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# FEASIBILITY OF AN IMPACT SHELL FOR COMBAT HELMETS

by  
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Final Report  
October 2015 – September 2017

**Approved for public release; distribution is unlimited.**

**U.S. Army Combat Capabilities Development Command Soldier Center  
Natick, Massachusetts 01760-5000**

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IMPACT	VELOCITY	MTBI(MILD TBI)	IMPACT ATTENUATION		
WEIGHT	CONCUSSION	PADS(CUSHIONS)	WOUNDS AND INJURIES		
TRAUMA	CUSHIONING	CRASH VELOCITY	PROTECTIVE COVERINGS		
HELMETS	PROTOTYPES	HEAD(ANATOMY)	PROTECTIVE EQUIPMENT		
REMOVAL	HELMET PADS	IMPACT VELOCITY	PARACHUTE LANDING FALL		
AIRBORNE	IMPACT TESTS	ARMY EQUIPMENT	TRAUMATIC BRAIN INJURIES		
APPLIQUES	HEAD INJURIES	HEAD PROTECTION	SHELLS(STRUCTURAL FORMS)		
HEADGEAR	BLUNT IMPACT	LOAD DISTRIBUTION	TBI(TRAUMATIC BRAIN INJURY)		
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## Preface

An Impact Shell was developed to attenuate acceleration at higher velocities (14.1 ft/s and 17.3 ft/s) than the current Army blunt impact requirements (10 ft/s). Baseline blunt impact testing was completed using the Army Combat Helmet (ACH) at 14.1 ft/s and 17.3 ft/s and a variety of commercially available materials were evaluated as potential external energy absorbers. Two materials were down selected, evaluated and compared to the baseline using the Army's standard blunt impact test methodology at elevated impact velocities (14.1 ft/s and 17.3 ft/s).

This project was funded by Natick Research, Development and Engineering Center's (NSRDEC's) core Science and Technology (S&T) funds under Project Number IMTP-16-147. The Infantry Combat Equipment Team at NSRDEC executed the project from October 2015 through September 2017.

## Acknowledgements

Product Manager (PM) Soldier Protective Equipment is acknowledged for their contribution to this project. They provided all the necessary ACHs for the testing. John Fitek is acknowledged for initiating this project.

# FEASIBILITY OF AN IMPACT SHELL FOR COMBAT HELMETS

## Introduction

Work for this project was performed by the Natick Soldier Research, Development and Engineering Center (NSRDEC) from October 2015 to September 2017.



Figure 1 NSRDEC's monorail drop tower

This study revisits the concept of a blunt impact attenuator external to the Army Combat Helmet (ACH). The impact attenuator, referred to as an impact shell throughout the report, is a removable applique that can be used in situations where impacts to the head are more likely to occur. The impact shell is aimed at reducing head trauma by further attenuating blunt impacts above the capabilities of the ACH.

As stated in a previous study [1], all Soldiers in the U.S. Army could benefit from improved blunt impact head protection. However, those Soldiers in an airborne situation have the most need due to high velocity landings, which can result in high energy head impacts if executed improperly [2]. Although the External Impact Cover (EIC) from Davenport's effort showed promise and reduced peak accelerations above the ACH, it was never transferred to the user community as a fielded item. The lack of transition may be due to the additional mass that this concept added to the ACH. This study's intent was to further reduce mass and transmitted acceleration above and beyond the EIC.

The U.S. Army's target is to reduce peak acceleration to less than 150 g ( $1 \text{ g} = 32.2 \text{ ft/s}^2$ ) at 14.1 ft/s (threshold) and 17.3 ft/s (objective) [3] through multiple research and development (R&D) efforts aimed at updating the helmet suspension system. This project targets the

same goals without disrupting the current internal suspension system.

There are three possible scenarios when adding an external impact attenuating material to the ACH. Greatly simplifying the material response, it could be assumed that each material is represented as a spring; where  $K_1$  is the spring constant for the helmet liner and  $K_2$  is the spring constant for the Impact Shell.

- (1)  $K_1$  and  $K_2$  are in a similar range and thus the following equation can approximate the resulting combined spring constant where the two layers of padding will work together during impact with a resulting stiffness lower than that of either individually.

$$\frac{1}{K_{eq}} = \frac{1}{K_1} + \frac{1}{K_2}$$

- (2) If one material is much stiffer than the other, the less stiff material will compress first until full densification. Once full densification occurs, the stiffer material will begin to compress.

- (3) The third case is a mixture of the first two cases where the less stiff material becomes stiff enough to result in the first case sometime between the onset of compression and full densification.

Scenarios (2) and (3) are more likely to yield better results. These scenarios lend themselves to load distribution when impacting a curved or pointed surface (e.g. the anvil) and will not require modification to the internal padding system to achieve the desired stiffness like scenario (1).

## Methodology

The ACH is in short supply, making it difficult to procure samples for this test. Product Manager (PM) Soldier Protective Equipment supplied enough ACH helmets for this effort with the caveat that not all of the helmets were from the same production lot or same manufacturer and that some helmets were supplied with installed Helmet Sensors while others were not. All helmets were provided with full suspension systems, including the Team Wendy Zorbium® Action Pads (ZAP™) and the ACH Retention System. The ACH blunt impact test method was used to evaluate all materials throughout this effort.

### ACH Test Methodology

The purchase description CO/PD-05-04 [4] for the ACH specifies that helmets meet the Department of Transportation (DOT) Federal Motor Vehicle Safety Standard (FMVSS) 218. The DOT test method leaves considerable room for tester interpretation, which is thought to account for variation in test results seen in historical data [5]. The U.S. Army Aberdeen Test Center (ATC) recently developed an Internal Operating Procedure (IOP) that incorporates all requirements from the ACH purchase description and removes a significant amount of user interpretation from the test method. This effectively improves the reproducibility of the procedure. All tests and collected data for this effort complied with ATC's IOP.

### Preparation

Helmets were prepared prior to testing. The helmets were weighed and labeled, and the Team Wendy pads were placed into the appropriate locations as specified in the ATC IOP. Those samples that were to be evaluated as hot and cold conditioned helmets were placed into an environmental chamber at  $54.4 \pm 3$  °C and  $-10 \pm 3$  °C respectively for at least 12 h. Ambient conditioned helmets were left at  $21 \pm 10$  °C for at least 12 h.

### Test

Each helmet was impacted in seven different locations (Figure 2) twice, with the second impact occurring between 60 and 120 s after the first. Each helmet was dropped onto a hemispherical anvil, apex to apex, meaning the lowest point of the helmet would contact the highest point of the hemispherical anvil upon impact. The seven locations were impacted in the following order: Crown, Front, Rear, Left Side, Right Side, Left Nape and Right Nape. The front straps are tightened to 50% for all impacts and the back straps are tightened until the helmet is snug after each impact. The helmet was positioned to what is known as Helmet Position Index (HPI), a measured distance between the brim of the helmet and the first line on the DOT head-form. A laser gate velocity detector was used to record the velocity at every impact and a uniaxial accelerometer (vertically located at the head-form's center of gravity) was used to record acceleration during impact.

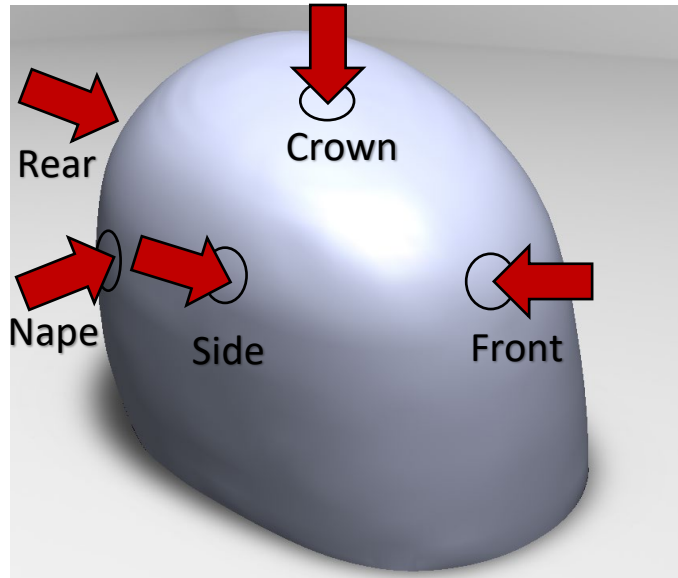


Figure 2 Impact locations shown on the DOT head-form (left nape and left side not depicted)

Head-form acceleration and drop velocity data were collected for each impact. Although the entire acceleration curve is collected, the interest of the team solely lies in the peak or maximum acceleration the head-form experiences during impact. Figure 3 depicts an acceleration curve collected from a rear helmet impact at 17.3 ft/s.

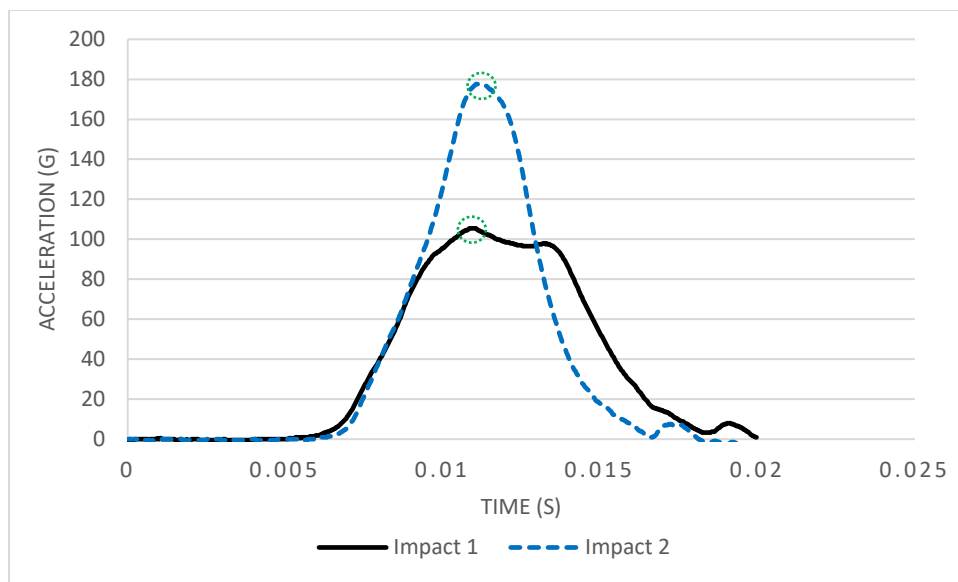


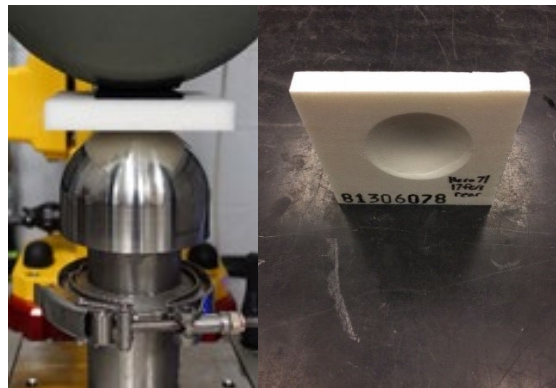
Figure 3 Acceleration data showing first and second impacts with peak values circled

All impact testing was performed using NSRDEC's Cadex monorail drop tower (Figure 1). Baseline testing at 14.1 ft/s and 17.3 ft/s was performed using the ACH without any external materials as the control for this study. As per the test method, two helmets were tested at each velocity and temperature conditions for a total of 12 helmets.

## Material Selection

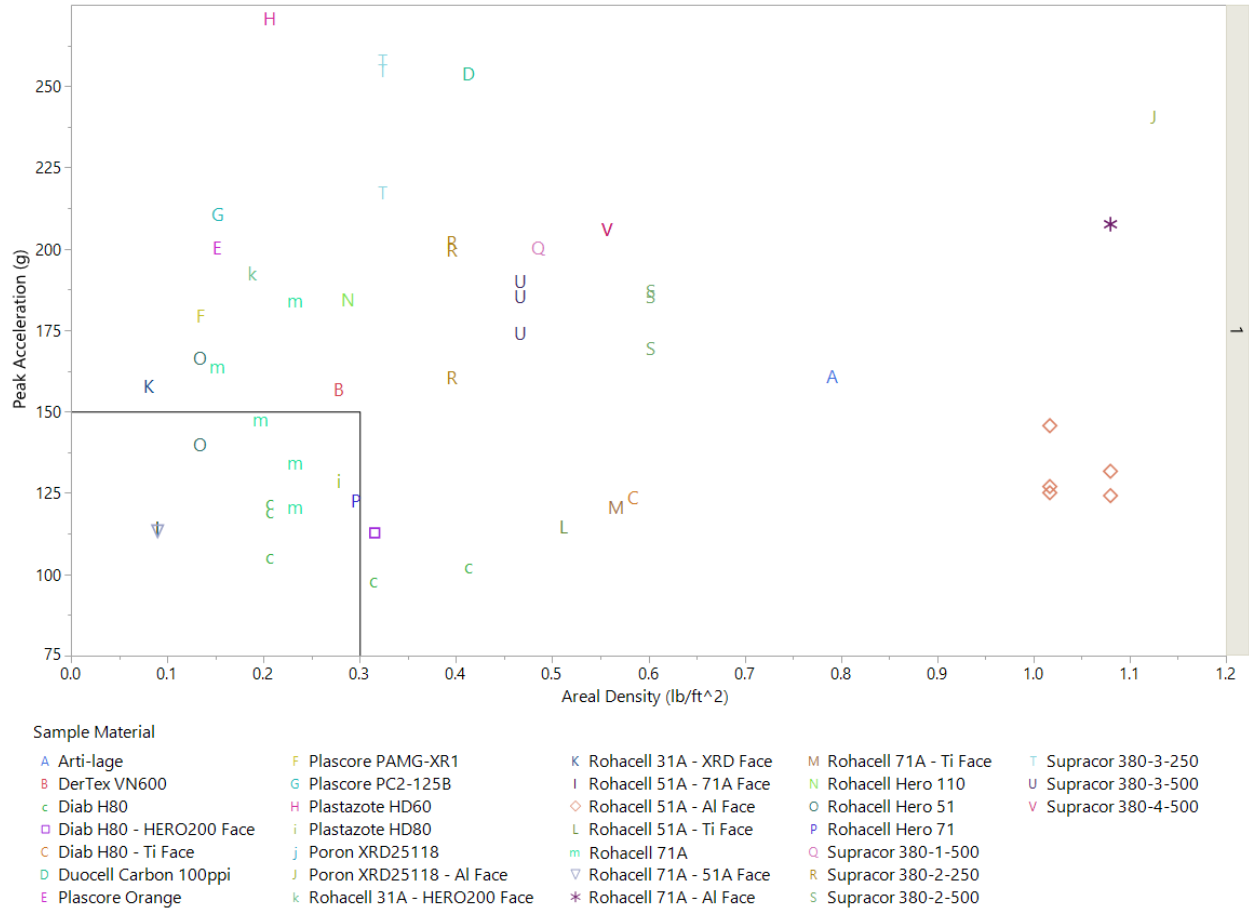
Various foam and impact attenuating materials were purchased for this study. Materials were mostly chosen to have higher strength and initial stiffness than the Team Wendy ZAP™ suspension system. This design choice enabled the external material to begin attenuating energy once the Team Wendy system was near its limit as per scenario (2), described previously.

The candidate materials were cut into 4 inch squares and affixed to the rear impact location of the ACH for blunt impact testing. The squares were attached via hook and loop at the center of the square. Team Wendy pads were replaced after each candidate sample was tested and the ACH shell was reused unless damage was observed visually (paint chips, slight indentations, etc.). The test evaluated the rear impact location at ambient temperatures in the same manner as the ATC IOP. All tests were performed at an impact velocity of 17.3 ft/s onto a hemispherical anvil. Figure 4 depicts a sample lined up just prior to impact testing (left) and a sample post impact (right).



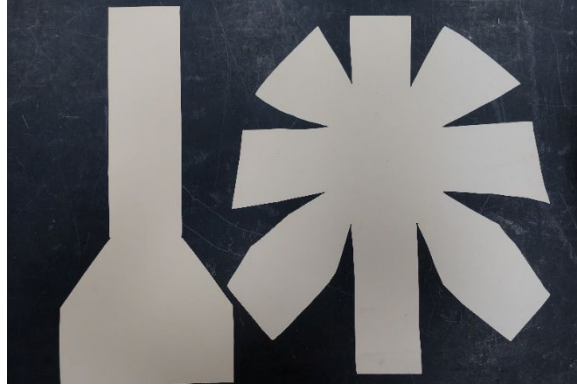
The materials were evaluated based on five criteria: peak acceleration of the head-form, mass, cost, thickness and ease of forming. Mass and peak acceleration were the most important criteria as it was assumed that prior efforts were never transitioned due to the additional mass and bulk placed onto the helmet system. The results are depicted in Figure 5. In the figure, the materials are labeled by letter and named appropriately when hybridized with another material. A bounding box was placed in the figure with the vertical line set at an areal density of 0.30 lb/ft<sup>2</sup> and the horizontal line set to 150 g. Some hybrid solutions were created, combining either a metal face plate or multiple foams stacked. Some of these solutions showed potential, in that they were able to reduce peak acceleration below the threshold. However, they often weighed significantly more, added complexity and were much more difficult to fabricate. For these reasons the hybrid solutions were not included in the down selection.

The final down selection included Rohacell® Hero 71, Hero 51, 71A and Diab Divinycell® H80. Hero 71 was chosen instead of 71A despite its better results due to the higher elongation to break which reduced the possibility of cracking upon impact. Diab Divinycell® H80 was chosen due to its low cost and ease of fabrication while showing similar performance to the Rohacell® products. Tabulated results can be found in Appendix A.

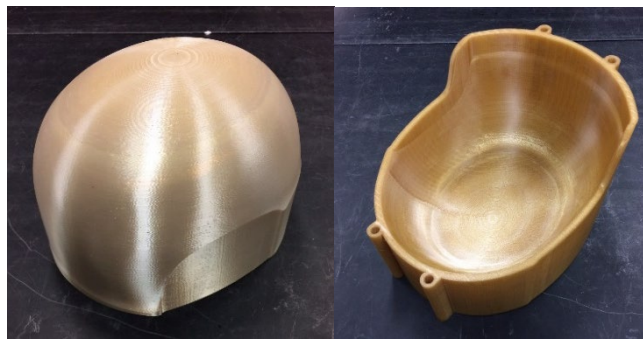


## Shell Fabrication

The final two candidates in this study were rigid foams that could be thermoformed into net shapes. When forming a flat sheet into a complex curvature, material will build up in the areas of curvature. That material must be removed by either forming in multiple parts or creating relief cuts. A “clover” pattern (Figure 6 right) was developed where the petals could fold down and form seams such that they abut when fully formed. The interior edge of each petal was chamfered on the inside. This is because the inner surface will contact before the outer surface. Due to the greater difficulty in forming Rohacell®, a “Y” shape pattern (Figure 6 left) was developed, simplifying the amount of bending required when forming the material.



Both the Diab and the Rohacell® foams were thermoformed inside a rapid prototype mold made from ULTEM 1010 (Figure 7). The mold was constructed based on the external dimension of the ACH. The offset difference between the core and cavity dimensions was calculated based on the desired shell thickness.



Unfortunately the molds were unable to withstand the temperatures and pressures they were exposed to during the forming process of Rohacell® Hero 71. Over time, the molds warped, resulting in shells that did not fit to the ACH as well as desired. Diab thermoformed at temperatures well within the rapid prototype mold capability with the caveat that Diab had a degree of spring-back that was not accounted for in the mold.



### Rohacell® Hero 71

Rohacell® Hero 71 required a drying period of 4 h at 125 °C and an internal temperature of 190 °C for thermoforming per the manufacturer’s guideline. The material rapidly lost heat upon removal from the oven, which resulted in poor mobility and cracking during the thermoforming process.

Numerous attempts at forming were made before arriving at a viable solution: overheating the exterior of the foam to get the core to the forming temperature. The foam “clover” was placed in an oven that was preheated to 230 °C for a 5 min soak. Following the soak, the foam was removed from the oven and placed over the cavity ULTEM 1010 mold to be hand formed. The core ULTEM 1010 tool was then pushed into the cavity and 40 lb of static weight was placed on top (Figure 9). The foam was allowed to cool to room temperature in the mold before removal. This process resulted in fast, simple production of the Rohacell® helmet shell.



Although this process worked to some degree, it did not produce a shell that closely conformed to the ACH. The shell did conform to the cavity mold in the crown and edge but not in the areas between. When attaching the Impact Shell to the ACH it was observed that a 1/2 inch offset existed between the helmet and shell in the crown region. When performing a drop test on the crown location, the offset resulted in the crown region shattering. The crown regions of the remaining shells were cut out, leaving the nine piece “turtle shell” pattern as seen in Figure 12, greatly reducing the gap. During each

subsequent drop the crown region still shattered after the first impact but did not affect the other regions. A crown piece that had better conformation was tested without breaking which reinforced the belief that shattering is a result of poor fit.

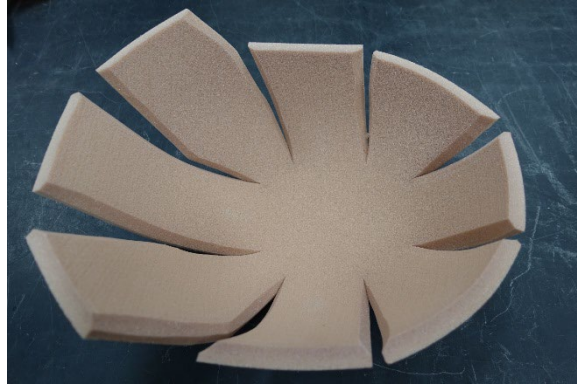
Due to the quantity of remaining material, a reduced coverage Rohacell® shell was designed. This “Y” shape pattern (Figure 10) was designed to cover the crown, front, rear and nape impact locations. The male tool was placed in the oven and heated to 230 °C. Once temperature was reached, the Rohacell® “Y” was placed on top of the tool. After a 5 min soak, the doors to the oven were opened, and the foam was formed by hand around the male tool. This method removed the gap at the crown, implying that further refinement in thermoforming should provide a more conformal “clover” style Impact Shell. The force exerted on the core mold resulted in deformation. The Heat Deflection Temperature (HDT) of ULTEM 1010 is between 210 °C and 217 °C.



*Figure 10 Rohacell® Hero 71 "Y"*

### Diab Divinycell® H80

Thermoforming Diab was a relatively simple process compared to the Rohacell®, as it is less brittle, thermoforms at a lower temperature, and retains heat longer. The material requires a core temperature of 125 °C per the manufacturer’s recommendation; for the team’s purposes, the foam was heated to 140 °C and soaked for 5 min, allowing the core to reach the thermoforming temperature. The foam was then hand pressed into the female cavity before the male tool was added. 30 lb of static weight was placed on top of the male tool to ensure that it did not shift or lose contact with the foam as it cooled. Once cooled, the foam was removed from the mold and mounted on an ACH to determine if the shell conformed adequately. Figure 11 depicts a freshly molded Diab Impact Shell.



*Figure 11 1/2in Diab Divinycell® H80 Impact Shell*

The 1 inch thick sample proved to be more difficult to form as it is much stiffer, resisted forming into the female cavity and tended to have more spring-back than the thinner material. The male tool and foam were placed in a vacuum bag and heated at 140 °C for 5 min. Vacuum was applied to slowly bend the foam into place around the male tool. Once the bag was fully evacuated, the bag and its contents were allowed to cool overnight. Upon releasing the vacuum, the foam sprang back considerably. This might require over-bending to compensate for the spring-back.

## Results

### Prototypes

In an effort to conserve material and successfully form Hero 71, two variants were developed. First the “Turtle” shell where a thermoformed “clover” pattern was broken into nine pieces and individually attached to the ACH providing full coverage (Figure 12, left side). The second was a “Y” shaped shell which proved easier to thermoform due to the reduced curvature (Figure 12, right side). This second variant did not cover the side locations. A future improvement could be to combine the two variants in order to achieve full coverage and conformance to the helmet.



Figure 12 ACH with Hero 71 "Turtle" (left), Hero 71 "Y" (right)

Unlike Hero 71, non-conformance to the shell was not a significant problem for the Diab material, as this material has a very high elongation to break and thus did not crack during impact. This was beneficial, as the Diab material did not conform to the ACH perfectly due to post molding spring-back or material relaxation. Figure 13 depicts Diab before and after testing, notably there was no cracking.

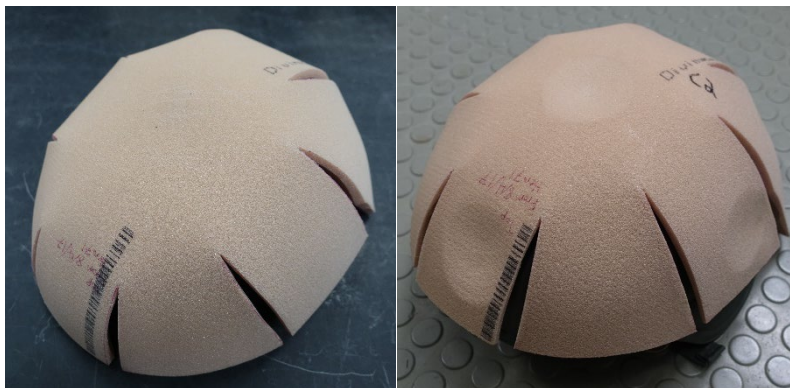


Figure 13 Impact Shell before blunt impact testing (left) after testing (right)

Each variant (Table 1) had its own set of tradeoffs. While Diab formed at a lower temperature and was the lowest cost, it also experienced the most spring-back, which made forming the 1 inch thick material difficult. Rohacell® was 10 times as expensive and formed at a much higher temperature, making the forming process more difficult with the equipment at hand. The Viconic material used in Davenport’s effort provides a benchmark for weight and performance, but not a material cost or ease of forming.

Table 1 Impact Shell variant thermoforming trade-offs

Variant	Thickness (in)	Mass (lb)	Coverage	Prototyping	Cost
Diab Divinycell® H80 - ½ inch	0.5	0.229	All locations	Easy	1x
Diab Divinycell® H80 - 1 inch	1	0.441	All locations	Moderate	1.75x
Rohacell® HERO 71 "Turtle"	0.5	0.236	All locations	Difficult	10x
Rohacell® HERO 71 "Y"	0.5	0.148	Front, crown, rear, napes	Difficult	10x
Davenport Variant 15 mm-.08 in (Viconic)	0.59	0.551	All locations	No Data	No Data

### Blunt Impact Testing – 14.1 ft/s

Ambient condition - Average peak accelerations at 14.1 ft/s are depicted in Figure 14. The first and second impacts are separated vertically in the figure. A line is drawn horizontally across each graph at an acceleration of 150g. This represents the maximum peak acceleration that is considered acceptable in order to pass the blunt impact test. As the data show, with the exception of the front impact location on the second impact, both the Diab and Rohacell® Impact Shells meet the 150g requirement at 14.1 ft/s at ambient temperature condition.

Impact locations are listed in order of impact (left to right) and each bar represents the Impact Shell variant in order from left to right. In this data set three Diab ½ inch shells, two Rohacell® ½ inch shells and two ACH baseline helmets are represented. For comparison, results from Davenport’s report were added to all graphs. The value depicted is the mean of each data set.

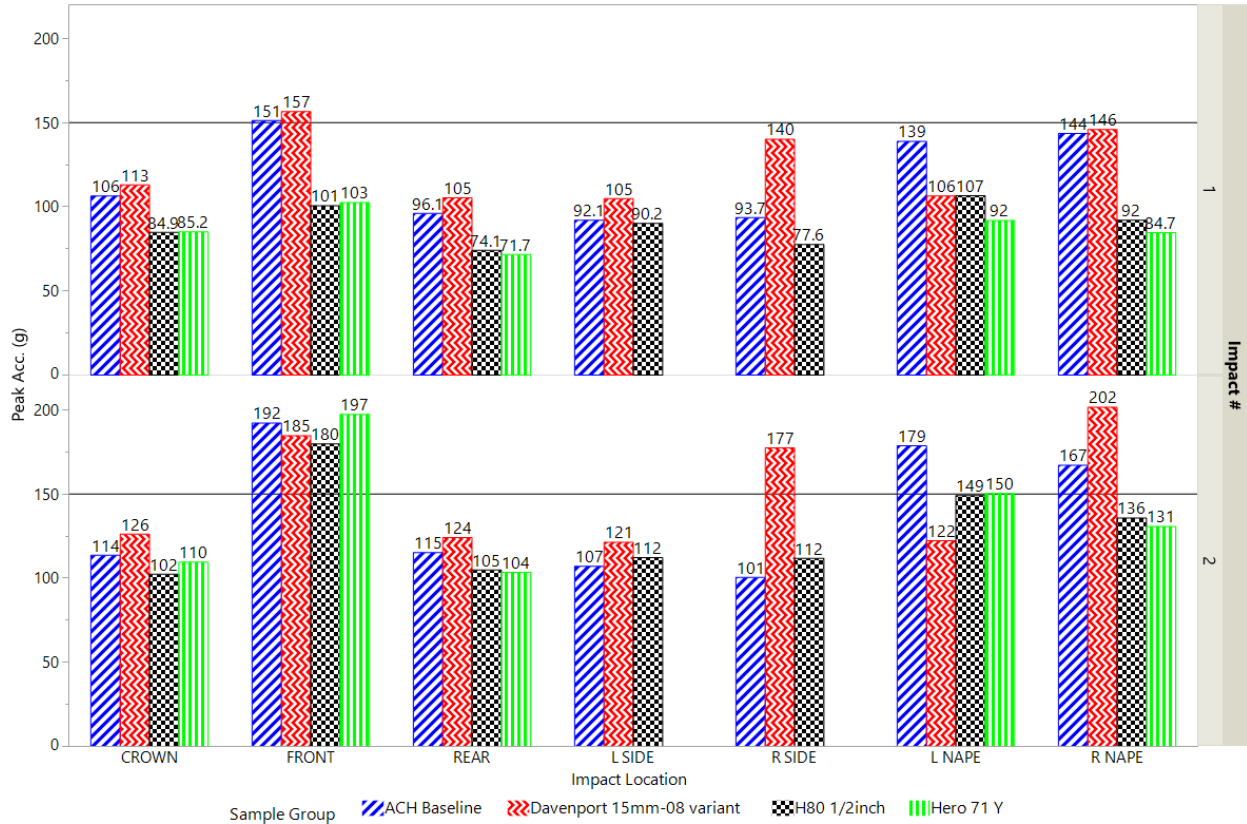


Figure 14 Ambient temperature condition, impact velocity of 14.1 ft/s, mean values

### Blunt Impact Testing - 17.3 ft/s

At an impact velocity of 17.3 ft/s, the Team Wendy ZAP™ liner reaches its limit. The foam pads can fully densify at this impact energy. When the pads reach this state of full densification, the pads can become so thin that the helmet shell makes contact with the head-form. This contact occurs between pads, making it likely to be more prevalent in larger helmets with wider gaps between the padding. This can cause large acceleration spikes, as can be seen at the rear and nape impact locations in Figure 15. This is an area where an Impact Shell can provide a significant benefit.

Due to the temperature stability and extremely low heat capacitance of the Diab and Rohacell® materials, it is thought that any changes in blunt impact performance between temperature conditions are entirely due to the internal Team Wendy pads as their material properties are more temperature dependent, as can be seen by the baseline results.

## Ambient Condition

The 1 inch thick Diab material shows the most promise at 17.3 ft/s, but still struggled to perform on the second impact due to the majority of its crushing stroke being used during the first impact. The Viconic material (as reported by Davenport) showed very good results on the second impact due to its elasticity compared to the crushable foams. In the data set shown in Figure 15, the mean values of two baseline ACH, three H80 ½” shells, three H80 1” shells, two Rohacell® “Y” shells, and four Rohacell® “Turtle” shells are represented.

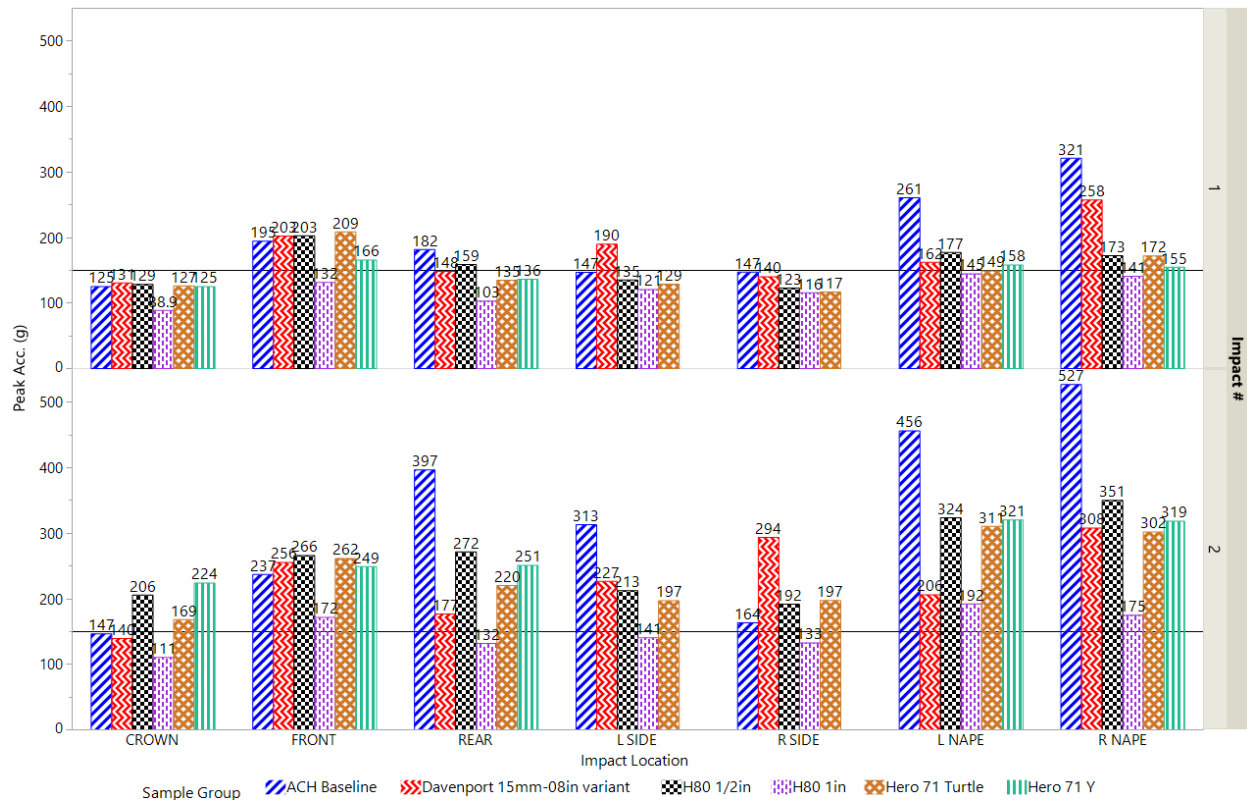


Figure 15 Ambient Condition 17.3 ft/s compare

## Hot Condition

As noted previously, the rear location poses a more significant challenge than normally expected. It appears this is caused by the Team Wendy ZAP™ placement locations defined in the IOP. There are no pads located at the rear impact location; usually at the lower velocity impacts this is not a problem because the surrounding pads are able to absorb energy from the impact. In the case of the hot condition at 17.3 ft/s, the Team Wendy ZAP™ pads are soft enough and the impact energy large enough that the pads fully compress and the helmet shell makes direct contact with the head-form during impact. Similarly this occurs at the nape locations, although high accelerations here are not as unique. The nape locations often see higher accelerations, similar to the front impact location even at lower velocities. In Figure 16, the mean values of two ACH baseline helmets, two Diab ½ inch shells, and two Rohacell® “Y” shells are represented.

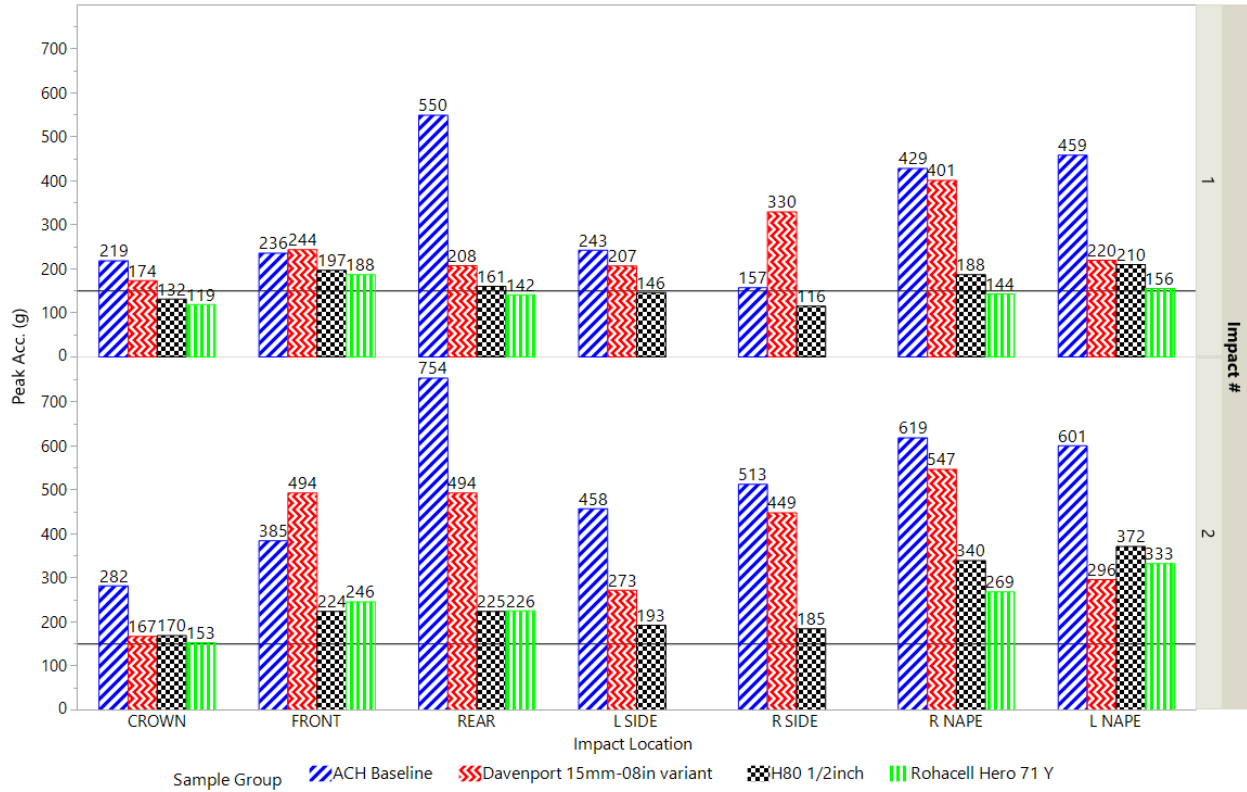


Figure 16 Hot Condition 17.3 ft/s compare

### Cold Condition

The cold condition stiffens the Team Wendy ZAP™ system, thereby greatly reducing peak acceleration demonstrated by all samples throughout the test. In some cases the baseline ACH (no Impact Shell) shows equal impact attenuation to the tests with an Impact Shell. The average peak acceleration of two ACH baseline helmets, two Diab ½ inch shells, and two Rohacell® “Y” shells are represented in Figure 17 below.

The Rohacell® “Y” variant did not survive the first impact at the nape location. Poor fit in the nape regions caused large bending strains, cracking the material due to its low elongation at break.

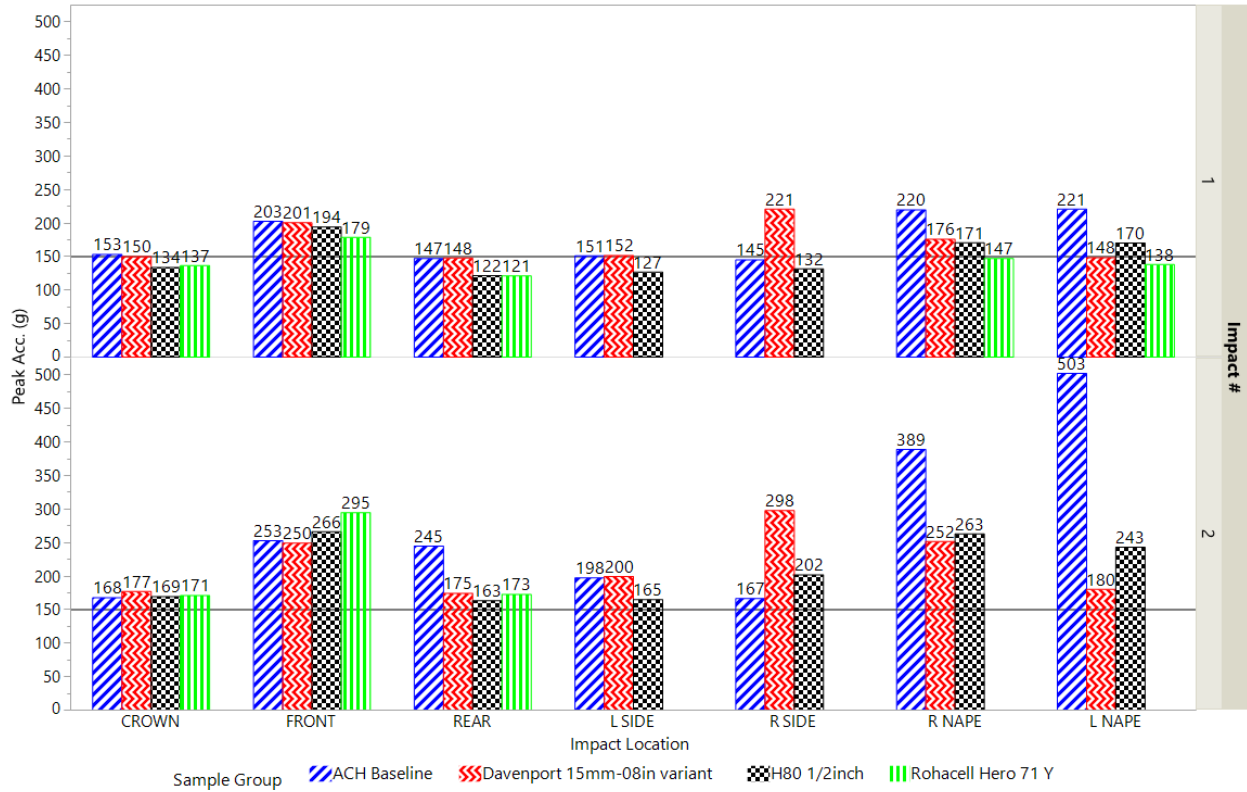


Figure 17 Cold Condition 17.3 ft/s Compare

## Conclusions

It has been shown that a light weight Impact Shell applique can significantly reduce acceleration at impact velocities of 14.1 ft/s and 17.3 ft/s as compared to the standard ACH configuration in some conditions. In the case of the Diab Divinycell® H80 solution, the Impact Shell materials are low cost and easily manufactured. However, the Impact Shell did not reduce acceleration below the 150g requirement for all seven locations for both first and second impact. Most importantly, this study has shown a reduction of peak acceleration below 150g in the rear and side locations on the first impact in ambient condition for both the 14.1 ft/s and 17.3 ft/s velocities. It is speculated that these locations would be of significant importance to airborne Soldiers due to an assumed higher probability of a rear impact upon landing.

Both materials had their own set of difficulties encountered when forming. The resultant Diab Impact Shells did not fit perfectly over the ACH due to spring back post molding. The Rohacell® Hero 71 Impact Shells were difficult to form with equipment on hand, resulting in imperfect forming and the use of alternative shaping techniques. Rohacell® Hero 71, although less brittle than other Rohacell® materials, would often shatter during blunt impact testing due to bending loads, especially at these higher velocities. If Rohacell® or other low elongation to break materials are used, it is suggested that a low profile attachment mechanism be considered to prevent early failure through bending. If a material like Diab was to move forward it would be suggested to create a mold that accounts for spring-back effects in order to more closely match the Impact Shell to the outside of a helmet.

Future work in product development could optimize material thickness providing more protection in the front and nape regions while possibly reducing material in other areas that are thought to be less prone to impact (e.g. crown). Other optimization efforts could include the development of improved internal pads which assist in boosting the performance of the impact shell.

## References

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## Appendix A – Down Selection Data

Sample Material	Sample Face	Thickness (in)	Face Thickness (in)	Mass (lb)	Face Mass (lb)	Total Mass (lb)	Areal Density (lb/ft <sup>2</sup> )	Impact Number	Peak Acceleration (g)	Velocity (m/s)	Drop Height (cm)
Rohacell® 51A - Al Face	7075 Aluminum	0.5	0.06	0.015	0.098	0.113	1.017	1	127	5.2	145
Rohacell® 51A - Al Face	7075 Aluminum	0.5	0.06	0.015	0.098	0.113	1.017	2	165.4	5.2	145
Rohacell® 71A - Al Face	7075 Aluminum	0.5	0.06	0.022	0.098	0.12	1.08	1	207.6	6.0	190
Rohacell® 71A - Al Face	7075 Aluminum	0.5	0.06	0.022	0.098	0.12	1.08	2	165.4	5.2	145
Rohacell® 51A - Al Face	7075 Aluminum	0.5	0.093	0.015	0.152	0.167	1.503	1	156	6.0	190
Rohacell® 51A - Al Face	7075 Aluminum	0.5	0.093	0.015	0.152	0.167	1.503	2	306.9	6.0	190
Arti-lage	Arti-lage	0.25	0.25	0.044	0.044	0.088	0.792	1	161.2	5.3	148
Arti-lage	Arti-lage	0.25	0.25	0.044	0.044	0.088	0.792	2	266.2	5.3	148
DerTex VN600		0.5		0.031	0	0.031	0.279	1	156.9	5.3	148
DerTex VN600		0.5		0.031	0	0.031	0.279	2	223.4	5.3	148
Diab H80		1		0.046	0	0.046	0.414	1	102.4	5.3	148
Diab H80		1		0.046	0	0.046	0.414	2	141.5	5.3	148
Diab H80		0.5		0.023	0	0.023	0.207	1	122.3	5.3	148
Diab H80		0.5		0.023	0	0.023	0.207	2	226.8	5.3	148
Diab H80		0.75		0.035	0	0.035	0.315	1	98.2	5.3	148
Diab H80		0.75		0.035	0	0.035	0.315	2	152.7	5.3	148
Diab H80		0.5		0.023	0	0.023	0.207	1	105.4	5.3	148
Diab H80		0.5		0.023	0	0.023	0.207	2	177.6	5.3	148
Duocell Carbon 100ppi		0.5		0.046	0	0.046	0.414	1	254	5.3	148
Duocell Carbon 100ppi		0.26		0.024	0	0.024	0.216	1	366	5.3	148.5

Sample Material	Sample Face	Thickness (in)	Face Thickness (in)	Mass (lb)	Face Mass (lb)	Total Mass (lb)	Areal Density (lb/ft <sup>2</sup> )	Impact Number	Peak Acceleration (g)	Velocity (m/s)	Drop Height (cm)
Rohacell® 51A - Al Face	7075 Aluminum	0.5	0.06	0.015	0.098	0.113	1.017	1	125.1	5.3	148
Rohacell® 51A - Al Face	7075 Aluminum	0.5	0.06	0.015	0.098	0.113	1.017	2	217	5.3	148
Rohacell® 51A - Al Face	7075 Aluminum	0.5	0.06	0.015	0.098	0.113	1.017	1	145.7	5.3	148
Rohacell® 51A - Al Face	7075 Aluminum	0.5	0.06	0.015	0.098	0.113	1.017	2	322.4	5.3	148
Supracor 380-2-250		0.25		0.044	0	0.044	0.396	1	200.1	5.3	148
Supracor 380-2-250		0.25		0.044	0	0.044	0.396	1	202.4	5.3	148
Supracor 380-2-500		0.5		0.067	0	0.067	0.603	1	169.6	5.3	148
Supracor 380-2-500		0.5		0.067	0	0.067	0.603	1	185.6	5.3	148
Supracor 380-3-250		0.25		0.036	0	0.036	0.324	1	258.2	5.3	148
Supracor 380-3-250		0.25		0.036	0	0.036	0.324	1	217.4	5.3	148
Supracor 380-3-500		0.5		0.052	0	0.052	0.468	1	174.3	5.3	148
Supracor 380-3-500		0.5		0.052	0	0.052	0.468	1	190.3	5.3	148
Rohacell® 71A - 51A Face	Rohacell® 51A	0.2	0.1	0.006	0.004	0.01	0.09	1	113.4	5.3	148
Rohacell® 71A		0.6		0.026	0	0.026	0.234	1	134.5		148
Rohacell® 71A		0.6		0.026	0	0.026	0.234	1	184.2	5.3	148
Rohacell® 51A - 71A Face	Rohacell® 71A	0.2	0.1	0.004	0.006	0.01	0.09	1	114.3	5.3	148
Expanded Polystyrene		0.75		0	0	0	0	1	185.1	5.3	148
Diab H80		0.5		0.023	0	0.023	0.207	1	119.5	508000.0	148.5
Diab H80		0.5		0.023	0	0.023	0.207	2	227.3	5.3	148.5
Diab H80 - HERO200 Face	Rohacell® Hero 200	0.5	0.1	0.023	0.012	0.035	0.315	1	112.9	5.3	148.5
Diab H80 - HERO200 Face	Rohacell® Hero 200	0.5	0.1	0.023	0.012	0.035	0.315	2	159.3	5.3	148.5
Diab H80 - Ti Face	TiFS*	0.5	0.016	0.023	0.042	0.065	0.585	1	123.7	5.3	148.5
Diab H80 - Ti Face	TiFS*	0.5	0.016	0.023	0.042	0.065	0.585	2	163.5	5.3	148.5

Sample Material	Sample Face	Thickness (in)	Face Thickness (in)	Mass (lb)	Face Mass (lb)	Total Mass (lb)	Areal Density (lb/ft <sup>2</sup> )	Impact Number	Peak Acceleration (g)	Velocity (m/s)	Drop Height (cm)
Plastazote HD60		0.675		0.023	0	0.023	0.207	1	270.9	5.3	148
Plastazote HD60		0.675		0.023	0	0.023	0.207	2	427.4	5.3	148
Plastazote HD80		0.675		0.031	0	0.031	0.279	1	128.9	5.3	148
Plastazote HD80		0.675		0.031	0	0.031	0.279	2	220.2	5.3	148
Rohacell® Hero 110		0.5		0.032	0	0.032	0.288	1	184.6	5.3	148
Rohacell® Hero 110		0.5		0.032	0	0.032	0.288	2	232.9	5.3	148
Rohacell® Hero 71		0.75		0.033	0	0.033	0.297	1	122.8	5.3	148
Rohacell® Hero 71		0.75		0.033	0	0.033	0.297	2	189.8	5.3	148
Rohacell® Hero 51		0.5		0.015	0	0.015	0.135	1	166.6	5.3	148
Rohacell® Hero 51		0.5		0.015	0	0.015	0.135	2	229.9	5.3	148
Rohacell® Hero 51		0.5		0.015	0	0.015	0.135	1	140.1	5.3	148
Rohacell® Hero 51		0.5		0.015	0	0.015	0.135	2	347.7	5.3	148
Plascore Orange		0.5		0.017	0	0.017	0.153	1	200.6	5.3	148
Plascore PAMG-XR1		0.5		0.015	0	0.015	0.135	1	179.5	5.3	148
Plascore PC2-125B		0.4		0.017	0	0.017	0.153	1	210.9	5.3	148
Rohacell® 31A - XRD Face	Poron XRD20236*	0.5	0.236	0.009	0	0.009	0.081	1	157.9	5.3	148
Rohacell® 31A - XRD Face	Poron XRD20236*	0.5	0.236	0.009	0	0.009	0.081	2	243.2	5.3	148

Sample Material	Sample Face	Thickness (in)	Face Thickness (in)	Mass (lb)	Face Mass (lb)	Total Mass (lb)	Areal Density (lb/ft <sup>2</sup> )	Impact Number	Peak Acceleration (g)	Velocity (m/s)	Drop Height (cm)
Rohacell® 51A - Ti Face	TiFS*	0.5	0.016	0.015	0.042	0.057	0.513	1	114.8	5.3	148.5
Rohacell® 51A - Al Face	7075 Aluminum	0.5	0.093	0.015	0.152	0.167	1.503	1	133.1	5.3	148
Rohacell® 51A - Al Face	7075 Aluminum	0.5	0.093	0.015	0.152	0.167	1.503	2	233.4	5.3	148
Rohacell® 51A - Al Face	7075 Aluminum	0.75	0.06	0.023	0.098	0.12	1.08	1	131.7	5.3	148
Rohacell® 51A - Al Face	7075 Aluminum	0.75	0.06	0.023	0.098	0.12	1.08	2	204.8	5.3	148
Rohacell® 51A - Al Face	7075 Aluminum	0.75	0.06	0.023	0.098	0.12	1.08	1	124.2	5.3	148
Rohacell® 51A - Al Face	7075 Aluminum	0.75	0.06	0.023	0.098	0.12	1.08	2	186	5.3	148
Rohacell® 71A		0.5		0.022	0	0.022	0.198	1	147.6	5.3	148.5
Rohacell® 71A - Ti Face	TiFS*	0.5	0.016	0.022	0.042	0.063	0.567	1	120.9	5.3	148.5
Rohacell® 31A - HERO200 Face	Rohacell® Hero 200	0.5	0.1	0.009	0.012	0.021	0.189	1	192.6	5.3	148
Rohacell® 71A		0.21		0.009	0	0.009	0.081	1	321	5.3	148
Rohacell® 71A		0.4		0.017	0	0.017	0.153	1	164	5.3	148
Rohacell® 71A		0.59		0.026	0	0.026	0.234	1	120.9	5.3	148
Rohacell® 71A		0.59		0.026	0	0.026	0.234	2	227.7	5.3	148
Supracor 380-1-500		0.5		0.054	0	0.054	0.486	1	200.6	5.3	148
Supracor 380-2-250		0.25		0.044	0	0.044	0.396	1	160.7	5.3	148
Supracor 380-2-250		0.25		0.044	0	0.044	0.396	2	193.5	5.3	148
Supracor 380-2-500		0.5		0.067	0	0.067	0.603	1	187.4	5.3	148

Sample Material	Sample Face	Thickness (in)	Face Thickness (in)	Mass (lb)	Face Mass (lb)	Total Mass (lb)	Areal Density (lb/ft <sup>2</sup> )	Impact Number	Peak Acceleration (g)	Velocity (m/s)	Drop Height (cm)
Supracor 380-3-250		0.25		0.036	0	0.036	0.324	1	254.9	5.3	148
Supracor 380-3-250		0.25		0.036	0	0.036	0.324	2	464.4	5.3	148
Supracor 380-3-500		0.5		0.052	0	0.052	0.468	1	185.6	5.3	148
Supracor 380-3-500		0.5		0.052	0	0.052	0.468	2	290.1	5.3	148
Supracor 380-4-250		0.25		0	0	0	0	1	322.4	5.3	148
Supracor 380-4-250		0.25		0	0	0	0	2	420.8	5.3	148
Supracor 380-4-500		0.5		0.062	0	0.062	0.558	1	206.2	5.3	148
Supracor 380-4-500		0.5		0.062	0	0.062	0.558	1	206.2	5.3	148
Poron XRD25118 - Al Face	7075 Aluminum	0.118	0.06	0.027	0.098	0.125	1.125	1	240.9	5.3	148
Poron XRD25118		0.118	0.06	0.027	0.098	0.125	1.125	2	315.4	5.3	148

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## Appendix B – Selected Graphs

