REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 27-04-2020	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 20-Dec-2016 - 19-Dec-2017

4. TITLE AND SUBTITLE

Final Report: Commercialization of Rate Sensitive Low Density Polyurea-Based Viscoelastic Foams For Head Health Applications

5a. CONTRACT NUMBER
W911NF-17-1-0054

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
106011

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

University of California - Los Angeles
Office of Contract and Grant Administration
11000 Kinross Avenue, Suite 211
Los Angeles, CA 90095 -1406

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
69979-SD-ICR.1

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON 19b. TELEPHONE NUMBER
UU	UU	UU	UU		Vijay Gupta 310-825-0223

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 28-Apr-2020

Agency Code:

Proposal Number: 69979SDICR **Agreement Number: W911NF-17-1-0054**

INVESTIGATOR(S):

Name: PhD Vijay Gupta
Email: vgupta@ucla.edu
Phone Number: 3108250223
Principal: Y

Organization: **University of California - Los Angeles**
Address: Office of Contract and Grant Administration, Los Angeles, CA 900951406
Country: USA
DUNS Number: 092530369 EIN: 956006143
Report Date: 19-Mar-2018 Date Received: 27-Apr-2020
Final Report for Period Beginning 20-Dec-2016 and Ending 19-Dec-2017
Title: Commercialization of Rate Sensitive Low Density Polyurea-Based Viscoelastic Foams For Head Health Applications
Begin Performance Period: 20-Dec-2016 **End Performance Period:** 19-Dec-2017
Report Term: 0-Other
Submitted By: PhD Vijay Gupta Email: vgupta@ucla.edu
Phone: (310) 825-0223
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 1 **STEM Participants:** 3

Major Goals: The aim of this I Corps @ DoD grant was to seek commercialization of a new class of polyurea-based viscoelastic foams developed at UCLA for Head Health applications that in the lab-setting outperformed the state of the art polyurethane foams and their currently marketed protective headgear products by a significant margin.

Accomplishments: Two manufacturing processes were explored-a conventional “pour in place” box approach and the continuous sheet casting process. Given that Foam A application domain was helmets that requires 0.75” -1.25” foam sections, it was decided that this foam would be best manufactured by the pour in place box approach. Foams B and C with much thinner sections were ideally suited for the continuous casting process. We had two industry partners. For the box approach, we worked with TMI, Inc. (Corona, CA), under direct supervision of one of its owners Mr. John Tuccinardi. The continuous sheet casting process was developed for Foams B and C at the United Specialty Foam (USF) located in Newark, Delaware. Dr. Chiu, the owner of USF, with over 30 years of experience in the foam casting business worked directly on this effort.

Details of these processes are discussed in the attached pdf.

Training Opportunities: EL Ramirez, a graduate student, was trained to manufacture novel foams using industrial processes.

PI Gupta and EL Ramirez took the NSF I Corps course and learned about product development and marketing analysis.

Results Dissemination: 1. Foams were used in the shoes of US Olympians and few professional basketball players for reducing impact-related injuries.
2. A major multi-national shoe company is presently testing the UCLA foam for making the midsoles.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Foams were used in the shoes of US Olympians and few professional basketball players for reducing impact-related injuries.
2. A major multi-national shoe company is presently testing the UCLA foam for making the midsoles.
3. Full90, Riddell, O'Neil are ready to market products with the UCLA technology.

PARTICIPANTS:

Participant Type: PD/PI
Participant: vijay gupta
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Brian Ramirez
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Final Report: Commercialization of Rate Sensitive Low Density Polyurea-Based Viscoelastic Foams For Head Health Applications

I Corps @DoD Grant

Vijay Gupta, Professor, Principal Investigator
Department of Mechanical and Aerospace Engineering,
Department of Materials Science and Engineering,
Department of Biomedical Engineering, UCLA
vgupta@ucla.edu

1. Project Goals

The aim of this I Corps @ DoD grant was to seek commercialization of a new class of polyurea-based viscoelastic foams developed at UCLA for Head Health applications that in the lab-setting outperformed the state of the art polyurethane foams and their currently marketed protective headgear products by a significant margin. During the course of commercialization, additional shock testing of foams was performed at UCLA using shock tubes where the shock pressures could be carefully monitored, and also at the Naval Surface Warfare Center, MD, under realistic blast conditions, all of which confirmed the potential benefits of UCLA foams over the currently used Wendy foams inside the ACH helmets. These additional tests showed that the shock performance of UCLA foams could be enhanced further by reducing their density to 64 kg/m^3.

The report is organized in the following manner. In the next section, a background to UCLA foams is provided, including prior test data that highlights the potential benefits of UCLA foams over the state of the art helmet technology. This is followed by a discussion on the commercialization efforts that were taken under the I Corps @ DoD grant that resulted in the development of process variables and foam recipes for large-scale production of UCLA foams with identical microstructure and impact properties as the lab samples. A summary of the results from the NSF I Corps workshop is provided next. Data from further shock tube testing and blast loading of foams made using the commercial recipe is discussed next. The report ends with recommendations and preliminary results from a new viscoelastic composite foam concept that is able to absorb more energy than the ubiquitously used EPS foams even under ordinary strain rate conditions. Being viscoelastic, the composite foams recover fully after each impact while their EPS foam counterparts which deform plastically must be replaced after each impact.

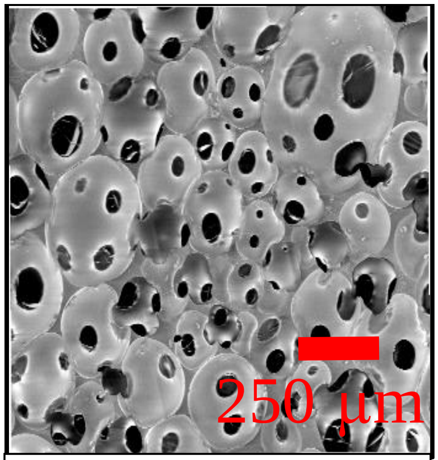


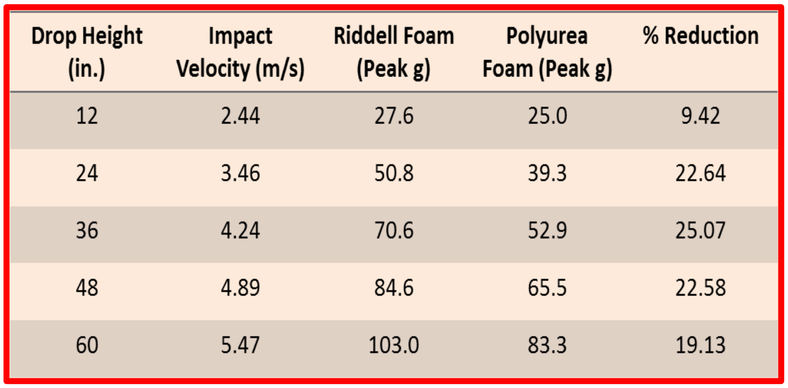
Figure 1

2. Introduction and Background-UCLA Foams

A new class of polyurea-based viscoelastic foams with a novel microstructure for *Head Health applications* was recently developed at UCLA. These foams outperform the state-of-the-art polyurethane foams *and* their currently marketed protective headgear products by a significant margin when tested in various industry and government standard helmet tests. The transmitted g's through the same foam thickness (0.5"-1") in ACH and Riddell football helmets are reduced by an additional 18% to 32%, depending upon the magnitude of the impact force and test temperature. The superior impact properties of the UCLA foams are due to their unique microstructure (Figure 1) that comprises of large polyhedral cells (300μm -500μm) covered with perforated membranes with small apertures (20μm-70μm). This makes them strain rate sensitive as the rate at which the air escapes the cells depend upon the loading rate. Thus, even with their uniform microstructure, they behave as an elastically modulated layered composite because the cells stiffen or soften in response to the changing loading rate within the same impact event. At lower strain rate, typically at the start of the loading event, big cells simply collapse with air escaping freely through tiny perforations. This limits the excess buildup of stress like any other viscoelastic foam. As loading proceeds, both strain rate and level of material stress increases. During this phase, the rate at which the air escapes the cells cannot catch up with the rate of loading. Consequently, the air that remains inside each cell acts to stiffen the cell while the air that escapes adds to viscoelastic damping. Each cell essentially acts like a viscoelastic damper on the microstructural length scale. Therefore, UCLA foams are able to manage the <u>**varying material strain rate that occurs within the same loading event**</u> without the need to modulate the material density or stiffness. It is well known that such composite layered structures with modulated stiffness or density are the most efficient in managing impact. Such structures are however merely theoretical as they cannot be manufactured in a *single* low cost manufacturing step. UCLA foams effectively function like one with their *uniform* microstructure.

Table 1 shows the performance of football helmets made using UCLA foams in comparison to Riddell helmets that are cushioned by the state-of-the-art vinyl nitrile (VN) foams. Transmitted g's were measured when both helmets were dropped from different heights in the NOCSAE standard test under ambient conditions. This was motivated by the fact that in a typical NFL season there are over 200 hits that correspond to the lower NOCSAE drop heights and very few that relate to the 60" drop. Most commercial foams are designed to perform at the highest drop height but unfortunately that makes them stiff at the lower drop heights. UCLA foams have the remarkable property to stiffen up with the increase in the strain rate (drop height). This property allows UCLA foam helmets to outperform the Riddell helmets at every drop height of the NOCSAE test by 19% to 25%. This is equivalent to additionally reducing the probability of

Table 1



Drop Height (in.)	Impact Velocity (m/s)	Riddell Foam (Peak g)	Polyurea Foam (Peak g)	% Reduction
12	2.44	27.6	25.0	9.42
24	3.46	50.8	39.3	22.64
36	4.24	70.6	52.9	25.07
48	4.89	84.6	65.5	22.58
60	5.47	103.0	83.3	19.13

concussion in a NFL player by the same amount. This dependency of the foam stiffness on the strain rate can be the key to reducing injuries in all sports.

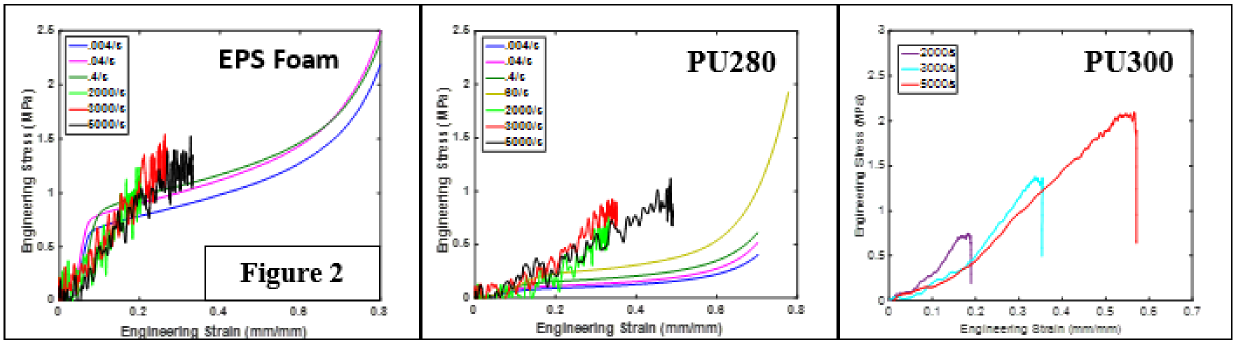


Figure 2

To highlight the effect of aperture size in strain rate strengthening and energy absorption without increasing the foam density, two foams of very similar densities, PU280 (280 kg/m^3) and PU300 (300 kg/m^3), were manufactured. The nominal cell size in both foams was 550 µm with aperture diameters of 66 µm (PU280) and 20 µm (PU300). Samples with 17 mm diameter and 19 mm nominal thickness were tested in the split-Hopkinson pressure bar setup at Caltech. These dimensions allowed development of dynamic equilibrium as previously shown for soft materials. EPS of density 72 kg/m^3 was chosen as the reference material. Tests were also done at low strain rate ($\leq 10^{-1}$ s^{-1}) on a 2kN capacity Instron Micro-Tester (Model 5942) and intermediate strain rate (10-100 s^{-1}) using the drop tower facility. The measured stress-strain characteristics for the PU280, PU300, and EPS72 materials at strain rates of 3000 s^{-1}, 4000 s^{-1}, and 5000 s^{-1} are shown in Figure 2. At these high strain rates, it can be seen that EPS is still strain rate insensitive, having a consistent plateau stress around 1.2 MPa across all strain rates. However, the difference in strain rate sensitivity between PU280 and PU300 can be seen. PU280 tends to become strain rate insensitive at strain rates above 1000 s^{-1}, while PU300 exhibits an increase in plateau stress with increasing strain rate. The aperture size in PU300 foam is about three times smaller than in PU280 foam and therefore requires more force to expel the air out of the cells. This makes PU300 rate sensitive even at higher strain rates. Therefore, the ability to control the aperture size in low density foams can give rise to an increase in strength with increasing deformation rate. The energy absorption as a function of strain rate (high strain rates) is displayed for PU280, PU300, and EPS72 materials in Figure 3. At these high strain rates, the UCLA foams have similar energy absorption capabilities as the EPS72 material while also maintaining the peak stress below the TBI threshold of 1.5 MPa. EPS is however a single hit material that absorbs energy through plastic crushing and therefore must be replaced after each hit, whereas UCLA foams are viscoelastic and recover fully after each hit. This is an amazing feat that no other viscoelastic foam has ever accomplished. This high strain rate property of UCLA foams can be exploited in the military helmets which unlike sports and motorcycle helmets are exposed to blast waves that subject the brain/helmet system to loading rates generated in the Hopkinson bar setup. The capability of the UCLA foams to recover fully after each impact was demonstrated by impacting the same sample of Foam A repeatedly every 30s with a 5.5kg mass indenter head.

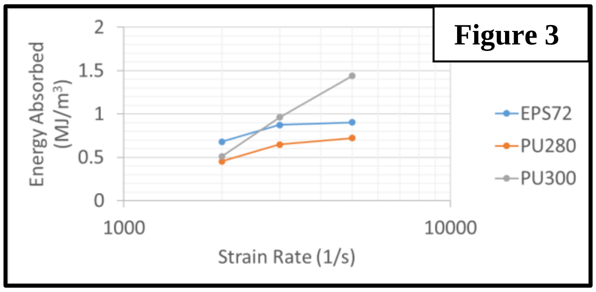


Figure 3

After 50 hits, peak forces from all tests fell within the 0.967 ±0.03kN data band. This shows that even the most viscoelastic of our material (Foam A) can fully recover within 30 seconds.

Figure 4 demonstrates how even with a density of only 95kg/m^3, the UCLA Foam A outperforms VN foam (density of 109 kg/m^3), the UCLA/HRL lattice material that was one of the recipients of the Head Challenge II prize (density of 245kg/m^3), and the widely used thermoplastic polyurethane (TPU) foam with a density of 170kg/m^3. These tests were done using a 1kg 25mm-dia flat indenter impacting the sample placed on a large rigid flat plate.

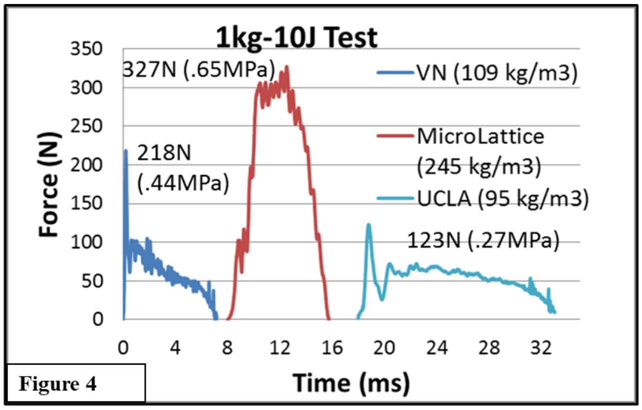


Figure 4

The most attractive feature of our material is that through innovative processing steps we have learned how to tailor the mechanical properties of the micro-scale struts and control microstructural features (cell size, cell wall thickness, number and size of apertures) *independently* by changing the degree of hardness and level of cross-linking. This is done by increasing the material index and through the use of suitable additives. This allows us to retain the above microstructural features in a wide range of foam densities (90 kg/m^3 to 400 kg/m^3) in sections of 50 mm (2 inch) thicknesses. Our ability to tailor the local mechanical properties of the foam skeleton, *independent of the pore size distribution and structure*, is demonstrated in Figure 5 which shows the transmitted impact force data for two dramatically different foam densities (95 kg/m^3 and 170 kg/m^3) to be identical! This expands the application domain of our material considerably as it can be tailored to withstand a range of dynamic forces and impact velocities. Foams were then developed for two more applications in addition to those developed with the use of a hard shell (**Foam A**) as discussed above. **Foam B** with a density of 200kg/m^3 was developed for Head Health applications that do not involve the use of a hard shell (soft helmets, soccer headbands, and skull caps, midsoles of shoes), and **Foam C** was developed for applications where the performance of *existing* products, such as helmets and shoes, is significantly enhanced by putting a thin layer of UCLA foam on top of the existing foams in these products. For example, using a 3-4 mm thick layer of Foam C material as a sock liner in running shoes, a reduction in the heel impact force between 20% and 27% was accomplished depending upon the weight of the runner. The same layer when used on top of the EPS foam in a DOT-approved motorcycle helmet resulted in an additional attenuation of 25%.

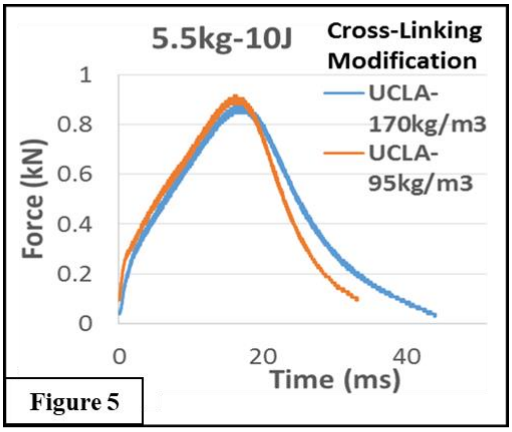


Figure 5

Under the I Corps program we sought to develop industrial manufacturing processes for Foams A, B, and C and explore their commercial viability.

3. Commercialization of UCLA Foams

Two manufacturing processes were explored-a conventional “pour in place” box approach and the continuous sheet casting process. Given that Foam A application domain was helmets that requires 0.75” -1.25” foam sections, it was decided that this foam would be best manufactured by the pour in place box approach. Foams B and C with much thinner sections were ideally suited for the continuous casting process. We had two industry partners. For the box approach, we worked with TMI, Inc. (Corona, CA), under direct supervision of one of its owners Mr. John Tuccinardi. The continuous sheet casting process was developed for Foams B and C at the United Specialty Foam (USF) located in Newark, Delaware. Dr. Chiu, the owner of USF, with over 30 years of experience in the foam casting business worked directly on this effort.

Pour In Place Box Approach

TMI is a relatively small molded foam manufacturer and therefore was very open to new process development and innovation. They had a single-mold pilot facility that was dedicated to create the industrial version of the UCLA foam recipe. TMI’s close proximity to UCLA was a great help. Both PI Gupta and Entrepreneur Lead (EL) Ramirez worked at the TMI site to develop the recipe. Unlike the lab samples that were prepared by hand mixing the A and B components in a bucket and then poured into a mold, the industrial samples were manufactured by using the material supply lines connected to 55 gallon tots with computer-controlled pumps and metering heads. Component B was compounded with surfactant, catalyst, water, and other ingredients as per the lab recipe. We started with the lab recipe and then fine-tuned the process variables to reduce the undesired foam splitting and non-uniform mold fill which could be visually spotted.

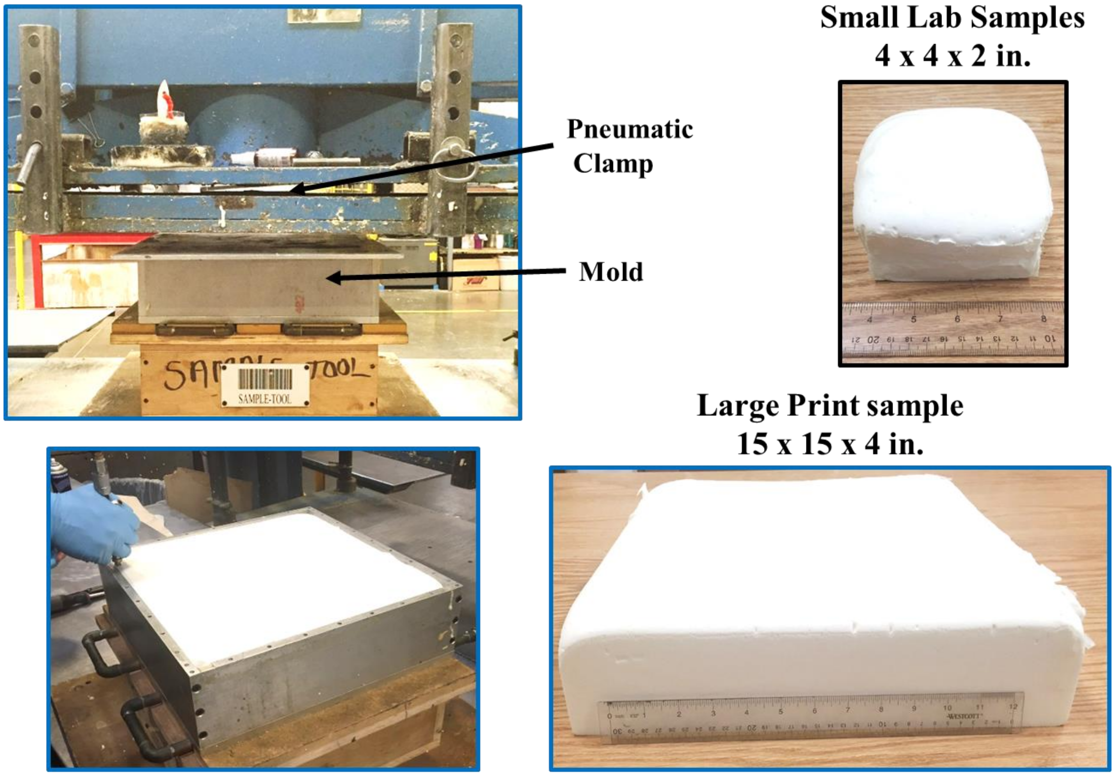
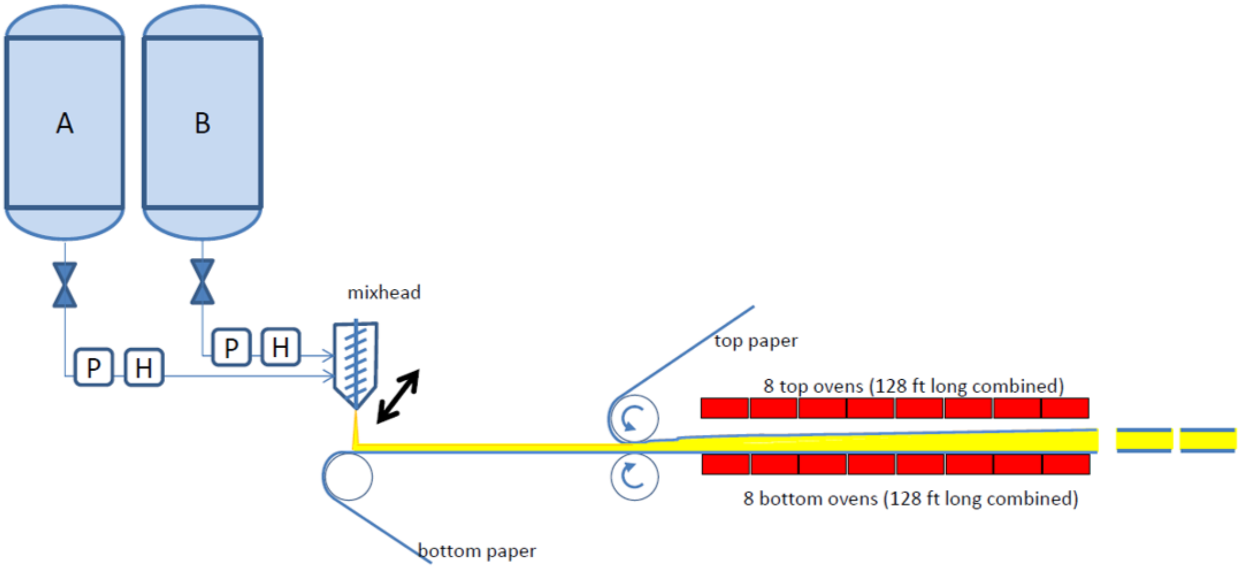


Figure 6. Large Scale Manufacturing

The most attractive part of our manufacturing process is that it does not require any curing after the foam has been fully blown. It has a cream time of 20 seconds and the foam block is fully formed in 120 seconds. Figure 6 shows a snapshot of the industrial mold foaming process that resulted in a successful foam brick of the desired density. Once this process was perfected we then took samples from the industrial foam brick and matched the microstructure and impact properties with that of the lab samples. These tests were carried out at UCLA. This process led to fine tuning of the surfactant, water, catalysts, material index, and cross-linking agent ratios till the desired impact properties were obtained. This process was tedious but ultimately resulted in the development of an industrial foam recipe that showed identical microstructure and impact properties as the lab samples. This was confirmed by making ACH, football, and motorcycle helmets and subjecting them to DOT, NOCSAE and military standards at the ACT and DRI labs. This process from the single mold pilot facility can be uploaded onto a carousel that is capable of simultaneously handling 8 molds, each connected to computer-controlled metered dispensing heads. Our manufacturing process does not require any curing after the foam has been fully blown in 120 seconds. Thus, with 8 trays, there is significant capacity at TMI to undertake the full scale manufacturing volumes for the head Health market, including foams for the military helmet market.

Continuous Sheet Casting Process

For manufacturing 0.25” thick foam strips for motorcycle helmet, shoe sock liners, and all soft headgear products such as skull caps and soccer head bands with thicknesses less than 0.5”, a continuous sheet casting process was developed. In this process, the two components A and B from their respective tanks were pumped into a metering head and the resulting mix was dispensed along the width (1’-3’) of a paper which was then pulled between two rollers with a



isocyanate and polymaine are pumped through heat exchangers for precise flowrate and temperature control

traversing mixhead dispenses liquid reactive mixture sandwiched between top and bottom paper

foam height is controlled by gap between nip rolls

top and bottom ovens control temperature profile for curing

cutoff saw cuts foam to specified length

Figure 7. Sheet - Casting Production Line

gap equal to that of the desired foam thickness. Sometimes a second paper covering the top of the foam was also fed through the roller such that the foam creamed as a sandwich between the two papers. The rate of pulling was adjusted based on foam's cream, blowing, and gelling times, and ultimately by the final density of the desired foams. We started with the lab recipe and adjusted it through a coordinated microscopy and impact testing program, similar to that described above for foams produced using the box molding process. Initial experience showed that there was a need to slow down the cream time from 17 seconds to at least 30 seconds by use of suitable catalyst. Once the process parameters were set, further refinement to the processing steps and chemical recipe was done by carrying out the Industry standard tests for soccer headband and DOT helmet tests in collaboration with the O'Neal and Full90 companies that sell these products in the world commerce. Large sheets of UCLA foams can now be continuously produced in ready-to-use thicknesses. Our recipe is such that no curing is required once the foaming process has completed within 120 seconds. This process was developed at United Specialty Foam (USF) located in Newark, Delaware, under the direction of Dr. Chiu. Figure 7 shows a schematic of the sheet casting production line at USF.

4. NSF I-Corps Workshop

PI Gupta and EL Ramirez attended the NSF I-Corps workshop that was required as part of receiving the I Corps@ DoD grant. The workshop was focused on evaluating the need and potential demand for the commercial product being touted and performing sets of interviews with the end customers as well as potential vendors that would eventually sell the product. All this was evaluated with respect to the readiness of the technology at hand. We pitched in all three foam products. The metrics that controlled the decision regarding "go" vs. "no go" with respect to commercialization was driven solely by large volume. The panel felt that the volume of the product for the helmet market was quite low. The panel asked us to focus on the shoe/insole market where the volumes were enormous. The military helmet application with a limited market was thus tabled.

We followed through with the shoe application and have fitted several high profile US Olympians and professional basketball players with UCLA foams. PI Gupta is now working with the Lakers organization to see if impact injuries to the players can be minimized by use of UCLA foams as inserts. A major LA-based multi-national shoe company is presently exploring making midsoles using the UCLA foam material to see if the benefits can be realized by ordinary runners through their running experience.

5. Further Shock Testing of UCLA Foams for ACH Helmet Application

Despite the no-go outcome at the NSF Workshop, the UCLA team also focused on the military helmet application as we felt that our I Corps @ DoD grant was directed to benefit the Army and the larger DoD community. To this end, we took Foam A samples that were developed using the commercial recipe and shock tested them under highly controlled shock conditions using a shock tube. Figure 8 shows the schematic of the shock tube setup in which the foam sample is placed behind a plate that simulates the ACH helmet section. The sensor in the tube records the impinging shockwave while the one behind the foam records the transmitted pressure that ultimately goes through the warfighter’s brain. The percentage reduction in the transmitted pressure can be used as a metric to compare the effectiveness of various foam-based systems.

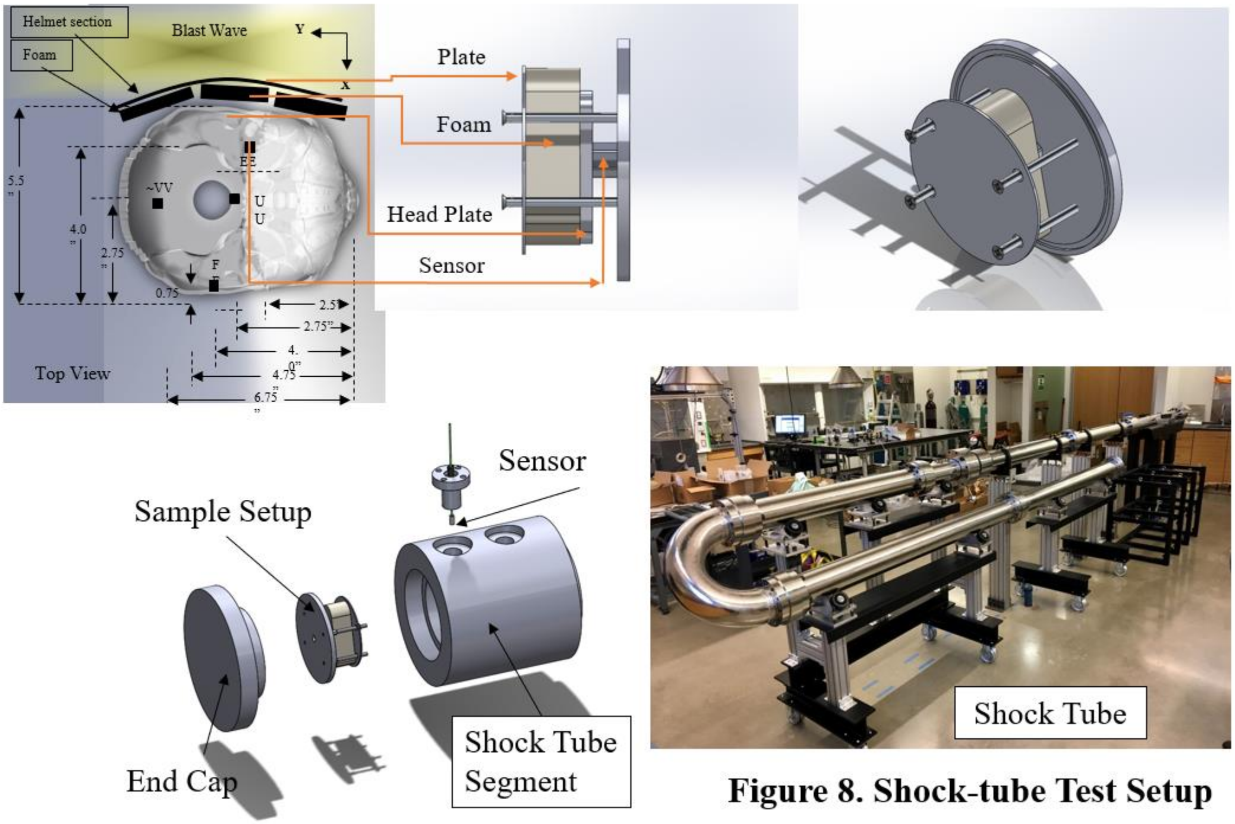


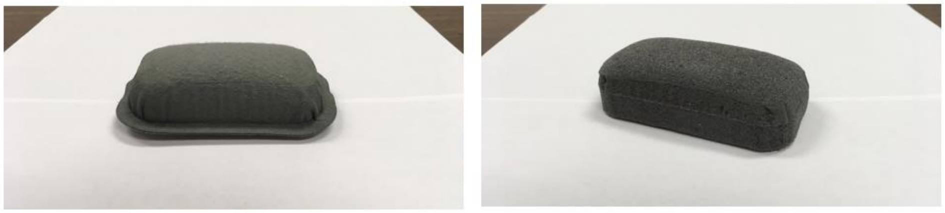
Figure 8. Shock-tube Test Setup

Figure 9 shows pictures of UCLA and Wendy foam samples of the same thickness that were tested. Wendy foams are presently used in the ACH helmets and have a fairly advanced two-layer construction inclusive of a pouch. UCLA foams have one uniform density throughout their thickness and require no special construction. It is noteworthy that Wendy foams are the state of the art so it serves as an excellent benchmark for comparing the performance of UCLA foams. Figure 10 shows the test results. UCLA Foam A with a density of 110 kg/m^3 reduces the shock pressure by 25% compared to Wendy foam of 11% and this superiority is maintained at the lower temperature (53% vs. 34%). During the I-Corps @ DoD program we also developed a recipe for 64 kg/m^3 density foam which is designated as Foam B in Figures 9 and 10. This foam significantly outperformed the Wendy foam. It reduces the pressure by 52% compared to Wendy’s 11% at room temperature while it performed at the same level at the lower temperature. To confirm results from these highly controlled tests, UCLA samples were sent to the Naval Surface Warfare Center where Philip Dudt tested them in his blast facility. Figure 11 shows his setup and Figures 12 and 13 summarize the results. The identity of the commercial ACH foams is not disclosed here. The results show about 13-20% difference in the performance between UCLA foams and the commercial foams. It is noteworthy that this data is for the higher density UCLA Foam A as we were unable to do these tests on the lower density (64 kg/m^3) foams due to limited resources at NSWC.

All samples tested at 1” thickness and same cross sectional area

UCLA Foam A (110 kg/m^3)

UCLA Foam B (64 kg/m^3)



Commercial Foam (66 kg/m^3)

Commercial Foam without cover

Figure 9. Foam Samples

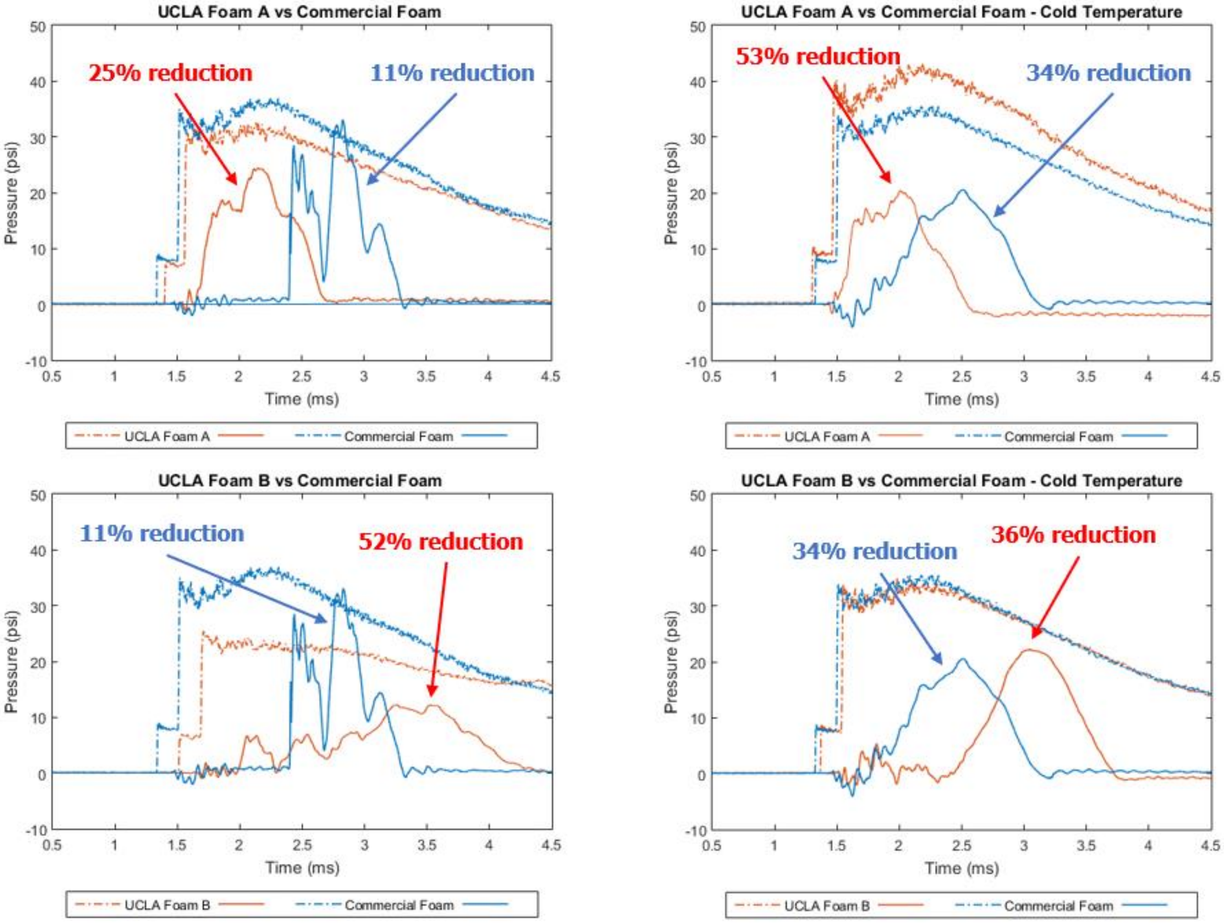


Figure 10. Shock Test Results

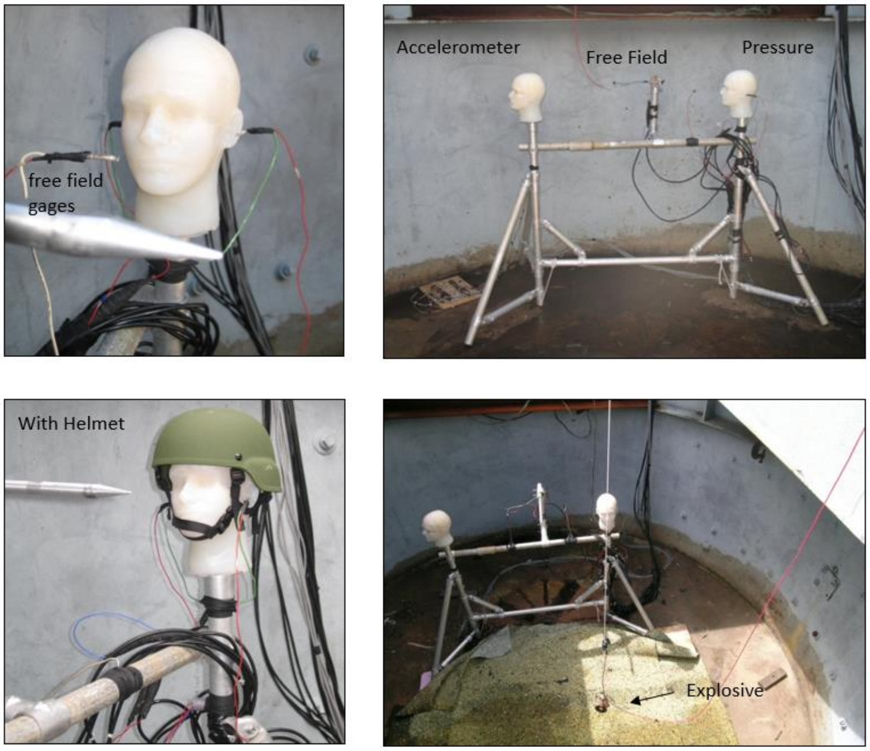
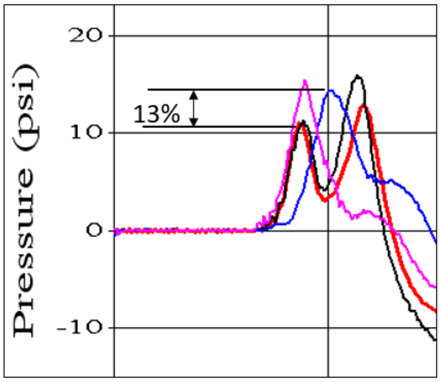
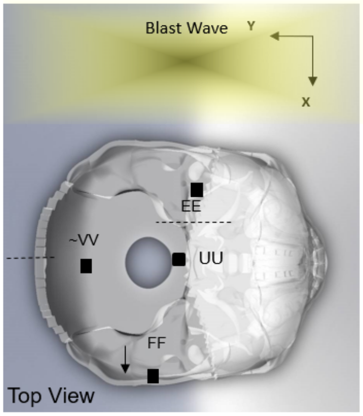


Figure 11. Test Set-Up in Blast Pit

Gage Location	Pad Type	Pressure (psi)		Impulse (psi-msec)	
		Pulse 1	Pulse 2	Pulse 1	Pul
EE	Commercial W	14.37	9.26	4.46	
	Commercial X	15.40	20.48	3.11	
	Commercial Y	16.59	15.57	3.29	
	Commercial Z	15.49	16.21	3.66	
	0.18 B UCal	11.01/12.69	14.50	3.70	
	0.20 UCal	10.64/15.99	26.61	4.17	
FF	Commercial W	-4.23		-1.86	
	Commercial X	-7.14		-1.32	
	Commercial Y	-6.96		-0.79	
	Commercial Z	-6.28		-0.87	
	0.18 B UCal	-4.65		-0.46	
	0.20 UCal	-4.54		-0.56	
VV	Commercial W	8.99		2.03	
	Commercial X	13.16		2.49	
	Commercial Y	11.30		2.43	
	Commercial Z	11.80		2.50	
	0.18 B UCal	6.56		2.05	
	0.20 UCal	8.11		2.45	





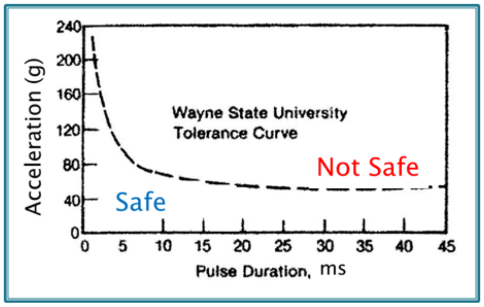
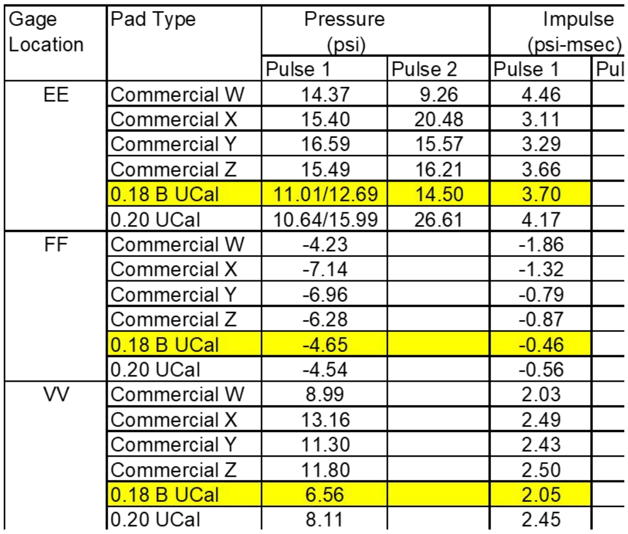
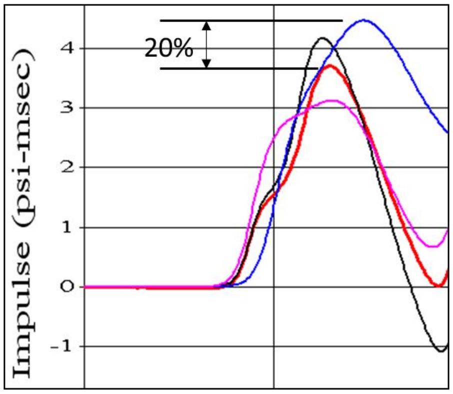
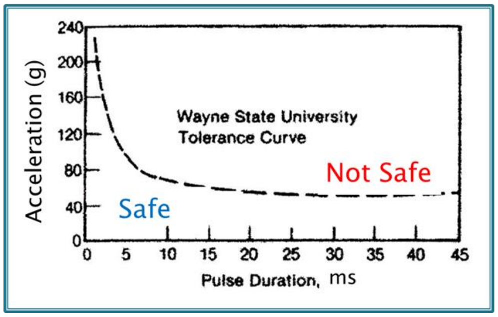


Figure 12



Gage Location	Pad Type	Pressure (psi)		Impulse (psi-msec)	
		Pulse 1	Pulse 2	Pulse 1	Pul
EE	Commercial W	14.37	9.26	4.46	
	Commercial X	15.40	20.48	3.11	
	Commercial Y	16.59	15.57	3.29	
	Commercial Z	15.49	16.21	3.66	
	0.18 B UCal	11.01/12.69	14.50	3.70	
	0.20 UCal	10.64/15.99	26.61	4.17	
FF	Commercial W	-4.23		-1.86	
	Commercial X	-7.14		-1.32	
	Commercial Y	-6.96		-0.79	
	Commercial Z	-6.28		-0.87	
	0.18 B UCal	-4.65		-0.46	
	0.20 UCal	-4.54		-0.56	
VV	Commercial W	8.99		2.03	
	Commercial X	13.16		2.49	
	Commercial Y	11.30		2.43	
	Commercial Z	11.80		2.50	
	0.18 B UCal	6.56		2.05	
	0.20 UCal	8.11		2.45	





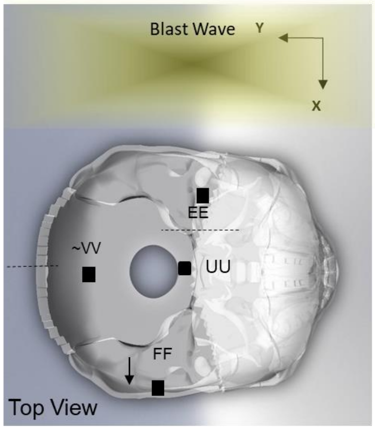


Figure 13

6. Recommendations

Based on the superior shock performance of UCLA Foam B with a density 64kg/m^3 and the fact that it can be produced in large quantities using a commercial manufacturing process, one should explore this technology for the ACH helmets. UCLA foams should easily pass the rigorous temperature and moisture related DoD standards as the glass transition temperature of polyurea is -50°C. Furthermore, polyurea shows chemical inertness to aggressive elements such as halides and has been certified by the Navy for seawater applications.

7. Composite Foams

UCLA Foams A, B, and C discussed above absorb more impact energy compared to single-hit EPS material ONLY at strain rates greater than 1000 per second. Most commercial motorcycle and bicycle helmets are not subjected to such high strain rates during accidents. This motivated us to explore if there is a way to create a viscoelastic multiple hit foam that would also absorb more energy compared to EPS at lower strain rates (50 to 200 per second). This led to the development of the Composite Foam.

The composite foam was fabricated (Figure 14) by taking a preform of polymer lattice consisting of a network of beams and columns and foaming it through its open lattice structure. The preformed lattice contains centimeter size struts that are arranged in a truss-like geometry. This truss can be made using elements of any size (sub-mm to cm) depending upon the application. The foaming material could be any of the UCLA foams discussed above. Since the foam polymer wets the preform polymer, the preformed lattice structure is completely embedded within the foam creating very strong bonding at all interfaces. This can be seen in Figure 14 and more closely in the scanning electron micrograph of the undeformed foam geometry in Figure 15. The dense shaded regions are sections through the lattice beams. The figure also shows a very coherent and strongly bonded interface between the foam and the structural elements. This is the key to their performance as the foam prevents *instantaneous* elastic buckling of the struts by supporting them from both top and below.

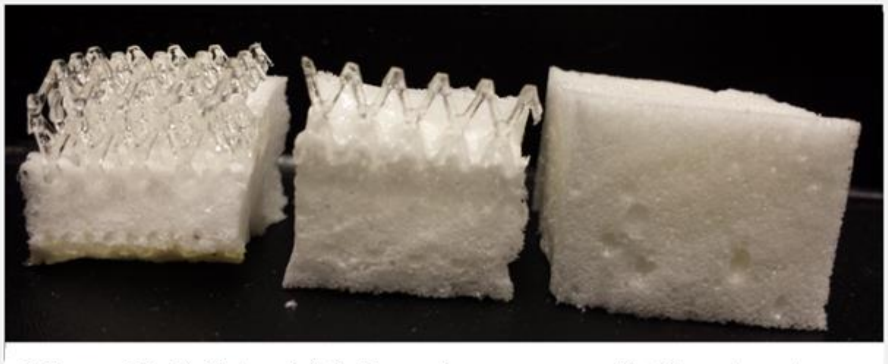


Figure 14. (left to right) Foaming process of lattice structure

The struts continue to bend and deform gracefully in this otherwise post-buckle region. On the continuum scale, this is realized as an extension of the stress-strain plateau region when the foam is compressed dynamically by impact loading. As one might expect there are regions of the foam that undergo tensile stretching that hold the strut from its top while it is undergoing bending over an elastic foundation made of the same foam. These tension and compression regions of the foam are shown in the SEM micrograph of the deformed foam in Figure 15. The longer plateau region adds to energy absorption and the peak force drops as a result of an increase in the impact duration. All these processes also prolong the densification of the foam itself. All local scale energy dissipation processes that were discussed earlier as part of Foams A and B are also operational here. These mechanisms operate simultaneously and sequentially at varying length scales (microns to centimeters in dimension). Furthermore, they operate

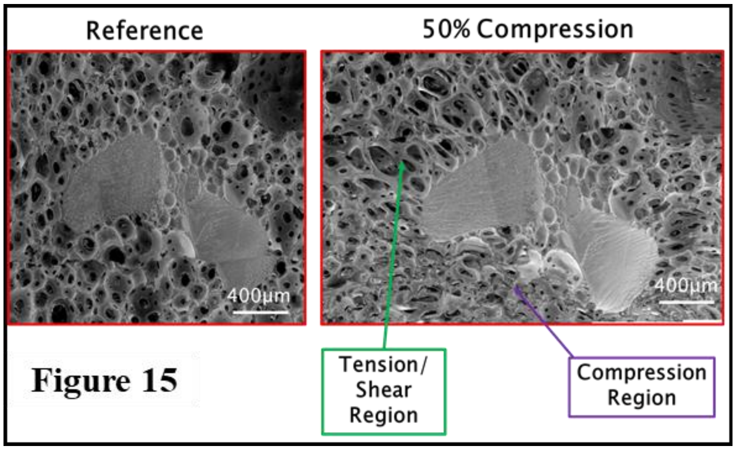


Figure 15

synergistically thereby significantly reducing the transmitted impact forces across the composite foam section.

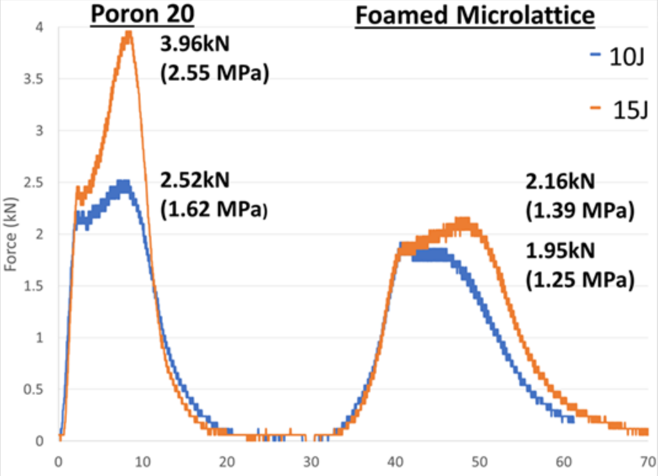
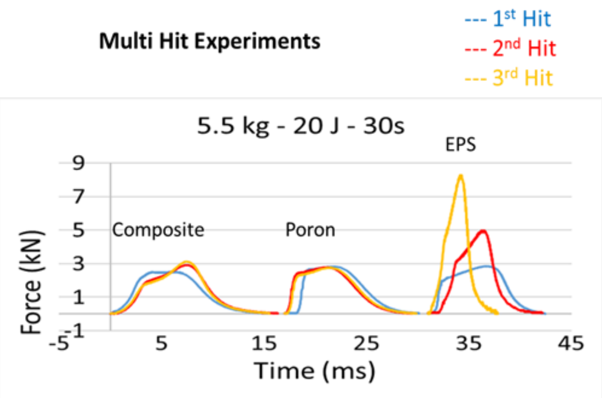


Figure 16

To test the impact absorption properties of the foamed microlattices, 45mm x 45mm x 10 mm thick samples were prepared. They were then tested using a 5.5 Kg weight indenter on a 45mm force plate at energies of 10J and 15J. The peak forces of the foamed microlattice were measured to be 1.95kN and 2.16kN, respectively, at these energy levels (Figure 16). It shows better performance compared to Poron20 which is widely considered as the best performing commercial foam. Poron20 is efficient only at ambient conditions because it absorbs energy through phase transformation due to its very high glass-transition temperature. Figure 17 shows that our composite foams are superior to Poron20 even at ambient condition.

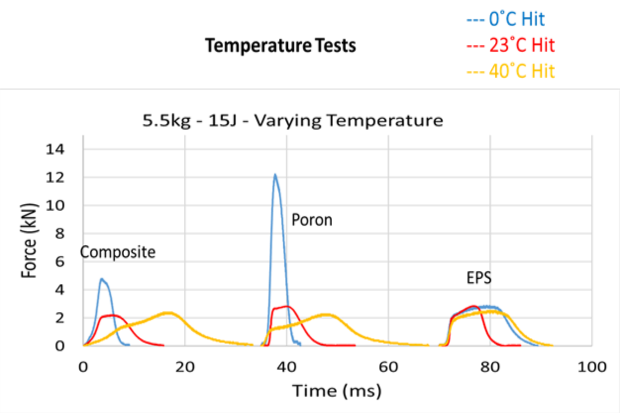


Max Force Per Hit (kN)			
Foam	**1st hit**	**2nd hit**	**3rd hit**
Composite	2.496	2.904	3.12
Poron 20	2.832	2.784	2.784
EPS 72	2.856	4.98	8.28

Figure 17

Figure 17 shows that the composite foam is able to limit the impact force to the same level as EPS foam of the same thickness. EPS material absorbs energy through plastic crushing and therefore it cannot be re-used after first impact as the EPS cannot recover to its un-deformed state. Typically, such foams are able to absorb more impact energy compared to elastic and viscoelastic foams. Quite remarkably our viscoelastic composite foam is able to absorb the same energy using the same section thickness and is also able to recover fully. This fact is also demonstrated in Figure 17 which displays the impact data under multiple hit conditions. That is, the same spot is impacted again two additional times. The peak force for the composite foam remains essentially unchanged whereas EPS stress increases dramatically after the first hit. The multiple hit capability of the composite foam while absorbing impact energy at the same level as EPS material is truly a major advance.

Finally, as shown in Figure 18, the composite foam displays impact property that remain stable over a wide range of cold and hot temperature conditions (-17°C to 50°C). As discussed before, this is directly a result of the UCLA polymer used to make the underlying foams with a T_g of -50°C. Thus, unlike Poron foam that displays superior impact resistance properties ONLY at room temperature our composite foams absorb impact energy even at cold temperatures. The data in Figure 18 clearly shows the superiority of the composite foam over EPS and Poron at all temperatures.



Max Force Per Hit (kN)			
Foam	0˚C	23˚C	40˚C
Composite	4.80	2.21	2.40
Poron 20	12.24	2.83	2.28
EPS 72	2.88	2.86	2.52

Figure 18

8. Future Work

In the future we will explore further development of the composite foam concept and its large-scale manufacturing. One method will be to free-rise the foam into sheets of prefabricated lattices. Since the foam rises fairly quickly this can be accomplished on moving chains with a very high throughput.

We will also explore manufacturing processes to create integrated helmet and armor systems. In such an embodiment of the composite foam, an open preform of 2D or 3D woven carbon or glass fibers can be infused with the foam such that it penetrates all the way through the entire thickness of the fiber preform and then exits on the upper side to form a uniform layer of the foam. That is, in this embodiment, the fiber/foam composite has now a layer of pure foam on the top to naturally create a bilayer structure of pure foam and composite foam. By placing the foam towards the body, head or the structure, this bilayer system can be essentially used as an armor with the composite section playing the role of a hard shell and thereby removing the need for placing the foam inside a separate shell.