Fluid-Filled Helmet Liner Concept for Protection Against Blast-Induced Traumatic Brain Injury

by

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ABSTRACT
Due to changes in modern warfare threats, as well as advances in body armor, soldier survivability in combat has increased, but blast-induced Traumatic Brain Injury (TBI) has become a prevalent injury in the battlefield. Often referred to as the “signature wound” of the current U.S. conflicts, blast-induced TBI is not a very well understood injury. In an effort to gain more insight on blast mechanisms and TBI, and to increase protection against this injury, our study investigates the development and exploration of a new Advanced Combat Helmet (ACH) liner for the modern day soldier.

The key component of the liner explored in this work is the addition of channels within foam that contain fluid or fluid-like materials. To support this goal, this thesis explores the response of these filler materials in a 2D sandwich structure at a range of pressures believed to be in the range of the occurrence of mild TBI, the most common TBI diagnosis among soldiers. Filler materials explored in this work are glass beads and glycerin.

Experiments were performed at Purdue University and the University of Nebraska at Lincoln, using two different shock tube setups to produce incident blast waves. Peak transmitted pressure was used to assess filler materials’ blast mitigation abilities, and any nonlinear behavior was explored over the range of incident pressures tested. Results indicate a nonlinear effect in the mitigation of blasts by solid foam and glass beads. These materials respond linearly to applied pressures at 15, 30, and 45 psi, but digress from linear behavior at 60 psi applied pressure. It was also determined that there is a significant advantage to using sandwiches with glass beads compared to solid foam at 60 psi applied pressure, but at 15 psi, 30 psi, and 45 psi, there is no significant difference among all three materials explored.

Thesis Supervisor: Laurence R. Young
Apollo Program Professor of Astronautics
Professor of Health Sciences and Technology
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I would like to thank all of the students and faculty of the MVL. I cannot thank each and every one in this lab for the countless amount of advice, feedback, intelligence, guidance, and most importantly, good times throughout my two years here. The MVL is a special place, and I do not think the culture can ever be replicated. I am most thankful for the lifelong friends I have gained through this research – ones that surely cannot be replaced.

Finally, I would like to thank my family and all of my friends. My parents have always been extremely supportive and reassuring, but I am also grateful they always remind me to keep things in perspective. To all my friends, new and old, you make things like this that much sweeter. Thank you for my sanity, as well as all the encouragement.

I would like to dedicate this work to all of the women and men who have served our country and those who have lost their lives in protecting the freedom of the United States.

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# Table of Contents

ABSTRACT ..................................................................................................................3  
ACKNOWLEDGEMENTS ............................................................................................5  
LIST OF FIGURES ......................................................................................................9  
LIST OF TABLES ........................................................................................................12  
LIST OF ABBREVIATIONS .........................................................................................13  
CHAPTER 1 INTRODUCTION ......................................................................................17  
  1.1 Motivation ..........................................................................................................17  
  1.2 Objectives and Methods .....................................................................................18  
  1.3 Thesis Organization ...........................................................................................19  
CHAPTER 2 SURVEY OF RELATED WORK ................................................................23  
  2.1 Blast Injuries and Blast-Induced Traumatic Brain Injury .....................................23  
  2.2 Blast Wave Physics .............................................................................................32  
  2.3 Blast Mitigation Strategies ..................................................................................36  
CHAPTER 3 The Use of Filler Materials in Channels for Helmet Liner Improvement .........................45  
  3.1 Sports Helmet Research at MIT ..........................................................................46  
  3.2 Blast Protection Utilizing Filler Materials ............................................................51  
CHAPTER 4 Blast Experiments Using Sandwich Structures: Purdue University .........................67  
  4.1 Experimental Setup .............................................................................................68  
  4.2 Experimental Results: Free Field Testing ............................................................71  
  4.3 Effects of Repetitive Testing on Single Sample .....................................................75  
  4.4 Experimental Results: Material Assessment .........................................................77  
  4.5 Experimental Results: Nonlinear Analysis ............................................................87  
  4.6 Oscillations ..........................................................................................................91  
  4.7 Discussion of Experimental Limitations ...............................................................92  
CHAPTER 5 Blast Experiments Using Sandwich Structures: University of Nebraska ...................97  
  5.1 Experimental Setup .............................................................................................97  
  5.2 Experimental Results ..........................................................................................105  
CHAPTER 6 Conclusions and Future Work ..................................................................113  
  6.1 Conclusions .......................................................................................................113  
  6.2 Suggestions for Future Work ..............................................................................115  
APPENDIX A Descriptive Statistics of UNL Data ................................................................119  
APPENDIX B Raw Data: UNL ....................................................................................120  
WORKS CITED ........................................................................................................122
List of Figures

Figure 2-1: “Predicted survival curves for man exposed to bursts where the thorax is near a flat rigid surface reflecting the blast wave at normal incidence [12]..............................27

Figure 2-2: Schematic of coup-countercoup injury [17].........................................................29

Figure 2-3: Development of explosive shock. Initial pressure pulse assumed in (a) and successive configurations (b) and (c) develop due to different speeds of different regions [32]............................33

Figure 2-4: Characteristics of an ideal blast wave [31].................................................................34

Figure 3-1: Channel mesh concept for helmet liner [86]............................................................47

Figure 3-2: Drop test apparatus per ASTM standards [88]..........................................................48

Figure 3-3: Results of VN600 w and w/o channel concept vs. EPS foam [88].............. 49

Figure 3-4: Ski helmets used for testing: Leedhom (L) and POC (R) [89] .......................50

Figure 3-5: Comparison of two ski helmets based on peak acceleration [89] .............50

Figure 3-6: Der-Tex VN600 foam “sandwiches”: solid (L), single cavity (center), dual (R) [89].................................................................51

Figure 3-7: Experimental Set up used by Alley [90].................................................................53

Figure 3-8: Experimental setup for sandwich structure blasting by Goel. Note in 3-8(b) the pressure gauge on the right measures the pressure through the sample, and that on the left measures the incoming blast without the sample [89]........................................... 56

Figure 3-9: Results from modified sandwich structure testing [89]..............................57

Figure 3-10: Top and bottom view of first prototype liner [34].............................................59

Figure 3-11: Prototype liner installed within ACH helmet shell [34]...............................59

Figure 3-12: Experimental setup for 3-D testing [34]...............................................................60

Figure 3-13: Example of raw data for first test performed with water as filler [34]........61

Figure 3-14: Example of data used in “best case” for gauge 2 [34].................................62

Figure 3-15: Mesh of helmet with prototype liner and filler [34].................................63
Figure 3-16: Contour plot of initialized pressure field and helmet [34] ......................... 64

Figure 4-1: Reported cases of various TBI severities [93] .................................................. 67

Figure 4-2: Schematic of test rig and explosively driven shock tube [88] ...................... 68

Figure 4-3: Sandwich test samples: (a) solid Der-Tex foam (b) single cavity sandwich [88] ......................................................................................................................... 69

Figure 4-4: Photo of aluminum plate configuration with labeled pressure gauges ....... 70

Figure 4-5: Photo of general experimental setup................................................................. 70

Figure 4-6: Effect of vacuum grease on gauges at 15.5 inches....................................... 72

Figure 4-7: Demonstration of average: trial 1, trial 2, and average displayed............... 72

Figure 4-8: Average pressure waveform at 19.0 inches..................................................... 73

Figure 4-9: Average pressure waveform at 15.5 inches..................................................... 74

Figure 4-10: Average pressure waveform at 12.0 inches.................................................. 74

Figure 4-11: Repetitive tests on single foam sample ......................................................... 77

Figure 4-12: Average pressure at various pressures for solid foam.................................. 78

Figure 4-13: Average pressure at various pressures for glass beads.............................. 80

Figure 4-14: Average pressure at various pressures for glycerin..................................... 81

Figure 4-15: Comparison of materials at 19.0 inches ....................................................... 82

Figure 4-16: Comparison of peak pressures recorded at 19.0 inches. Note: error bars indicate maximum and minimum for each material................................................. 83

Figure 4-17: Comparison of materials at 15.5 inches ....................................................... 84

Figure 4-18: Comparison of peak pressures recorded at 15.5 inches. Note: error bars indicate maximum and minimum for each material................................................. 85

Figure 4-19: Comparison of materials at 12.0 inches ....................................................... 86

Figure 4-20: Comparison of peak pressures recorded at 12.0 inches. Note: error bars indicate maximum and minimum for each material................................................. 86
Figure 4-21: Normalized transmitted pressure vs. applied open peak pressure for solid foam..................................................................................................................88
Figure 4-22: Normalized transmitted pressure vs. applied open peak pressure for glass beads..................................................................................................................88
Figure 4-23: Normalized transmitted pressure vs. applied open peak pressure for glycerin..................................................................................................................88
Figure 4-24: Visible “double hit” at 12.0 inch range.................................................93

Figure 5-1: (a) Side view photo of shock tube facility (b) Corresponding schematic of shock wave facility featuring 1) variable breech 2) membrane holder 3) shock tube and data acquisition region [93] ..................................................................................................................98
Figure 5-2: Zoomed in view of shock tube, membrane holder, and breech assembled together ..................................................................................................................98
Figure 5-3: Drawing of exploded view of membrane assembly with breech, shock tube, and connectors [93] ..................................................................................................................99
Figure 5-4: 2 mm thick Mylar membrane.........................................................................99
Figure 5-5: Top view of circular sandwich cavities (without top) .................................100
Figure 5-6: Side view of circular sandwich (a) showing cavity (b) with top attached .101
Figure 5-7: View of completely assembled sandwich samples and solid foam.............101
Figure 5-8: Cross-sectional view of fixture used to hold sample and measure transmitted pressure (surface mount sensor covered with tape for security reasons)..........................102
Figure 5-9: Cross-sectional view of fixture with sample in place ..................................102
Figure 5-10: Side view of fixture placed in test window of shock tube .........................103
Figure 5-11: Zoomed out view of test window. Camera was aimed at test window for data collection ..................................................................................................................104
Figure 5-12: Glass beads sample 1 raw pressure trace for 15 psi applied pressure .......106
Figure 5-13: Line plot of mean transmitted pressure; Error bars report +/- 1 standard error .......................................................................................................................108
List of Tables

Table 2-1: GCS scale [8] ..........................................................24
Table 2-2: DOD/DVA Severity of TBI Stratification [9] ........................................25
Table 3-1: Results from Alley’s experimental work with sandwich plates [90]...........54
Table 4-1: Summary of open field testing.................................................................75
Table 4-2: Statistical analysis of hysteresis test.........................................................76
Table 5-1: Membranes used for desired pressures.................................................105
**List of Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tr>
<td>“</td>
<td>inch</td>
</tr>
<tr>
<td>1D</td>
<td>One-dimensional</td>
</tr>
<tr>
<td>ACH</td>
<td>Advanced Combat Helmet</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>atm</td>
<td>atmospheres</td>
</tr>
<tr>
<td>CAE</td>
<td>Complete Abaqus Environment</td>
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<tr>
<td>CAT Scan</td>
<td>Computed Axial Tomography Scan</td>
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<tr>
<td>CDP</td>
<td>Computerized Dynamic Posturography</td>
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<tr>
<td>CEL</td>
<td>Coupled Eulerian-Lagrangian</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<tr>
<td>cm</td>
<td>centimeter</td>
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<tr>
<td>DAQ</td>
<td>Data Acquisition System</td>
</tr>
<tr>
<td>DoD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>DVBIC</td>
<td>Defense and Veterans Brain Injury Center</td>
</tr>
<tr>
<td>EBW</td>
<td>Exploding Bridge Wire</td>
</tr>
<tr>
<td>EPS</td>
<td>Expanded Polystyrene</td>
</tr>
<tr>
<td>EVE</td>
<td>E-glass vinyl ester</td>
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<tr>
<td>ft</td>
<td>foot</td>
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<tr>
<td>g</td>
<td>gram</td>
</tr>
<tr>
<td>GCS</td>
<td>Glasgow Coma Scale</td>
</tr>
<tr>
<td>HE</td>
<td>High Explosive</td>
</tr>
<tr>
<td>IED</td>
<td>Improvised Explosive Device</td>
</tr>
<tr>
<td>in</td>
<td>inch</td>
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<tr>
<td>i_s</td>
<td>impulse</td>
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<tr>
<td>kJ</td>
<td>kilojoule</td>
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<tr>
<td>kPa</td>
<td>kilopascals</td>
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<tr>
<td>lbs</td>
<td>pounds</td>
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<tr>
<td>LOC</td>
<td>Loss of Consciousness</td>
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<tr>
<td>LOCF</td>
<td>Levels of Cognitive Functioning Scale</td>
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<tr>
<td>MACE</td>
<td>Military Acute Concussion Evaluations</td>
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Chapter 1  Introduction

The research presented throughout this report concentrates on the continuation of a project focused on designing a military helmet liner for blast protection, and is supported under contract for the past four years by the Office of Naval Research (ONR). This chapter provides a brief overview of the motivation for this mission, as well as objectives and methodology performed along the way. Additionally, an organizational outline of this thesis is provided.

1.1 Motivation

Military combat helmets, currently the Advanced Combat Helmet (ACH), are designed to protect soldiers from a wide variety of threats and potential devastating injuries to the head such as skull fracture, burns, lacerations as well as death due to various sources such as bullet penetration, shrapnel, debris, and other objects that may impact the head. However, the current U.S. Army helmet is not effective for sufficient protection against blast related injuries, which derive from explosions from various sources. However, Traumatic Brain Injuries (TBIs) resulting from this type of exposure have become a significant portion of military personnel injuries, and have done so increasingly.

According to the Defense and Veterans Brain Injury Center (DVBIC), approximately 233,425 U.S. military personnel have been clinically confirmed and medically diagnosed with a TBI from 2000 to November of 2011 [1]. TBIs range from mild injuries, such as concussions, to severe, such as head penetration or permanent brain damage. In one study in 2010, Wojcik et al. found that 46.7% of TBIs found in soldiers from Operation Enduring Freedom (OEF) in Afghanistan, and 63.9% of TBIs reported from Operation Iraqi Freedom (OIF) in Iraq were due to explosions [2], leading others to tab TBI as the “signature wound” of the current U.S. conflicts [3].

A part of the cause for the prevalence of TBIs in both OEF and OIF is twofold. Modern warfare technology evolution and an increased use of Improvised Explosive Devices
(IEDs) allow a higher probability of exposure to blasts. In addition, body armor advances improve soldier survivability under circumstances that were previously lethal. However, blast-induced TBIs remain an increasing problem that needs action and attention [4]. This research endeavor focuses on improving protection from blast-induced TBI by developing a new helmet liner concept that would add blast protection abilities to the current standard issue helmet. The key component under investigation is the incorporation of filler materials (solid or fluid) in channels within a foam helmet liner. Our initial concept for embedding fluid and fluid-like materials inside a foam helmet liner to reduce TBI from blast waves was shown to be valid - but initially tested only at high pressure levels. The work of this thesis focuses on the effectiveness at lower incoming blast pressure levels, associated with the occurrence of Mild Traumatic Brain Injury (mTBI). Testing over a range of blast pressures from low to high was performed to better understand how each material performs over a wide range of shock wave profiles.

1.2 Objectives and Methods

The main goal of the new helmet liner project is to improve the current standard issue helmet and provide better protection from blast-induced TBIs. This thesis aims to contribute to this goal by exploring the response of the filler and channel concept in 2D at a larger range of pressures that was not previously tested. These pressures are set to be in the range of the occurrence of mild Traumatic Brain Injury (mTBI), which are the most commonly medically diagnosed TBIs amongst soldiers on the battlefield [1].

Previous work [34, 88, 89, 90, 92] has focused on two fronts: experimental testing and numerical modeling of both 2D sandwich structures and a 3D prototype. Experiments investigated an extensive variety of different filler materials. A blast chamber was used to provide the incoming pressure. Pressure transmission results were compared to those with standard ACH helmet pad. Numerical codes were also developed and showed good agreement between experiments and simulation. While the most recent work prior to this was using a 3D prototype, it was decided to revert to the 2D sandwich structure case to investigate more basic, fundamental science and behavior of the filler materials rather
than to complicate it with more geometrical features. There were also some experimental
defects with the 3D experimental setup that was utilized, so the 2D case was judged to be the best choice at this time. The key signal measured was transmitted peak pressure, for this thesis as for the preceding work.

Initial experiments were performed using the explosively driven shock tube setup located at Purdue University, as in previous work. Subsequent tests were performed at the University of Nebraska at Lincoln (UNL). Tests were performed with the most effective filler materials from previous experiments: glass beads and glycerin. The benchmark case against which the fluid filled samples were compared was a solid piece of the same foam that was used to construct the sandwich structures. Peak pressure transmitted through the samples was measured to determine the mitigation capabilities and response of the filler materials and channel concept over the range of pressures, and to investigate potential nonlinearities. In summary, the two main objectives of this work were to assess the filler materials’ blast attenuation capabilities at a larger range of pressures than previously tested, and to assess any potential nonlinear behavior of each material’s response over this range.

1.3 Thesis Organization

This thesis is divided into six chapters: a literature review, background on previous work on this project, and experimental methods, results, and conclusions.

Chapter 2 includes a literature survey of related blast-related research. It includes background information on shock wave physics, current and previously used blast mitigation techniques, and an examination of TBIs.

Chapter 3 provides a detailed narrative of the progression of the fluid-filled helmet liner project here at MIT. A description of the various experiments and numerical work performed over the past few years leading up to this thesis, including the sports helmet
application work of the helmet concept, are included and provide key information that is useful to understanding the work in this thesis.

In Chapter 4, the experimental work performed at Purdue University is provided. Details regarding the experimental set up, data acquisition, and results are presented. Discussion of the results and possible experimental limitations are also included.

In Chapter 5, the experimental work performed at the University of Nebraska at Lincoln is presented.

Finally, in Chapter 6, conclusions from this work as well as suggestions for future work are presented in detail.
Chapter 2   Survey of Related Work

This research effort focuses on the development of a new helmet liner for improved protection against blast induced traumatic brain injury (TBI). This chapter concentrates on current and previous blast mitigation methods. It also includes background information on shock wave physics, interaction of air blasts with various structures, and a survey of the causes, diagnosis, and treatment of TBI. It is clearly important to understand blast wave attenuation strategies. Understanding the characteristics of shock wave loading and propagation, as well as the characteristics defining TBI are also vital for the design of mitigation strategies, as well as the progression of this project.

2.1 Blast Injuries and Blast-Induced Traumatic Brain Injury

Traumatic Brain Injury (TBI) is defined as a brain injury that occurs from the onset of a sudden trauma, causing damage to the brain. It is a complicated injury with an extensive range of symptoms and disabilities. The causes for TBI are also diverse. The primary mechanisms for TBI are reported as open head injuries (penetration of the skull), such as from bullet wounds, and yield a more local area of injury, closed head injury (no penetration of skull), such as auto accidents, slip and fall, and tend to be diffuse injuries, and deceleration injuries (also known as diffuse axonal injury). Deceleration injuries result when the brain moves relative to the skull. The differential movement can cause shearing of the fragile axons of the neurons in the brain. TBI can also result from metabolic disorders, hypoxia, stroke, tumors, and infections, but these injuries are secondary in reaction to their initial injury/disease; i.e. hypoxia comes first, and TBI is a result of this [4, 5]. Blast-induced TBI, as mentioned before, is also a leading cause of TBI, resulting from blast-induced shock waves. While it is clearly not considered an open head injury, there is some debate as to whether it fits within the constraints of a closed head injury, a deceleration injury, or both due to the complexities of the onset of injury, and because the exact injury mechanism(s) from blast waves is not entirely understood and/or agreed up to this date [4,5,6,8,9].
TBI causes a multitude of physical, emotional, social, and cognitive problems, and the effects range from complete recovery to permanent handicap/disability, or even death. The injury is classified based on severity into three categories: mild, moderate, and severe TBI [4,5,6,7]. The symptoms cover a wide range and vary on patient to patient basis, but in general, mild TBI is typically characterized by a loss of consciousness of less than 30 minutes, and a normal MRI, but includes cognitive problems such as, but not limited to, moodiness, frustration, attention deficits, severe headaches, and mild memory problems. Symptoms are typically headaches, dizziness, balance problems, vision change, sleep disturbance, and excessive fatigue. Mild TBI is the most prevalent TBI, and is often missed at the time of injury [7,8]. Severe TBI is characterized by more severe brain problems, non-verbal signal and language processing problems, sensory and motor skill reduction, social issues, sleep disorders, weakness/loss of feeling in extremities, seizures, repeated nausea, as well as loss of some senses (hearing/smell/vision) [7,8]. Moderate TBI lies somewhere within these two extremes. It is often difficult, however, to diagnose because a person with moderate or severe TBI may exhibit symptoms of mild TBI at first, but have symptoms quickly escalate.

There are several systems for classifying TBI into mild, moderate, and severe categories in the literature, but the Glasgow Coma Scale (GCS) is the most widely used clinical severity classification [7,8]. The GCS is based on a scale of 3-15, and scoring is based on a patient's responses to stimuli in three categories: eye opening, verbal function, and motor function. Typically, a score of 13-15 is mild, 9-12 is moderate, and <9 is severe TBI. Occupational/physical therapists, or neurologists typically perform evaluations. The scoring scale can be seen in the table below. However, the GCS scoring system has limited predicting capabilities, and clearly employs a subjective scoring system, so it is limited in its applicability.

<table>
<thead>
<tr>
<th>Glasgow Coma Scale Scoring</th>
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<tbody>
<tr>
<td><strong>Eye Opening</strong></td>
</tr>
<tr>
<td>Spontaneous : 4</td>
</tr>
<tr>
<td>To Speech: 3</td>
</tr>
</tbody>
</table>
A recent model developed by the Department of Defense and the Department of Veterans Affairs uses the GCS in conjunction with duration of post-traumatic amnesia (PTA), and time of loss of consciousness (LOC) to better classify the severity of TBI [8]. This more comprehensive test can be seen in Table 2. An alternative to the GCS is the Ranchos Los Amigos Scale, aka the Rancho Los Amigos Levels of Cognitive Functioning Scale (LOCF), which is based on cognitive and behavioral function on a scale from 1 to 8, where 8 is fully functional [5].

Some other subjective tools such as historical evaluation of patients and self-report questionnaires are used as initial tests. The Military Acute Concussion Evaluations (MACE) and the Walter Reed Army Medical Center Blast Injury Questionnaire are two of these, but again, are only self-reported measures and are not as strong as GCS (assessed by a physician). Other self-report procedures include the Dizziness Handicap Inventory and the Activities-specific Balance Confidence Scale [6]. Furthermore, some computerized behavioral methods like dynamic visual acuity tests and computerized
dynamic posturography (CDP) can be applied to TBI analysis, but are not specific to TBI [9]. Other alternatives use MRI and other neuro-imaging to classify results, or some tests combine a few of the tests listed above to determine severity. Diagnosis is often performed using Brain Imaging, i.e. CAT Scan, MRI, etc. and a neurological examination, in addition to evaluations by physical therapists, but because of its wide variability, TBI remains a difficult injury to diagnose, categorize, and treat.

The focus of this project is blast-induced TBI. Blast-induced TBI can be much more complex than other TBI causes since effects from exposure to air blasts are typically concurrent with other injuries from impact, can affect the body in many different ways, and also can be highly variable because of the widely different blast variables such as type of explosive, distance from blast, type of environment, etc. Possible effects of blasts include acceleration or deceleration of the head, passage of the blast wave directly to the brain, and passage of the blast wave to the brain via a thoracic mechanism.

The effects of blasts fall into four categories: primary (direct effects of pressure), secondary (effects due to debris), tertiary (effects due to blunt trauma), and quaternary (all others). Primary blast injuries are injuries due to barotrauma - either overpressurization or underpressurization of the brain relative to atmosphere. There injuries are results from dynamic pressure changes causing stress and shear waves to pass through the body, via tissue density interfaces or organs themselves. Secondary blasts consist of any fragmentation or penetrating impact, which is energized by the blast, and penetrates the skin. Injuries may come from primary fragments (fragments that are from the weapon) or secondary fragments (fragments resulting from the explosion). Blast effects that are tertiary are due to blunt impact, including falls, body translation or rotation, direct contact with some surface such as vehicle interiors, etc. [8, 10, 11]. Quaternary effects encapsulate all other effects, including thermal exposure, burns, and toxic inhalants [8]. Both secondary and tertiary injuries can be considered as impact injuries, which are commonly studied in automotive and sports helmet industries. Quaternary effects are outside the realm of this project's focus. Primary blasts, however, are unique to blast wave exposure, are the main focus of this research. The direct
impingement to the brain remains a complex problem and a source of uncertainty in blast injury literature.

Blast effects on humans have been a research topic for years. In 1968, Bowen, et al collected and analyzed data from studies on thirteen animal species exposed to blast waves in order to determine tolerance indices. A mean for large species was used to create a tolerance for human survivability to varying blast wave intensities (but only for specific orientations) [12]. An example is shown in Figure 2-1, where a tolerance curve was created for a lateral loading position. This could have implications directly to primary blast induced TBI.

![Figure 2-1: Predicted survival curves for man exposed to bursts where the thorax is near a flat rigid surface reflecting the blast wave at normal incidence [12]](image)

A large effort has been made to understand blast-induced TBIs, though the mechanisms that yields them remains an active and controversial topic of research. In 1996, Cooper investigated lung injury and thorax acceleration in pigs exposed to blast loading, and he found that there was a direct relationship between incident shock wave and thorax injury [13]. However, no correlation to brain damage was made. Courtney and Courtney
provided a large work suggesting that the onset of TBI is actually a thoracic mechanism, in which the blast waves propagate to the brain through the chest [14]. They performed blast-loading experiments with raccoons. Another supporter of thoracic mechanism is Cernak, who hypothesized that energy transfer through the abdomen and thorax via blast overpressure in blood vessels transfers to the brain, causing brain injury [15]. Animal models in blast testing by Courtney and Courtney supported his hypothesis [14]. Despite being a valid hypothesis for a means of TBI onset, this effect is not included in our research study.

Another study by Courtney and Courtney, attempts to find thresholds for TBI due to mechanical mechanisms of blast wave transmission. It suggests that more than one mechanism can lead to brain injury, and that while thoracic mechanisms are important, they are not mutually exclusive. They also noted that both blast pulse duration and peak overpressure play roles [14]. According to Chafi et al., induced blast loading causes acceleration and deceleration of the brain, which can result in the brain impacting the hard skull due to the sudden changes in direction and forces of acceleration [16]. This can result in contusions on the brain tissue, but also can create shearing within the brain due to dynamic and variable acceleration rates. This ultimately can stretch axons, causing brain impairment. In addition, Chafi et al. note that blast waves can impair the brain via tissue stresses and strains, and local bending, fracture, and changes in density or volume of brain matter, all leading to effects on functionality [16]. This injury is most commonly known as coup-countrecoup injury [17].
Cavitation from negative pressure at the countercoup site was shown by Wardlaw and Goeller with simulations to occur during blast events [18]. Using a simplified numerical head model, it was suggested in all results that cavitation forms regions of tension in the brain when loaded with a shock load, and that skull deformation can also impact cavitated regions [18]. Finally, Moore et al., also describe that data suggests that tissue shear material properties can exhibit differing properties/equations of state across a range of high strain rates. It is also mentioned that diffuse axonal injury is the associated structural change with mild blast-induced traumatic brain injury [19].

Several experimental and numerical/computational efforts have been performed in order to investigate the mechanisms of blast-induced TBI further. In a study by Moss, King, and Blackman, numerical blast simulations showed significantly different loading modes on the brain than from impact, and rippling of the skull occurred even at pressures as low as 1 bar above ambient [20]. It was suggested that if this proves to be a primary mechanism for TBI, then an "effective mitigation strategy would be to deny the blast wave access to the airspace under the helmet" and "prevent motion and deformation of the helmet from transferring to the skull" [20]. Chaloner studied the impact of blast injury in enclosed spaces [21]. He noted that simple blast waves in a free space creates a rise in pressure of approximately 10 ms, but in an enclosed space, the body is at much greater

![Figure 2-2: Schematic of coup-countrecoup injury [17]](image_url)
risk, as the shock wave will reflect from other surfaces and thus have a longer duration [21].

In another modeling study, Taylor and Ford studied the importance of stress wave interactions in blast-induced TBIs [22]. A finite-volume code was used to model a human head with an induced blast wave, and results suggested that stress waves lead to localization of stress, which in turn can cause damage to the axons. Furthermore, the code results suggest that blast-induced TBI onset can occur before the linear and rotational accelerations that cause injury due to these early-time stresses [22]. In a different simulation project, Nyein et al. used a computational model to assess the effects a blast on the human head wearing the Advanced Combat Helmet (ACH) [23]. Results found that the ACH does not enhance the blast wave, that the liner pads of the ACH provide insignificant mitigation, and that the main means of wave transmission is the soft tissue of the brain in contact with the wave [23, 19]. Most notably, they found that a face shield could provide substantial blast mitigation to the brain [23].

A different study by Ganpule et al. investigated effects of overpressure in a human head and the role of the helmet as well [24]. A computational model was used to study brain tissue injury, and results were compared to available injury thresholds. Shear stress and intracranial pressure were quantified, and the overall pressure and stress level was highest for the head without a helmet, and smallest for a head covered by a helmet with a uniform foam layer within the helmet [24]. Continuations of this study analyzing shock wave-head/helmet interactions concluded that the highest levels of overpressure occur in regions of concavity and that the curvature of a helmet can greatly dictate the flow field around it, and influence the overpressure [25]. They also determined that a gap between the head and helmet yields an increase in overpressure, and noted the existence of an under wash effect, where a shock front enters the gap between the head and the helmet, traveling beneath the helmet, and producing a higher peak pressure on the head, especially when the front beneath and above the helmet meet [25].
In a study by Dixon, numerical animal models using gas-driven shock tubes were developed to simulate blast-induced TBI and similarly used experimental set-ups in literature [26]. The models can replicate various neuropathological responses and impairments, which provides useful information to examine various therapies and conduct studies using biomarkers. Dixon also demonstrated potential in using biomarkers with clinical studies from patients with TBI [26]. Biomarking includes developing diagnostic and prognostic procedures by measuring biological substances released during and after a TBI.

Miniature pressure sensors were implanted into rat brains that were exposed to blast loadings in an experiment performed by Chavko [27]. The magnitude of the blast was small (up to 5.8 psi), but short pressure waves of a few ms were detected within the brain at a strength high enough to create damage, suggesting that there is some direct cranial mechanism in the blast-induced TBI that results in direct pressure-changes due to blast exposure. Long et. al also investigated blast overpressure in rats [28]. An explosively driven shock tube was used to induce an air blast on rats wearing a Kevlar vest in order to determine if the shock wave can trigger TBI, as well as to determine the effectiveness of the vest. The results showed remarkable neuropathological changes in rat brains when exposed to 125 and 147 kPa blasts, and demonstrated that induced air blast loadings can cause TBI in rats [28].

Another study with rodent brains was performed by Pun et. al. to investigate the effects of a single sub-lethal blast in an open field setting [29]. An overpressure of 7.1 psi or 11.3 psi (low pressure) was applied to the rats, and brain tissue was sampled to perform various analyses. Findings showed an immediate change in neurons, white matter damage, and an altered expression of over 5786 genes in the brain, while pulmonary injuries were delayed. They also conclude there is mild cellular injury to the brain at the blast overpressure levels tested in this study [29].

Despite the efforts to understand blast induced TBI, much more research is still necessary to better characterize the mechanisms behind it, and to fill in research gaps.
There are currently no well-developed tools to estimate primary blast brain injury risk. Risk assessments would be useful in order to establish potential for TBI, guide experimentation, and improve mitigation approaches and design [30]. However, the threat of blast-induced TBI continues, and is the source of motivation for this research project.

2.2 Blast Wave Physics

The research at hand focuses on the mitigation of the blast wave, a product of any explosion in air, whether it be from chemical release, like the IEDs used in the Middle East, or other sources like nuclear or electrical energy discharges. The blast wave is generated when a force, due to the gases produced from the explosive, is applied to the atmosphere surrounding the detonation, causing the air to continuously push back adjacently. Because air is a compressible gas, the front of the wave will initially steepen as it moves, and result in near discontinuities in pressure, temperature, and density [31, 32].

Figure 2-3 illustrates this formation of a blast wave. An initial pressure pulse will move outward, with separate areas moving at their own speed. Because high pressure is associated with high temperature, and thus is more energetic and has greater velocity, the regions of high pressure expand more quickly, creating a wave front that becomes increasingly sharper. As this continues, a discontinuity, or explosive shock, occurs, which becomes the front of the blast wave as it grows. As the gases continue to expand, the pressure at their center decreases more rapidly than at the wave front. As a general rule, the pressure at the detonation zone drops to approximately half of that at the edge in the early moments after an explosion. As the expansion continues, overexpansion occurs due to inertial effects, producing rarefaction at the detonation center [32].
It is important to note that the characteristics of the blast wave are much different than an acoustic wave. For one, the shock front of a blast wave moves supersonically, faster than the speed of sound through air. In addition, only infinitesimal pressure changes occur in acoustic waves, while large pressure gradients are typical of blast waves. An acoustic wave front also does not “shock up”, compressing the air and creating a high level of discontinuity. Finally, the characteristics and formation of blast waves in air are nonlinear, and are defined by nonlinear equations of motion, while acoustic waves are effectively described with linear equations [31, 33].

Typical blast waves are characterized by three independent variables: peak overpressure (or another term to describe shock intensity, such as Mach number), duration of the wave, and the impulse per unit area (providing the pressure forces in the blast). An ideal blast wave pressure-time history is illustrated in Figure 2-4 in order to describe the typical nomenclature. In the ideal case, it is assumed that a homogeneous atmosphere and spherical, symmetric detonation occurs, yielding a blast wave that is only a function of distance and time [31, 32, 33].
In addition, a perfect discontinuity is assumed to occur at the arrival time, $t_a$ (though in real blast waves this is only abrupt, but not perfectly discontinuous). As seen in Figure 2-4, at some distance from detonation, the air is initially at atmospheric pressure, $P_o$. At $t_a$, the pressure jumps to the blast peak overpressure, $P_s^++P_o$, and then decays back to ambient at $t_a+T^+$. The pressure continues to drop to slightly below atmospheric pressure, $P_o-P_s^-$, and then eventually returns to atmospheric pressure over a time of $T^-$. As mentioned before, it is important to note that the rise in pressure is not discontinuous in reality, and a key parameter of interest is the time for taken for the pressure to reach the peak overpressure, typically called the rise time [31]. The impulse is often used as a means to describe the blast wave as well, and is defined by the following equation [31]:

$$i_s = \int_{t_a}^{t_a+T^+} (P(t) - P_o) \, dt$$

**Equation 2-1**

It is often desired to describe the pressure-time history seen in Figure 2-4 with a functional form to completely define the blast wave. Various functional forms are used throughout the literature, many of which were fitted with experimental or theoretical data, but perhaps the most widely used expression is the Friedlander equation [31]. This.

![Figure 2-4: Characteristics of an ideal blast wave [31]](image)
Equation is given in equation 2-2, where b is the “waveform parameter” and is a function of the peak overpressure. It should be noted that this equation fits only the positive phase of the shock wave [31, 32, 33].

\[ P(t) = p_2^+ \left[ 1 - \frac{t}{T^+} \right] \exp \left\{ -\frac{bt}{T^+} \right\} \]

Equation 2-2

An air blast wave can also exhibit several repeated shocks with smaller magnitudes at various times after the arrival time, due to rarefaction waves. These secondary and tertiary waves do not heavily change the blast wave variables in the positive phase in Figure 2-4, but can interrupt the negative phase. Though the positive phase is of primary interest, it is important for better understanding and interpretation of experimental results to note that these can occur. The blast wave physics described thus far does not take into account any interaction with any surfaces, however, on encountering any denser object or matter, air blast waves will both reflect and diffract. Several models exist with varying complexity to capture the reflection from the interacting object and diffraction around it, many of which can be found in the book by Baker [31].

It is also useful to understand how the blast wave actually travels through the air, better known as air blast theory. A detailed description of the equations that describe the properties at the blast discontinuity is found in Vechart’s thesis [34], as well as the governing equations on the transmission of blast waves through air [32, 33]. The key assumption that is made is that the pressures from a blast wave are within the range of classifying air as an ideal gas [33].
2.3 Blast Mitigation Strategies

Our emphasis in this project is to develop proper blast wave mitigation for the application of an improved military helmet liner. There are a variety of methods throughout the literature suggesting means of decreasing the effects of an incoming blast wave.

One theory of mitigation is to exploit the acoustic impedance of materials. Acoustic impedance is the product of the density of a material and the speed of sound through a material. If a sound wave passes through different media, the ratio of impedance mismatches of the media determines the amount of energy transferred. Thus, large impedance mismatches may lead to reflection of waves. That percentage which is not reflected is transmitted and absorbed through the material.

Several studies suggest selecting materials with properties such that there is an acoustic impedance interface, presumably attenuating the transmitted blast wave magnitude. In a study by Cooper, the idea of an acoustic “decoupling” layer was recommended to reduce the overall peak transmitted pressure, which in its simplest form consisted of two materials in series: a high acoustic impedance layer and a low acoustic impedance layer [35]. The high impedance layer was to be rigid and as heavy as possible, and Cooper recommended resin-bonded Kevlar, a metal, or fiberglass. The low impedance material was to have high compliance and high air content, like a foam. It was stressed that foam alone without a high acoustic impedance with it should never be used as sole protection, as it acts as a coupler and increases the damage of the blast [35].

Zhuang et al. also examined the utilization of acoustic impedance mismatches. In their study, scattering effects of pressure waves within layered composite materials were investigated [36]. They concluded that a longer rise time for the shock wave resulted when there were large impedance mismatches at interfaces of materials. This has important implications as if one can maximize the rise time, the pressure gradients that are often dangerous to the brain can be lessened. Hui and Piyush note, however, that stress concentrations and reversals at the interfaces of impedance-mismatched materials
are a primary source of failure of the protective material; thus, they introduce a new concept of materials that are one continuous material with a continuous impedance gradient. They suggest that the blast wave can be dissipated effectively, without interfacial failure [37].

The superior performance, in terms of strength, stiffness, and energy absorbance, of composite materials, such as sandwich structures, compared to a monolithic layer is well known, and gaining an increase in use in research for blast mitigation analysis [37, 38]. In one numerical study using ABAQUS, Xue and Hutchinson analyzed layered materials, or sandwiches, consisting of two circular, parallel plates that surrounded a rigid, low-density, cellular core, and assessed responses to an applied uniform blast loads [38]. The sandwiches were to be kept light, as to use the fluid-structure interaction concept suggested by G.I. Taylor [39]. Taylor assessed shock wave-fluid interactions and found that the lighter structures gain less momentum relative to heavier structures for a given blast. This was based on that pressure built up can be alleviated by deformation. Deformation of the foam yields a larger space for the pressure to occupy, thus reducing its magnitude [39]. However, it should be noted that this effect in air is small, while in fluids like water, there is much a more substantial effect. Nevertheless, Xue and Hutchinson found that sandwich plates do indeed outperform solid plates, though the findings were tentative based on a few modeling uncertainties [38].

In a sequel to that work, they assessed the advantages and disadvantages of metal sandwiches relative to solid plates of the same material, this time varying the internal core three ways: a pyramidal truss, a square honeycomb, and a folded plate [40]. The cases studied imply metal sandwich structures could certainly have potential for blast resistant structures. The honeycomb and folded cores yielded better mitigation than the truss, though all performed better than the solid plates. No optimizations were performed [40]. Fleck and Desphande, however, have performed broad optimizations of these sandwich plates using their numerical and analytical code [41]. Xue and Hutchinson then went on to modify the model by Fleck and Desphande with other collaborators, to include assessing minimum weight designs, and identified optimal designs and parameters [42].
Though their primary motive is to design optimal sandwich plates for water shock mitigation, where attenuation can be two to three times less than a solid plate, there are certainly opportunities to apply these concepts in air blasts. Their model does include models for both air and water environments and the different requirements [42].

Kambouchev et al. also investigated air-blast loading on plate like structures, though the focus on their numerical analytics was on fluid structure interactions and non-linear compressibility. Extremely light and extremely heavy plates were studied for various blast intensities, and it was concluded that nonlinear fluid compressibility plays a role in reducing the transmitted blast with fluid-structure interactions [43].

Aluminum was a common suggestion for a core material in the sandwich structures. An aluminum foam layer on a rigid plate exposed to a close range blast was investigated by Hanssen et al. [44], where the aluminum foam was found to lengthen the duration of the shock wave front, and lessen the magnitude. An experimental and numerical study by Karagiozova et al. also compared the responses of sandwich-like plates of steel with polystyrene cores and steel plates with aluminum honeycomb cores when exposed to a blast-induced loading [44]. They found that the aluminum core performed better (for similar mass) [45]. Aluminum allow foam cores sandwiched by steel plates were also suggested by Radford et. al, as they were found to provide better blast mitigation compared to solid plates of equal mass [46]. They found good agreement between experimental and computational efforts. However, blast tests performed by determined that structures with glass-fiber reinforced epoxy layers provide better blast mitigation compared to aluminum alloy layers [46].

Tekalur et al. investigated the use of polyuria (PU) and E-glass vinyl ester (EVE) composite in composite shock wave mitigation studies, and determined that the addition of polyurea on a layer of the impacted face substantially decreases the transmitted blast pressure. Results also indicated that sandwich structures with polyurea between two composite layers produced the best blast protection compared to all other tests they performed [47]. A unique suggestion involving various “layers” was proposed by Su et
al., who recommend a novel piston-cylinder assembly as a means for blast wave mitigation [48]. This numerical simulation aimed to model various design parameters, and determined that when the blast wave propagates into the device, it is reflected repeatedly, yielding a peak pressure reduction of as much as 98% [48].

Another prevalent method of blast wave mitigation being researched is utilizing water as a defense against a blast. In one numerical approach, Schwer and Kailasanth studied the effect of a water mist [49]. They concluded that water mist can be effective via extracting momentum, and that it is not dependent on how diffuse or compact the mist is, though they suggest that an ideal droplet size may optimize the mitigation. The results also indicated that the mist does not need to be applied directly to the detonation zone [49]. Resnyansky and Delaney also examined water mist mitigation using an experimental set up that tested different water mist sizes and nozzle figurations [51]. Bulk and disperse water mists were also tested, and glycerin was assessed as well in order to vary the viscosity. Results indicated that mitigation may be through energy loss due to phase change [51].

Water was also shown to be an effective means of blast attenuation by Chong et al. based on their finite element model. This model, however, considered a volume of water surrounding the detonation zone, and it was determined that peak pressure and impulse are both reduced via vaporization [51]. These results were consistent with their earlier experimental work. Ananth et al. used a computational simulation as well to study the behavior of a water droplets and a confined blast in a chamber [52]. The fluid mechanics solver demonstrated that the dominant mechanism of the interaction is latent heat absorption. The results also indicated that at the shock front, the gas density increases while the gas temperature decreases due to water vapor formation oppose one another, and thus the pressure is only moderately decreases [52].

Because various mechanical properties play a large role in dictating the transmission and reflection of an incoming shock wave, as well as the acoustic impedance, a common theme in the literature is to investigate various material properties to assess blast...
mitigation. A popular suggestion was the use of “soft” condensed matter, like granular, porous, or foam-type materials. In 2003, Nesterenko et al. suggested granular materials and explained that these materials can be used successfully for blast mitigation by exploiting the energy absorbed by densification (compression) [53]. They also noted that a scattering effect could play a part [53]. Later, Langhorst et al. also supported the use of granular materials based on results with full-scale blast loading. They used pumice granules (a remnant of volcanic lava), and pearlite (which also comes from volcanic activity but differs in density), and results found that these granular materials are effective if used properly. They concluded that the granulates must be arranged in a way that can compress and reposition properly [53].

Granular chains in a tapered formation were suggested for mitigation via energy and impulse absorption by Pfannes et al. [55]. In this work, chains of grains that gradually decrease in size were linearly assembled so they just barely contacted one another. Results indicated that this method is useful because when an impulse load is applied to the largest grain, wave propagation acts non-linearly, and results in a higher velocity, but lower energy bundle for the smallest grain far down the chain because momentum is conserved, but energy is not [55].

In a different work, experimental and numerical studies demonstrated that a composite granular chain could disintegrate a shock wave and confine impulse loading [56]. This chain alternated grains of various elastic moduli, and results suggest that energy is trapped within the softer grains, and transferred to the stiffer ones via a slow, pulsing wave over a long time frame [56]. Granular filters using small spherical particles were also investigated by Britan et al., who simulated the pressure profile inside the filter to compare to experimental data [57]. They found that attenuation does occur, and can be well predicted by a one-dimensional simulation. They also found that the presence of an air gap between the surfaces one is attempting to protect and the filter eliminates peak pressure and stress on the surface, and lengthens the rise time [57].
Other soft materials were suggested in literature as well, such as the use of cellular or porous media, like foam. A numerical study by Li and his colleagues analyzed the compressive shock wave propagation in the solid phase of a cellular media [58]. They made several observations, including that in general, attenuation can be achieved with cellular media due to cell collapse. However, upon large blast-induced loads, the densification stage of cellular media reactions can actually contribute to enhancing the effect of blast mitigation [58]. Porous layers and blast mitigation were studied experimentally by Kitigawa et al, where polyurethane foam and sand layers were exposed to micro-explosive blast waves [59]. Results indicated that peak pressures decrease in these layers compared to air, between 10-40% of the peak overpressure in air, and that the mechanism is likely due to the blast wave collapsing into compressive waves when it intersects a complex media with three-dimensional porous media [59]. In one unique study, Zhao et al. suggest that energy can be dissipated with the use of nanoporous particles that are in a suspension of a non-wetting fluid [60]. The authors propose that when an external load or driving force is applied, the fluid can permeate into the nanopores, causing work to be lost both due to friction and due to interfacial energy between the air in the pores and the fluid entering the pores [60].

Some researchers have looked into modifying foam in some way to achieve blast mitigations. In 2008, Barger and Hamel determined that aqueous foams provide suitable blast mitigation by diffusing the incoming pressure wave at the bubble interface, and also through energy dissipation by displacing the bubbles that exist within the foam [61]. Britan et al. studied the propagation of shock waves through aqueous foam as well [57]. Because the foam is an unstable structure of bubbles, and therefore has continuously changing mitigation features, as well as limited data on this topic, the experimental results were used to expand the available data. Data suggests an advantage to aqueous foams, most likely due to high compressibility of air bubbles, but the authors indicate that for better fundamental understanding, free field tests must be done due to the complexities of this foam [61]. The use of aqueous foams is also examined numerically by Del Prete et. al with a flow model and Riemann solvers [62]. They justify that aqueous foams provide mitigation of blast waves via the two-phase interactions between
the liquid and gaseous phases by comparing the computational results with experimental data with favorable results [62].

Allen et. al performed a parametric study that searched various material properties for blast mitigation capabilities [63]. They tested water, glycerin, Perlite, and sand and assessed the reaction surrounding a detonated blast. Ultimately, experiments determined that porosity, density, and thermal dissipation all play important roles in blast mitigation. It was determined that the denser the material, the better attenuation, and that the porosity of a material can and should be optimized per each material [63]. In a different study, Lind et al. used a CFD code to model the attenuation of blast waves that pass through shields that vary in complex geometries, such as intersecting rods with variable cross sections and surface areas. In this study, the effect of geometry, placement, and porosity were assessed to determine how to optimize materials for blast mitigation [64].

Some work has been done on blast wave interactions with helmets, specifically. Gruijcic et al. used a computational model to study the blast mitigation capabilities of polyurea as a suspension-pad material in a military helmet [65]. Two levels of peak overpressure were assessed, and stress and velocity were measured and then compared to the conventional pads. They determined that there was a substantial decrease in the peak overpressure with polyurea than conventional pads [65]. Li et al. also analyzed the mechanical coupling between the head and the helmet with blast overpressure [66]. Simulations performed using a finite element code demonstrated that blast overpressure amplifies with a gap between the helmet and head, but when pads are placed between the two surfaces, the pressure can decrease [66].

Two other means of mitigation that have been mentioned in the literature are mitigation by thermal dissipation and by using fluids. A study by Absil and Bryntse suggests a theory of using a liquid to dissipate thermal energy [67]. Referencing a study by Keenan and Wager from 1992, they propose that upon a blast-induced load, the liquid disintegrates, creating a larger surface area, thus allowing better heat transfer efficiency [68]. With better heat transfer, more heat can be removed, and the liquid can evaporate,
creating a reduction in gas pressure. The use of a liquid to prevent pressure increase was also suggested by Eriksson and Vretblad, who proposed that by using a liquid, the temperature, and therefore pressure increase is smaller due to prevention of afterburning from a detonation [69]. Zhu examined a different type of fluid in his thesis, where he simulated the use of a shear thickening fluid for blast mitigation [70]. While it was not his original idea to use this type of fluid, his analysis included the addition of rigid particles within the fluid, and demonstrated the importance and sensitivity of size, arrangement, shape, and volume of these particles for blast protection. While there was no conclusive data, the analysis suggests that the addition of particles may be useful for blast mitigation [70]. Dawson and McKinley investigated a model for the stress-strain response of a reticulated elastomeric foam filled with shear thickening fluids when under dynamic compression [71]. In 2009, this was the first analytical model that goes beyond the shear-thickening regime, and the authors claim it can play an indispensable part in developing protection and armor against shock waves due to its ability to provide insight into wave propagation and energy absorption by Non-Newtonian fluid filled foams [71].

Finally, other researchers have spent time looking at ways to deflect or redirect the incoming blast wave as a means of protection. Curry suggested producing a layer of plasma on top of the layer one is trying to protect in order to mitigate the blast [72]. Waschel et al. also looked to deflect the blast wave by utilizing a magnetic field, though focus is placed on the location of detonation [73]. However, these concepts are primarily for large-scale applications, such as protection of infrastructure or vehicles, and also propose ideas that would be dangerous to humans.
Chapter 3  The Use of Filler Materials in Channels for Helmet Liner Improvement

Improvement and advancement of helmets has been an active research topic throughout the years. The idea to utilize channels filled with a fluid to provide better protection in helmet technology is not an original idea. Similar ideas including some form of fluid inside a helmet have been suggested as far as four decades ago. In 1971, Morgan [74], proposed the first patent that consisted of a series of intertwined and connected chambers set up with valves, filled with an incompressible fluid, within a helmet. The idea proposed that upon impact, the fluid would be forced into another set of chambers that are empty, and then return to the original chambers after impact. Since then, there have been several other attempts to utilize fluid channels or air bladders (Holt [75], Villari [76], Gooding [77], Hosaka[78], Calogne[79], and Mendoza[80]), but none have emerged into the market and gone beyond research.

Other research beyond patents exists in helmet improvement as well. Rueda et al. studied various designs for equestrian helmet liners using a finite element code [81]. They compared two designs, one with various layers of foam that vary in density, and another with a typically used single layer of foam. Results suggested that varying the density of foam decreased peak accelerations compared to single foam, and that this reduction is dependent on contact area, distribution of stress, and dissipated energy density. In a subsequent study, foam with graded density was assessed instead of varying layers to eliminate interface stresses and failures, and similar results were obtained [82]. In a relevant topic, a military helmet was investigated in simulations performed by Aare and Kleiven [83]. Their simulations used the predecessor of the ACH, the Personal Armor System Ground Troops’ helmet (PASGT), to determine an optimal external shell stiffness to prevent transmission of stress waves to the skull. However, no mention of pressure transmission was mentioned [83].
However, while valuable, the majority of the approaches in helmet advancement have been for impact mitigation, with the goal to improve helmets for sports applications or ballistic impacts. One patent that does address blast mitigation is by Ponomarev, who proposes a partially evacuated chamber filled with gas to be placed between the protected surface and the blast source [84]. It explains that the relative vacuum pressure will “suck up” the ambient air from an incoming pressure wave when the chamber bursts, creating a negative pressure than can partially oppose the incoming pressure, ideally reducing the overall peak transmitted pressure [84]. Stuhmiller proposed another relevant idea of a cushion including fluid chambers for shock mitigation in body armor. Assuming the fluid could transport to an empty reservoir, there was hope that the shock magnitude could be decreased via energy transport [85].

The majority of the literature in blast mitigation remains related to material properties and experimental work in order to gain better understanding of how a blast wave is attenuated, or simulations demonstrating how a helmet may react in various configurations or with material changes, as shown in the previous chapter. The project here is unique in that it proposes a novel idea for blast mitigation, and uses both experimental and theoretical work in order to test a new helmet concept, while attempting to learn the basic mechanisms for blast protection.

3.1 Sports Helmet Research at MIT

At MIT, the idea to implement fluid and fluid-like filler materials in helmet liners for improved protection originated in 2004 for sports helmet applications [86]. Professor Larry Young teamed up with Chan and Ruchelsman in an effort to construct a helmet liner with channels and reservoirs for an incompressible fluid that interconnect within closed-cell foam [86]. The idea was that upon impact, the fluid would spread either within the foam cells, or through the channels, distributing the impact over a larger area, relieving the impact site, and thus reducing the overall force. It was also proposed that the duration of impact would be longer, therefore reducing gradients that could be damaging [86]. The original concept can be seen in the figure below.
The possibility for energy dissipation through viscous forces was investigated by Claire and Vue [87]. They compared the peak acceleration data for Der-Tex Corporation’s (www.dertexcorp.com) VN600 foam, a closed-cell vinyl nitrile foam, with channels filled with a highly viscous fluid, and a sample with just the foam alone. Results showed a reduction in acceleration and up to a 35% attenuation of peak forces by the viscous fluid-foam combination. Results also indicated that the distribution of force in both space and time were improved [87].

In his Master’s thesis, Stewart performed a comprehensive study to determine the possible advantages of incorporating fluid channels into the DerTex VN600 foam, and compared the performance to typically used Expanded Polystyrene (EPS) foam [88]. He also examined the effect of viscosity and channel diameter on peak acceleration by performing parametric studies that test the sensitivity of varying these parameters. The key testing parameter used to assess behavior in all cases was peak acceleration reduction. The experimental setup used consisted of a drop test setup built at MIT to conform to the ASTM F1447-06 bicycle helmet drop test standards [88]. The set up can
be seen in the figure below, where a standardized steel headform is raised to a specified height, dropped in free fall onto a test sample that rests on a flat anvil.

![Drop test apparatus per ASTM standards](image)

**Figure 3-2: Drop test apparatus per ASTM standards [88]**

The test samples that were used were two-dimensional “foam forms” that consist of a rectangular foam sample with channels cut into the sample. This was to eliminate any complications associated with the complexity of helmet liner geometry. Two data acquisition systems were used to measure acceleration and velocity. Acceleration data was collected using accelerometers embedded in the headform, and light gates were used to calculate the velocity before impact. Tests were performed with constrained and unconstrained channels, and multiple drops were performed on each sample in order to test consistency over multiple impacts [88]. Air, water, and various concentrations of glycerin were used to test the effect of varying viscosity [88].

Results showed that DerTex VN600 outperformed the standard EPS foam for all impacts in terms of reduced peak acceleration. The constrained channel setup that used air and water as varying filler materials yielded higher peak accelerations compared to solid foam, but the unconstrained channel setup substantially differed. Water in unconstrained channels showed reduction in peak acceleration, with the best attenuation resulting from
channel diameter of 3/8”. The water and glycerin mixtures also demonstrated reduction in peak acceleration, with the best results coming from a 30% glycerin by weight mixture. Air did not demonstrate any substantial difference to solid foam [88]. Results can be seen in Figure 3-3. It is clear from this study that viscosity can provide a means for impact attenuation and all results gave confidence to proof of concept.

![Figure 3-3: Results of VN600 w and w/o channel concept vs. EPS foam [88]](image)

The work by Stewart was extended to continue to pursue the development of a helmet liner with channels filled with fluid or fluid-like substances by Goel [89]. Goel tested the deformation and acceleration responses of two types of currently used ski helmets: a conventional and a high-end brand. Then, tests were also performed on a number of foam forms with various materials in order to further test the effectiveness of the approach in previous works [87, 88]. For both sets of tests, the drop test assembly used by Stewart was used, and settings were made to conform to the ASTM F2040 06 drop test for recreational snow sports. Again, acceleration and velocity was measured by the drop testing apparatus data acquisition system.
For the ski helmet tests, two brands, Standard X and POC, were dropped six times, and results demonstrated superior performance by the high end brand, POC in terms of reduced peak acceleration, consistency over series of tests, and in terms on permanent deformation and cracks in the foam (helmets were taken apart after testing). Figures 3-4 and 3-5 show the helmets tested and a sample of results.

![Ski helmets](image)

**Figure 3-4: Ski helmets used for testing: Leedhom (L) and POC (R) [89]**

![Graph](image)

**Figure 3-5: Comparison of two ski helmets based on peak acceleration [89]**

Different channel configurations and materials were tested in foam forms, as mentioned, that appeared like foam “sandwiches”, as shown in Figure 3-6.
Figure 3-6: Der-Tex VN600 foam “sandwiches”: solid (L), single cavity (center), dual (R) [89]

Single and dual cavities were tested, and water, glycerin and glass beads were tested (however only water was tested in dual cavity). Multiple tests were performed and results indicated that glycerin out-performed the other filler materials, and for the dual scenario, having smaller channels filled with water provided better impact mitigation than the single cavity with a larger surface area. These preliminary results suggest again that viscous dissipation plays a role in impact attenuation, and showed promise for the continuation of this project as a form of head protection.

3.2 Blast Protection Utilizing Filler Materials

The positive results from impact testing and sports helmet applications confirmed an advantage using the fluid channel helmet liner concept, which supported an idea to transfer it over to the problem of blast-induced traumatic brain injury. However, impact mitigation and blast mitigation are different mechanisms, as well as the fact that blast mitigation is not an extremely well understood field. Therefore, blast testing needed to be done, and filler materials for investigation for the channels were not just limited to fluids, but materials were selected to cover a range of properties and possible means of mitigation based on literature suggestions. Therefore, an approach of an exploratory phase of the concept was taken, and the first stage aimed to vary different materials within the simplified, two-dimensional “sandwich” geometry of a channel within the VN600 foam. Using sandwich structures is a straightforward way to investigate various filler materials’ capabilities in blast mitigation because it eliminates any excess factors such as complex geometry playing a role in blast wave interaction. Then, the research
transitioned to the development of helmet prototype liner and development of a 3-D computational model. However, there were still gaps in research, and eventually, the next stage of research aimed to go back to the two-dimensional case to learn more about blast mitigation mechanisms, which is the topic of this thesis.

In this Master's thesis, Alley, a colleague of the MIT study at Purdue University, used these sandwich structures to analyze various filler materials responses to blast experiments [90]. An explosively driven shock tube aimed at various samples was used to produce an air blast load. Samples were made of Der-Tex foam, and were 10 in x 10 in x 1 in, with channel cavities 8 in. x 10. x 0.5 in. Controls were solid pieces of foam the same dimension of the sandwich. In order to perform blast testing, an explosively driven shock tube was used, and placed 12 in. from the face of the sandwich. The key testing parameter was transmitted peak pressure, recorded with a pressure transducer recessed 2.75 in. behind the center of the sample. In order to secure the sample, they were placed between two pieces of poly(methylmethacrylate), also known as PMMA. In an attempt to prevent any reflections or the shock wave from converging around the sample, Alley and colleagues attempted to isolate the transmitted shock by enclosing a test area with a PMMA rectangular enclosure [90]. A drawing of the experimental setup for data acquisition can be seen in Figure 3-7.
Various filler materials representing different properties were investigated with blast testing in a basic, 2D sandwich structure in order to examine the best potential filler materials on a fundamental level. Materials were selected to cover a broad range of specific properties, primarily: density, particle size, viscosity, and acoustic impedance [90]. Viscosity was hypothesized to attenuate through viscous dissipation, and based on its success in Stewart’s work in impact attenuation [88]. As previously mentioned, acoustic impedance is a function of the density of a material and the speed of sound through a material. If a sound wave changes media, the ratio of impedance mismatches of the media determines the amount of energy transferred. So, large impedance mismatches may lead to reflection of waves [35, 36, 37]. In addition, particle size may affect wave transmission due to large number of interfaces, and possible more elastic collisions and energy loss due to friction [55]. It is also possible that if the particle size is heterogeneous, then there could be impedance mismatches. Finally, density was selected
because it dictates the acoustic impedance as well as the speed of sound through a medium. It also creates an “inertial” effect of just having a more dense material might provide a larger barrier for a wave [53, 63].

Materials used were CAB-O-SIL®, Aerogel, expanding foam, volcanic tuff, glass beads (glass shot), glycerin, and water. Results from these tests are provided in Table 3-1, and indicate that the denser filler materials, such as glass beads, water, glycerin, and tuff provide the best mitigation capabilities in terms of reduce peak pressure and impulse. An interesting result, however, was that there was no discernable difference between water and glycerin, suggesting that viscosity does not necessarily play a role in mitigation of blast-induced waves. Regardless of these results, however, Alley noted that it was likely that most blast mitigation was due to the PMMA plates that were sandwiching the test samples [90], and that clearly the experimental set up needed to be modified.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Impulse [psig-ms]</th>
<th>Arrival Time [ms]</th>
<th>Duration [ms]</th>
<th>Rise Time [ms]</th>
<th>Peak [psig]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.57</td>
<td>1.13</td>
<td>0.02</td>
<td>15</td>
</tr>
<tr>
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<td>0.74</td>
<td>1.27</td>
<td>0.10</td>
<td>0.86</td>
</tr>
<tr>
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<td>1.00</td>
<td>0.98</td>
<td>0.40</td>
<td>0.98</td>
</tr>
<tr>
<td>Aerogel</td>
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<td>0.81</td>
<td>1.14</td>
<td>0.55</td>
<td>0.91</td>
</tr>
<tr>
<td>Expanding Foam</td>
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<td>0.80</td>
<td>1.42</td>
<td>0.82</td>
<td>0.80</td>
</tr>
<tr>
<td>Tuff</td>
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<td>1.26</td>
<td>1.31</td>
<td>0.57</td>
<td>0.56</td>
</tr>
<tr>
<td>Glass Shot</td>
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<td>0.76</td>
<td>1.63</td>
<td>0.43</td>
<td>0.47</td>
</tr>
<tr>
<td>Water</td>
<td>0.38</td>
<td>0.83</td>
<td>1.53</td>
<td>0.60</td>
<td>0.57</td>
</tr>
<tr>
<td>Glycerin</td>
<td>0.34</td>
<td>0.86</td>
<td>1.58</td>
<td>0.43</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Table 3-1: Results from Alley’s experimental work with sandwich plates [90]

On the computational front, Christou attempted to validate the results from Alley with a finite element model of the response of the test samples to induced air-blast loading [91]. Using ABAQUS/CAE® and a coupled Eulerian-Lagrangian formulation for the air/structure interaction, he aimed to simulate blast loading, and find the simulated peak pressure of these samples. In order to test his model, Christou first modeled a simple, planar shock wave that intersects a rigid surface and reflects according to the shock wave physics model [91]. Results agreed with theory, and though there were errors with increased applied pressure values, for values associated with Alley’s work, the errors
were small (~1%). This confirmed that ABAQUS® could be used to model air blast events.

In order to simulate blast loading, a decaying pressure load consistent with the measured experimental pressure profile was applied at the front of the air domain. A planar, symmetric wave was used, and simulations were performed for the solid foam sandwich sample and a sandwich sample filled with water [91]. Ultimately, the numerical results matched experimental results in order of magnitude, but the values did not demonstrate good agreement, and the waves were out of phase [91]. Christou explained that a possible reason for this discrepancy was likely due to the experimental setup and the lack of sensitivity of the pressure transducers used. Because of the low pressures used in testing, and the sensitivity issue, Christou acknowledged there may have been as much as 50% disagreement between the measured results and the actual incident pressure on the sensor [91].

To investigate this issue and to attempt to improve experimental results, Goel considered adapting the experimental setup in order to attain better data [89]. Smaller sandwich structure samples were used, with dimensions of 5” x 5” x 1” and cavities 5” x 3” x 0.5” [89]. The setup was also redesigned. The test samples were secured with transparent packing tape vertically against an aluminum plate, which was supported by angle aluminum bars fixed to an optical table. The samples lied flush against the plate and perpendicular to the blast axis. Pressure transducers were inserted into the plate to measure both transmitted peak pressure as well as to use as a reference. This experimental setup can be seen in Figures 3-8a and 3-8b.
Figure 3-8: Experimental setup for sandwich structure blasting by Goel. Note in 3-8(b) the pressure gauge on the right measures the pressure through the sample, and that on the left measures the incoming blast without the sample [89]

Blast loads were applied using an explosively driven shock tube again (details discussed later). The distance the test sample was placed from the shock tube was based on the overpressure range of interest and determined based on a blast profile plot at various distances from the shock tube. The same filler materials as Alley [90] were used for the sandwich structures, only one additional material was used: AgileZorb™. AgileZorb™ is an advanced material that consists of a hydrophobic gel with nanoporous spheres in suspension. This material was blasted directly, with no foam sandwich surrounding it. A suspension pad from the ACH was also blasted as an additional control to the solid foam case [89]. Transmitted peak pressures were measured, and results for each sample are provided below.
Performance in terms of reduced transmitted peak pressure compared to the applied open field pressure (12” distance selected for testing) can readily be seen in Figure 3-9. All samples except for Aerogel produced some blast mitigation of the peak pressure. The best results came from AgileZorb™, and then glass beads and glycerin. However, the company that produced AgileZorb™ did not wish to continue working with this project, and therefore glycerin and glass beads were taken to be the most capable filler materials [89]. Other results that demonstrated the pressure traces of each sandwich structure indicated that for glycerin and water, there was an increase in rise time of the pressure, which can be an important component for minimizing damage to the brain [89].

Goel then went on to model this new experimental setup using the finite element software ABAQUS® (which was updated and included an air blast module). This new release provided accurate loading with dynamic pressure on structures based on a detonation location/point and an equivalent mass of TNT provided by the user [92]. This reduced the computational effort, and Goel found good agreement between the pressure traces from the experimental and numerical data. Similar peak pressures and rise times were observed. Goel also found very good agreement between peak transmitted pressure data from experiments and simulations performed with sandwich structures with solid foam, glycerin, and glass beads, though discrepancies were evident for both aerogel and water [89].
This validated finite element model was also used for parametric and sensitivity studies. Goel varied both the viscosity of the fluid filler as well as channel geometry in order to gain insight into their roles in blast mitigation. Results from varying viscosity over several orders of magnitude demonstrated that, contrary to results from impact studies, viscosity does not play a large role in mitigation. In addition, results from various geometries of sandwich structure channels, including interconnected channels and variable number of channels, indicated blast mitigation has little dependence on channel configuration. The simulations did indicate that the amount of filler material in the channels does play an important role, suggesting that perhaps blast mitigation may heavily be an “inertial effect”, depending on density more than anything [89].

Vechart progressed this project further by designing and manufacturing a 3-dimensional helmet prototype with channels for filler materials, and performing experiments with the experimental setup at Purdue [34]. He then developed a nonlinear finite element model that captures the dynamic response of a helmet and head surrogate to an induced air blast load, which was used to compare experimental and numerical results [34].

The prototype was made to fit into the ACH helmet shell, and replace the ACH pads. It was constructed out of Der-Tex foam, and contained five parallel channels 3 cm wide to incorporate the technology being researched in this project. The prototype liner can be seen in Figures 3-10 and 3-11. It was stressed by Vechart that this prototype in no way represents an optimized design for the liner, and was constructed as an initial idea, primarily useful for insight in comparison between experimental results and numerical simulations. Additionally, the current ACH helmet utilizes a modular padding system, where as this model shields the entire interior of the ACH helmet shell. This may or may not be the ideal case, and further research will provide insight as to whether a modular design of full covered design is ideal for blast mitigation capabilities [34].
Blast experiments were performed with the prototype liner installed into the ACH helmet and with the ACH helmet as a control. The shock tube was aimed at the “face” of the ACH, and the closest point of the helmet was maintained 12” away from the shock tube.
mouth. Figure 3-12 shows the experimental set up. Filler materials investigated were: water, glycerin, glass beads, and Aerogel [34].

![Figure 3-12: Experimental setup for 3-D testing [34]](image)

Vechart used an experimental setup that had the helmet supported by a “headform” that consisted of a PMMA hemisphere attached to a PMMA cylinder. This PMMA headform was kept in place by a steel pipe connected at its base. Five pressure transducers were installed circumferentially, which were used to measure the induced pressure [34].

Two tests were performed on the standard ACH helmet and each prototype liner filled with water, glycerin, glass beads, or Aerogel. Vechart analyzed the data obtained during testing two different ways. First, the pressure response at all of the gauges for a given trial of a given filler material was assessed in order to obtain a general spatial trend of the pressure, and to get a feel for the consistency of the test setup. Second, a comparison of the various filler materials at a particular gauge was assessed in order to gain insight into the mitigation potential of the different liner fillers. The results acquired in the comparison by filler materials yielded a few general trends that were consistent between each of the filler materials. Overall, for each material, the shapes of the waveforms were qualitatively similar for both tests. However, the peak pressures tended to have
discrepancies between the two tests. In the solid materials, the ACH standard (control), and glass beads, the peak pressures tended to be higher in the second trial compared to the first for each material. There was not much difference in Aerogel tests, and in the two fluid fillers, glycerin and water, the peak pressured seemed to decrease in the second trial compared to the first. An example of the raw data can be seen in the figure below [34].

To assess the mitigation capabilities of the different filler materials, the results for each material were compared at each gauge location individually. Because of variability between the two tests as just described, averaging the two tests was not an ideal comparison. Thus, Vechart used a “best” and “worst” concept that compared each material, i.e. the test with the lower pressure transmitted was designated “best”. Ultimately, water, Aerogel, and glycerin all performed similarly, and the glass beads consistently recorded the highest pressures throughout the blast event. Based on the comparisons for both cases, results seemed to suggest that the ACH standard pads demonstrated the best protection from blast loading [34].
Figure 3-14: Example of data used in “best case” for gauge 2 [34]

The results obtained experimentally in regards to material performance seemed to be somewhat contradictory to expectations based on results using the same materials in sandwich structures. As discussed previously [89], data using sandwich structures suggested a clear advantage to using Der-Tex foam with filler materials, specifically glass beads, water, and glycerin, over ACH standard helmet and pads in regards to decreasing peak pressures transmitted, increasing rise times, and increasing positive durations [89]. Aerogel was determined to decrease the performance compared to a solid sample of foam [89].

However, based on Vechart’s experimental work, the ACH standard remains to appear the most promising, and glass bead filled liners consistently performed poorest at all gauges, while in sandwich structures it was the best performer [34]. Vechart acknowledged several potential reasons for why this is the case. The main area of concern was that there were large gaps between the “headform” and the helmet during testing. Because a shock wave will take the path of lease resistance, this gap allowed pathways for air and compressive shock waves to travel through and reach the “headform” without intersecting any material proposed for mitigation. This could have
produced the high peak pressures on the transducers. The ideal fitting should be as flush as possible, Vechart noted, which will force the shock wave through the liner/pads, forcing dissipation and reflections [34].

On the numerical front, Vechart spent a significant effort developing the dynamic behavior to blast loading to a complicated geometry of helmet, liner, and headform support structure. A coupled Eulerian-Lagrangian analysis was used in ABAQUS®/Explicit and ABAQUS®/CAE to model the fluid-structure interaction. All geometry, boundary conditions, section assignments and material definitions were made using ABAQUS® as well. The initial conditions were written into an input file with a script. Because the blast loading of interest was centered on the front face of the helmet, only half of the model was created and meshed and symmetry was applied. The filler materials were modeled as a single part with the helmet and liner as well, and the mesh of the proposed prototype liner inside the current ACH shell is shown in the figure below [34].

![Figure 3-15: Mesh of helmet with prototype liner and filler](image)

Simulations were run for the helmet with prototype liner filled with water, glycerin, glass beads, and Aerogel, as well as with the ACH standard pads. For direct comparison with the experimental results, the main variable of interest in the simulation was the pressure values recorded at the simulated pressure transducer locations. After some debate, it was
determined the most accurate way to do so was to utilize the contact pressure reading at each node of the PMMA tube which corresponded to the experimental locations. Contact pressure characterizes the stress formed in resisting air penetration into the tube geometry [34].

![Image](image_url)

**Figure 3-16: Contour plot of initialized pressure field and helmet [34]**

Results were compared similarly as they were in the experimental work, and then each representative simulation was compared to the experimental data to determine the extent of correlation. Overall, there was good agreement between the numerical simulations and experimental results, which suggests the validity of both the model and its assumptions. In his thesis, Vechart also warned readers to be careful in drawing conclusions about the success of the fluid filled liner idea based on the results presented experimentally and numerically. Though the results seem to have indicated that the ACH standard helmet surpasses the prototype filled liners in blast mitigation performance, it is important to note that the results obtained in experimentation were likely an artifact of the setup and helmet liner geometry rather than the composition and structure [34].
Chapter 4  Blast Experiments Using Sandwich Structures: Purdue University

Our initial concept for embedding fluid and fluid-like materials inside a foam helmet liner to reduce TBI from blast waves was shown to be valid using 2D sandwiches - but initially tested only at high pressure levels associated with severe TBI. However, mild TBI, as demonstrated in Figure 4-1, constitutes the majority of TBI injuries in the battlefield. In order to examine the effectiveness at lower incoming blast pressure levels, consistent with the occurrence of Mild Traumatic Brain Injury (mTBI), we extended our testing over a range of blast pressures from low to high.

![Figure 4-1: Reported cases of various TBI severities [1]](image)

Experimental testing was carried out at the Zucrows Laboratory at Purdue University to gain better insight into the behavior of previously tested materials during blast exposure. Formerly, glass beads, water, glycerin, and Aerogel were exposed to blast testing in both sandwich structures and our first helmet prototype at “high” levels of peak overpressure (approximately 110 psi). It is believed that, unlike other types of loading conditions, under induced air blast loading, the materials exhibit nonlinear behavior due to a nonlinear strain rate. Tests performed here were used in conjunction with an explosively...
driven shock tube at low, mid-range, and high peak overpressures in an attempt to better understand how each material reacts over a wide range of shock wave profiles. Sandwich structures rather than the 3-D prototype were used to assess material behavior in a more basic, fundamental method and eliminate geometrical complexity, and to have good comparison with previous sandwich structure testing at the high pressure levels. This also allowed for more time to explore alternative options for future 3-D experimental set ups, as to eliminate the errors explained at the end of Chapter 3. The most promising materials from previous tests were used: glass beads and glycerin.

4.1 Experimental Set up

As mentioned above, blast experiments were performed with the explosively driven shock tube located at Purdue University and under the advisement of Professor Steve Son. A schematic of the shock tube can be seen in Figure 4-2. Though specifics have been discussed in previous theses [89, 90, 91], a brief explanation can be found here. The shock tube consists of two regions, a driver section, or detonator chamber and a driven section, or high explosive (HE) chamber. The detonator used was a Teledyne RISI RP-502 exploding bridge wire (EBW) detonator. 3 grams of Primasheet 1000, a plastic explosive with PETN, made by Ensign-Bickford Aerospace & Defense was formed into a ball and connected to PETN detonation cord, which connects the two chambers. An equivalent explosion of 2.87 g of TNT or 13.24 kJ is produced using this setup.

![Figure 4-2: Schematic of test rig and explosively driven shock tube [88]](image-url)
Test samples of 5 in x 5 in x 1 in Der-Tex foam sandwiches with 5 in x 3 in x 0.5 in cavities were used (to correspond with previous tests). These were filled with either glass beads or glycerin, and were compared to a solid sample of Der-Tex foam for a control. The procedure for experimentation with sandwich structures followed the procedure in Goel’s thesis [88], where samples were secured with transparent packing tape vertically against an aluminum plate apparatus used to fix the sample.

Figure 4-3: Sandwich test samples: (a) solid Der-Tex foam (b) single cavity sandwich [88]

This aluminum plate configuration consisted of a thick plate perpendicular to the blast axis, which is supported by angle aluminum bars fixed to an optical table. The pressure transducers used for measurement were inserted into the plate, but with one notable change: three pressure transducers were inserted into the aluminum plate, rather than using two and a pencil gauge. One was placed centrally, one was offset a distance outside the boundary of the sample, yet still on the plate and at the same vertical distance, and another was placed in the lower right corner of the plate. The corner gauge was used in order to test consistency between trials at the same blast level. The gauges were recessed 2 mm into the plate, and vacuum grease was used in order to transmit the signal. Ultimately, the data from the gauge located next to the sample was not useful for analysis due to its close proximity to the sample. It was believed that the shock wave was curving around the sample, producing inaccurately high peak pressures at this gauge. Data from this gauge was eliminated for analysis.
Figure 4-4: Photo of aluminum plate configuration with labeled pressure gauges

Figure 4-5: Photo of general experimental setup
Experimental Results: Free Field Testing

Pressures were varied by varying the distance of the experimental set up. The magnitude of the induced air blast is defined by the distance between the explosively driven shock tube mouth and the aluminum plate. Based on previous calibration tests, it was believed that 12.0 inches would yield a "high" peak pressure (~80 psi), 15.5 inches would yield a "mid" peak pressure (~40 psi) and 19.0 inches would yield a "low" peak pressure (~20 psi). These pressures were based on a study that determined that blast waves greater than 20 psi can cause mild TBI, 30-75 can cause lung damage and increasingly worse TBI, and greater than 100 psi one risks fatality [31]. Levels below 100 psi were therefore used to test a loading condition in the field that produces injury, but not fatality, and to explore a pressure range that contains mild TBI. Open field tests were performed with no sample on the plate in order to determine the exact peak pressure values that occur at these distances. Two tests at each distance were performed. One test was with the gauge recessed 2 mm and vacuum grease applied, and one with the gauge flush with the plate without any grease. This was in order to explore any effects the grease may have on the pressure readings.

Figure 4-6 provides results of the sample gauge for free-field testing at 15.5 inches for the greased and ungreased gauges. The curves were separated in time for visibility. Peak pressures are nearly identical, and the waveforms show clear similarity. This demonstrates that the grease does not affect the peak pressure reading, and therefore for the rest of the analysis, the greased and ungreased curves were averaged in order to acquire an average applied peak pressure at each distance.
Figures 4-8, 4-9, and 4-10 are the average of the two free field tests at 19.0 inches, 15.5 inches, and 12.0 inches, respectively. Averages were taken by using a built-in function in DPlot©, a scientific graphing software, which takes a sample of curves and produces a new curve with Y values equal to the average of all amplitudes of the sample curves. The new curve has the identical X values as the first encountered curve. For accurate averaging, each sample curve was aligned such that the first instant of a pressure rise occurred at the same time. Thus, the results were averaged at each instant for all curves. The sample interval was 2 µs. Figure 4-7 displays both trials (greased and ungreased) and the average curve on one plot to demonstrate this technique and to show repeatability.
Figure 4-7: Demonstration of average: trial 1, trial 2, and average displayed

Figure 4-8: Average pressure waveform at 19.0 inches
Figure 4-9: Average pressure waveform at 15.5 inches

Figure 4-10: Average pressure waveform at 12.0 inches
Ultimately, based on these open field plots (Figures 4-8, 4-9, 4-10), it was determined that the 19.0 inch range yields approximately 40 psi peak overpressure, the 15.5 inch distance yields approximately 60 psi, and the 12.0 inch yields approximately 70 psi. It should be noted that three sets of data were taken for the 12.0 distance because there was a misfire, and a second blast for the greased open field test was performed in case the misfire might affect results. Ultimately, it did not and the third data set was excluded in the average because it exhibited abnormalities from all other pressure traces and for consistency with the averaging procedure at other test distances. Table 4-1 summarizes the results.

<table>
<thead>
<tr>
<th>Distance (in)</th>
<th>Average Peak Overpressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.0</td>
<td>~ 40 (39.7)</td>
</tr>
<tr>
<td>15.5</td>
<td>~ 60 (58.4)</td>
</tr>
<tr>
<td>12.0</td>
<td>~ 75 (73.8)</td>
</tr>
</tbody>
</table>

Table 4-1: Summary of open field testing

4.3 Effects of Repetitive Testing on Single Sample

Because numerous tests were going to be performed on each sample (which is not ideal), a calibration test of sorts was performed using solid foam in order to investigate any potential type of mechanical memory effects in the foam that could skew results. Based on previous research with impact loading, a decrease in performance by the foam was anticipated with repeated tests due to material degradation. A solid foam sample was blasted four times at 15.5 inches, and the plot of the sample gauge reading for each trial can be seen in Figure 4-11. A brief statistical analysis demonstrated that there is, indeed, some change in response in the foam over multiple tests. As shown in Table 4-2, a standard deviation of 6.6 was calculated for the sample gauge, while a standard deviation of only 1.9 was calculated for the corner gauge, corresponding to percent error of 16.06% for the sample and only 6.4% for the corner gauge.
<table>
<thead>
<tr>
<th>Gauge</th>
<th>Sample Gauge</th>
<th>Corner Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>Peak Pressure (psi)</td>
<td>Peak Pressure (psi)</td>
</tr>
<tr>
<td>1</td>
<td>33</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>39</td>
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</tr>
<tr>
<td>Average</td>
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</tr>
<tr>
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<tr>
<td>Stand. err</td>
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<td>0.97168239</td>
</tr>
<tr>
<td>percent error</td>
<td>16.06%</td>
<td>6.40%</td>
</tr>
</tbody>
</table>

Table 4-2: Statistical analysis of hysteresis test

The corner gauge error lies within the range expected from test to test based solely on the experimental setup variability, though the sample gauge does not, suggesting the blast loading was relatively consistent and that the foam does not recover its original condition after each blast. This type of mechanical memory has been seen in previous studies, primarily due to the fact that the material is plastic and degrades. This ultimately was not used in any calculations in the material testing which follows, but it was useful to note the potential effects this may have on the results, and was taken into account when analyzing the relative agreement between Trial 1 and Trial 2 for all results obtained during the subsequent testing of each material at various blast levels. It also should be noted before drawing any conclusions from any comparative analysis between sample materials.
4.4 Experimental Results: Material Assessment

Each material (solid foam, glass beads, and glycerin) was tested twice at each distance before changing distances. The tests were performed from low to high pressures (19.0", 15.5", then 12.0"), and the sample was kept the same through all six tests. After some in-depth study, and based on the knowledge that each test using the experimental set up and diagnostics can only be expected to have +/- 10% repeatability, it was determined that there was good agreement between trials and therefore Trial 1 and Trial 2 at each distance could be averaged. The corner gauge proved to be very useful in determining repeatability between trials, and results at this gauge were generally extremely close in value. Therefore, the averages of sample gauge results were then used in all comparative analyses that follow.
Sample response as a function of pressure

The following plots show the average pressure responses of the two trials for each distance (pressure). Figure 4-12 shows results for Solid Foam. It should be noted that for analyses sake, all times were shifted so that each abrupt rise in pressure in each curve began at the same time.

![Solid Foam
Average pressures at various distances](image)

**Figure 4-12: Average pressure at various pressures for solid foam**

There is some apparent nonlinearity in the response. Although transmitted pressures decrease with distance from the blast, they do not appear to be proportional to the applied pressure. This supposed nonlinear behavior will be discussed further in the subsequent section. Some what is believed to be blast pressure mitigation is visible at each distance. Considering only the initial pressure peak, as seen in Figure 4-12 for solid foam, we see that at 12.0 inches, the peak pressure is approximately 10 psi less, at 15.5 inches it is approximately 28 psi less, while at 19.0 inches it is only approximately 8 psi less than the...
free field pressures (40, 60, and 75 psi, respectively). This corresponds to a percent reduction of 12.8%, 45.7%, and 10.5% at 40, 60, and 75 psi, respectively. Unexpectedly, almost the same peak pressure was recorded for both 15.5 inches away and 19.0 inches away even though the induced peak pressure at 15.5 inches is about 20 psi greater. Importantly, there is a clear distinction between the two waveforms after the peak pressure occurs. At 15.5 inches (applied pressure ~60 psi), the waveform is wider, and a pressure level close to the peak is maintained for nearly 1 ms before decreasing. At 19.0 inches (applied pressure ~40 psi), there is a quick decrease in pressure after the peak until a lower pressure about 10 psi less than the peak is maintained for about 0.5 ms, and then the pressure slowly decreases.

Results for glass beads are presented in Figure 4-13. Again, there seems to be some possible nonlinearity in the response. The transmitted pressures were not proportional to the free field applied pressures at the three distances tested. The peak transmitted pressures for 12.0", 15.5", and 19.0" are approximately 60 psi, 38 psi, and 31 psi, respectively. These lead to percent reductions of 20.1%, 36.7%, and 22.5%, correspondingly. The glass beads performed closer to expectation than the solid foam results, in that the lowest free field test resulted in the smallest peak pressure for glass beads. However, once again, the 15.5 " distance plot (free field of ~ 60 psi) reduced the peak overpressure by 22 psi, while at 19.0", the peak pressure was only reduced by 10 psi. The best mitigation appears to occur at 15.5 inches, regardless of the filler material (solid foam, glass beads, or glycerin).

It should also be noted that at 12.0", while the pressure was mitigated, it was not nearly as drastic as seen in Goel's thesis [88]. This could be due to the effects seen from multiple tests on one sample, since the highest peak pressures were tested last, and therefore these results were the average of the 5th and 6th blast on the same sample. However, it is not possible to determine what percentage is due to any sort of mechanical memory an effect vs. mitigation capabilities at this time. Additionally, in Goel's thesis the average applied peak pressure at 12.0 inches was recorded at approximately 108 psi, while in this study data suggests it is only ~75 psi [88]. This restricts direct comparison of results, and
suggests that perhaps the experimental setup varied in some way despite our attempts to follow the same procedure. Also notable, a second peak occurs right after the peak pressure in the 12.0 range and, to a lesser extent, in the 15.0 range, but this was not seen in other samples.

Figure 4-13: Average pressure at various pressures for glass beads
Figure 4-14: Average pressure at various pressures for glycerin

Transmitted pressure results for glycerin at various pressures are presented in Figure 4-14. Once again, the responses appear nonlinear in some way. Percent reductions were calculated as 23.5%, 32.8%, and 25.3% at 40, 60, and 75 psi, respectively. As also seen with the other samples, the best mitigation appears to occur at 15.5 inches, and the peak transmitted pressures at 15.5" and 19.0" are again very close in range. Compared to the other materials, glycerin actually performs the best at the high and low pressures (12.0" and 19.0"), though only marginally. Glass beads and glycerin seem to have almost identical transmitted pressures, which is similar to Goel's findings [88]. Further discussion comparing the materials' performances follows in the subsequent section. Overall, each sample type appears to demonstrate a possible nonlinear response in peak pressure. While all sample types are in the same range of blast mitigation capabilities, the results suggest an improvement to transmitted pressure when glass beads or glycerin is used.
Sample results: Comparison of Materials

In order to assess the blast mitigation capabilities of each material, plots were made at each distance (pressure) with each material's pressure response. For each distance (pressure) tested, two figures were plotted: one showing the pressure waveform as a function of time, and one showing the peak pressure recorded for each trial, and the average. Note, the figures with the waveform are averages of the two trials. Figures 4-15 and 4-16 provide results at 19.0". Again, all results were shifted in time to align the pressure rises.

Figure 4-15: Comparison of materials at 19.0 inches
Figure 4-16: Comparison of peak pressures recorded at 19.0 inches. Note: error bars indicate maximum and minimum for each material.

At 19.0", the average open field pressure was approximately 40 psi. It is clear based on these plots that the data suggests there was some blast mitigation exhibited by each material. At this distance, glycerin performed the best, but only marginally. Glass beads and glycerin did outperform the solid foam sample, but again, mitigation was not very large. This is interesting, since in Goel's thesis [89], at high pressures (~108 psi) glass beads and glycerin significantly reduced the peak pressure (nearly 50% less than solid foam). However, it should be noted that at 19.0" the induced peak pressure was low, at ~40 psi. Also interesting, the curves for solid foam and glycerin were wider than that for glass beads, which is a key component to blast protection as it reduces the pressure gradients that can be harmful to the brain.

Results for 15.5" (~60 psi) are presented in Figures 4-17 and 4-18. Results at 15.5" seem to conclude the opposite that was found at 19.0". Here, the data suggests that solid foam outperforms both glycerin and glass beads, and glycerin actually appears to perform the worst at this distance. However, once again, the differences in reduced pressure for each material are marginal, unlike those seen at high pressures in Goel's work [89]. Another point of interest is that the most blast mitigation seems to occur at the 15.5 " (~60 psi) distance, compared to the other two distances. This also gives confidence to the
nonlinearity expected in blast mitigation mechanisms (to be discussed in the next section). Once again, the glass bead response seemed to have the narrowest waveform as well, but only slightly.

### Figure 4-17: Comparison of materials at 15.5 inches

<table>
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<th>PRESSURE (psi)</th>
</tr>
</thead>
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</tr>
<tr>
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<td>5</td>
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<td>1.7</td>
<td>60</td>
</tr>
</tbody>
</table>

- Glass Beads
- Glycerin
- Solid Foam
- Open

Comparison of Materials @ 15.5 inches
Average pressure curves used
Results for 12.0" (~75 psi) can be seen in Figures 4-19 and 4-20. Results indicate that glycerin performs best in blast mitigation as it yields the lowest peak pressure, but glass beads and glycerin have very close values in transmitted peak pressures. It is also interesting to note that the peak for glycerin occurs slightly later than the other materials. However, once again, the difference between each material is not large, though there is decent reduction in pressures for glycerin and glass beads (though not as much as at 15.5").
Comparison of Materials @ 12.0 inches
Average pressure curves used

Figure 4-19: Comparison of materials at 12.0 inches

12.0” from plate (~75 psi)

Figure 4-20: Comparison of peak pressures recorded at 12.0 inches. Note: error bars indicate maximum and minimum for each material.
Another interesting point to note from Figure 4-20 is that the peak pressures recorded for each trial appear to have less agreement and consistency than at previous distances. This could be an artifact of the multiple tests of the foam, especially since blasts at 12.0 inches were the 5th and 6th tests per sample. However, it could also be due to how the blast mitigation mechanism reacts at higher pressures versus lower pressures, perhaps. It is possible that there is a range of open field peak overpressures that materials react more effectively against or more consistently in terms of blast mitigation. This could be due to the nonlinear behavior anticipated in blast mitigation mechanisms, and is a topic that should be researched further. It is a possibility that, based on these results, it seems as though the most mitigation occurs at 15.5 inches, or ~60 psi peak pressure, even though higher and lower pressures were tested. It is also clear from the results that the data suggests there is an improvement in using glycerin and glass beads for blast mitigation.

An additional point to mention here is that 12.0 inches was the distance which Goel tested in his thesis, and where he saw not only greater open field pressures, but also significantly greater pressure reductions by glass beads and glycerin. One possible reason for this is that there was some discrepancy in the distance that the pressure gauges were recessed. In Goel's thesis, it states that the gauges were recessed 3 mm, while in a published paper by Goel, 2 mm was listed [89]. Because it was unclear as to if this were a typo, and if 2 or 3 mm were the correct recessed distance, we decided to use 2 mm. The testing performed here is extremely sensitive to pressure gauge placement and setup. Not only does the distance change the reading, but also the slightest bit of air between the sample and the gauge can provide variable amounts of mitigation and skew results. These are all factors that could possibly explain variations between Goel's work and the work presented here.

4.5 Experimental Results: Nonlinear Analysis

Our previous studies [88, 89, 90, 92] all demonstrated the relative effectiveness of our embedded fluid-in-foam concept for reducing transmitted blast pressures at high blast levels, at pressures consistent with severe TBI. The current work extends the
measurements to lower blast pressures in order to examine the effectiveness of the fluid-in-foam liner to counter mild TBI (mTBI). Induced blast loading is a unique loading condition, and we anticipate that materials exhibit nonlinear responses to this type of loading mechanism, possibly due to a nonlinear strain rate.

To explore if any nonlinear behavior was exhibited, a normalized transmitted peak pressure vs. applied peak pressure curve was created for each material. By doing this, we could assess to what extent the transmitted pressure reduction might be proportional to the applied pressure. If the behavior were linear, the points would likely lay in a straight line, where if it is nonlinear they would not. The normalized transmitted peak pressure was calculated by dividing the transmitted peak pressure by the applied peak pressure (for each distance). However, it should be noted that the open field applied peak pressures of 40, 60, and 75 psi are rounded values. The true calculated values are 39.7, 58.4, and 73.8 psi, respectively. For normalization, the transmitted peak pressures were divided by these precise values and plotted at these points for more precision than what is attainable with the rounded values. The normalized transmitted pressures for solid foam, glass beads, and glycerin are given in Figures 4-21, 4-22, and 4-23, respectively.

![Solid Foam](image)

**Figure 4-21:** Normalized transmitted pressure vs. applied open peak pressure for solid foam
Ultimately, for all three materials, the data suggests that there is some nonlinear behavior exhibited. There also appears to be a minimum in transmitted pressure, or "sweet spot" in pressure at which there is more mitigation compared to other induced peak pressures. For each material, this "sweet spot" seems to occur at the mid-pressure range of 58.4 (~60) psi. However, we cannot be positive that the true “sweet spot” occurs at 60 psi.
because we did not test the full range of pressures, and thus do not know what the entire response curve looks like. The effectiveness of the different materials in reducing transmitted pressure appear very similar at both the low and high applied peak pressures, and ranges from approximately 10% to 30% decrement, as seen in Figures 4-21, 4-22, and 4-23 depending on the applied pressure. In addition, there seems to be a shift in which material yields the best mitigation at the mid-pressure "sweet spot" compared to the other pressures tested. At low and high applied peak pressures (39.7 psi and 73.8 psi), both glass beads and glycerin have lower fractions of the transmitted applied pressure, where glycerin just barely outperforms glass beads for best mitigation. However, at the mid pressure range, the solid foam exhibits the smallest normalized transmitted peak pressure, outperforming glass beads and glycerin by 9.3% less and 13.2% less, respectively.

It is also interesting that the difference between the normalized transmitted peak pressure at the mid range compared to the low and high range of pressures is largest for the solid foam, then glass beads, and then glycerin (though differences between filler materials is small), suggesting that different materials have more consistent mitigation responses than others. However, it should be stressed that we cannot be positive that these points are statistically significant due to the small sample size (n=2) and the variance of +/-10% reported by Purdue, so there are only possibilities. However, if proven to be statistically significant with later tests, these findings could have important implications for implementation into helmet liners as soldiers are exposed to a wide range of pressure blasts based on varying blast sources and distance from detonation. Ideally, material that can perform most consistently would provide the best protection. Or, if you could layer with different materials that perform better at different pressure levels, one might get the most mitigation out of the layer technique.

In considering any possible errors that could have lead to these nonlinearities, rather than a real phenomenon, it was considered whether there could be an error in the transmitted pressure, specifically only at the 15.5" distance, or an error in the applied peak pressure measurements which could skew the data and disrupt results. However, we believe that it
is extremely unlikely that there is any error in the transmitted peak pressure at a specific distance because of the way the tests were performed. For each sample, two trials at each distance were performed in the order from low to high open field pressure (i.e. from the farthest distance to the closest distance). It is extremely improbable that results in the middle of this testing path would be erroneous, but that the tests right before and after would be accurate. In addition, the corner gauge was used to measure repeatability between tests. Though it was not known exactly what peak pressure value it should read at each distance since it was off center from the blast axis, it was expected that for each material at one of the given distances, it should read about the same. This was true for results obtained throughout this experimental work. It is also unlikely that there was an error in the open field peak pressure values obtained through experimentation. As shown earlier, two open field tests were performed at each distance, and these trials had very good agreement and similar waveforms. This suggests that there is some mechanism in a reaction to an induced blast that results in the nonlinear behavior shown above.

4.6 Oscillations

We note regular oscillations in the pressure traces obtained throughout testing and consider whether they are present in the incoming induced blast wave or if they can be attributed to the data acquisition system. It was considered at first that the oscillations were due to some sort of material response; however, this was ruled out because the pressure waveforms obtained during open field testing exhibited similar oscillatory behavior. Because no sample was attached to the aluminum plate during open field testing, it is feasible to rule out material response as a cause for these oscillations. Another thought was that perhaps the vacuum grease applied to the pressure gauges was to blame for the oscillations, but results in Figure 4 indicate that similar oscillations occurred when the grease was not applied to the pressure gauges. Therefore, it is likely that these oscillations are due primarily to the pressure transducers used in acquiring the data, or it may simply be noise in the data. Another very possible cause for these oscillations is vibration of the aluminum plate fixture. According to our colleagues in the
Zucrows Laboratory at Purdue University, the most likely causes for the oscillations seen are primarily error in the measurement system and a vibrating test frame.

4.7 Discussion of Experimental Limitations

The current series of testing suggests that there is an improvement to the pressure transmitted through a sandwich structure when using the filler materials of glycerin or glass beads at low to intermediate pressure levels. It also brings out a nonlinear behavior of the foam and fluid-in-foam sandwich during blast loading and potential differences in material behavior at various pressures. While at the mid-range applied peak pressure solid foam outperformed filler materials, overall it appears that glycerin and glass beads improve mitigation across the three applied pressure values tested, and do so a bit more consistently. However, we cannot draw indisputable conclusions due to some of the limitations of the experimental set up.

One of the main limitations with the experimental set up utilized is that it is expensive and time consuming, and we currently do not have our own blast chamber set up to use at our own convenience at MIT. Therefore, due to constraints placed on us at Purdue, a sample size of 2 had to be used, while the variance Purdue reports can be as high as +/- 10%. If one is conservative and assumes this variance at all times, as mentioned before, proper statistics cannot be performed to prove that the data points are statistically significant. Additionally, in order to speed up experimentation time, the same sample was kept for all 6 trials. Therefore, it is possible that there is some material degradation in the foam after subsequent tests. While it may be the same for each series of tests, we cannot be sure, and it would certainly be ideal to use a new sample for each test.

Another possible limitation to be aware of is that it was determined that Purdue’s setup likely yields a 3D shock wave rather than a 1D planar wave. The experimental set up at Purdue places the diagnostic system and samples outside of the shock tube, rather than inside the tube. This results in a turbulent flow with unknown boundary conditions, as the shock front exits the tube due to edge and exit effects. This yields a waveform where
the pressures along the front vary three dimensionally. This 3D wave also lacks repeatability, which makes it difficult to measure what the true pressure intersecting the sample is. It would be ideal to recreate the experiments with a 1D planar wave, with more trials, so that the results could be verified with statistics.

Additionally, in the data, which can be seen here, there is a “double hit” where there are two quick peaks in pressure, as seen in Figure 4-24.

![Glass Beads Graph](image)

**Figure 4-24: Visible “double hit” at 12.0 inch range**

This could be due to the wave interacting at the boundary differently, perhaps due to reflections with the aluminum plate support. Or, the sample could possibly be moving relative to the mounting surface when intersected with the wave. Nevertheless, it is something to look into in the future, try to characterize, and try to eliminate in future test setups.
However, significant progress has been made on the development of a new helmet liner utilizing filler materials, and the results have confirmed an improvement to pressure transmitted through sandwich structures using glycerin and glass beads as fillers at low to intermediate pressure levels (as well as high, as shown in previous results [89, 91]). What is believed to be nonlinear behavior of the structures was observed, with possible improved blast protection at middle pressures (60 psi). To draw more confident conclusions (or to be more confident in the ones we made), we need to first recreate the experiment with 1D wave so we fully understand and capture our BC’s and ensure that they are not influencing any behavior exhibited in testing. A new colleague, with a more ideal test facility has been identified. A current collaboration with Dr. Namas Chandra, at the University of Nebraska at Lincoln, has ensued, where there is access to three different sized shock tubes, which are large enough to place the test sample within the chamber to ensure a 1D planar shock wave. Initial experimentation at UNL has been performed, and results are provided in Chapter 5. Glass beads and glycerin are the materials that continue to be tested against the benchmark case. Because their mitigation capabilities are very close based on experimental results, one is not chosen over the other for future testing, though eventually perhaps deciding factors such as temperature sensitivity, weight, manufacturing cost, or fragility may play a factor in future decisions.
Chapter 5  Blast Experiments Using Sandwich Structures: University of Nebraska

The experiment performed at the Zucrows Laboratory at Purdue University provided interesting data regarding possible nonlinearities and effectiveness of embedding filler materials within a foam liner at low to mid-range incoming blast pressures. However, the small sample size and an experimental set up with large variability per test limited result validity. In an effort to confirm the data from Purdue, subsequent tests were performed at the BioMechanics and Materials Laboratory at University of Nebraska at Lincoln, under the direction of Dr. Namas Chandra. There were two goals of this follow up experiment. One, to confirm the results from Purdue by increasing the sample size and using an experimental facility that reports a variance of only 1-2 psi per applied incident pressure as compared to +/-10% at Purdue. Two, to extend the range of pressures further than tested previously in order to gain more insight into any dependence of the transmitted pressure on the applied pressure. The same filler materials were used as in previous tests at Purdue: glass beads and glycerin.

5.1 Experimental Set up

Blast experiments were performed using a unique blast facility, featuring a shock tube, designed for the University of Nebraska’s High-Pressure Shock Wave Generation Facility. The shock tube currently has three differently sized tubes to test an array of materials: a 4” round, a 9” square, and a 28” square tube. The 9” square tube was used for this series of testing based on sample size and desired pressures. The shock tube assembly consists of three main components: a breech, a membrane holder, and the main shock-tube and data acquisition system. It also features a test window that allows the user to load and unload any sample, as well as record any video or desired images during testing.

The shock wave system here operates differently than at Purdue, as no explosives are used to generate the 1D blast wave. In this set up, membranes are sandwiched between
the breech and shock tube using cylindrical clamps and O-ring seals, and the breech is pressurized with Nitrogen gas. As the gas pressurizes the breech, the membranes balloon out until they burst, releasing a 1D pressure wave.

Figure 5-1: a) Side view photo of shock tube facility b) Corresponding schematic of shock wave facility featuring 1) variable breech 2) membrane holder 3) shock tube and data acquisition region [93]

Figure 5-2: Zoomed in view of shock tube, membrane holder, and breech assembled together
The membranes consist of a polyester film made from stretched polyethylene terephthalate (PET), known as Mylar, and vary in both thicknesses and quantities. These are stacked to achieve desired blast amplitudes for an experiment. Overall, three variables determine applied pressure in the shock tube: membrane quantity and thickness, the amount of gas used to pressurize the breech, and the breech volume. The facility at UNL uses a variable breech that adjusts to a length from 1” to 72”, where a small breech volume yields short duration blasts and a high volume breech yields a longer blast. This feature allows one to not only control the blast pressure, but also the blast duration. For all tests in this series, a breech length of 17.625” was used based on desired blast pressures, sample size, and blast duration.
Test samples of 1 in. thick, 4 in. diameter circular DerTex sandwiches were used to accommodate the Nebraska testing fixtures that required round samples. A circular cavity of 0.5 in. thickness and 3 in. diameter was used to conserve the same volume fraction of filler material as was used in samples at Purdue (~30% filler). These circular sandwiches were filled with glass beads or glycerin, and were compared to solid 1” thick, 4” diameter DerTex foam for a control. The sandwich samples were constructed using three pieces: two 0.25” solid discs and one washer-like foam ring with a 4” OD and 3” ID, leaving a gap of 0.5” thickness and 3” diameter for the filler materials. These were sealed using 3M Hi-Strength 90 Spray Adhesive, as was done in previous experiments. The solid sample was constructed using two ¼” solid discs and one 0.5” solid disc in order to remain consistent with production of the sandwiches and to have the same number of interfaces.

Figure 5-5: Top view of circular sandwich cavities (without top)
During blast testing, samples were secured to a steel test fixture. This fixture consisted of a hollow steel cylinder with fringed ends that attach to the shock tube walls in the test window, providing a rigid stand. The cylinder was filled with glycerin and capped with a polycarbonate plate, which moves laterally in the same direction as the blast wave translation. This plate served as the interface between the sample and the glycerin/DAQ. A Kulite probe was recessed 1.5 inches from this plate and extends to the back of the cylinder. On the other side of the polycarbonate, the cylinder extends 1 inch forming a circular recession that fits the sandwich samples, made to hold the sample perfectly. The overall fixture is 5” diameter and 11” long. The inner cylinder that was filled with glycerin and capped by the polycarbonate disc is 4” diameter and 9” long.
The fixture was designed to act like a piston or plunger, measuring the energy transmission from the blast wave through the sample, through the plate, and to the glycerin. The Kulite probe ideally measures the energy transmission of the wave that a sample allows through, but eliminates any contact between deforming foam and the sensor. Samples were secured to the polycarbonate plate using carpenter tape and rubber cement.
Three different pressure sensors were utilized for data acquisition throughout this experiment. A piezoelectric PCB pressure gauge was placed within the sidewall of the shock tube to measure the incident pressure. This was used to check repeatability between tests, and measures what blast is produced from the burst of the membrane (incident pressure). A surface mount piezo-resistive sensor was secured to the test fixture surface, though no further details about the sensor are available due to security restrictions under contract. This sensor measures what is called the reflected pressure, which is the pressure that is felt by the sample, and can be assumed to be the applied pressure for each test during this study. It is important that one understands the difference between the incident pressure and reflected pressure in this testing. The incident pressure is what is produced from the initial blast in this set up, and is not considered the applied pressure to the samples for this work. Because of changing geometry, boundary conditions, and a change in material or medium, the incident pressure traveling through the shock tube is amplified when it intercepts the fixture/sample. The sensor located on the fixture surface measures this reflected pressure, which is what impinges the sandwich samples, and what we will consider to be the applied pressure to the samples in this study.

Figure 5-10: Side view of fixture placed in test window of shock tube
Finally, the Kulite probe located in the test fixture measures the transmitted pressure behind the sample. This sensor set up was designed to measure a “global” pressure transmitted through the sample. While it is not a holistic average because typically the pressure wave is larger in the center axis than the outer edges, this set up reduces the chance of a single point anomaly. It also eliminates the problem of the foam deforming into any recessed hole made for a pressure sensor, which can produce skewed and high pressures caused by foam impacting the sample or pressurizing any air between the two. Rather than selecting the pressure wave to be measured at one point on the back of the sample, the glycerin acts as a means to transmit the pressure wave through the entire cross sectional area of the sample to the Kulite sensor. Glycerin is used to fill the fixture space that houses the probe. It acts as a medium to transmit the pressure. The medium was chosen to be glycerin, rather than air, because it produces a more averaged, less oscillatory pressure than air according to simulations performed at UNL. Videos of each blast were also recorded using an Aramis high-speed camera in conjunction with FASTCAM SA1.1 Photron software. The camera was aimed at the test window section and data was recorded at 10,000 frames per second.

Figure 5-11: Zoomed out view of test window. Camera was aimed at test window for data collection
5.2 Experimental Results

The goal of this test series was to assess the effectiveness of glycerin sandwiches, glass bead sandwiches, and solid foam samples in mitigating a broad range of blast pressures applied to the samples. Two samples of each material were tested, for a total of six samples used for testing. This was to examine repeatability. The objective was to perform blasts at 15 psi, 30 psi, 45 psi, 60 psi, and 75 psi, thereby overlapping the range of pressures used at Purdue (40, 60, 75 psi) while extending the range at the same time. However, sensor sensitivity forced the 75 psi test range to be eliminated from the test matrix, as calibration tests showed damage to the sensor in the fixture at this high-pressure level. Thus, pressures were varied from 15-60 psi in 15 psi increments. As described above, this was accomplished by varying the number and thickness of membranes used in the shock tube configuration. Table 5-1 provides the quantity and thickness of membranes used to achieve each desired pressure, determined during calibration tests.

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<tr>
<td>60.0 psi</td>
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Table 5-1: Membranes used for desired pressures

Three blasts were performed at each pressure, for each material. To investigate the role of sequence and any material degradation, one sample for each material was tested in a sequence from low to high pressure, and the second sample was tested in a reverse order from high to low. Ultimately, this was done only for glass beads and solid foam. Because the glycerin samples proved to leak at high pressures, both glycerin samples were tested from low to high in an attempt to gather as many data points as possible before leakage. Any leakage was likely due to the glycerin eating away the adhesive, compromising the seal of the sandwiches. Glycerin Sample 1 leaked upon the
first blast at 45 psi, and Glycerin Sample 2 leaked upon the third blast at 45 psi. Thus, the data sets for the glycerin samples are not complete and stop at 45 psi. In addition, data sets are not complete for Solid Foam 1 and Solid Foam 2 at 15 psi due to the DAQ trigger misfiring. For this test range, two data points are available for each sample.

Figure 5-12 provides an example of the raw data obtained from testing. The red curve shows incident pressure, the green curve shows reflected pressure, and the blue curve is the transmitted pressure. Ultimately, we are only concerned with the reflected (applied) and transmitted pressures for this series of testing. The PCB surface sensor measuring the reflected pressure has an overshoot, however. To determine the true reflected pressure value impinging on the sample, 100 data points after the overshoot were averaged to arrive at an average reflected pressure value.

![Glass Beads Sample 1](image)

**Figure 5-12: Glass beads sample 1 raw pressure trace for 15 psi applied pressure**

The key variables extracted for this study are average applied (reflected) pressure and peak transmitted pressure. The peak transmitted pressure was defined as the maximum pressure level recorded on the pressure trace. Before any data analysis, it is important to note that for all results, the transmitted pressures for all materials at all pressures were greater than the applied pressures, suggesting that the pressure is actually
amplified. While this is thought to be a result attributed to the data acquisition set up (to be discussed later), the data does not demonstrate any mitigation capabilities strictly based on pressure reduction. However, the data nevertheless provides useful information for a comparative analysis between materials. It is also interesting to note the regular oscillations seen in the transmitted pressure waveform in Figure 5-12. These oscillations are seen in all pressure traces for all materials. Because it is unique to the transmitted pressure only, and because it is not unique to any material, it seems that the oscillations represent oscillatory movement in the foam as it compresses and expands repeatedly. However, this was not the main focus of this thesis.

A line plot of the mean transmitted pressures for each material at each applied pressure is provided in Figure 5-13. The data suggests a few trends. One, as expected, as the applied pressure increased, the transmitted pressure also increased. Secondly, it appears that all three materials behave very similarly in the 15-45 psi range. Looking closely, glass beads and glycerin yield lower pressures than solid foam, except at 30 psi, and glass beads perform best at higher pressures (45, 60 psi) and glycerin performs better at lower pressures (15, 30 psi). Most notably, there is a distinct separation in material behavior at 60 psi. Because the pressures leading up to 60 psi behave very similarly, it was determined to analyze the data in two separate manners: data from 15 through 45 psi was analyzed using an analysis of covariance (ANCOVA) model to assess the performance of each material and a paired t-test was utilized for data at 60 psi. For all tests, $\alpha = 0.01$. 
The ANCOVA model was performed with material set as the fixed factor, the applied pressure as a covariate, and the dependent variable set as transmitted pressure. This test was first performed with sample number as a random effect, but it was not found to be significant (F(1, 3.043) = 10.959, p = 0.044). The model was then re-built eliminating sample number as a random variable, and results indicated that applied pressure was very significant (F(1, 45) = 310.363, p = <0.0005), which comes as no surprise. However, material was found to have no significant effect on transmitted pressures for tests at 15, 30, or 45 psi (F(2, 45) = 1.950, p = 0.154). This is in contrast to the data from the Purdue, which suggests that glycerin and glass beads both outperform solid foam at 40 psi, which is within the same pressure range.
At 60 psi, however, a paired t-test concludes there is a significant difference between glass beads and solid foam \((t(5) = 11.947, p<0.0005)\). At 60 psi, glass beads transmit significantly less pressure than solid foam. This result is inconsistent with the results at Purdue as well, where at 60 psi applied pressure solid foam was found to outperform glass beads and glycerin. (Recall: glycerin data was not collected at 60 psi).

While it appears based on Figure 5-13 that there is clearly some form of nonlinear behavior in response to applied pressure due to the jump at 60 psi, a lack of fit test was performed to analyze it statistically. The lack of fit test was performed twice, once including the 60 psi points and once without. For the three pressures of 15, 30 and 45 psi, the test showed the transmitted pressure was not statistically different from linear \((F(19, 26) = 1.35, p = 0.252)\). However, repeating the lack of fit test including 60 psi yielded that the data was significantly different from linear \((F(36, 21) = 6.25, p = <0.0005)\). This suggests that the materials all perform linearly at 15, 30, and 45 psi, but some nonlinear response takes over at 60 psi for glass beads and solid foam.

This result provides a good discussion point, because the results from Purdue also suggest some nonlinearity. As discussed in Chapter 4, it appears in the Purdue experiment some sort of sweet spot exists, an area where more pressure is mitigated than any other. For all materials, this sweet spot occurred at 60 psi. While we do not see this same phenomenon in the data here, as the transmitted pressure still increases at 60 psi from the pressure at 45 psi, some nonlinearity was determined. It is very interesting that this is the point in both experiments where the response digressed from a linear to a nonlinear response. Unfortunately, no data points above 60 psi were able to be collected at UNL, but it is highly recommended in future tests to create a data acquisition system that can test at least 75 psi in order to see the full curve that overlaps the Purdue data.

Overall, the data from experimentation at UNL demonstrates that at lower incoming blast pressures of 15, 30, and 45 psi, there is no advantage to using any one material over another, and thus no improvement to using a sandwich structure. However, at 60 psi, there was a significant reduction in the pressure transmitted by glass beads as compared
to solid foam. The differences are not a function of any variance or lack of repeatability in applied pressure, as very sound consistency was found between trials (see Appendix). This nonlinear behavior could have important implications for design, depending on the range of pressures one wishes to focus on. As mentioned in Chapter 4, soldiers are exposed to a wide range of pressure levels, and this data suggests it may be possible to optimize protection by determining the material that performs most consistently, or by layering materials that perform at better pressure ranges. It could also be possible to specialize a design for an anticipated pressure level. While further data is clearly needed to advance the idea, the data provides an insightful first step into the nonlinear behavior and provides great confidence in that two experiments yielded a similar lack of linear response, one with statistical significance.

While this data provided noteworthy comparison between materials, we must recall that all transmitted pressure values were greater than the applied pressures. This is inconsistent with most preceding work, as well as the results from Purdue. However, we do not believe that the amplified pressures are a result of the materials, but rather due to the design of the steel and polycarbonate fixture and Kulite data acquisition design. Because the fixture was designed to act like a piston and measure the energy transmission from the foam to the pad to the probe, it is believed that not only was the pressure wave recorded, but any kinetic energy due to the motion of the sample and plate was recorded as well. Thus, the transmitted pressure was a combination of multiple effects. While this was not intended in the design, the pressure effect alone cannot be extracted from the data. It was considered to attempt to calculate and remove the kinetic energy based on the high-speed video, but the steel fixture blocks part of the motion of the sample and thus no further data reduction could be performed. The data provides useful information of a comparative nature amongst materials, but we cannot be sure what the true mitigation capabilities of the materials are with the current data acquisition system in place.
Chapter 6  Conclusions and Future Work

Findings obtained from experimental testing of foam-fluid sandwich structures discussed in previous chapters are summarized here.

6.1 Conclusions

The overarching goal of the ongoing blast helmet research at hand is to investigate if the concept of a helmet liner with channels filled with various filler materials provides better protection from blast waves than the current ACH standard liner. While our initial concept for embedding materials inside a foam helmet liner to reduce TBI from blast waves was shown to be valid, it was initially tested only at high pressure levels. The main focus of the work presented in this report was to assess this concept’s effectiveness at lower incoming blast pressure levels, associated with the occurrence of mild TBIs, thereby extending the tested blast range. The two objectives were to assess the filler materials’ blast attenuation capabilities at a larger range of pressures than previously tested, and to assess any potential nonlinear behavior of each material’s response over this range. Sandwich samples with glycerin or glass beads inserted, as well as solid foam samples, were used to explore the 2D case, and were subjected to blast loading using shock tubes. Peak pressure transmitted through the samples was measured to determine the mitigation capabilities of the filler materials. Experiments were performed at both Purdue University and the University of Nebraska at Lincoln.

At Purdue, the results were as follows:

1. There is an improvement to the pressure attenuation through a sandwich structure when using glycerin or glass beads compared to solid foam at low to intermediate pressure levels (40, 60, 75 psi).

2. For all three materials, some nonlinear behavior appears to be exhibited. Most notably, a “sweet spot”, where more mitigation occurs compared to other induced
pressures, was discovered at 60 psi for all materials. The data suggests a shift in which material yields the best mitigation at this sweet spot, as solid foam exhibits the best result here, while glass beads and glycerin outperform foam at all other tested pressures.

(3) The difference between the normalized transmitted peak pressures at 60 psi compared to 40 psi and 75 psi is largest for solid foam, then glass beads, and then glycerin, suggesting different consistencies in mitigation responses depending on material.

However, we could not draw statistical significant conclusions from this data due to several experimental limitations. The experiment had a small sample size (n=2) and a variance of +/- 10%, which prevented statistical analysis. In addition, Purdue’s experimental set up was thought to yield a 3D shock wave rather than a planar wave. Therefore, it lacks repeatability and results in unknown boundary conditions and a non-uniform pressure front. To draw more confident conclusions, subsequent testing was performed at the University of Nebraska at Lincoln, where the test facility was thought to be more ideal.

In an effort to overlap the data from Purdue, blast tests were performed at 15 psi, 30 psi, 45 psi, and 60 psi using UNL’s shock tube facility. 75 psi was also aimed to be tested, but proved damaging to the DAQ sensors used for testing and was eliminated from the test matrix. Glycerin, glass beads, and solid foam samples were tested. Results from this test series lead to the following conclusions:

(1) At lower incoming blast pressures (15-45 psi), there is no advantage to using any material over another. There is no improvement to using the sandwich structure.

(2) There is a significant difference in the pressure transmitted by glass beads compared to solid foam at 60 psi applied pressure. Glass beads yield significantly lower pressure than solid foam.
The materials respond linearly at 15, 30, and 45 psi, but a nonlinear response appears at 60 psi.

While this data provided significant comparison between materials, all transmitted pressure values were greater than the applied pressures for all materials. This is inconsistent with the results from Purdue, as well as preceding work, and limits our ability to conclude the true mitigation capabilities of each material from these results. However, this is likely due to the data acquisition apparatus in place rather than the material behavior. Because the fixture design allowed some movement of the polycarbonate plate behind the samples, it is believed that any kinetic energy due to plate motion was also recorded by the sensor, resulting in a transmitted curve that was a combination of multiple effects, not just transmitted pressure. Nevertheless, the data provides useful insight in a comparative nature amongst materials.

Perhaps most interesting is the comparison of the nonlinear behavior at Purdue and UNL. As discussed, the sweet spot seen in the Purdue experiment occurs at 60 psi for all materials. While this exact behavior is not replicated in the UNL data, it is very curious that this is the pressure level where the response demonstrates nonlinearity in both experiments. Unfortunately, data points above 60 psi were prevented by the sensor system at UNL, but it is highly suggested in future work to test greater pressures of at least 75 psi to investigate a complete overlap of the Purdue data.

6.2 Suggestions for Future Work

The current series of testing confirms that there is a nonlinear effect involved in the blast mitigation abilities of glycerin, glass beads, and solid foam, and that this effect takes over at the 60 psi range. While the results from Purdue and UNL do not completely agree on how this response behaves at 60 psi and beyond, it is essential that this is a point of focus moving forward with the project. It is known that nonlinearity exists, but the next step is to understand why and what basic mechanisms produce these results. To explore this
behavior on a more fundamental level, we plan to collaborate with the experts in the Materials Science department in order to determine if some mechanism on the macromolecular level can be attributed to the behavior seen in our results. Further testing should capture the full range of pressures tested in this work, so that a full set of data that overlaps the UNL and Purdue test ranges is available. Another interesting direction for experimental work to progress is to test multiple layers of fillers within a sandwich structure to explore any possible enhancement of acoustic impedance. This may provide insight into the mechanism of wave reflection and transmission.

Additionally, because experimentation with shock tubes is extremely expensive in both time and costs, it is highly recommended to concurrently develop a computational code that can test a large range of different properties to learn what key components in glass beads, glycerin, or solid foam induces both mitigation ability and nonlinear behavior. This would also provide the ability to test other material properties that have not yet been explored experimentally.

Frequency and spatial distribution of the transmitted wave forms should also be studied. One aspect of the results from UNL that was not assessed in this work was the very regular oscillations present in the transmitted pressure curve (as shown in Figure 5-13). These oscillations only appeared in the transmitted data, and were present for all materials. Frequency directly relates to amount of energy transferred, thus an attempt to study if these frequencies are due to the material itself or due to the data acquisition should be made, as well as to determine if there are any differences in such oscillations for each material.

The data also confirmed an advantage to using filler materials over solid foam, though the UNL results concluded there was only an advantage to glass beads at 60 psi applied pressure (of the tested pressures). While the results here are promising, experimental testing was performed using the basic geometry of the two dimensional sandwich structure. Eventually, it is ideal to replicate results using the filler materials in a helmet prototype. The prototype could be similar to that in Vechart's thesis [34], and would be
compared to the benchmark: an ACH with ACH pads. The shock tube setup at UNL has the capability to test models of this size by means of the 28” shock tube, and features a 3D head surrogate fitted with pressure transducers called the RED (Realistic Explosive Dummy) head. This could be used in conjunction with a 3D model of a Der-Tex foam helmet liner containing channels. Again, a series of low, mid-range, and high peak pressures would ideally be applied to obtain comparable results to what was seen with sandwich structures and to continue to learn about any nonlinear behavior. If favorable results are obtained, the ultimate step would be to perform the same tests using live fire testing at the Carderock Division located in Potomac, Maryland. For all tests moving forward, glass beads and glycerin are the materials that are recommended for continued testing against the benchmark case. Because their mitigation capabilities are very close based on experimental results, one will not be chosen over the other for future testing, though deciding factors such as temperature sensitivity, weight, manufacturing cost, or fragility may play a factor in future decisions.
Appendix A: Descriptive Statistics of UNL Data

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<th>Max (psi)</th>
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# Appendix B: Raw Data from UNL

## Glass Beads #1

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<th>Transmitted Peak (psi)</th>
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Works Cited


[65] *Blast-wave impact-mitigation capability of polyurea when used as helmet suspension-pad material*. Grujicic, M., Bell, W. C., Pandurangan, B., He, T., s. l.: Elsevier Science Ltd., 2010, Materials and Design, Vol. 31, No. 9, pp. 4050-4065.


[92] ABAQUS v6.10 Documentation.

