6 total drops regardless of energy and 15-minute wait times were

¹ Certain commercial products are identified in this report to specify the materials used and procedures employed. In no case does such identification imply endorsement by the National Institute of Standards and Technology, nor does it indicate that the products are necessarily the best available for the purpose.

kept between tests. The foams were tested at 23 J and 43 J of impact energy. In order to follow the NIJ standard, the viscoelastic damper should be the same material as the polyethylene used in the stab pack. For this study, a well-characterized foam was used for the viscoelastic damper in order to minimize the number of variables that change during testing of the various vendor supplied packs. This allows a better comparison between the performance of the materials against each other. Previous testing at NIST has shown that the substitution of an LD45 damper compared to an LD33 damper is a conservative approach that increases the deceleration measured at the accelerometers. The two-mass system was designed to be compliant with regard to length and materials with the NIJ 0115.00 specifications. Figure 2 shows a CAD drawing and a picture of the system in the drop tower. The system is mounted with two 3-axis accelerometers to capture the acceleration of the upper and lower mass. The data acquisition system (DTS Systems) is powered using a Li-ion battery that rides onboard the upper mass. The system collects data at a rate up to 50 kHz with a storage capacity of 8 Gb. The two 3-axis accelerometers are mounted within the upper and lower mass. The drop mass has the capability to carry NIJ stab threats in addition to the flat punch. The system has been described in previous PASS proceedings [6].

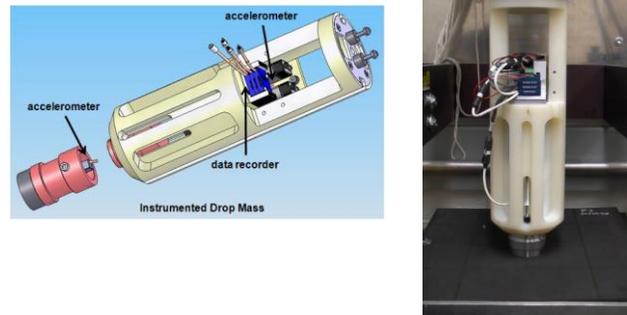


Figure 2. Schematic diagram and photograph of the instrumented drop mass and a picture of the instrumented drop mass inserted into the stab tube.

3. RESULTS AND DISCUSSION

3.1 Properties

Table 2 lists the hardness and density measured on all of the neoprene and polyethylene foams obtained for this study. The neoprene materials fell into two different groups based on the hardness and density. The materials with a higher hardness had a higher density ($\sim 245 \text{ kg/m}^3$) and the materials with a lower hardness had a lower density ($\sim 150 \text{ kg/m}^3$). The variability in density for the majority of foams was within the measurement standard deviation of 5%, with the S2 and S5a exhibiting the highest variation at 10% standard deviation. It is worth noting that these two samples came from the same supplier. There is no direct model between foam hardness and density since hardness is sensitive to the surface of the foam. The stress vs. strain behavior and the density of the unfoamed material is required to better understand the energy absorption properties of these materials [5]. This may be the result of the NIJ standard specification of a *firm* neoprene with a thickness of 6 mm. The thicknesses of the measured foams ranged between 5 mm and 6 mm, with a standard deviation of 50 μm within each supplier material.

Table 3 shows the results for the polyethylene foams. Two different densities were supplied and the groups gathered by density. Since the densities were not far off from each other, compared to the neoprene, the hardness values tended to overlap. The NIJ standard allows for either a 45 kg/m^3 (U.S.) or 30 kg/m^3 (Europe) closed cell polyethylene with a thickness of 30 mm. None of the supplied foams met the NIJ thickness standard of 30 mm. NIJ compliant materials that had skin removed (skinless) had thicknesses measured between 25 mm and 31 mm, while those with skin present (skin-on) had thicknesses between

32mm and 34 mm. The height was well controlled within a batch, with a maximum standard deviation of 50 μm for the neoprene and 150 μm for the polyethylene samples.

Table 2: Hardness and density measured on the neoprene foam materials

	Designation	Type	Hardness Shore [OO]	Standard Deviation	ρ (kg/m ³)	Standard Deviation
Group 1	SCE 41	Neoprene	51	1	89.3	0.8
	S4N	Neoprene	64	1	149.0	2.5
	S3Nb	Neoprene	67	1	153.9	1.0
	S3Na	Neoprene	57	1	158.6	2.6
	S6N	Neoprene	75	1	229.9	4.7
Group 2	S2N	Neoprene	77	1	231.2	13.4
	S5Na	Neoprene	70	1	234.8	9.9
	SCE 45	Neoprene	81	0	240.1	0.9
	S7N	Neoprene	79	1	248.7	4.0
	S1N	Neoprene	75	1	249.2	2.1
	S5Nb	Neoprene	74	1	252.2	4.1

The NIJ standard does not specify whether the skin, inherent from manufacturing, should be removed, but a range of skin-on and skinless materials were supplied. There are several comparisons that may be made for support of removing the skin. The skin occurs because the material at the edges of the foam has a much higher density, closely approximating the unfoamed material. Skin-on materials exhibited a higher hardness than skinless materials. A comparison of LD45s and LD45ns shows that the skin layers make a significant contribution of the foam density. In Group 2, EVA 50 has the same density as LD45s (skin-on) but a much lower Shore OO hardness because the ethylene-vinyl-acetate base material is softer than polyethylene.

Materials that originated from the same source were consistent with each other. S3Nb and S4N were obtained from the same manufacturer and exhibit a similar hardness and density. S7N and SCE 45 were also obtained from the same manufacturer with similar properties. The S3P and S4P were obtained from two different laboratories with the same material supplier and the measurements are within experimental error. Similarly, LD45s was obtained from the manufacturer that supplied foam to the supplier S7P.

Table 3: Hardness and density measured on the polyethylene foam materials

	Designation	Type	Hardness Shore [OO]	Standard Deviation	ρ (kg/m ³)	Standard Deviation
Group 1	S1P	Polyethylene Blue	75	2	33.2	0.3
	S3P	Polyethylene	59	1	30.1	0.1
	S4P	Polyethylene	57	1	30.5	0.2
	LD 33	Polyethylene	71	1	31.2	0.2
	LD45ns	Polyethylene	66	1	38.6	0.3
Group 2	S5Pa	Polyethylene	64	1	42.1	0.2
	S6P	Polyethylene Tan	75	1	42.5	0.4
	S5Pb	Polyethylene	75	1	43.6	0.2
	S2P	Polyethylene	79	1	44.8	0.4
	LD45s	Polyethylene	80	1	45.5	0.4
	S7P	Polyethylene	79	1	45.9	0.4
	EV50	EVA	56	2	48.3	0.5

3.2 Compression of foams

Density and hardness provide a simple route to identify differences between foams from different suppliers. NIST has shown that the stress vs. strain behavior for foams should be measured as a means to understand energy absorption [6]. The stress vs. strain behavior was measured for each of the individual foam layers. For both the neoprene and polyethylene materials, the stress vs. strain curve (not shown) increased with density which indicates an increase in the stiffness of the foam. The increase was less for the polyethylene materials, likely due to the smaller differences between density. In order to develop a specification, the stress at different levels of compression was determined for all foams tested. The stress at three different levels of strain (10%, 25%, and 50%) was required to specify each foam material. These levels were chosen because these strain levels are available through the ASTM D3575-08 standardized test method [7]. The test rate used for testing was 10 mm/min.

3.3 Dynamic Results

The current understanding of the force and momentum involved during a stab event has come from the previously mentioned studies [2,4]. The stab standard was developed using the impact energies and velocities identified in those studies, but it has employed a dual mass sabo, angled attack, and multiple weapon geometries (knife and spike) to better reflect the threats from a stabbing event. Unfortunately, it is not possible to make a direct comparison between the historical instrumented stab impacts or baseline the currently available materials to either the original PSDB material systems or standard reference foams. The strategy employed here is to compare impact parameters with a foam stab pack sourced from CAST (Centre of Applied Science and Technology) in the United Kingdom, since these are the best representatives of a legacy material available to date. The CAST compliant packs are labeled M1 and M5.

The relevant impact parameters to quantify the dynamic event are:

- Maximum deceleration during impact (M_{DEC});

- Time to stop the sabo prior to rebound (T_{V0});
- The full duration for the initial impact (T_{diff});
- The change in velocity as the sabo rebounds off the foam (A_{ACC}).

All of these quantities are derived directly from the Z-axis output of either the upper or lower accelerometer in the instrumented drop mass. In this proceeding, only the maximum deceleration (M_{DEC}) is evaluated since it shows the most significant differences in foam laminate behavior.

Figure 3 shows the maximum deceleration for the lower accelerometer at 43 J. Similar to the physical properties, the data are stratified according to the stiffness of the foam pack components. The softest packs exhibit the lowest deceleration, at 43 J, which occurs within a range of 100 g to 110 g. These stab packs include M1, M5, M6, and M12. The M1, M5, and M6 are the packs based on the European specification and those shown by CAST to meet the ball bounce criteria in the standard and align with the European material specification. These are also believed to be closest to the original PSDB formulation. The stiffer packs have a higher deceleration range between 150 g and 220 g. These include those foam packs composed of the LD 45 polyethylene and the SCE 45B neoprene, essentially M2, M3, and M7 to M11.

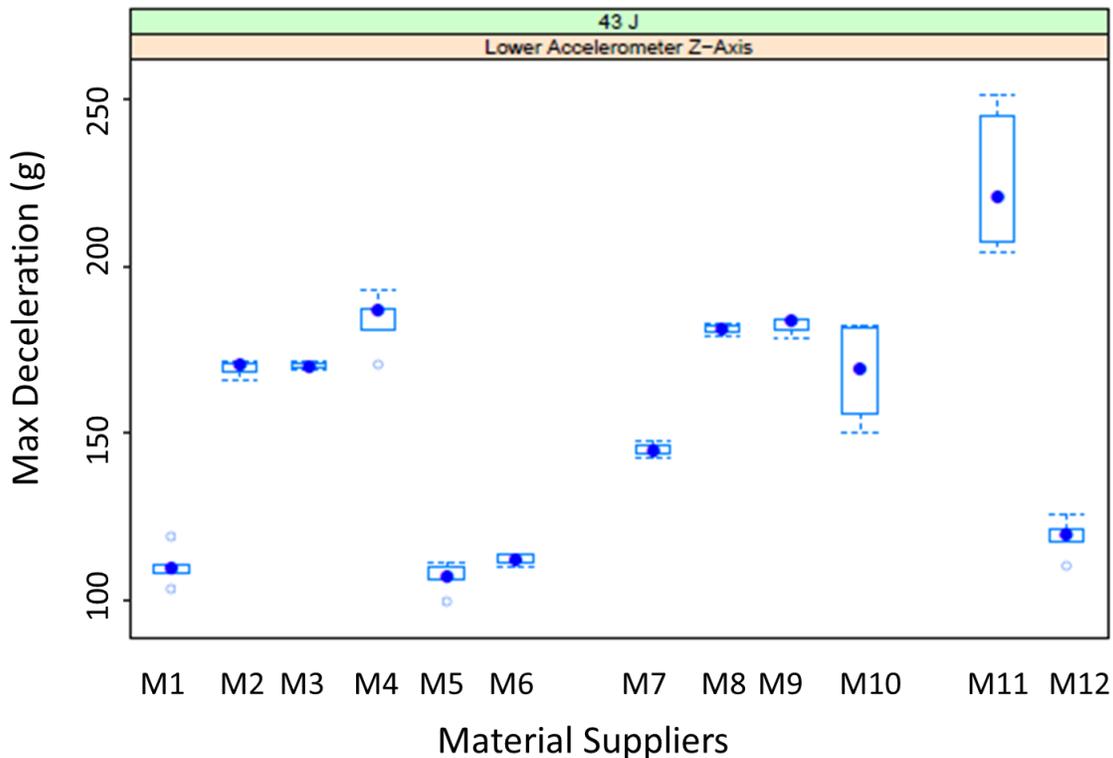


Figure 3. The maximum deceleration measured at the lower accelerometer during the initial impact from a drop energy of 43 J. Y-axis is the max deceleration [g] and the x-axis is the designation for the foam stab pack. This is a box plot representing the median (filled circle), inter-quartile range (IQR) (solid box), 1.5xIQR (dashed line), and outliers (unfilled circle) determined from six tests on each material.

The lower impact energy of 24 J (not shown) displays similar separation, but the differences between the soft and stiff stab packs are not as large. M1, M5, M6, and M12 have a slightly lower maximum deceleration range of 80 g to 90 g. The stiffer packs exhibit a higher separation between 120 g and close to 160 g. The M7 supplied stab packs continue to fall between the low and high ranges, which is not surprising because quasi-static measurements showed this pack consisted of a medium density neoprene and a lower density polyethylene.

The results show that U.S. sourced stab packs were generally stiffer and of higher density than the international counterparts. These packs were closer to the U.S. specification within NIJ 0115.00, but there

was still a significant difference in density of neoprene depending on the supplier. The international packs were closer to the U.K. specification in the standard and were less stiff with a lower density. Based on the results from quasi-static and dynamic measurements on all the materials, a neoprene and polyethylene foam specification was developed. The M5 and M1 packs, which were sourced from the United Kingdom and Canada, were used as the baseline for the specification.

The specification is composed of measurements of:

- density,
- thickness,
- Shore OO hardness,
- Compression deflection at 10%, 25%, and 50%.

Table 4. The proposed neoprene specification

	Test Method	Neoprene/EPDM/SBR
color		black
Type		Closed
Standard Specification	ASTM D1056-07	2A3
Density (kg/m ³)	ASTM D3575-08 (2008)	150 +/- 25
Thickness (mm)		6 +/- 0.5
Compression Deflection (kPa), % strain ^s	ASTM D1056-07	
10%		50 +/- 5
25%		75 +/- 10
50%		130 +/- 20
Shore Hardness [00 Scale]	ASTM D2240-05	55 +/- 5

Table 5: The proposed polyethylene specification

	Test Method	Low Density Plastazote Crosslinked Polyethylene
color		black
Type		Closed
Standard Specification	ASTM D4819-96 (2005)	D4819 Type I - B4
Density (kg/m ³)	ASTM D3575-08 (2008)	32 +/- 2
Thickness (mm)		28 +/- 2 (no skin)
Compression Deflection (kPa) ^s	ASTM D3575-08 (2008)	
10%		50 +/- 5
25%		69 +/- 10
50%		135 +/- 20
Shore Hardness [00 Scale]	ASTM D2240-05	60 +/- 3

CONCLUSIONS

NIJ compliant stab foams were purchased from twelve different suppliers. These suppliers covered both national and international sources of stab packs available for testing stab armor to NIJ 0115.00. It was

found that most of the materials were compliant with either the U.S. or the U.K. specification in the standard. It was found that the U.S. specification resulted in stiffer foam materials of higher density, than obtained internationally. However, there was more variability in the U.S. sourced materials between suppliers. It was found that, in general, material specified in the same manner exhibited smaller variance in behavior and was not dependent on the batch. The U.K. sourced foam was used to develop a neoprene and polyethylene specification for future testing of stab armor.

Acknowledgements

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