DEVELOPMENT AND CHARACTERIZATION OF SHOCK TUBES FOR LABORATORY SCALE BLAST WAVE SIMULATION

Aaron D. Holmberg
University of Nebraska - Lincoln, Holmbergaaron@hotmail.com

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DEVELOPMENT AND CHARACTERIZATION OF SHOCK TUBES
FOR LABORATORY SCALE BLAST WAVE SIMULATION

By

Aaron Douglas Holmberg

A THESIS

Presented to the Faculty of
The Graduate College at the University of Nebraska
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Under the Supervision of Professors Ruqiang Feng and Professor David H. Allen

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The prevalence of traumatic brain injury (TBI) in American soldiers exposed to a blast wave has created an urgent need to better understand the effects of blast wave insult to the head. Developing techniques that can experimentally simulate well controlled blast waves in a laboratory environment is a critical component of the research efforts towards this goal. For this work, a 4-in. cylindrical uniform shock tube and a non-uniform shock tube combining a 4-in. cylindrical gas driver with a 9-in. square driven section have been developed. The hosting laboratory, gas handling system, multichannel data acquisition systems, and the related network and software for computerized remote operation were also developed. These shock tubes were designed for generating shock waves with the overpressure and underpressure profiles mimicking those of the Friedlander wave. This wave form is a commonly used representation of the typical blast wave-form in an open-field. Tests have been performed to validate the designs and to characterize the shock waves generated by the two devices.

The results of experiments with the 4-in. shock tube show that shock waves with sub-microsecond rise times can be reliably generated with the membrane burst mechanism used. Various thicknesses of Dura-Lar® (biaxially oriented polyethylene
terephthalate) were examined as a membrane material, the burst pressure was found to
depend linearly on the number of sheets used. It was also found that the shock front
propagation speed and amplitude agree with the one-dimensional shock wave theory for
ideal gas even at the tube wall indicating a planar wave front in the shock tube. Hence,
the device can be used to accurately calibrate pressure sensors mounted through the wall.

The 9-in. square shock tube is a novel set-up. It enables the use of flat windows,
which are necessary for digital imaging, optical measurements and provides sufficient
space and versatile sample mounting for in-tube blast testing not feasible with the
cylindrical design. It also employs a unique adjustable reflector near the tube exit to
achieve underpressure profile control, which is critical for blast testing of animal models.
Systematic testing has been performed for this device. Although the transitional flow
between the driver and the driven section is multi-dimensional, the test results show that
an essentially planar shock wave is formed before entering the test section. The peak
overpressure and wave profile were found to vary with location. The correlation between
the membrane burst pressure and the peak overpressure in the test section was determined
experimentally. These experiments have demonstrated for the first time that the
Friedlander type of blast wave can be generated in such a shock tube with a right
combination of driver gas, driver length, burst pressure, and reflector position. The set-
up can thus be a powerful tool for TBI-related studies.
DEDICATION

 to God for my life,

to my loving wife,

and to my family for their guidance through strife.
ACKNOWLEDGMENTS

Working on the project of building a blast simulation lab from scratch has been a challenging development with many learning experiences found along the way. I would like to thank all of the people who made this experience possible.

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CHAPTER 1

INTRODUCTION

Traumatic Brain Injury (TBI) has become the signature wound of recent U.S. military conflicts. In 2007, it was estimated that 60% of all combat casualties in Operation Iraqi Freedom (OIF) were due to explosives (Shanker, 2007). A 2008 RAND Corp. report claimed that approximately 20% of the deployed forces potentially suffer from a TBI totaling 320,000 people (Tanielian & Jaycox, 2008). The prevalence of TBI caused by blast exposure has created an urgent need to better understand the effects of explosive injury to the head.

Blast injuries can also occur in the industrial or civilian world. Civilian blast injuries are typically due to industrial accidents as well as the common use of bombs in terrorist attacks. The Total Anti-US Attacks in 2003 were reported as 60 events with over 65 percent of those events involving explosives. The various different tactics used during terrorist attacks and their frequencies are shown in Figure 1.1.

During previous military conflict, the primary form of injury was due to gunshot or shrapnel wounds. This is a focal type injury, therefore easily understood and treated. Now during OIF and Operation Enduring Freedom (OED) the primary source of soldier injury is from explosives. Most of the time, this is a very complex poly-traumatic injury which is currently not well understood (Hoge et al., 2008). Often, there are injuries caused by blasts that are not visibly evident and without immediate symptoms.
The number of soldiers experiencing blast injury is currently an area of great concern. In a 2005 study, 88% of military personnel treated in Iraq at the Echelon II medical unit had been injured by an improvised explosive device (IED) or mortar with 47% of them involving head injuries (Murry et al., 2005). Due to the advances made in protective gear used by the military, a decrease in fatalities caused by typical blast injuries has been observed. The lethal blast tolerance of soldiers has increased dramatically in recent conflicts (Tammie et al., 2009). In previous wars, before the development of light-weight body armor, soldiers’ chests were exposed to direct loading via an explosive-generated shock wave and shrapnel during the blast. This often caused lethal lung damage and penetrating wounds to the thorax.

Shown in Figure 1.2 is a U.S. soldier wearing full body armor used during training for OIF. This armor is primarily designed to protect a soldier from projectiles such as bullets and shrapnel. The portion of armor used to protect the thorax from projectiles has also proven effective at mitigating some of the effects of blast-generated
shock waves (Long et al., 2009). Before the use of this armor style, blast tolerance thresholds typically set by the lungs, were below that which would cause significant neurological damage (Tammie et al., 2009). During OIF, blast-induced traumatic brain injury (bTBI) has become far more prevalent than blast lung (Bauman et al., 2009).

**Figure 1.2** Current (2008) body armor used by soldiers in Operation Iraqi Freedom (personal pictures from a National Guard private)

The three main measures of blast exposure typically used are peak overpressure, impulse, and positive phase duration. The peak overpressure and positive phase duration can be better understood after an explanation of the Friedlander wave-form. The Friedlander wave-form is the simplest form of blast-generated shock wave. It occurs in open-field blasts where no obstructions are present to generate complex wave reflections. A schematic of the Friedlander wave can be seen in Figure 1.3.
The maximum overpressure and positive overpressure duration are both functions of the quantity and type of explosive as well as the distance from it. The Friedlander wave changes form as it propagates away from the explosion. Its amplitude decreases and the duration increases. Impulse is the integral of pressure over time, which gives another dimension to the description of the wave form.

![Friedlander wave-form](image)

**Figure 1.3** Friedlander wave-form

The shock wave pressure history shown in Figure 1.3 is only associated with blast in a free-field. If there are obstructions to the shock wave such as a vehicle or building, transmission and reflection make it much more complex. The Friedlander wave-form is no longer representative of this more complex wave.

A blast-generated shock wave has a very complex interaction with a soldier. It has proven difficult for researchers to pinpoint the exact mechanisms behind blast-induced mild traumatic brain injury (mTBI). Solely focusing on blast injury pathology associated with the shock waves, there are many hypotheses on what causes the central nervous system (CNS) to be damaged. The high strain rates coupled with the rapid relaxation typical in blast exposure may have more significant effects on tissue damage.
that the peak amplitude (White et al., 1965, Vawter et al., 1978, Morrison et al., 2000, Garner, 2000).

There is a pressing need for accurate and repeatable simulated IED shock waves to study its effect on the human head. Blast studies performed with high explosives tend to be dangerous, expensive and slow to perform. Development of a laboratory scale device to generate controlled repeatable blast waves would be convenient and efficient. Repeatability is necessary to study the fundamental interaction of the blast wave with various objects and biological systems.

A shock tube was proposed to replicate blast waves. The burst diaphragm shock tube was originally invented in 1899 (Vieille) to study the speed of sound (Gaydon & Hurle, 1963). It later became a popular laboratory instrument for physics, chemistry and aerodynamic studies in the 1940’s (Gaydon & Hurle, 1963). The shock tubes designed for these applications have a completely different set of design constraints relative to that of generating an explosive shock wave.

The shock tube was later used to simulate blast-generated shock waves to study their effects on animals (Richmond et al., 1966, Bauman et al., 2009, Mayorga, 1997, Cernak et al., 2000, Long et al., 2008). These data were then used to understand the effects of shock wave exposure on the animal’s body and even more recently, their brain.

The specimen is commonly placed immediately outside of the shock tube for these experiments. The shock wave characteristics such as wave speed and overpressure are then measured on the side wall of the tube near the open end. For example, the experimental setup done by Long et al. for a rat experiment can be seen in Figure 1.4.
Typical experimental set-up for blast tolerance studies performed on animals (Long et al., 2008).

Figure 1.4 Typical experimental set-up for blast tolerance studies performed on animals (Long et al., 2008)

It has been found that when the boundary conditions imposed on a fluid flow change, the flow characteristics change also. Therefore, when a shock wave originally confined by a tube is suddenly released to open air as it does when exiting a shock tube, its characteristic abruptly changes, becoming very complex (Jiang et al., 1997). The rapid state change of the gas exiting the shock tube makes specimen loading conditions unpredictable. Samples placed in front of the shock tube do not experience a true Friedlander wave as assumed by reporting the pressure history measured on the wall just inside the shock tube. In fact, the Friedlander wave-form measured near the exit of the shock tube is an artifact of a rarefaction wave generated at the exit traveling back into the
barrel. A true blast wave is not shaped by two rarefaction waves propagating in opposite
directions. A better understanding of this concept will be developed in Chapter 4.

An article published by Jiang describes the complex wave-forms generated by the
sudden change in the cross-sectional area in a shock tube (1997). The schematic on the
left side of Figure 1.5 shows the abrupt change in cross-sectional area used in the
experiment. This is very similar to a shock wave exiting the shock tube into a larger
room as done in most previous blast tolerance animal studies. The shadow graph shown
on the right side of Figure 1.5 depicts the complexity of the shock wave generated near
the exit of a shock tube.

![Figure 1.5](image)

**Figure 1.5** Left: schematic of cross-sectional change in a shock tube (Jiang et al., 1997). Right: Complex wave-forms developed after a cross-sectional area change in a shock tube experiment (Jiang et al., 1997).

This brings into question the methodology used in previous animal blast tolerance
studies. It also clearly defines the need for well-characterized instruments for simulating
blast waves for simple accurate loading of samples. No defined conclusions can be made
about blast experiments without known loading conditions. A well-characterized shock
tube which generates a simple Friedlander wave would be ideal for studies relating shock
wave mechanics to TBI. This would assist with the development of better treatments and protective gear for the soldiers’ most important organ.

A blast generated shock wave is typically accompanied by a fire ball generated by the reaction, shrapnel propelled by the expanding gas and electromagnetic radiation. These components of the explosion are unable to be produced with the current shock tube designs. The fireball generated by a high explosive is small relative to the volume affected by the shock wave. If a human is close enough to be affected by this component of the explosion it is generally fatal. Shrapnel injuries are generally localized and the mechanism of injury is relatively well understood. Therefore, this complication will be avoided for the current studies. The electromagnetic radiation emitted during an explosion is considered insignificant. These alternative pathologies for injury associated with explosives are not the area of focus for this thesis.

1.1 RESEARCH OBJECTIVES

The main objective of this research is to better understand the interaction of a shock wave with the human head and aid in the development of improved protective gear for U.S. soldiers. To accomplish these objectives, it is essential to develop a laboratory scaled shock tube that can accurately and repeatedly load a specimen with a Friedlander form shock wave. Explosives can be used for these experiments but they tend to be cost prohibitive due to requirements such as a blasting range, a permit, and trained personnel. Explosives also present challenges with their repeatability.

The shock tube designed for these experiments must replicate a Friedlander form shock wave. To ensure accurate standardized measurements of the loading, sensors must
be calibrated. The shock tubes must also be well characterized to ensure the loading conditions are as expected. If the shock wave generated is not well characterized the loading conditions would be unknown and injury pathology difficult to determine. Accomplishing these objectives will enable validation of finite element analysis (FEA) models and exploration of blast injury pathologies.

1.2 RESEARCH SCOPE

A better understanding of the mechanisms involved in blast injuries was established. A test facility was then built to replicate the conditions typically experienced during a blast injury. Two different shock tubes have been designed and built for the facility with a third in the process of being fabricated. The 4-in. uniform cross section shock tube is primarily used for calibration of sensors and small, high pressure experiments. The 9-in. square shock tube was used for characterization of the shock wave in transition from a 4.04 in. diameter breech to a 9.06 in. square tube and testing of small samples. The use of a square barrel was essential for installation of flat windows used for viewing sample reactions with high-speed video cameras for later analysis with ARAMIS (computer program for video based surface strain analysis).

The shock tube operating system was developed for remote operation and data collection. All operations related to firing the shock tube and collection of data from sensors can be done from a remote room. This was done for safety purposes.

One-dimensional shock theory was established to correlate well with shock waves generated in the uniform cross section shock tube. This theory, in conjunction with the
initial conditions in the lab and the shock wave speed, was used to calibrate the dynamic pressure sensors.

Membrane burst pressures were established for various thicknesses of biaxially-oriented polyethylene terephthalate (boPET). These burst pressures were correlated to the overpressure measure in both shock tubes. The planarity of the shock wave at the test section and at various distances from the breech was measured. Ideal breech lengths and reflector plate offsets were established to accurately replicate a Friedlander wave. The effect of the sample presents on shock wave propagation inside the test section was also observed.

1.3 ORGANIZATION OF THE THESIS

This thesis is composed of 6 chapters. Chapter 2 is a literature review of research previously performed in this area along with general research done on blast injury. Chapter 3 covers one-dimensional (1-D) shock wave theory and how it applies to the design and development of the blast generation facility. The application of 1-D shock wave theory to dynamic pressure sensor calibration will also be covered, including the results from the Dytran 2300V1 sensor calibrations. Chapter 4 presents the design features of the 9 in. square shock tube. It also presents characterization results for the shock tube using nitrogen as the driving gas. The results can be used for determining the settings of various parameters of the shock tube to produce a predetermined loading condition. Validation of shock wave planarity and characterization of internally reflected shock wave experiments are also covered in Chapter 5. The thesis is concludes with concluding remarks and recommendations for future studies in Chapter 6.
CHAPTER 2

LITERATURE REVIEW

A better understanding of human’s injury threshold related to primary blast injury (shock wave induced injury) is needed. This knowledge will help in devising constraints for the design of the blast facility and later in the development of relevant experiments to assist in understanding blast induced traumatic brain injury (bTBI). The majority of earlier research covered in this section focused on blast injury to gas filled organs of the body due to their susceptibility to primary blast injury. With the advent of personal body armor that better protects the lungs and abdomen, TBI has recently surfaced as the topic of focus.

2.1 BACKGROUND

People have used explosives for various purposes ever since the invention of gun powder thousands of years ago. Since then, more effective form of explosives, called high explosives, were created for military and industrial purposes. In more recent decades, terrorists have began using high explosives as their weapon of choice in the form of IEDs.

According to globalsecurity.org an IED is a “homemade device designed to cause death or injury by using explosives alone or in combination with toxic chemicals, biological toxins or radiological materials.” IEDs take various different forms depending on the material available to their creator. Explosives can be procured from old military
munitions, commercial sources, or made at home with easily purchased commercial chemicals and available instructions. Their delivery methods fall into three major categories of IEDs; packaged type, vehicle borne, and human borne.

Ease of transporting the explosive devices and their highly effective nature make them an attractive tool for insurgents. The extensive information readily available to the general public on how to construct and detonate IEDs also makes them ideal. Explosives became terrorists’ weapon of choice for the Irish Republican Army during their fight against British occupation mainly during the 1960-1990’s (Gregory, 2008). This may be due to the aforementioned properties of high explosives. Due to the endless ingenuity of terrorists, high explosives have become a highly destructive tool used for damage of property and humans alike. In 2006, over half of the U.S. military casualties in OIF and 30% in Afghanistan were attributed to IED attacks (Wilson, 2006).

It is common for shrapnel to be attached to bombs in hopes of creating additional damage. Material such as nails, ball bearings, marbles, etc. are placed around the explosive so they are accelerated to high velocities during the blast. Special configuration and detonation of explosives create a shape charge. It is suggested and generally agreed upon shape charges can easily penetrate heavily armored vehicles (Ritzel, 2009). A photo of a high mobility multipurpose wheeled vehicle (HMMWV) which fell victim to a shape charge generated by two anti tank mines is shown in Figure 2.1. The driver was killed and the passenger was seriously injured. The passenger had to be flown to a U.S. Military hospital in Landstuhl, Germany for immediate medical attention (personal discussions with a National Guard private).
Explosives have been used by the military ever since their invention. The various pathologies of blast injuries have been studied for nearly a century now. The term “shell-shock” used as a general description of primary blast injury (injury from a shock wave) was originally coined by Southborough (1922).

It was soon after the invention of the atomic bomb that the effects of explosive-generated shock waves became an area of concern and one of extensive research. Research indicated that gas-filled organs such as the lungs, lower intestines and tympanic membrane were the most sensitive portions of the human body to blast-generated shock waves (Richmond et al., 1966; Katz et al., 1989, DePalma et al., 2005). Although the susceptibility of the central nervous system to primary blast injury was recognized and described in detail by various authors in the 1940s, it was not the main area of concern in research at that time (Fulton, 1942; Pollock, 1943; Fabing; 1947; Aita, 1946; Cramer et al., 1949). Today, it has become an area of great concern due to its prevalence.
2.2 BLAST INJURY

Many researchers like to classify blast injuries into four categories: primary, secondary, tertiary, and quaternary. The blast injury classifications are defined as follows. Primary blast injury is any injury caused by the blast-generated shock wave traveling through the body. Secondary blast injury refers to injury caused by shrapnel and debris propelled by the explosive into the body. Tertiary injuries are caused by the body being propelled by the blast wind into surrounding objects. Finally, quaternary blast injury encompasses all of the injuries not covered in the first three categories. Some of the most common examples are burns or inhalation of foreign/toxic material.

As observed by Gawande (2004), another aspect of modern war that has increased the survival rate of blast victims is improvements in first response medical treatment. During World War II, 30% of injured United States soldiers died. During our conflict in Vietnam, that percentage dropped to 24%. Currently in Iraq and Afghanistan, that number has dropped to an astounding 10%. This means U.S. soldiers exposed to explosions are now more likely to survive than ever before. This has also amplified mTBI prevalence in veterans of OIF and OED.

Typically, gas-filled organs such as the lungs, tympanic membrane, and the gastrointestinal tract were found to be the most sensitive to primary blast injury. These various organs have a wide range of tolerances to shock intensity and must be considered individually.

A great deal of research was performed on human tolerance to primary blast injury following the invention of the atomic bomb. These studies were performed by
exposing various mammals to blast waves generated by explosives or simulated by a shock tube (Richmond, et al., 1966). All of the data from these experiments were compiled by L. G. Bowen into what is now known as the Bowen curves (Bowen, et al., 1968). The Bowen curves were used to estimate an unarmored human’s tolerance to explosives with duration, amplitude, lung to body weight ratio, and body orientation as the variables taken under consideration. One of the Bowen curves can be seen in Figure 2.2. Negative aspects associated with how these blast experiments were performed will be covered later. But they still give an acceptable benchmark for blast injury estimations.

![Bowen Curve](image)

**Figure 2.2** Estimation of man’s blast tolerance (Bowen, et al., 1968)

As illustrated in the Bowen curve depicted in Figure 2.2, there are many characteristics of a blast exposure that will affect its lethality. The three largest factors are body orientation with respect to the wave propagation, maximum incident overpressure, and duration of positive overpressure. Overpressure refers to the amount of
pressure over atmospheric pressure carried by the shock wave in free field propagation. This is not to be confused with reflected pressure, which consists of overpressure plus the pressure created by stopping the gas flow behind the shock wave front (kinetic energy). This is also known as the “blast wind.” These terms will be covered in greater detail later in the thesis.

Body orientation relative to the shock wave has a major effect on injuries sustained during blast exposure. According to the Bowen curves, the smaller the cross-sectional area presented perpendicular to the wave front, the more tolerant the animal. For example, a shock wave propagating over a human from head to foot does much less damage than one propagating from front to back.

In the past, research concentrated on the blast injury to the lungs because these injuries were the most life-threatening injuries to civilian and military victims of explosives before the advent of good personal body armor. This approach was taken because a standard needed to be established for mammalian tolerance to blast waves as a function of overpressure, duration and orientation (Richmond, DR, et al., 1966). This study was documented by Richmond, in which 264 dogs, 115 goats, 200 mice, 110 hamsters, 150 rats, 120 guinea pigs, 48 cats, and 40 rabbits were exposed to various shock wave amplitudes and durations. The lethal dose for 50% of the animals (LD₅₀) was calculated by probit analysis. The shock waves used for these experiments ranged from 9.2-35.8 PSI (63.4-248.8 kPa) overpressure with durations from 1.5 to 400 milliseconds.

Various different forms of shock tubes were employed for reflected pressure experiments. This means the end of the shock tube was capped off with the animal
mounted on the plate. The pressure vs. time profiles on these experiments were often flat-topped, which is never the case with explosive shock waves. Also, because it was reflected pressure, the animal only experiences energy associated with the overpressure without the particle velocity. Therefore, the results of these experiments may be questionable. Depending on the speed of the wave, the overpressure duration and the thickness of the animal, intense tensile forces referred to as spallation may occur inside the animal’s body, causing extensive damage not necessarily associated with in-field primary blast injury. Richmond’s (1966) results were then used in the report, “Estimate Man’s Tolerance to the Direct Effects of Air Blast” (Bowen et al., 1968). The blast loadings used in these experiments were not very characteristic of those experienced by soldiers exposed to IED blasts. Therefore, the resulting graph’s accuracy shown in Figure 2.2 should be taken into consideration.

Many studies followed in the footsteps of Bowen and Richmond to better understand the damage done to humans by blast exposure via animal testing with shock tubes. Earlier than 2001, research focused primarily on injury inflicted on gas-filled organs rather than the brain and nervous system.

Hearing damage is the most common form of blast injury. It is said that hearing loss is one of the largest forms of disability given to U.S. veterans totaling over $3.5 billion 20 years (Mayorga, 1997). There are conflicting reports as to the pressure at which the tympanic membrane will rupture. In the literature viewed, the lowest blast overpressure that was reported to have ruptured the membrane was 34.4 kPa (Bonding, 1993), with the highest being 57 kPa (Richmond et al., 1989). Tympanic membrane rupture is not fatal and when no hearing protection is worn, it gives an indication of the
direction and intensity of a shock wave on the human head. Hearing damage is irreversible and can be debilitating. For a soldier, it can be dangerous because impaired hearing reduces the soldier’s ability to hear critical instructions or incoming threats.

Finkel states that, “Pulmonary barotraumas are the most fatal primary blast injury” (2006). Blast exposure causes hemorrhage, pulmonary contusion, pneumothorax, hemothorax, pneumomediastinum, pulmonary edema, and subcutaneous emphysema (Leibovici et al., 1999, Coppel, 1976, de Candole, 1967). Another common symptom of blast exposure is hypoxemia which is also linked to lung damage (Elsayed, 1997). Hypoxemia is linked to the reduced ability of blood to retain oxygen along with reduced lung volume caused by pulmonary edema. These symptoms were observed by Elsayed (1997) in sheep exposed to shock waves generated in a 12 in. (30 cm) diameter shock tube using Mylar® membranes.

The lung of an animal will often increase in mass after a blast exposure due to internal hemorrhaging or edema fluid accumulation (Elsayed, 1997). An increase in lung mass has proven to be proportionate to blast intensity. It is used as a gross index of lung injury by some researchers but is not universally accepted as such.

2.3 PROTECTION FROM BLAST WAVES

Soon after the liberation of Iraq in 2003, high explosives became the weapon of choice used by insurgents in the form of road-side bombs. This tactic proved to be an efficient method to injure U.S. military personnel and destroy equipment. After discovering the prevalence of explosives used as road-side bombs in Iraq, the military decided to heavily armor the bottom and sides of the HMMWV. A photo of a fully
armored HMMWV can be seen in Figure 2.3 with heavily armored windows and body. During missions in Iraq, one soldier is always standing in the gunner position at the top of the HMMWV. This position is especially susceptible to blast exposure since the soldier is protruding out of the vehicle’s top.

![Figure 2.3 Photograph of fully armored HMMWV (personal picture from a National Guard private)](image)

As the U.S. army invents new methods to protect soldiers from explosions, terrorists counter the measures by devising new forms of IEDs. Insurgents have discovered how to create shape charges which easily penetrate the HMMWV’s armor.

Personal body armor currently used during OIF and OEF has been proven to mitigate the effects blast waves have on the lungs as well as protect against shrapnel (Long et al., 2009). Long (2009) exposed rats to 126 and 147 kPa air blasts generated from a shock tube. The rats, wearing a miniature Kevlar™ vest secured with Velcro® around their chests, had a 100% survival rate. Compared to unprotected rats with
survival rates of 5/8 and 7/11, this was a significant improvement. Reduction of this blast injury mechanism has elevated the significance of TBI.

2.4 TBI RELATED TO BLAST INJURY

Primary blast injuries to the central nervous system are extremely difficult to study for various reasons. There often is a delay between a bTBI and the symptoms arising. This makes the exact pathology of the injury difficult to trace.

Some behavioral changes observed after a bTBI include increased aggression, impulsiveness, anxiety, and impaired social interaction and judgments (Agoston et al., 2009). Some of these symptoms associated with bTBI are also associated with post-traumatic stress disorder (PTSD). Due to these shared symptoms, it is often difficult to differentiate between these two pathologies.

There are many different hypotheses on what causes bTBI. One hypothesis is that the cerebral infarctions from air emboli are accountable for bTBI (Guy, 2000; Chiffelle, 1966; Rossle, 1950; Benzinger, 1950). This can cause localized areas of necrosis in brain tissue due to emboli’s ability to disrupt blood flow.

There are a few different ideas on how these emboli enter the blood stream. Some research has found correlation between extensive blast-induced lung damage and emboli (White et al., 1971). Yet another study research reported the appearance of emboli with very little blast induced lung damage. A study demonstrated that less than 10% of the lung displayed ecchymosis and / or petichia in sheep exposed to shock tube generated blast waves (Matorga, 1997). Ecchymosis and petichia found in blast lung is believed to
be due to alveolar hemorrhaging caused by a pressure wave passing through the lungs. This damage to the alveoli could be an origin of emboli.

Another theorized mechanism of bTBI is chemical changes in the brain and body following a blast exposure. A significant increase in free radicals in tandem with a decrease in antioxidants has been observed in rabbits and rats following blast exposure (Elsayed, 1997). It follows that there is an increase in lipid peroxidation products (Elsayed et al., 1997, Guy et al., 2000) which may cause cell damage and more specifically myelin breakdown. Myelin debris has been found in the hippocampus of rats following blast exposure (Guy et al., 2000). This may be linked to diffuse axonal injury which is one of the hallmarks of bTBI. Cascades of calcium ions have also been observed in rats given mechanically induced TBI (Kelso, TBI Presentation UNL, 2009). This can cause a chemical imbalance in the brain which could lead to apoptosis of neuronal cells.

Another hypothesis for the pathology of bTBI is that the pressure wave travels through the vascular system into the head (Cernak et al., 2001). In the study that Cernak performed, rats were taught an active avoidance task for 6 days. Their performance on this task was measured before exposing some of them to a whole-body blast injury or a local chest blast injury. The negative effects of whole-body blast injury on the rat's performance persisted much longer than that of the local chest blast injury. In both instances, the performance was substantially diminished for the first 3 hours following the blast exposure. Chemical changes in the brain were also observed in both instances even though the head was “protected” with a steel plate during the local chest blast injury.
One issue with this experiment is that the blast wave is transmitted through a fluid. The overpressure is not completely mitigated by a barrier such as the steel plate. The overpressure on a surface facing away from the explosive is typically decreased by a factor of 3 (Remennikov, 2006). Therefore, the rat’s head is still exposed to pressure as the shock wave passes.

It has been proven that physical impacts of high-velocity particles can send pressure waves into the brain and damage the nervous system (Suneson et al., 1990). Over 20 pigs were subjected to impact on the left thigh via a 0.88g 6mm-diameter projectile with velocities around 1500m/s. Pressure measurements were taken at various locations in the brain and near the sciatic nerve. High-frequency (100 – 200 kHz) pressure waves with amplitudes near 150kPa were observed in the brain. Necropsies were performed on the animals immediately or within 48 hours. No hemorrhaging was observed in the brain, however, myelin invaginations, shrinkage of axoplasm, and reduction in microtubule numbers were found in larger axons and neurons.

2.5 TOLERANCE OF BRAIN TISSUE TO DYNAMIC LOADING

Traumatic brain injury is not isolated to the pathology of shock wave exposure. It was originally observed as resulting from head impacts. These head impacts can be caused by anything from industrial to sporting accidents to motor vehicle collisions. TBI is estimated to result in 56,000 deaths and 83,000 disabled people every year in the U.S. alone (Sosin et al., 1996). It is the leading cause of death for children and adults under the age of 45 post motor vehicle accident (Pope & Tailer, 1991). This is why it has
become an area of concern in the U.S. It has spurred many studies on the human brain tissue tolerance to strain and strain rates.

Both in vitro and in vivo experimental methods have been employed along with finite element models to help determine the brain’s tolerance to the strain experienced during impact loading. One experimental method to evaluate tissue-level tolerance to strain was stretching of a guinea pig’s optical nerve (Bain & Meaney, 2000). A sling was placed around the guinea pig’s eye and the optical nerve was stretched to various different lengths on different specimens. Functional impairment of the optical nerve was then evaluated by measuring changes in the visual invoked potential. Visual invoked potential are the electrical signals generated by the eye and transmitted through the optic nerve. Degradation of this potential indicates neuronal damage.

In Bain and Meaney’s study it was found that Lagrangian strains below 0.14 gave no false positive morphological or functional injuries (2000). Above strain levels of 0.34, no false negatives were reported. Between these strain levels there were mixed results. This study gives a good strain threshold of the optic nerve at very low strain rates. This is not particularly applicable to blast TBI given the extreme difference in loading rate.

Morrison et al. considered the variable of higher strain rates and time after injury in brain tissue damage (2003). Similar injury observations were made at low strain rates. At higher strain rates of $50s^{-1}$ the cell injury was significantly higher than strain rates of $10s^{-1}$ with the same applied strain.

2.6 HISTORIC TEST METHODS TO ASSESS BLAST TOLERANCE
There are two main types of macroscopic shock loading employed by experimentalists in this area. One is shock tube induced shock waves and the other is actual explosives. Since a permit, highly trained personnel and a blasting range are required to use high explosives, shock tubes are typically the preferred method.

Shock tubes come in various different types. In some instances, high explosives are used as the driver in a shock tube (Bauman et al., 2009). More commonly, compressed gas is used as the energy source (Richmond et al., 1966; Elsayed et al., 1997; Wang et al., 1998; Cernak et al., 2001; Long et al., 2009). The compressed gas is quickly released into the barrel to generate a shock wave. This is typical for laboratory settings due to its relatively simple and safe operation.

A schematic of the shock tube used in the Richmond et al., (1966) mammalian blast tolerance studies can be seen in Figure 2.4. The wave-forms generated by these shock tubes can also be seen directly below each schematic. The animal being tested was mounted directly on the end plate of the shock tube, exposing it primarily to reflected pressure. Hundreds of animals were passed through these shock tubes to help define the Bowman curves (1968). The pressure profiles depicted are flat-topped shock waves which are not accurate reproductions of a Friedlander wave.
Shock tubes also found their place in helping estimate the blast loading experience by a building near an explosive. Kingerly and Gion characterized a 1-in. (2.54 cm) diameter shock tube and a 4-in. diameter (10.16 cm) tube for this purpose (1990). The shock tube configurations used for these experiments can be seen in Figure 2.5. Equations 2.1 relating the shock wave overpressure and duration to its pressure at various distances from the muzzle were derived empirically through experiments:

\[
\frac{I_S}{(I_w)^{1/3}} = 1.9 \times \frac{R}{(D_T)^{13/5}}^{-1.35} \tag{2.1}
\]

where:

- \( R \) = Radial distance from the shock tube muzzle
- \( D_T \) = Shock tube diameter
- \( I_w \) = Impulse near exit (kPa – msec)
- \( I_S \) = Impulse at \( R \) (kPa – msec)
This equation is only good for pressure measurements taken along the center axis of the shock tube and at distances greater than $R = 1.0$. It clearly indicates that the impulse rapidly decays with distance after the shock wave exits the barrel.

Figure 2.5 Kingerly and Gion’s shock tube configurations (1990)

Figure 2.6 shows a drawing of the shock tube used in Elsayed’s studies published in *The Journal of Toxicology* (1997). Shock tolerance of sheep was explored by mounting the specimen directly at the shock tube’s muzzle. Since the barrel only has a diameter of 12-in. (30 cm), only a portion of the chest is directly exposed to the shock wave. This may cause some ambiguity in the experiments performed, making it difficult to compare their results with those of other researchers.

Figure 2.6 12-in. (30 cm) diameter shock tube used to study lung blast tolerance of sheep (Elsayed, 1997)
2.7 SETTING CONSTRAINTS FOR SHOCK TUBE DEVELOPMENT

Setting constraints for developing a shock tube to simulate explosive blast waves could be approached from two directions. Given accurate repeatable data from literature on blast injuries, it would be easy to estimate a reasonable upper bound for human tolerance to blast. This would be the simplest method of setting shock tube constraints. But since most studies performed earlier often involve animals placed near the end of a shock tube, the loading conditions are not accurately known. Therefore, the symptoms observed in the animals cannot be correlated with an unpredictable experimental loading.

The second method is slightly more ambiguous but is presumed to be a more accurate methodology. The graph shown in Figure 2.7 depicts the average size of IED found in Iraq and Afghanistan during U.S. occupation. This gives a general idea of what size of explosives will be encountered by soldiers in the field. The size of explosives can then be correlated with the amplitude and duration of the shock wave produced, given the distance the soldier is away from the explosive.

Explosive characteristics can be empirically derived based on US Army Technical Manuals: TM 5-1300. This manual is typically used by military and civilian engineers in building design to determine explosive loading conditions. This manual was referenced in Remennikov (2005) but proved to be unobtainable by various methods. The following graphs in Figure 2.8 and Figure 2.9 were taken from Esparza’s report, “Airblast Measurements and Equivalency for Spherical Charges at Small Scaled Distances” (1986). Explosive strengths are typically related to Trinitrotoluene (TNT) for simplification and scaled accordingly. TNT peak overpressure equivalency for various different explosives
can be found in Figure 2.10. Care should be taken when using these graphs to observe the units.

Using the average mass of an IED at a given distance, an approximation of peak overpressure and positive pressure duration can be made to determine the loading conditions a soldier may experience. For example, if an explosive is encountered at ground level and the soldier is exposed to a blast while standing, the head’s distance to the explosive can be estimated as approximately 5 ft. (1.52 meters) or more. An average IED in Iraq has around 25 lb of explosives. The scaled distance for this scenario is \( \approx 2.92 \),

![Figure 2.7 Average sizes of explosives encountered by soldiers in Iraq and Afghanistan (Dreazen, 2010)](image)

**Figure 2.7** Average sizes of explosives encountered by soldiers in Iraq and Afghanistan (Dreazen, 2010)
which indicates a peak overpressure of \(~110\) PSI and duration of \(~3\) msec. This gives a reasonable form of estimation to determine the blast loading a soldier’s head experiences.

![Figure 2.8 “Side-on” overpressure vs. distance from detonated TNT (Esparza, 1986).](image)

In the case of soldiers exposed to an explosive while inside a HMMWV, reflections of the shock wave inside the vehicle introduces an increase of shock duration and repeated exposure over short time duration. This is an important phenomenon to
understand, but the fundamentals of the problem must be explored and understood before additional complications such as this are introduced. A simple Friedlander wave will be used for experiments so the effect of relatively simple, known loading conditions can be studied.

Figure 2.9 Scaled positive duration vs. scaled distance from detonated TNT (Esparza, 1986)
Figure 2.10 TNT peak overpressure equivalency relative to scaled distance (Wharton, 2000)
CHAPTER 3

THEORY OF SHOCK TUBE FOR BLAST WAVE SIMULATION

To gain a fundamental understanding of how explosive-generated shock waves interact with the human head and to validate FE models, simple, repeatable shock wave experiments must be performed. To design an apparatus for replicating blast waves, general shock wave theory and assumptions made must be understood. One-dimensional (1-D) shock wave propagation through fluid will be covered in the first portion of this chapter. To help understand wave propagation graphically $x-t$ diagrams are used to relate distance and time. This theory is then applied to designing features of the shock tube breech to be tunable for replication of blast waves. The 1-D theory will also be utilized in calibration of dynamic pressure transducers used for measuring the shock wave.

3.1 THEORY OF ONE-DIMENSIONAL SHOCK WAVES

One-dimensional shock wave theory, also known as the Rankine-Hugoniot (R-H) jump relations, is helpful in understanding the relationship between the state of a fluid before and after a shock front passes. With the initial conditions of the fluid and the speed of the shock wave known, the overpressure associated with the initial shock jump can be determined using the R-H jump conditions. This theoretically determined pressure can then be used to relate the sensor voltage output to the shock overpressure after justifying the simplifications made.

The laws of conservation of mass, momentum, and energy are used to relate the gas states before and immediately after the shock front passes. All derivations described
in the following section assume one-dimensional plane shock wave in an infinite gas medium. Also, cross-sectional area $A$ will be considered unity for simplicity.

When sound propagates through air, the wave consists of compressions and rarefactions of the gas molecules. It is transmitted through the action of molecules bumping into each other. There is no net movement of gas molecules in the direction of wave propagations and the compression is isentropic, meaning it is completely reversible since there is no significant entropy gain. The speed of sound, denoted hereafter as $a$, is dependent on the physical properties and the state of the transmission media. The application of weak adiabatic compression conditions to an ideal gas provides the following equation to describe the speed of sound:

$$
a = \sqrt{\frac{\gamma P}{\rho}} = \sqrt{\gamma RT}$$

(3.1)

where $P$ is pressure, $\rho$ is density, $T$ is absolute temperature, $R$ is the universal gas constant and $\gamma$ is the specific heat ratio of the gas $\gamma = \frac{C_p}{C_v}$. At a temperature of 68°F (20°C) and in dry air, the speed of sound is approximately 1125 ft/s (343 m/s). The Mach number is a common ratio used to describe the speed of something relative to the local speed of sound. For example, an object or wave traveling at Mach 2 in room-temperature air is traveling at 686 m/s.

When a mechanical disturbance is forced through air faster than the speed of sound, a shock wave is generated. The strength of the disturbance, along with the initial state of the fluid determines the state of the fluid, immediately behind the shock front.
This statement will be quantified through derivations using the ideal gas law, unity area, and adiabatic compression.

Two different frames of reference can be used when describing a planar shock wave traveling through a fluid medium. The laboratory-fixed coordinates consider the observer to be stationary relative to the laboratory while the shock wave moves at velocity $D$ through the fluid with initial particle velocity $v_1$ and final particle velocity $v_2$. The shock-fixed coordinates consider the shock wave to be stationary (the observer moving with the wave) with the fluid entering the shock front at velocity $u_1$ and exiting with velocity $u_2$.

In the following two equation derivations the shock front will be considered stationary while the fluid passes through it. The shock front can be thought of as a plane defining a jump change in the fluid state variables. Ambient state variables are denoted with the subscript 1 and the shocked state variables will be denoted with the subscript 2. An illustration with the shock-fixed coordinate system is shown in Figure 3.1.

![Figure 3.1 Fixed shock coordinates illustration.](image-url)
To relate the fluid speeds between laboratory-fixed coordinates and shock fixed coordinates, the following equation can be used:

\[ u_1 = D - v_1 \]

\[ u_2 = D - v_2 \]  (3.2)

If \( v_1 \) is considered to be stationary as would be the case in a shock tube, then \( u_1 = D \). Now consider the volume of fluid that passed through the stationary shock front in the time interval \( \Delta t \), i.e., \((A*D)\Delta t\). During this time, \( \rho_1 D \Delta t \) material passes through the shock front. The material exiting the shock wave has a velocity \( u_2 \) imparted on the fluid particles. The shocked material travels \( u_2 \Delta t \) during this same time interval. So the amount of gas contained in the region \((A*D-u_2)\Delta t\) can be defined as \( \rho_2(D-u_2)\Delta t \). Given the conservation of mass it follows that:

\[ \rho_2(D - u_2)\Delta t = \rho_1 D \Delta t \]

which simplifies to:

\[ \rho_2(D - u_2) = \rho_1 D \]

Using Newton’s second law along with impulse-momentum theory and the first R-H jump condition the second R-H equation can be derived.

Impulse-momentum theory:

\[ \text{Force}\Delta t = \text{mass}\Delta \text{velocity} = \text{mass}(\text{velocity}_2 - \text{velocity}_1) \]  (3.3)
where:

\[
\text{Force} \Delta \text{time} = (AP_1 - AP_2)\Delta t = (P_1 - P_2) \tag{3.4}
\]

\[
\text{mass} = \rho_1 u_1 = \rho_2 u_2 \tag{3.5}
\]

\[
\Delta \text{velocity} = u_1 - u_2 \tag{3.6}
\]

Combining these equations creates the second R-H equation as follows:

\[
P_1 + \rho_1 u_1^2 = P_2 + \rho_2 u_2^2 \tag{3.7}
\]

To derive the last jump condition, laboratory-fixed coordinates are the most convenient. The work exerted on the fluid by shock compression during the time interval \(\Delta t\) is:

\[
\text{work} = PA \times u_2 \Delta t \tag{3.8}
\]

The shock wave will perform work by adiabatically compressing the material (enthalpy change) and accelerating it (kinetic energy):

\[
\text{work} = \text{mass}(H_1 - H_2) + \frac{1}{2} \text{mass} \times \text{velocity}^2 \tag{3.9}
\]

By substituting equations 3.5, 3.6, and 3.8 into 3.9 the third R-H equation is derived:

\[
H_1 + \frac{1}{2} u_1^2 = H_2 + \frac{1}{2} u_2^2 \tag{3.10}
\]

All three R-H jump condition equations are summarized as follows:

\[
\rho_2(D - u_2) = \rho_1 D \tag{3.11}
\]

\[
P_1 + \rho_1 u_1^2 = P_2 + \rho_2 u_2^2 \tag{3.12}
\]

\[
H_1 + \frac{1}{2} u_1^2 = H_2 + \frac{1}{2} u_2^2 \tag{3.13}
\]
The R-H equations are used to describe the jump conditions at the shock front. $H_1$ and $H_2$ represent the initial and final enthalpies per unit mass of the working fluids. Equations 3.11-3.13 are accurate under the assumption that the shock compression is adiabatic, meaning no heat transfer occurs during the process. This assumption is made since the short rise time of the shock front (typically less than a microsecond) does not present enough time for significant heat conduction across the shock front. The low emissivity of gases also facilitates negligible radiant heat loss. Enthalpy may be defined by the following equation of state:

$$ H = E + RT $$

(3.14)

where: $E = \text{internal energy}$

If the working fluid is considered to be ideal, the specific heats $C_p$ and $C_v$ are constant and independent of temperature. This simplifies the definition of enthalpy to $H = C_p T$. With this simplification enthalpy can also be written as:

$$ H = \left( \frac{\gamma}{\gamma - 1} \right) RT $$

(3.15)

For shock tube experiments at UNL’s facility, it is not likely to have overpressures exceeding ~650 kPa, meaning the ratio $P_2/P_1$ is less than 6.3. According to the shock table from Anderson (2007), the $T_2/T_1$ ratio for this magnitude of shock is approximately 2. Shock tables are easily found in most aerodynamics textbooks or even on Wikipedia. This means that when $T_1$ is around room temperature, the shock wave will generate a temperature around $T_2 = 600$ K. At these temperatures the specific heat ratio of air $\gamma = \frac{C_p}{C_v}$ deviates approximately 1% from the assumed constant of 1.401. For low
pressure shock waves such as those associated with mTBI, the assumption of $\gamma = \frac{c_p}{c_v} =$ constant is presumed sufficiently accurate.

Typically shock tables are only for gases such as air, where $\gamma = 1.401$. The accuracy of the shock table deviates from reality by up to 10% for Mach numbers over 5 due to the specific heat ratio not being constant at higher temperatures and pressures. This is far beyond the shock levels that are survivable or will be used in the blast lab.

The following equations are shock wave relations derived assuming constant specific heat. They are the same equations used to derive the shock tables in most references (Gaydon & Hurle 1963):

$$\frac{P_2}{P_1} = \frac{2\gamma M^2 - (\gamma - 1)}{(\gamma + 1)}$$  \hfill (3.16)

$$\frac{T_2}{T_1} = \frac{2\gamma M^2 - (\gamma - 1)[(\gamma - 1)M^2 + 2]}{(\gamma - 1)^2 M^2}$$  \hfill (3.17)

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)M^2}{(\gamma - 1)M^2 + 2}$$  \hfill (3.18)

Where $M$ is the Mach number, specifically for shock waves, given by the ratio:

$$M = \frac{D}{a_1}$$  \hfill (3.19)

One can determine $a_1$ from equation 3.1 using the initial conditions of the blast lab measured before a shot. The initial conditions are recorded in the shot log for each shot performed with the shock tube. Derivation of these equations and a better understanding of shock waves can be found in D.B. Hayes lecture notes on, “Introduction to Stress Wave Phenomena.”
The shock wave inside of the 4-in. shock tube is assumed to be 1-D so these equations can be used for calibration of sensors. The low viscosity of air limits the boundary effects induced by the shock tube walls. If air viscosity has a significant effect on the shock wave planarity, its velocity would decrease as it propagates down the shock tube. The constant velocity over distance of a flat-topped wave in the 4-in. shock tube has been confirmed experimentally.

Transient waves in the shock front can cause it to become non-planar. With a constant cross-sectional area, the only transient waves introduced are artifacts of membrane burst form. Since the membrane does not open to full diameter instantaneously, there is some shock formation time associated with this method of gas release. The transient waves typically reach equilibrium within a short distance from the breech. The distance (ft) at which equilibrium is reached as a function of Mach number is shown in Figure 3.2 (White, 1958). Shock waves generated in this shock facility will not exceed $M = 5$. This means that with all the sensors and tests performed farther than 5 ft (1.54 m) from the membrane, there will be no issues related to this phenomenon.

Given a 1-D shock wave, the most important equation for calibration of sensors is 3.16. The shock speed is easily determined by measuring the pressure change arrival time at each sensor, along with the measured distance between them. This equation can be used to correlate the voltage output of the pressure transducer with the theoretical pressure. The set-up, procedures, and results for this calibration method will be given in section 4.10.
3.2 WAVE PROPAGATION IN UNIFORM SHOCK TUBE

After the membrane ruptures, a shock wave is propagated down the driven section of the shock tube and a rarefaction wave is simultaneously propagated back into the driving section. The rarefaction wave travels at a greater speed than the shock wave because it is traveling through the compressed gas and a stable shock front is subsonic with respect to the compressed medium behind it.

To understand the relation between various parts of the shock event, an $x-t$ diagram will be used. An $x-t$ diagram is a common tool used by investigators to help visually understand what is happening during the propagation of a shock wave. Time is plotted on the vertical axis and distance along the shock tube’s length “$x$” is on the
horizontal axis. Speed is the inverse of the line’s slope in an $x$-$t$ diagram (the steeper the line, the slower the wave).

The sloped lines plotted on the $x$-$t$ diagram pictured in Figure 3.3 depict the waves generated immediately after the membrane fracture. The vertical line near the center of the $x$-$t$ diagram represents the location of the membrane. The solid line with a low slope represents the shock front. As seen in the pressure graph below the $x$-$t$ diagram, the shock front represents an immediate jump in pressure from section 1 to section 2. The shock wave velocity is directly related to the change in pressure through the shock front as described by the R-H jump conditions.

In Figure 3.3 each section of the $x$-$t$ diagram is labeled with a number. Section 1 represents ambient conditions in the shock tube before the shock wave arrives. Section 2 contains the conditions found immediately after the shock wave passes. Section 3 is the state found after the contact surface arrives and before the rarefaction fan passes. Section 4 is the state of the gas contained in the breech before the membrane fractures.

The dashed line with a positive slope represents the contact surface. This is the plane between the driving gas and the driven gas. Theoretically, these gases do not mix during the shock event. But in actuality, turbulence created by the finite time needed to completely fracture the membrane creates an undefined boundary. The pressure across the contact surface remains constant as does the particle velocity since there is negligible gas flow across the surface. There is typically a significant temperature and density change at the contact surface. This drop in temperature and rise in density is because the rapid expansion of the driving gas cools it significantly.
The contact surface is not representative of a blast since explosives drive the shock wave with expanding hot gases. Therefore, ideally the contact surface will not propagate far enough down the barrel to interact with the sample. It is easily visualized on high-speed video due to the condensation formed by the low temperature air, so the contact surface’s presence in the test section can be detected visually. The breech length and pressure will dictate the distance a contact surface will propagate down the barrel.

Figure 3.3 Shock tube wave propagation after membrane fracture (Gaydon & Hurle, 1963)
The horizontal dashed line in the graph represents an instant in time. The points at which the horizontal lines intersect the different features of the shock event indicate changes in gas properties. Wave propagation directions are indicated by the arrows attached to the vertical dashed lines below the $x-t$ diagram. The free arrows indicate the particle direction.

Changes in pressure at this instant in time are shown at the bottom of Figure 3.3. $P_1$ and $P_4$ are known from the initial conditions of the lab and the burst pressure of the membrane. $P_2$ and $P_3$ are equal and can be determined via equation 3.16 and the measurable quantity shock speed. Pressures in the rarefaction fan are difficult to theoretically determine because it is continuously expanding in a nonlinear manner.

The rarefaction head travels faster than the shock front so they eventually meet after reflecting off of the breech back. The higher velocity is due to the denser medium it travels through. This can be observed with the rarefaction’s shallow line slope in Figure 3.3. The length of the breech and the burst pressure dictate when the rarefaction wave catches up to the shock front. If the breech is too long, the resulting shock wave will have a “flat-top” or constant pressure when it arrives at the test section. This is ideal for calibration of sensors because steady state pressure can more easily be measured by averaging multiple data points together to accurately determine the voltage / pressure correlation. This will be covered in greater detail in section 4.10.

If the breech is short enough, the rarefaction head will catch the shock front before it arrives at the test section, creating a “sharp” shock wave. This type of shock wave is similar to a Friedlander wave and is considered more representative of an actual
blast wave than a flat-topped wave. If the breech is too short, the rarefaction will overtake the shock front before it reaches the test section. In this case, the peak overpressure is reduced before its arrival. This degrades the shock test’s efficiency.

The $x$-$t$ diagram shown in Figure 3.4 represents the ideal breech length to use for blast experiments. The rarefaction head can be seen crossing the shock front just before it enters the test section. Once the rarefaction tail catches the shock front, the shock wave is reduced to noise, characterized by the boom associated with explosives, supersonic flight, and lightning. As the shock amplitude is eroded away by the rarefaction wave the duration is lengthened and the peak amplitude is reduced.

![Figure 3.4 Ideal breech length x-t diagram for explosive shock wave replication](image-url)
The effects of breech length on pressure history are shown in Figure 3.4. The black line is the pressure history created in the test section with a 35.6-in (90.5 cm) long breech. The gray line is the pressure history in the test section with a 9.6-in. (24.4 cm) breech. Fine adjustment of the breech between these two extremes enables the ideal Friedlander form to be generated. This ideal wave form occurs when the peak over pressure of the sharp wave in the test section is equivalent to that of a flat-topped wave generated with the same number of membranes.

![Figure 3.5 Effects of breech length on pressure history in the test section. Black: Flat topped pressure history created with a 35.6-in. (90.5 cm) breech length. Grey: Friedlander form pressure history created with a 9.6-in. (24.4 cm) breech length.](image)

3.3 SHOCK TUBE OPERATION

Operation of the shock tube is as simple as pressurizing the breech / driver section until the membrane fractures. A dual-membrane system will eventually be used to more accurately control the burst time and pressure, but first the single-membrane system needed to be experimentally verified and characterized. The pressurized gas contained in
the breech holds a great deal of potential energy. When the membrane (a thin plastic sheet placed between the driver and driven section) fractures, this energy is quickly released into ambient air. This quick release of compressed gas shocks the air up, generating a shock wave that carries both kinetic and potential energy with it as it propagates down the barrel at supersonic speed.
CHAPTER 4

4-IN. CYLINDRICAL UNIFORM SHOCK TUBE

Shock tubes are typically designed with a specific application in mind. The 4-in. cylindrical uniform shock tube creates the ideal platform for dynamic calibration of sensors with 1-D shock theory because of the constant cross-sectional area. Design and development of the various components and supporting systems use for this shock tube facility will be covered in this chapter.

4.1 INTRODUCTION

The 4-in. shock tube provides a predictable shock generator due to the constant cross-sectional area from the driver section to the driven section. This creates an ideal shock tube for calibration of sensors. It also creates a test bed for high-pressure shock wave experiments (0 – 1.0MPa) if needed.

A stable base was provided by a W24 X 104 wide flange beam leveled with adjustable feet and fastened to the ground with concrete lag bolts. The beam is approximately 24 in. (61 cm) tall, 13 in. (33 cm) wide, and 30 ft (9.14 m) long. Holes were drilled through the top flange of the beam to provide various different shock tube support configurations. The different sections and components of the shock tube are labeled in Figure 4.1. These components are standard on most shock tubes independent of their application.
The compressed gas is held in the driver section on the right side of the model in Figure 4.1. The dual-membrane holder retains the plastic sheets, which are used as membranes. The gas control system regulates flow of gas into and out of the driver and the dual-membrane section. The data acquisition system captures pressure data associated with the shock wave. The function of various components of the shock tube and their design will be covered in detail in the following sections.

4.2 COUPLING MECHANISMS

The 4-in. (10.16 cm) I.D. shock tube consisted of three different segments. The breech consists of a 6-ft (182.7 cm) portion of 4140 seamless tubing with a 7/8-in. (2.22 cm) wall thickness. The breech is capped on one end and has the membrane holder on the other side. The membrane holder is described in section 4.4. The breech cap is held in place with a coupler.

The coupler is a 7.25-in. (18.41 cm) outside diameter piece of mild steel with 5.75 x 5 ACME-2G-LH (left hand threads), 5.75 x 5 ACME-2G-RH (right hand threads)
threads on the inside and a 0.5-in (12.27 mm) wide relief cut between them. An isometric view of the coupler model is shown in Figure 4.2. The slots depicted on the outer diameter provide grips for a spanner wrench to lock into for tightening or loosening. The coupler is threaded with right hand and left hand threads so that the components being coupled can remain non-rotational while being drawn together by rotating the coupler. ACME threads were selected because they are standard threads used in industry, therefore tooling for machining them was readily available. They are also excellent for axial stress load bearing. A coupler of the same type is also used to fasten the two 10-ft segments of 4-in. barrel together.

![Figure 4.2 Coupler used to couple 4-in. barrels and hold the driver cap in place](image)

4.3 DRIVER SECTION

The driver section, also known as the breech, is the component which holds the compressed gas used to generate the shock wave. The gas must be held in a highly compressed state to store the potential energy needed to simulate a blast wave. The breech used is made of an annealed 4140 steel cylinder with 7/8-in. (2.22 cm) wall thickness. The inside is honed to a diameter of 4.040-in. (10.26 cm).
The breech was designed to hold 9000 psi (62.0 MPa). The fittings used in the gas handling system are NPT (national pipe thread) connections. Although typical \(\frac{1}{4}\)-in. NPT thread made from high-grade material is rated for 8000 psi (55.1 MPa), American Society for Testing and Materials (ASTM) requires gas systems to maintain a safety factor of 4 for all commercially sold components. The designed pressure limit is therefore believed to be appropriate considering that pressurization and firing is remotely controlled.

The NPT threads found in the side of the breech are less than ideal. Material was torn from the thread crests due to either a poor cutting edge on the tape used or lack of cutting oil used during the machining operation. For this reason, it is recommended that these holes be welded closed and new holes be machined if pressures over 41.4MPa (6000 psi) are desired. Failure of these threads would allow the breech to leak faster than it could be filled.

A cross-sectional view of the breech is shown in Figure 4.3. The light colored components inside of the breech are core inserts used to change the volume / length of the breech. Breech core lengths of 1, 2, 3, 6, 12, and 24-in. (2.54, 5.08, 7.62, 15.24, 30.48, and 60.96 cm) were created. This allows the breech’s length to be varied in 1-in. (2.54 cm) increments from 0.62 - 71.62 in (0.016 - 1.83 m). The small, black components shown in Figure 4.3 are \(\frac{1}{2}\)-13 threaded studs used to hold the various segments of the breech core together during installation and firing.

Great care should be taken to tighten the breech core segments together as well as to the breech cap. Two strap wrenches are typically used for tightening these
components together. Leaving gaps between the breech core segments could potentially
damage threads or create a projectile during depressurization (firing a shot) due to high
pressure gas trapped between them. The internal breech length can easily be measured
with a tape measure inserted into the cavity while the membrane is removed. This should
be done between shots to verify the breech core is still held in place. The measurement
should be in increments of 1-in. with a remainder of 5/8 in. e.g. 10 5/8 in. or 22 5/8 inch. If
anything other than a 5/8 in. remainder is measured, the core should be removed and
checked for tightness.

![Figure 4.3 Cross-section of the breech with four segments of the breech core installed](image)

An exploded model of the breech core assembly is shown removed from the
breech in the left portion of Figure 4.4. The core is directly connected to the breech plug
via threaded studs to insure they do not become projectiles during the shock wave
experiments. A photograph of the fully assembled breech core removed from the breech
is shown on the right of Figure 4.4.
Breech adjustments can be done by one person, although two people can make the operation much easier. To adjust the size of the breech, the cap must be removed by loosening the coupler. Once the coupler is completely unthreaded from the cap, the cap may then be pulled out of the breech with the core attached. The assembly should be set on the beam horizontally with the cap hanging off of the end. C-clamps may be used on the beam flange to prevent it from rolling off. Segments of the core may be loosened and tightened by using two strap wrenches to twist apart abutting segments. After loosening the segments, it is best to remove them in the vertical position.

Care should be taken to not impact the breech plug threads with anything during this operation. Damaged threads will create great difficulties in future operations. One should securely tighten segments of the breech core together with the strap wrenches before reinsertion into the breech. Ramming the cap and core assembly into the coupler can cause thread damage, which may require thread repair before proper assembly.
4.4 FIRING SYSTEM

Consistency and repeatability are two highly desired qualities in any experiment. Membrane (diaphragm) burst is a common valve mechanism used for gas-driven shock tubes. This method was selected as the firing mechanism for the shock tubes developed in this work. One of the largest variables found in shock tube tests with this type of firing mechanism is the pressure at which membranes burst. There are a few different design factors that contribute to a more consistent burst pressure.

The technique used to fasten a membrane in place becomes important at higher pressures. Improperly clamped membranes may be subject to pull-out. It is critical to clamp the membranes with a large evenly distributed pressure to ensure a consistent burst pressure. Membranes left under clamping pressure for a long period of time also exhibit a considerably lower burst pressure than typical. Conversely, membranes left under gas pressure for an extended period of time exhibit higher burst pressures.

4.4.1 Determination of Membrane Burst Pressures

The membrane material of choice to date has been Dura-Lar®, which is a biaxially oriented polyethylene terephthalate (boPET). It is similar to the material from which pop bottles are made. Biaxial orientation gives the material a greater tensile strength and mostly isotropic properties. Even with the biaxial orientation, the membrane material has displayed anisotropic behaviors during fracture. Therefore, it is ideal to use multiple layers of thin Dura-Lar® as opposed to a single, thicker layer for more consistent burst pressures. The layers should be rotated relative to each other to randomize their orientation.
Burst pressure is measured with by the gas control program. After the membrane bursts, the program must be stopped before the “Max Pressure (PSI)” is displayed by the program. The pressure measurement is taken on the breech’s side wall with a static pressure sensor. The breech is filled in small increments to allow the sensor to equilibrate. The reported pressure is recorded into the shot log for every shot performed since March 9, 2010, with the exception of pull-out membrane failure and improperly recorded sensor signals. The fill rate at the time of burst affects the maximum pressure reported due to the pressure sensor’s time constant and the 20 point (3msec sampling rate) averaging used to reduce noise.

The membrane material was purchased in bulk sheets 25 in. x 40 in. (63.5 cm x 101.6 cm) in various thicknesses. The sheets were supplied by Grafix®. Each thickness was tested to determine the approximate burst pressure and consistency before ordering a large quantity of the material. The preliminary test results can be seen in Figure 4.5.

Membranes of thicknesses exceeding 0.010 in. (0.25 mm) were found to experience perforations instead of fracture. The perforation occurred at a much lower pressure than expected and caused a gradual release of pressurized gas instead of the rapid release needed to create a shock wave. An image of the improper rupture of thick Dura-Lar® can be seen in Figure 4.6. A proper rupture of a 5 mil Dura-Lar® membrane is provided for comparison in Figure 4.7.
All of these burst pressure tests were performed with a single layer of Dura-Lar®. The use of multiple layers is needed to obtain higher burst pressures required to simulate blast waves at closer proximities to the explosive. Therefore, the cumbersome task of cutting out circular membrane was contracted to Stone Enterprises of Omaha, Nebraska. They used a water-jet cutting machine to cut multiple membranes at once with computerized numerical control. A great deal of time was saved when performing multi-membrane shock tests, and this should be considered for future membrane ordering.

Since a single layer of Dura-Lar® membrane generally bursts at a low pressure, multiple layers were used to reach higher burst pressures. A series of tests were carried out to determine burst pressure as a function of the number of membrane layers for 5 mil (0.127 mm), 7 mil (0.178 mm) and 10 mil (0.254 mm) Dura-Lar® sheets. The results are presented in Figures 4.8-13. Membrane burst pressure tends to be very consistent, except
for the few anomalies seen towards the higher pressures in the 10 mil membranes. These low burst pressures could be accounted for by variations in tightening techniques or the data acquisition programming used during early shock tube operation. It is clear that for each type of membrane, the burst pressure vs. membrane quantity data can be well represented by the corresponding best linear fit to the data, indicating an essentially linear relation between the burst pressure and the number of membrane layers used. The equation for each best fit line can be found in the upper right corner of each graph.
accompanied by an $R^2$ value. It should be noted that a defect on a single layer becomes statistically less significant as the number of layers increases. The membrane material also tends to be anisotropic in nature. Since the material orientation becomes random during the installation procedure, the anisotropy becomes less significant.

**Figure 4.8** 5 mil membrane burst pressure relative to quantity (U.S. conventional units)
Figure 4.9 5 mil membrane burst pressure relative to quantity (SI units)

\[ y = 0.3696x - 0.0698 \]
\[ R^2 = 0.9689 \]

Figure 4.10 7 mil membrane burst pressure relative to quantity (U.S. conventional units)

\[ y = 102.48x - 3.5046 \]
\[ R^2 = 0.9892 \]
**Figure 4.11** 7 mil membrane burst pressure relative to quantity (SI units)

**Figure 4.12** 10 mil membrane burst pressure relative to quantity (U.S. conventional units)
4.4.2 Double Diaphragm System

There have been many different methods used to obtain a consistent burst pressure from membranes used in shock tubes, including laser-induced bursts, membrane pierce and dual-membrane systems. Dual-membrane burst pressure control was selected for two reasons: its simplicity and the ability to obtain higher burst pressures.

Metallic membranes, typically made of aluminum or austenitic stainless steel, because of their malleability, are often used in shock tubes. Occasionally, pieces of the membrane completely fracture off and are accelerated down the tube by the high pressure gas. This can be extremely detrimental if sensors or samples are impacted by these unintended projectiles. The Dura-Lar® membranes tend to stay in one piece, but when they do create fragments, the projectile is relatively harmless to instruments and samples.
The dual-membrane system design is shown as a solid model in Figure 4.14. The membrane holder is designed to function in either single- or dual-membrane made without major modifications. When used in single-membrane setting, the center membrane holder is removed and shorter clamping bolts are used.

The advantage of using a single-membrane as opposed to a dual-membrane system is the reduced number of membranes that are needed for each shot. It also requires less control from the gas system, which makes it easier to begin operation with before the dual-membrane system is established. Gas system control will be covered in detail in section 4.8.2.

If the membrane is not clamped between the sealing surfaces with evenly distributed and sufficient pressure, pull-out may occur. This means the membrane will slip from between the sealing surfaces and release the gas without fracturing. This is an undesired event, as the shock wave generated is unpredictable in shape and amplitude.
To prevent pull-out, a few measures were taken. The membrane holder was designed to help prevent pull-out by inducing wrinkles in the membrane. These wrinkles are caused by the offset o-ring grooves in the opposing sealing surfaces. This can be seen in the cross-sectional view shown in Figure 4.15.

When tightening the clamping bolts labeled in Figure 4.14, one should start by lightly torquing each bolt. Then work around the flange in a star pattern to prevent the ring from being pulled off to one side due to initial over-tightening of one side before the other. If one bolt is completely tightened before the opposing bolt, the flange will be prevented from seating properly and pull-out may occur.

Figure 4.15 Assembled dual-membrane system coupled between the 4-in. breech and barrel.

Proper alignment of the barrel to the breech is also crucial to prevent membrane pull-out. Rough alignment of the breech will allow the membrane holders to slide together without interference. The lip around the female membrane holder should slip over the male membrane holder to allow the face o-rings to be in contact when the breech is rolled up to the barrel. A membrane should then be installed with the proper bolt tightening sequence observed. An impact wrench is often used to speed up this process.
Once the impact wrench has reached its maximum torque output for all bolts, a hex key with a 1-m-long pipe extension is used to finish the tightening. The same star pattern sequence should be used with each tool.

Once the clamping bolts are fully tightened, the rollers on which the breech sits should be checked for contact. The four adjustment screws labeled in Figure 4.17 on the base plate of the breech support can be used to adjust the rollers’ position relative to the breech. All four wheels should be in contact with the breech and snug enough to prevent rotation by hand but not too tight that the barrel is lifted out of alignment.

For low-pressure shots, anything with a burst pressure below 6.9 MPa (1000 psi), 4 clamping bolts need to be installed. For any shot over this pressure, all 8 bolts should be utilized. The threads and load bearing surface of the bolt should be sufficiently greased such that efficient transfer of torque to clamping pressure is achieved.

4.5 PIEZOELECTRIC PRESSURE SENSORS

Sensor holes were machined near the end of the 4-in. shock tube and one near the center. The sensors mounted near the end of the barrel are specifically machined to fit Dytran 2300 or PCB 111A20 sensors.

The sensor hole was machined near the coupler on the 4-in. shock tube, tapped with a ¾ - 11 thread to allow an insert to be adapted for accommodation of various sensors. Two different inserts were machined, one out of steel and the other from nylon. The hypothesis that isolating the sensor from the barrel wall would reduce vibration noise was tested with the nylon insert. It was found that mounting the sensor in the nylon insert increased the sensor’s noise to signal ratio significantly. The nylon insert isolation
method induced more noise than it inhibited. Therefore, the steel insert has since been employed from that time on in this sensor position.

![Figure 4.16 Dytran 2300V1 sensor mounted in Nylon near the 4-in. coupler.](image)

**4.6 BARREL SUPPORTS**

The 4-in. barrel and breech is supported on cam rollers. This allows the entire assembly to roll freely along its axis. Allowing the barrel to roll, as opposed to slide, reduces noise associated with vibration caused by sliding during recoil. It also enables easy removal and replacement of the membrane after firing a shot since the membrane holder can be rolled open.

The 4-in. barrel support can be seen on the left side of Figure 4.17. These supports are fastened into place with two 5/8 – 11 socket-head cap screws with clearance holes through the side tabs. This allows the 4in. barrel support to be removed from the base plate without taking the entire assembly off of the beam. This is ideal when changing shock tube configurations.
The support plate onto which the barrel supports are fastened allows adjustment of the barrel’s height and angle. This enables precise alignment of the barrel to the breech. Without accurate alignment of these components, membrane pull-out may occur and membrane replacement would be inhibited.

4.7 RECOIL DAMPING

When a shot is fired, the reaction to the force driving the shock wave creates an acceleration of the shock tube backwards. The acceleration of the shock tube will be referred to as recoil since it is similar in nature to recoil experienced while firing a gun. Since the 4-in. barrel is allowed to roll along its axis, recoil damping becomes an issue. Depending on the peak overpressure and shock wave duration, this recoil force can become quite significant. A dampening mechanism, as shown in Figure 4.18, is used to absorb the recoil energy. Shocks designed for use in race-car suspension systems are employed as the dampeners in this system. A shock-to-tube mount designed with an interference fit is bolted in place on the 4-in. barrel or breech. This allows it to be placed anywhere convenient along the shock tube. If the 9-in. square barrel is being used, the
dampening mechanism can be fastened to the breech. A beam-to-shock mount is used to transfer the force to the shock tube base. This mount has the same bolt-hole pattern as used for mounting the barrel support base plates. It can be mounted in various locations along the length of the beam.

Figure 4.18 Dampening mechanism used to reduce the effects of recoil.

4.8 GAS SYSTEM

The gas system enables the shock tube operator to control gas flow into and out of the driver section and dual-membrane section from a remote location. Remote operation is essential for safety purposes while performing high-pressure blasts. A photograph of the gas system is shown on the left side of Figure 4.19. A model of the gas system with all of the major external components labeled is shown on the right of the figure. The valves on the right side of the gas system are used to control the flow of gas to and from the breech. The valves on the left side of the system are used to control gas for the dual-membrane. Exhausting of the breech is done when a shot has to be aborted. This
typically happens when insufficient gas pressure is available in the bottle to burst the membrane.

Figure 4.19 Left: High-pressure gas handling system. Right: Model of the shock tube electronically controlled gas system.

The electronically controlled regulator on the lower left side of the gas handling system board is used to control the inlet pressure of the gas system. It can remotely change the system’s pressure while filling the dual-membrane portion of the system. For instance, when firing a shot at 2 MPa, the regulator will be set to 1 MPa while filling the breech and dual-membrane cavities. Once both have been filled to 1 MPa the regulator will be set to 2 MPa and the breech will be pressurized the rest of the way.

4.8.1 Gas System Hardware

This section will cover the various hardware components of the gas system. The system was put together with off-the-shelf items and designed to be highly versatile. One of the most adaptable components selected is the Swagelok fitting. This fitting comes in various different forms and types. It is used to connect smooth-walled tubing together for high-pressure applications. A picture of a tubing-to-NPT adaptor is shown in Figure
4.20. This type of fitting was used to connect tubing to the solenoid valves and the regulator.

The gas line used for this application is 0.250 in. outside diameter (6.35 mm) 0.065 in. (1.52 mm) wall 316L stainless steel tubing rated for 15,000 psi (103 MPa) operating pressure. All fittings ordered are compatible with this tubing. Extra tubing and fittings were ordered enabling adaptations to the current gas system to be made when needed. This will allow an easier application of the Haskel booster (high-pressure air-driven gas compressor) when it is needed.

![Tubing to NPT Swagelok style adaptor](http://www.airoil.com/manufacturers/Tylok.html)

Figure 4.20 Picture of a tubing to NPT Swagelok style adaptor from http://www.airoil.com/manufacturers/Tylok.html

A Clark Cooper EH30 series solenoid valve was used for gas shut off and release. This valve is rated for 10,000 psi (62.05 MPa) operating pressure. Its inlet and outlet port are threaded with ¼ NPT thread as shown in the schematic to the right in Figure 4.21. Unlike most solenoid valves, this particular valve does not require 100 psi pressure for pilot assist of the solenoid. The solenoid used to operate the valve requires 120VAC with an operating current of 0.22A.

Solid state relays were used as the electronic solenoid valve interface. These relays offered two great advantages over conventional, mechanical relays. One of the advantages is their ability to be operated directly from a 5VDC logic level input due to its high impedance input. This enabled us to control the solenoid valves directly from a
National Instruments module without a transistor or MOSFET to increase the signal amperage. The other advantage is how the power is switched on by the relay. Typical mechanical relay contacts are similar to a household light switch with an electromagnet to switch its position. The contacts are drawn close together via the electromagnet. Once they are close enough, a spark jumps the gap and electricity is conducted through the relay. When the spark jumps, an electromagnetic pulse (EMP) is emitted. This EMP can trigger the data acquisition system.


With a solid-state relay, the AC power is turned on when zero potential is across the power pins. This eliminates the EMP associated with the spark generated when switching a mechanical relay. There have been no issues with false triggering due to the gas system.

![Figure 4.22](http://www.clarkcooper.com/eh30.html) Solid-state relay used to power solenoid valves.
The relays and connector blocks associated with the gas system can be found inside of the gas system mounting board. Three cords exit the back of this enclosure. One of them is a typical power cord, which provides power for the solenoid valve activation. The small black cord is the signal wire used to control the solid state relays. Table 4.1 contains the wire colors that are associated with each solenoid valve. The third cord is associated with the regulator control unit. Refer to the regulator manual for determining wire color correlations.

<table>
<thead>
<tr>
<th>Wire Color</th>
<th>Application</th>
<th>Module NI-9403 pin #</th>
<th>Channel Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>Fill Membrane</td>
<td>1</td>
<td>DO0</td>
</tr>
<tr>
<td>Yellow</td>
<td>Fill Breech</td>
<td>2</td>
<td>DO1</td>
</tr>
<tr>
<td>Red</td>
<td>Exhaust Membrane</td>
<td>3</td>
<td>DO2</td>
</tr>
<tr>
<td>Green</td>
<td>Exhaust Breech</td>
<td>4</td>
<td>DO3</td>
</tr>
<tr>
<td>Black</td>
<td>Ground</td>
<td>5</td>
<td>DO9</td>
</tr>
</tbody>
</table>

The regulator provides the gas system with the ability to precisely control pressure. Tescom ER-3000, shown in Figure 4.23, is the electronic regulator control selected for this task. This control unit uses a 4-20mA analog input to control the pressure output of 0-100 psi (0-690 kPa) shop air. The 0-100 psi output is then used to pressurize the diaphragm of a high-pressure regulator to regulate the bottle pressure input to the gas system.

The high-pressure regulator has an input pressure range of 0-10,000 psi (0-69 MPa) and an outlet pressure of 0-2,500 psi (17.2 MPa). The regulator’s 0-2,500 psi
output directly correlates to the 4-20 mA input signal respectively. The regulator can be used to precisely control the pressure used to fill the dual diaphragm section. This will allow that section to be completely filled to a set pressure before proceeding to fill the breech with a higher pressure.

Figure 4.23 Tescom ER-3000 Electronic Control Regulator.

4.8.2 Remote Gas System Control

The unit used to remotely control the gas system and gather environmental data is National Instruments cRIO-9073. This system is a control and monitoring system with a 266MHz industrial real-time processor. The cRIO has 8 slots available for proprietary modules and uses field programmable gate arrays (FPGA) in its so-called “back panel” to allow reconfigurable, low-level, on-board code execution. It is remotely connected to the control room computers via an Ethernet connection. The cRIO shown in Figure 4.24 contains two modules that are shown in the center of the figure.

Module NI-9403 is a 32-pin digital I/O module. The module can be used to read the digital status of a pin or outputs a 5V logic level signal. It is currently functioning solely as 5 VDC output to trigger the solid-state relays connected to the solenoid valves.
The second module shown in Figure 4.24 is the NI-9203. This module has 8 channels with analog input capabilities. The input range is 4-20 mA with 16-bit resolution at 200kS/s aggregate sampling rate. This also features a National Institutes of Standards and Technology (NIST)-traceable calibration. This module is used to monitor quasi-static pressures inside the dual-membrane sections, the breech, and the gas system. It is also used to measure and report the initial conditions in the blast facility such as the temperature, atmospheric pressure, and relative humidity. All of these initial conditions are recorded in the shot log for each shot.

The third module used in the gas control system is not shown in Figure 4.24. This NI 9265 is a four-channel 4-20mA analog output. One channel of this module is used to control the pressure regulator. The current regulator can control the pressure going into the gas system between 0-2500 psi (17.2 MPa). An additional regulator, not integrated into the gas system, is available that can handle 0-10,000 psi (68.8 MPa).

The cRIO provides a versatile tool for remote monitoring and control of the shock tube systems. There are additional channels available on all modules currently installed.
and 5 additional slots available for new module installations if expansion is needed in the future.

4.8.3 LabVIEW Control Program

The LabVIEW program written for the gas system serves multiple different functions. To access the program, one can follow this file path: Desktop > Current Gas Control > Reg. Control.lvproj. Once the project explorer window opens: Project: Reg. control.lvproj > NI-cRIO9073-01446B71 > Reg. Control.vi. LabVIEW should display the front panel shown in Figure 4.25.

To connect to the cRIO inside the blast lab, click on the small arrow in the upper left corner. The power strip inside the gas system’s cabinet must be switched on before connection can be established. Once the program is deployed and the connection established, the grid on the background of the front panel will disappear. The current room conditions will be measured, averaged, and then displayed. The graphs will begin tracing a pressure readings for the breech and dual membrane sections.

Sensor range data fields need to be changed only if the static pressure sensors are swapped with another sensor of a different pressure range. The “Max pressure (PSI)” readout will display the maximum breech pressure that was obtained before the burst. The program must be stopped with the “STOP PROGRAM” button before the burst pressure is reported. Never use the little stop sign in the upper left corner of the screen to terminate the program. That button can cause the code to become mysteriously dysfunctional. If this occurs, it is necessary to completely exit LabVIEW without saving, and restart the program.
The “Fill Breech” button will open the breech fill valve for the “Fill Time (s)” specified. Generally, small increments are used to fill the breech, allowing minimal gas to be wasted after the membrane bursts. The “Dump” button opens the breech pressure relief valve for the amount of time specified in “Dump Time (s).” The default value of dump time is 30 seconds. This provides sufficient time to bring the breech pressure well below burst level if a shot needs to be aborted.

If the shock tube is being fired with a dual-membrane, the “Fill Membrane” button should be used. The “Regulator Setting (PSI)” should be set to the desired shock pressure. The appropriate membrane should be installed with a combined rupture pressure greater than the regulator setting. An equal number of membranes should be placed in each holder. For example, if a 650 PSI (4.5 MPa) shot is desired, a set of three
10-mil membranes should be placed in each holder and the “Regulator Setting” set to 650. The program will fill the dual-membrane to 325 psi (2.25 MPa) and the breech to 650 psi (4.5 MPa).

4.9 DATA ACQUISITION

There are two systems used for data acquisition in the blast lab. The quasi-static measurement system is used to gather information about the gas system and the initial conditions of the lab environment. The dynamic measurement system is used to gather information at high rates during the blast event. The two systems are completely autonomous from each other.

4.9.1 Quasi-Static Measurements

Quasi-static pressure measurements are taken from the side of the breech and the dual-membrane section. The pressure measurements are performed with a Dwyer series 626 pressure transducers. These transducers have an accuracy of 1% of full scale including linearity, hysteresis, and repeatability. Various different pressure ranges were ordered from Grainger including 0-500, 0-1000, (2) each 0-3000, 0-5000, and (2) each 0-10,000 psi. This enables accurate pressure measurements over a wide range of pressures. All of these sensors have ¼ NPT connections on them. The wiring specifications can be found in Figure 4.26.

The initial laboratory conditions are critical when calibrating dynamic pressure transducers. The initial conditions are used in the 1-D shock theory to determine the theoretical overpressure. This will be covered in greater detail later in Chapter 5. The most crucial initial conditions are atmospheric pressure and temperature.
To measure the atmospheric pressure, a Comet T2114 programmable atmospheric pressure transmitter is used with a 4-20 mA output. Calibrated at the factory, the sensor has an accuracy of $\pm1.3$ mBar at $T=23^\circ C$. The temperature at which this sensor was calibrated is similar to that found in the lab. The 4-20 mA signal is fed directly into AI3 of module NI-9203. The wiring schematic can be found in Figure 4.27, where $U_{ss}$ is the current measured by the NI module.

Dwyer Series RH Temperature / humidity transmitter also has a 4-20 mA output with an accuracy of $\pm2\%$ on the relative humidity and $\pm0.9^\circ F$ ($0.5^\circ C$). Relative humidity is not crucial information to 1-D shock theory, but it is recorded in the shot log since the information is available.
4.9.2 Dynamic Measurements

Measuring dynamic pressure variations during a blast event is quite challenging. Various different pressure transducers have been purchased and tested. Currently, the most popular sensor is the Dytran model #2300V1. One of these sensor is shown in Figure 4.28. The linear range for this pressure transducer is 0-250 psi (0-1.03 MPa) with a burst pressure of 5,000 psi (34.4 MPa). It is a sealed unit with a 0.217-in. (5.5 mm) diameter diaphragm for the pressure sensing surface. The typical output sensitivity is 20 mV/psi (2.9 mV/kPa). Different versions of the same size sensor can be purchased for various pressure ranges. A 5/16-24 thread is provided for mounting purposes and a 10-32 connector for signal output.

The Dytran 2300V1 sensor is a low-impedance sensor. They contain a unity gain MOSFET charge amplifier within the sensor housing. This design prevents signal degradation over long cables due to the sensor’s low impedance (~150Ω). Other sensor styles have the charge amplifier as a separate unit. An external charge amplifier is advantageous because the sensor’s pressure range / sensitivity can be changed without replacing the sensor. However, the external charge amplifier adds size to the sensor and needs to be mounted close to prevent signal degradation.

The Dytran power module used with the 2300V1 sensors can be seen in the center of Figure 4.28. The module is a four-channel current source with a 10V bias. There is a bias monitor on the upper portion of the front which should always read in the center on each channel before a test. If the bias meter reads 0V, it indicates a short circuit that needs to be addressed before a test is performed. If the bias meter reads 24V, then an
open circuit is present. The sensor may not be connected properly, the cable damaged or the internal charge amplifier could be burnt out.

**Figure 4.28** Left: Dytran dynamic pressure sensor model #2300V1. Center: Dytran current source sensor power module model # 4114B1. Right: 10-32 connector for sensor output with BNC connector on the power module side.

The signal output from the Dytran power module or any other sensor signal conditioning unit is fed into the NI PXIe-1082 chassis. The blast lab’s chassis contains two NI PCI-6133 data acquisition cards. Each card contains 8 analog-to-digital channels capable of 2.5 MHz simultaneous, continuous sampling. Sixteen channels are available for dynamic data acquisition. If needed, additional data acquisition cards can be installed in the chassis.

Remote operation of the data acquisition system is done through the Windows remote desktop. Once the computer in the control office and the NI chassis is turned on and fully booted, the connection can be created by double-clicking the icon labeled “192.168.1.2” on the office computer desktop. Once the connection is confirmed, LabVIEW functions the same as on any other computer but through a remote connection.

The control room / shock tube floor plan is shown in Figure 4.29. The dynamic data acquisition system and the gas control / static data acquisition systems are contained
inside cabinets mounted alongside the beam. Their locations inside the blast lab are labeled in Figure 4.29.

Figure 4.29 Blast lab / control room floor layout.
4.10 DYTRAN SENSOR CALIBRATION

Calibration of sensors is extremely important to ensure data accurately represents the event. Without proper calibration of sensors, results will not be comparable to other research being performed in this area. All dynamic sensors ordered for the blast facility come with a factory calibration. The calibrations provided for the Dytran 2300V1 sensors are performed with the apparatus shown in Figure 4.30. This schematic was extracted from Dytran’s calibration document TP-2004 Rev B 2008 provided by the company.

![Figure 4.30 Calibration set-up for Dytran piezoelectric sensors 2300-V1 (Varka, 2004)](image)

The pressure sensor is placed in a manifold beside a standard. The standard is a sensor with a known calibration factor. The hand-operated hydraulic pump is used to
“quickly” pressurize the manifold. The voltage output of the sensor is recorded via the oscilloscope and its sensitivity determined by comparison to the standard.

This calibration methodology is on a different time scale than shock tube tests. Therefore, the sensitivity provided by the company for each sensor was not trusted. R-H jump conditions (1-D shock theory) was used to calibrate the sensors for shock tube use.

All calibration shots were performed in the 4-in. (10.6 cm) round tube. Since the driven section and the driving section retain a uniform cross section area along their length, no transverse waves are introduced after the burst. This insures a more consistent 1-D shock wave for calibration purposes. A breech length of 35.625 in. (90.5 cm) was used to create an extra long flat-topped wave so multiple points could be averaged together for greater accuracy.

4.10.1 Sensor Locations and Mounting

Dytran piezoelectric pressure transducers (model 2300V-1) were mounted directly in the side wall of the 4-in. I.D. shock tube wall. The 0.216-in. (5.5 mm) diameter diaphragm of the sensor is slightly recessed from the inner wall with the direction of shock wave propagation parallel to its surface. The sensors are slightly recessed because any protrusion into the barrel will create an interaction with the wave which has been experimentally proven to affect the pressure measurements. Details of the mounting holes can be found on Dytran’s web site. An image of the sensor arrangement at the end of the barrel can be seen in Figure 4.31.
Six sensors were installed into the side wall at approximately 10-in. (25.4 cm) increments with the last sensor approximately 1.5 in. (3.81 cm) from the barrel’s exit. The sensors are spaced apart so the time needed for the shock wave to travel between the sensors can be measured and used to determine the wave velocity. Since there are three sensors in a row, the acceleration of the wave can also be determined. This information is used to calibrate the sensors and determine characteristics of the wave before it exits the barrel.

There are sensors directly on the opposite side wall across from the top sensors pointed out previously in Figure 3.8. Each one of these sensors can be used to verify the pressure reading measured by the opposing sensor after calibration and with the assumption of a uniform pressure distribution. It also allows 6 Dytran – 2300-V1 sensors to be calibrated at the same time.

The velocity measurements are used to determine the wave’s overpressure using Equation 3.8. Accurately measuring the distance between sensor holes is crucial to reducing uncertainties associated with velocity measurements. These measurements
were performed by calibrated 12-in. dial calipers. Sensors were screwed into place and the distance between them was determined by measuring the distance between the sensors’ protruding components. The accurately (+-0.003 in.; 0.01 mm) measured distances between these sensors are shown in Figure 4.32. These distances were used for calibration calculations.

Figure 4.32 Actual measurements between sensors in the 4-in. shock tube. Dimensions are given in millimeters and [in.]

Caution should be practiced when installing sensors into this shock tube. Many of the holes were drilled off center and the seating surface was not machined to the proper depth. This allows the sensor tip to protrude if it is completely torqued into place. The sensor’s threads were wrapped with Teflon® tape before being screwed to the proper depth. This insured a tight fit without tightening the sensor into a protruding position.

4.10.2 Measurements and Results

The eight Dytran 2300V1 sensors were calibrated using the R-H jump conditions described earlier. A list of the Dytran sensor serial numbers along with their factory-
provided calibration factors are listed in Table 4.2 Factory calibration factors for Dytran sensors. These calibration factors were used for the first few shots but were soon found to be inaccurate due to the large pressure variation read at each sensor during a flat-topped shock event. There should be little to no pressure variation with this type of test, therefore in-house calibrations were pursued.

<table>
<thead>
<tr>
<th>Serial #</th>
<th>Factory Calibration</th>
<th>Units</th>
<th>Sensor Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>4189</td>
<td>0.0209</td>
<td>V/PSI</td>
<td>0-250 PSI</td>
</tr>
<tr>
<td>3988</td>
<td>0.0202</td>
<td>V/PSI</td>
<td>0-250 PSI</td>
</tr>
<tr>
<td>3953</td>
<td>0.0181</td>
<td>V/PSI</td>
<td>0-250 PSI</td>
</tr>
<tr>
<td>3987</td>
<td>0.0191</td>
<td>V/PSI</td>
<td>0-250 PSI</td>
</tr>
<tr>
<td>4130</td>
<td>0.021</td>
<td>V/PSI</td>
<td>0-250 PSI</td>
</tr>
<tr>
<td>3946</td>
<td>0.0214</td>
<td>V/PSI</td>
<td>0-250 PSI</td>
</tr>
<tr>
<td>4190</td>
<td>0.019</td>
<td>V/PSI</td>
<td>0-250 PSI</td>
</tr>
<tr>
<td>4188</td>
<td>0.00213</td>
<td>V/PSI</td>
<td>0-250 PSI</td>
</tr>
</tbody>
</table>

Six Dytran sensors were installed near the end of the 4-in. diameter shock tube driven section. The atmospheric conditions in the lab were measured and recorded in the shot log before each shot. These initial conditions were used to determine the pre-shock sound speed used to calculate the Mach number.

Various different driver pressures were used for the calibration shots. This provides a wide range of pressures to determine the calibration factors to help insure their accuracy and check for linearity. Eleven calibration shots were performed with overpressures ranging from 26.1 to 65.6 psig (180 to 452 kPa). Due to only having six
sensor positions and eight sensors to calibrate, not all of the sensors received all eleven shots.

The shot number used for the calibration shots are listed in Table 4.3. This table also contains the burst pressures of the membrane for each shot and the corresponding overpressure. The overpressure was determined by using R-H jump equations with the initial conditions and wave speed as inputs.

<table>
<thead>
<tr>
<th>Shot #</th>
<th>Breech P.</th>
<th>Overpressure (PSI)</th>
<th>Breech P (Mpa)</th>
<th>Overpressure (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>413</td>
<td>43.5</td>
<td>2.85</td>
<td>0.30</td>
</tr>
<tr>
<td>52</td>
<td>740</td>
<td>53.9</td>
<td>5.10</td>
<td>0.37</td>
</tr>
<tr>
<td>53</td>
<td>987</td>
<td>59.3</td>
<td>6.81</td>
<td>0.41</td>
</tr>
<tr>
<td>54</td>
<td>1255</td>
<td>62.9</td>
<td>8.66</td>
<td>0.43</td>
</tr>
<tr>
<td>58</td>
<td>141</td>
<td>26.1</td>
<td>0.97</td>
<td>0.18</td>
</tr>
<tr>
<td>59</td>
<td>703</td>
<td>52.9</td>
<td>4.85</td>
<td>0.36</td>
</tr>
<tr>
<td>60</td>
<td>422</td>
<td>43.9</td>
<td>2.91</td>
<td>0.30</td>
</tr>
<tr>
<td>61</td>
<td>547</td>
<td>48.1</td>
<td>3.77</td>
<td>0.33</td>
</tr>
<tr>
<td>62</td>
<td>266</td>
<td>34.8</td>
<td>1.83</td>
<td>0.24</td>
</tr>
<tr>
<td>63</td>
<td>1285</td>
<td>65.6</td>
<td>8.86</td>
<td>0.45</td>
</tr>
<tr>
<td>64</td>
<td>971</td>
<td>60.3</td>
<td>6.70</td>
<td>0.42</td>
</tr>
</tbody>
</table>

The wave speed is determined by dividing the known distance between each sensor by the time it takes to travel this distance. The travel time between each sensor is determined by finding the time at which each sensor reaches half of its maximum value. A visual explanation of this can be seen in Figure 4.33. All calibration shots were performed with a DAQ sampling rate of 1 MHz. Therefore, a time resolution of 1 μsec was realized.

As seen in Figure 4.33 the wave is noisy immediately following the initial jump. The noise is hypothesized to be an artifact of sensor membrane vibration. For this
reason, the first 125 data points are averaged together to obtain the actual voltage output of the sensors. This number of data points was selected because it is the least number of points, which when averaged together, give a smooth flat-topped wave. This was determined by trial and error on many different data sets and sensor signals. It was found that the signal began to drift to a lower voltage if too many points were averaged together. This may be an artifact of the boundary layer growth after the shock wave has passed. It could also be related to the Dytran sensors / signal conditioning time constant.

![Sensors are spaced ~10 in. (25.4 cm) apart at the end of the barrel](image)

**Figure 4.33** Shock wave speed determinations for calibration.

The shock tube was left open-ended but the rarefaction wave from the open end does not reach the forward-most sensors within the time needed to gather 125 data points for averaging. A list of calibration factors determined using this method is given in Table 4.4. A calibration factor was determined for each shot the sensor was exposed to, and then these were averaged together for the final calibration factor used.

The calibration factor vs. overpressure is graphed in Figure 4.34. Conversion from psi to MPa can be achieved by dividing by 145.04 (psi/MPa). If the sensor output relative to pressure is constant, the sensor is considered linear. All the best-fit lines were
found to have a slight slope, the greatest of which is $5 \times 10^{-5}$ from sensor 4189. This would introduce an error of ±7.25 kPa over a range of 0-1000 kPa. This is an acceptable error for these experiments.

Figure 4.34 Calibration factors at various pressures for Dytran 2300V1 sensors determined by R-H jump conditions.

Table 4.4 Averaged calibration factors used to Dytran 2300V1 sensors

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4189</td>
<td>18.2</td>
<td>20.9</td>
<td>1.53</td>
</tr>
<tr>
<td>3988</td>
<td>18.0</td>
<td>20.2</td>
<td>0.19</td>
</tr>
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<td>19.3</td>
<td>18.1</td>
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<td>3987</td>
<td>9.4</td>
<td>19.1</td>
<td>1.17</td>
</tr>
<tr>
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CHAPTER 5

9-IN. SQUARE SHOCK TUBE AND EXPERIMENTS

The second shock tube design was a 9-in. (22.9 cm) square inside dimension tube 20 ft (6.1 m) long. The same breech was retained to test how the shock wave forms while expanding into a larger cross-section. The 9-in. square shock tube is characterized to help future experimenters select settings such as breech length, membrane thickness and reflector plate offset to best replicate the blast wave desired. Information gathered from operation of the 9-in. (22.9 cm) shock tube will be used in the development of a 28 in. square shock tube.

Enlarging the cross-sectional area of the shock tube allows the sample to be placed inside without a major flow restriction. The square cross-section enabled the installation of flat windows, which enable optical surface strain measurement of the sample with high-speed cameras during blast loading. To confirm proper loading of the specimen, experiments were performed to explore the planarity of the shock front and the magnitude of internal reflections.

5.1 SQUARE DRIVEN SECTION

The 9-in. square driven section works on the exact same principles as the 4-in. round shock tube. There are a few key differences that prompted its development. The first is its larger cross-sectional area. This area increase allows for larger samples to be tested inside the tube without significant boundary effects. A suggested guideline, given
by David Ritzel from Dyn-FX Consulting Ltd., is 10% or less of the driven section’s cross-section should be blocked by the test sample (2009).

The square driven section was also developed out of the need for windows. Two high-speed cameras and a program called ARAMIS gives stereoscopic image recording capabilities enabling visualization of surface strain and body motions at very high sampling rates.

A complete model of the installed 9-in. driven section is shown in Figure 5.1. The various key components that are labeled will be discussed in greater detail in the following sections. The 4-in. driven section can be seen hung on the side of the beam in storage. This storage placement enables the barrels to be easily exchanged for different experiments.

![Figure 5.1 Model of 9-in. square driven section installed with 4-in. driven section on storage mounts.](image)

5.2 TRANSITION FROM DRIVER TO DRIVEN SECTION

The same breech was used for both the 4-in. round and the 9-in. square driven section. This enabled the continued use of the same Dura-Lar® membranes for both setups. It also minimized the cost associated with developing a new shock tube. A cross-sectioned view of the circle-to-square transition is presented in Figure 5.2.
The transition is composed of ¼-in. (6.35 mm) thick hot rolled steel. It was brake-formed in two pieces and welded together. It has a 5.9-degree taper from the driver to the driven section. This angle was kept small to minimize turbulence caused by boundary layer separation as the driver is discharged.

The transition is welded to a retainer plate which is held flush to the barrel’s back via four ½-20 socket-head cap screws (SHCS). It is easily removable by taking out the SHCSs and sliding the transition to the end of the barrel.

5.3 TEST SECTION

When exiting the shock tube, the shock wave converts a significant portion of its potential energy (overpressure) into kinetic energy (particle velocity) and the wave front becomes highly non-planar and rapidly evolves with propagation distance. Therefore, the test section was placed in the center of the shock tube barrel as opposed to the end. This ensures the shock wave properties are at a relatively steady state before interaction with the sample. The test section with two windows and one sample mounting insert installed can be seen in Figure 5.3.
Figure 5.3 Test section of the 9-in. square tube centered along the barrel’s 20-ft (6.1 m) length.

The test section of the driven section has three cut-outs. All cut-outs are identical, allowing windows and sample mounting inserts to be interchangeable. Changes in sample mounting and sensor configurations can easily be accommodated by using various mounting holes in the mounting insert or by using a different mounting insert designed specifically for the intended test configuration. Quick clamps are used to hold the window/mounting insert in place. This specialized design enables efficient reconfiguration and low-cost versatility for the test section. The window clamps are designed for high-pressure clamping yet allow for quick removal and installation of windows and test inserts. The clamp bolts can be loosened and the clamping mechanism can be rotated out of the way, allowing the window to be lifted out of place.
5.4 WINDOW DESIGN

The sole purpose of the windows is to allow visualization and measurement of the sample response during a blast event via high-speed cameras. Using a square tube allows the use of flat windows so that the image is not distorted by lensing effects of a curved window, which would be needed for a cylindrical driven section.

A model of one installed and one removed window is shown in Figure 5.4. As seen on the removed window (the top portion of the figure), the window material protrudes below the window frame 0.460 in. (11.7mm). This places the window surface flush with the inner wall of the tube to minimize its disturbances to the shock wave. Angle iron was welded to the top surface of the window frame to stiffen the assembly. The window is glued into the frame to prevent it from being sucked into the tube during the period(s) of underpressure. It is supported around the entire edge by a 3/8-in. (9.5 mm) wide surface to distribute the pressure load from the shock overpressure. An o-ring groove is provided on the mating surface between the window frame and the tube to ensure good sealing when clamped in place.

Four different windows were made for this shock tube. Two of them were made of ¾-in. (19.0 mm) thick polycarbonate and two from glass laminated with a thin piece of polycarbonate in the center. The glass was received as a laminated blank from The Glass Edge, of Lincoln, NE and water jet cut to size by Stone Enterprises, of Omaha, NE. The glass provides a less distorted image due to its lower refractive index and higher modulus of elasticity. The polycarbonate windows were made in case the glass windows experienced issues with fracture.
Special care should be taken when handling the glass windows so the corners are not chipped. The polycarbonate windows are susceptible to scratching so cleaning should always be performed by spraying a liquid cleaner on the surface before wiping with an abrasive free cloth.

5.5 ADJUSTABLE END REFLECTOR

When a shock wave reaches the open end of the shock tube, a jet of air is released with high velocity and low pressure (Haselbacher et al., 2007). The state change also sends a rarefaction wave back into the shock tube which interacts with the rarefaction from the back wall of the breech. This interaction can cause an exaggerated amplitude and duration of underpressure (pressure below atmospheric). This does not accurately simulate the desired loading conditions and is harmful for animal model testing because excessive underpressure may subject an animal sample to an increased risk of unrelated cavitation injuries.
Reducing this problem was approached with a mechanism referred to as the reflector plate. This component can be seen installed on the end of the 9-in. square barrel in Figure 5.5. The primary purpose for the reflector plate is to shape the negative portion of the shock wave to behave similar to a Friedlander wave. The gap between the end of the barrel and the reflector plate can be adjusted with the four threaded adjustment rods at the corners. This allows the operator to finely tune the proper amount of reflection back into the tube.

![Figure 5.5 9-in. square shock tube with reflector plate assembly installed.](image)

For applications where the shock tube is being used to produce blast waves to validate Finite Element (FE) models, the extended negative phase of the shock wave is not critical. This is due to most of the material being used to validate FE models that will be affected very little by a vacuum. But if the shock tube is being used to study the effects of blast waves on animals, the negative portion becomes critical. The effect of a sudden, large vacuum on an animal is thought to be detrimental to their health and is an
inaccurate replication of a Friedlander wave. Figure 3.18 shows the pressure history measured at the shock tube wall near the test section with and without the reflector plate.

![Graph showing pressure history with and without reflector plate](image)

**Figure 5.6** Test section pressure history with (gray) and without (black) reflector plate N\(_2\) driven.

The pressure traces in black show the pressure history without the reflector plate installed. The shock wave is allowed to exit the barrel uninhibited. The first rapid pressure drop indicates the arrival of a rarefaction wave from the back wall of the breech. The next pressure drop is seen at approximately 18k μsec indicates the arrival of the rarefaction wave from the open end of the shock tube. As seen from the black pressure trace in Figure 5.6, the rarefaction from the open barrel end can be replaced by a relatively small shock wave from the reflector plate. The amplitude of this small
reflected shock wave can be adjusted by moving the reflector plate closer or farther from the open end of the driven section.

5.6 CONFIGURATION OF SENSOR ARRANGEMENT

Sensor inserts were purchased to simplify the mounting holes needed for installation of sensors in the shock tube wall. Mounting holes with 3/8-24 threads, 0.310 in. (7.87 mm) deep are needed for proper mounting. They are placed in approximately 20-in. (508 mm) increments centered along the shock tube wall. Measurements between the sensor holes along the length of the tube are provided in Figure 5.7. These measurements were made using 60-in. Vernier calipers.

![Sensor Placement Along 9\" Square Tube Wall](image)

**Figure 5.7** Sensor layout along the 9-in. square shock tube barrel measurements given in in. and [mm].

Each sensor location along the driven section is labeled, allowing the exact sensor serial number to be matched with the sensor location for documentation purposes. Sensor locations labeled with “T” are in the shock tube driven section wall. This information is tracked by the data acquisition program. Also, a unique calibration factor for each sensor
is matched to its location. All information about the sensors is noted in the header of each data set.

Putting sensors along the barrel length enabled the shock tube to be tuned for accurate blast simulation. Ideally, the shock wave is formed such that the rarefaction wave from the back wall of the breech reaches the shock front just as it passes the test section. If the rarefaction is too late, a flat-topped wave passes though the test section and if it is premature, the shock front amplitude is eroded, resulting in a less efficient experiment.

Unused sensor holes can be plugged with 3/8-24 socket-head cap screws. These screws were purchased over-length and ground to the appropriate length and installed in unused sensor holes to minimize the leaking and the perturbation of the seal screws to the shock wave. Various sensor arrays can be configured in the test section also. The plate of the sample mounting insert can be custom made with the desired sensor configuration. Two test inserts are currently in use. Figure 5.8 shows one of the sample mounting inserts used for the test section.

Figure 5.8 Top view of sensor installed on the 9-in. square shock tube and the test insert A.
5.7 SHOCK TUBE TUNING FOR BLAST WAVE SIMULATION

As a shock wave propagates away from the epicenter of an explosion, its form and characteristics change. Not only does its amplitude decrease as a function of distance, but the duration of the overpressure increases also. To accurately simulate the shock wave at different distances, various adjustments can be made to the shock tube.

The adjustable variables include membrane thickness, membrane quantity, driver (breech) length and reflector plate configuration. Membrane thickness correlates directly with the burst pressure, which partially dictates the overpressure experienced in the test section. The driver length will be experimentally correlated with the overpressure amplitude in the 9-in. square shock tube. Finally, the reflector plate’s ability to shape the negative portion of the shock wave will be demonstrated and quantified.

5.7.1 Burst Pressure Correlation to Peak Overpressure

The peak overpressure in the test section is highly dependent on three variables. Membrane burst pressure is the most influential of all the variables. The second variable is breech length. The peak overpressure seen in the test section can be decreased by an extremely short breech. The third variable of great importance is the type of driver gas. In general, a gas with a lower average molecular weight will generate a higher peak overpressure.

If the breech is extremely short, the rarefaction wave will reflect off the breech insert and catch up to the wave front before it arrives at the test section. This is indicated by a Friedlander-form wave. Once the rarefaction wave catches the shock wave front, the
peak overpressure is gradually decreased until it is only noise. Breech length effects will be covered in greater detail in Section 5.7.2.

Membrane burst pressure has a positive correlation to peak overpressure, meaning that an increase in burst pressure causes an increase in overpressure. The relation between burst pressure and overpressure changes with the different driven sections. The correlation of burst pressure vs. overpressure using the 4-in. (10.16 cm) inside diameter driver with the 4-in. (10.16 cm) inside diameter driven section can be seen in Figure 5.9. The overpressure measurements were made on the driver section wall near the open end. They were determined using R-H jump conditions for calibration of the Dytran 2300V1 sensors.

The tests were performed with a 35.625-in. (90.5 cm) long breech. The wave generated had a long duration of flat-topped profile. This gives the wave a large steady-state overpressure to measure. All tests were performed with nitrogen as a driving gas. This is a low-cost gas with similar properties to air, making it less important to evacuate the barrel after each shot.

If higher overpressures are needed, a lower atomic mass gas should be used, such as helium. This gas is considerably more expensive and care should be taken to evacuate the barrel between shots to ensure known initial conditions. The speed of sound is approximately 3 times greater in helium compared to nitrogen. Therefore, a longer breech will be needed to obtain a flat-topped wave. Care should also be practiced when doing animal tests, not to asphyxiate the animal due to oxygen displacement with the driver gas. After a shot has been fired, animals should be removed immediately to limit
the effects of oxygen deprivation. This would introduce an uncontrolled variable that may affect the test results.

Burst pressure can be related to the overpressure near the end of the 4-in. shock tube with the graph in Figure 5.9. A logarithmic trend line was curve fit to the points on the graph in. The equation for this line can be used to estimate the overpressure that will be observed for a given burst pressure. This can be useful when determining the number of membranes needed for a particular test. The relation is given in Equation 5.1 if the overpressure wanted is known and the burst pressure can be calculated to determine the number of membranes needed.

All pressures used should be in MPa. This empirically derived relation should only be used for the 4-in. breech with the 4-in. barrel using a sufficiently long breech to prevent peak overpressure decay due to rarefaction. This equation is also limited to nitrogen-driven shock waves. Temperature and atmospheric pressure have very small effects on overpressure. Since the shock tube is in a controlled-temperature environment and atmospheric pressure fluctuates little, these variables are not taken into account.

\[ y = 0.1233 \ln(x) + 0.1732 \]

\[ R^2 = 0.994 \]

Figure 5.9 Burst pressure related to overpressure near the end of the 4-in. shock tube barrel derived with flat-topped shock waves.
The 9-in. (22.9 cm) square shock tube has a completely different relation between the burst pressure and the overpressure observed in the test section. This relation can be seen plotted in Figure 5.10. The cross-sectional area of the driven section is approximately 6.45 times larger than the driver. The different curve is due to the extra adiabatic expansion experienced by the shock wave as it travels through the transition section into the larger driven section. This relation is only valid for nitrogen as a driver gas. Higher overpressures with shorter durations can be obtained using helium.

\[
\text{Burst Pressure} = e^{\frac{(\text{Overpressure} - 0.1732)}{0.1233}}
\]  

(5.1)

**Figure 5.10** Burst pressure relation to overpressure in test section of 9-in. shock tube with 4-in. driver derived with flat-topped shock waves

### 5.7.2 Breech Length Tuning

The breech length determines when the rarefaction wave catches up to the shock wave front. As shown in the x-t diagram depicted in Figure 3.4, after the membrane bursts the rarefaction wave travels back into the breech. Once it encounters the breech
core, the wave is reflected and travels in the same direction as the shock front. The rarefaction travels faster than the shock front because it is propagating through a denser medium with a net particle velocity in the same direction.

A cross-sectional view of the breech can be seen in Figure 5.11. Segments can be threaded onto the breech core to adjust the internal length of the breech. The breech plug must be removed to perform this operation.

![Figure 5.11 Cross-sectional view of the breech insert used to adjust the length.](image)

The burst pressure also affects the rate at which the rarefaction wave catches up to the shock front. Higher burst pressures increase the speed at which the rarefaction travels relative to the shock front. The effect of burst pressure on wave-form is not as significant as breech length but still noteworthy.

The apex of the shock pressure form is shaped by the breech length / burst pressure. A shock wave appearing to have a flat-top means the rarefaction wave has not caught the shock front. The flat-top duration of the shock wave is determined by finding the peak overpressure near the shock front and then determining the time it takes to decay.
to 95% of this initial value. The time measurement is called the flat-top duration of the shock wave. The average overpressure is then determined by averaging the first 75% of the flat-top duration points together. A reduced number of points are used because a sensor phenomenon artificially reduces the pressure reading.

The flat-top duration relative to burst pressure can be seen in Figure 5.12. The breech length was held constant at 11.625 in. (29.53 cm) while various burst pressures were used. A trend can be observed from 0-6 MPa but at some point between 6-8 MPa this trend breaks down, showing severe deviation. One hypothesis is that the contact surface is reaching the test section at these higher pressures. Another hypothesis could be that the transient waves created by expansion through the transition could still be present in the shock wave front at higher pressures.

![Figure 5.12](image)

Figure 5.12 Flat-top duration as a function of burst pressure: 11.625-in. (29.53 cm) breech length.
Figure 5.13 shows the pressure histories at various points along the barrel. Shot 141 was performed with a 29.52-cm breech. This breech length is sufficiently long to create a flat-topped wave in the test section. Most of the sensors are spaced on approximately 20-in. (50.8 cm) centers along the axis of the shock tube, flush with the inner surface. The pressure traces with flat-tops near the center of the graph are from two PCB sensors placed flush with the wall at the center of the test section. The PCB sensors tend to show lower susceptibility to noise caused by sensor dynamics. They do not overreact to the initial shock jump as seen with Dytran 2300V1 sensor signals. The two PCB pressure traces registered the shock front at approximately 9k µsec in Figure 5.13. All other traces are from Dytran sensors.

The wave evolves from a square shaped pressure pulse with a sharp rise and fall into a characteristic Friedlander shock wave can be observed in Figure 5.14. Also observable are the variations in the preak overpressure readings. This could be due to turbulence in the gas following the shock front.
As mentioned before, the peak overpressure is gradually reduced over a distance once the rarefaction wave catches the shock front. The graph in Figure 5.14 depicts this accurately. As before, the sensors were placed along the length of the shock tube barrel wall. The distance of each sensor from the test section is given in the graph’s legend.

![Figure 5.14 Overpressure drop as a function of distance from the test section due to rarefaction wave catching the shock front: 9.625-in. (24.45 cm) breech length – shot 143.](image)

Experiments were performed to determine the role of breech length in formation of the flat-top durations. Three different breech lengths were used with various different burst pressures. The flat-top duration of the wave was determined with the method described earlier. The duration as a function of breech length and burst pressure can be seen in Figure 5.15 Flat-top shock wave duration as a function of burst pressure and breech length. The breech lengths used for each data set can be found in the legend on the right.
As seen in Figure 5.15, the breech length has a dominant effect on the flat-top duration of a wave. The ideal shock wave experienced in the test section would become sharp just as it arrives. A flat-top duration of 250 µsec or less can be considered sharp using the measurement and analysis methodology described herein. It appears that the ideal breech length for burst pressures of 580 psi (4 MPa) or less is around 8.6-9.6-in. (21.9-24.4cm).

![Figure 5.15](image.png)

Figure 5.15 Flat-top shock wave duration as a function of burst pressure and breech length.

### 5.7.3 Adjustable Reflector Configuration

The current reflector plate configuration is a crude prototype used to test the hypothesis that the shock wave rarefaction tail could be shaped by adjusting the boundary condition near the end of the shock tube. A cross-section of the shock tube muzzle with the reflector plate installed can be seen in Figure 5.16. In this image, the initial shock wave will be traveling from right to left.
The reflector plate is held in place by four 3/4 – 10 all-thread rods. These enable infinitely variable adjustments to the reflector plate gap. The smaller the gap, the more back pressure is created when the wave hits the plate. An additional shock jump is created and sent back towards the test section.

Figure 5.16 Cross-section of driven section end with reflector plate installed.

If the reflector plate gap is too large, it behaves similar to an open-end test where a rarefaction wave is sent back to the test section. This rarefaction wave loads the test sample differently than it would be loaded in a free-field blast situation. A comparison between an open-ended shock tube versus the reflector plate with a 2-in. (5.08 cm) gap can be seen in Figure 5.17.

This test was performed with a 17.625-in. (44.8 cm) long breech, nitrogen driver gas and two 10-mil Dura-Lar® membranes. Two tests were performed with the same setup except for the end effects and then superimposed on the same graph. The
repeatability of the shot overpressure is exceptional. The data were sampled at 1 MHz with no filtering applied.

The reflector plate offers a trade-off of a small jump increase in overpressure as opposed to a severe drop in pressure. This small jump found at approximately 18k µsec in Figure 5.17 theoretically could be corrected by simple geometric modifications to the reflector plate. A surface oblique to the shock wave’s direction of travel would be less likely to generate a reflected shock sent back into the test section. It would theoretically still providing enough back pressure to prevent the severe negative portion of the wave characteristic of open-ended shock tubes.
The graphs depicted in Figure 5.18 demonstrate the effects of varying the reflector plate gap. The same setup was used to fire similar pressure shots while only varying the reflector plate end gap. The upper graph shows the long term pressure history of these shots while the lower graph zooms in on the portion affected by the reflector plate.

Figure 5.18 Upper: Overall pressure history of 4 different end configurations. Lower: Magnified portion of the pressure history related to end effects.
Lower-pressure shots were also performed to look at how the reflector plate gap would interact. The same pressure shots were performed while incrementing the gap with 1.27-cm increments from 0.5-4 in. (1.27-10.16 cm). The pressure history was measured on the wall of the test section near the center.

![Graph of pressure vs. time for different reflector gaps](image)

**Figure 5.19** Low-pressure reflector plate gap variation comparisons.

One dominating feature of the graph in Figure 5.19, not found on the higher-pressure shots, is at 10k µsec. It can be deduced from the order in which each sensor is affected along the barrel (data not presented), that this wave is traveling from the breech to the end of the shock tube. It is most likely a reflected shock from the breech. This reflection is not as significant in higher-pressure shots. The secondary shock wave is less than one-fourth the size of the primary. For low-pressure experiments, a conical breech insert may be considered to reduce the affects of this secondary shock.
5.8 EXPERIMENTS WITH 9-IN. SHOCK TUBE CONFIGURATIONS AND RESULTS

Due to the majority of the research time being spent on development of the blast wave generation facility and characterization of the shock tube, very little time was dedicated to experiments. Two tests were designed and performed to answer fundamental questions about the shock tube and its performance. The first question is: Is the shock wave truly planar after expanding through the transition from a 4-in. round breech to a 9-in. square tube? Non-uniformity in the shock wave would create complications in future experiments and attempted simulations. Planarity is also important to ensure 1-D shock theory is applicable. The other question is: How do experiments inside the shock tube load the sample differently than free-field blast loading? If internal reflections occur, what is their relative magnitude to the original loading and would it be significant in animal testing?

5.8.1 Testing Planarity of Generated Shock Waves

A shock wave traveling through a constant cross-section will reach equilibrium in a planar form normal to the direction of travel (Gaydon et al., 1963). Planarity of the shock wave could be reduced by two different factors. The first is transient waves generated from expansion through the transition into a constant cross-sectional area tube. The inflection point at the end of the transition is thought to introduce transient waves. The second possibility is boundary layer effects because air is not a completely non-viscous fluid, as assumed in ideal gas theory; friction along the walls may create issues.
To experimentally test the planarity of the shock wave in the test section the configuration depicted in Figure 5.20 was used. A ridged, cylindrical, aluminum sample was bolted into the test section. Sensors were mounted in the cylinder with the pressure sensing surface flush with the outer diameter oriented with the diaphragms pointing toward the driving section. The sensors were placed at various distances from the shock tube wall.

Geometry of the sample was not considered critical because the initial rise in sensor voltage was the only data used for these experiments. The placement of the sensor array perpendicular to the shock tube wall was checked with a square before tests were performed. Special care was also taken to ensure the cylinder was rotated and fixed in position with the sensor membranes perpendicular to the other shock tube wall.
A sample of the data collected from shot 112 is shown in Table 5.1. The arrival time of the wave is the first point at which the sensor voltage rises above ambient noise levels. These points are highlighted in yellow. A sampling rate of 2.5 MHz was used for all planarity tests. This is the maximum rate at which the data acquisition system can operate.

**Table 5.1** Sample data for determining wave arrival times shown in shaded cells

<table>
<thead>
<tr>
<th>Sensor #</th>
<th>Distance from center (cm)</th>
<th>Data point number</th>
</tr>
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<tbody>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>4189</td>
<td>10.89</td>
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</tr>
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<td>12515</td>
</tr>
<tr>
<td>4130</td>
<td>8.10</td>
<td>12516</td>
</tr>
<tr>
<td>4188</td>
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</tr>
</tbody>
</table>

For each shot performed, the arrival time was determined by observing the voltage rise of sensor outputs. Multiple shots were executed with burst pressures varying between .57 and 4.55 MPa. By using an additional sensor upstream from the aluminum cylinder, the wave speed was determined. The wave speed divided by the sampling rate gives the spatial resolution of the system. This resolution depended on the shock strength (due to variation in shock speed), but on average is ~0.2 mm.
The sensors were mounted inside inserts purchased from the sensor manufacturer. Variation in sensor length and insert dimensions put the sensor membranes on slightly different planes. Measurements with a depth micrometer indicated that sensor mounting variations were ±0.10 mm. This variation was inherent to the setup and therefore unavoidable. Along with a measurement uncertainty of ±0.10 mm due to digital time resolution, the best certainty obtainable is ±0.2 mm.

This uncertainty may seem large since the points in Figure 5.21 are very close together. To put it in perspective, the thickness of a sheet of paper is a little less than 0.1 mm. An uncertainty of ±0.2 mm is equivalent to the thickness of 4 sheets of paper.

![Figure 5.21 Planarity of the shock wave inside the test section at various pressures.](image)

The setup remained the same throughout all of the tests graphed in Figure 5.21. Imagine the two-dimensional center of the barrel is at zero on the Y-axis and 11.4 cm on the X-axis. The Y-axis is parallel to the shock wave velocity vector. The barrel wall is
represented by zero on the X-axis. The initial jump of the sensor closest to center was considered to be the absolute time of wave arrival. This is why all out of plane measurements are zero at 11 cm from the side wall.

The shock waves were observed to have very small deviations from planar form as seen from Figure 5.21. The greatest of these was 0.6 mm. Considering the uncertainty in this experiment these deviations are within an acceptable limit for IED blast wave simulation. The sample will typically be centered in the tube where the wave appears to deviate very little from planner. The effect of boundary conditions on side wall pressure measurements was not explored in this experiment and may need to be considered in the future.

5.8.2 Internal Reflected Shock Waves

When the sample is placed inside of the test chamber it will naturally interact with the wave during the wave test. The sample will partially reflect the shock wave in various different directions. In an open-field blast, these reflected waves travel off into infinity without significantly reloading the sample. But, since the sample will be inside the shock tube, there are boundaries that can reflect the shock wave back to the sample, loading it multiple times.

To better understand the characteristics of this re-loading, the same cylindrical aluminum sensor mount described in Section 5.8.1 was used. The photograph of the cylinder with sensors mounted is shown in Figure 5.22. An additional sensor is mounted directly beside the aluminum cylinder in the side wall. The sensor is not pictured because it was mounted in the test plate which was removed for this photograph.
Figure 5.22 Aluminum cylinder mounted inside the shock tube with pressure sensing surfaces facing the driving section; 0 degrees.

The signal wires are protruding out of the cylinder to the left and the pressure sensing surfaces are on the right surface of the cylinder. The aluminum cylinder was subjected to multiple shots at the same pressure with the sensors directed at various angles rotated about its axis.

The cylinder orientation shown in Figure 5.22 would be considered the 0-degree direction. The pressure sensing surface of the sensors are facing opposite the direction of shock wave propagation. In this orientation, the sensors would measure the reflected pressure. In the pressure history plots given in Figure 5.23, the sensor angle is given in degrees of rotation from this original orientation of pure reflected pressure measurement.
Figure 5.23 Pressure history with different internal sensor orientations.

The graphs were produced from shots 106-108. The pressure sensor readings from the shock tube wall surface are plotted as the grey line in the graphs above. These should be identical in each of the three graphs. The peak overpressures appear to be very close to identical. The initial step in the pressure trace is the incident overpressure associated with the shock wave. The second jump is the shock wave reflected pressure off of the aluminum cylinder to the sidewall.

The pressure history with the sensors facing the side wall (90 degrees) shows a distinct reloading of the sample by the reflected pressure pulse. The pressure reflected from the cylinder can be seen in the second jump in pressure measured on the side wall at approximately 1k µsec. The pressure is then reflected back from the wall to the sensors in the cylinder, which exhibit another jump in pressure at approximately 1,200 µsec.
After the cylinder is reloaded twice, the reflection amplitudes become insignificant relative to the sensor noise.

The reflection effects are greatest at 90 degrees with the reflected peak pressure reaching approximately 30 percent of the initial pressure measured on the cylinder surface. The internal reflections may introduce some error when blast loading animal specimens. The smaller and more pliable the sample relative to the shock tube cross-sectional size, the less reflected reloading the sample will experience. Also, an increase in shock tube size would greatly reduce the effects of reflections. Possible geometric or material changes could be made to the shock tube walls to reduce the amount of reflected pressure experienced by the internal sample.
CHAPTER 6

CONCLUDING REMARKS

6.1. CONCLUSIONS

A better understanding of the interaction of explosive-generated blast wave with human head is needed in both the military and civilian world. This understanding is imperative to the development of protective gear for the prevention of bTBI. A novel shock wave generation facility has been created specifically for laboratory scale simulation of blast waves. A 4-in. cylindrical shock tube and a 9-in. square shock tube have been developed along with a hosting laboratory and supporting systems. This facility provides an essential test bed for bTBI-related experimental studies, protective gear evaluation, and theory/model validations.

The typical profile of explosive-induced shock waves in open field can be represented by the Friedlander wave form. Therefore, the shock tubes were designed with tunable features to enable this unique wave form to be accurately and repeatedly produced. The design features and operation of the shock tubes have been described. Tests have been performed to validate the designs and to characterize the shock waves generated by the two devices.

The results of the experiments performed with the 4-in. cylindrical shock tube demonstrated that the membrane-burst technique used can consistently generate air shock waves with sub-microsecond rise times. It was found for Dura-Lar® membrane material that desired burst can be achieved with membrane(s) 10 mil or thinner. It was further
observed that the burst pressure depends linearly on the number of sheets used. Formulas
relating the membrane burst pressure to the overpressure near the end of tube were
derived by fitting the experimental data. The shock front propagation speed and
amplitude were found to agree exceptionally well with the one-dimensional shock wave
theory for ideal gas even at the tube wall. This indicates a planar wave front in the shock
tube and, more importantly, in conjunction with the shock wave theory, experiments with
this device can be used to calibrate pressure sensors. Sensor calibration is essential to
accurately measure the loading condition experienced by samples in the shock tube.
Calibration experiments with the 4-in. shock tube were carried out for the Dytran 2300V1
sensors used in this work. Their calibration factors were determined with an accuracy of
±5%.

It is understood that the shock wave diverges and changes its profile rapidly once
it exits an open ended shock tube. Therefore, for well defined and controlled loading
conditions it is desirable to place a sample inside a shock tube. For this reason, a unique
9-in. square shock tube was designed with the test section inside of the shock tube barrel.
This shock tube incorporated various adjustable features for tuning important
characteristics of the shock wave. A unique adjustable breech was used to control when
the rarefaction wave approaching from the breech catches the shock front. The breech
design used, enables fine breech length adjustments in 1-in. increment, which is
necessary for the desired wave profile shaping. An adjustable reflector plate was utilized
on an open-end shock tube, for the first time, to mitigate excessive underpressure
developed by the rarefaction wave approaching from the shock tube end. This shapes the
underpressure profile to possess desired characteristics. It effectively enables a finite
length shock tube to behave as if it was infinitely long. This is critical for replicating a free-field blast wave.

Systematic experiments with the 9-in. square shock tube were performed first to determine the correlation between the membrane burst pressure and the maximum overpressure in the test section. A formula relating these two variables was derived experimentally. This enables an estimation of the number of membranes needed for a desired overpressure. Next, the dependence of overpressure pulse duration on the breech length and the evolution of wave profile with propagation distance were studied experimentally for various burst pressures. The results were used to optimize the profile of shock wave as it enters the test section. It was demonstrated for the first time that the profile of air shock wave generated by a shock tube can be shaped to closely mimic that of a Friedlander wave form.

The 9-in. shock tube test section was integrated with windows for high-speed digital imaging of the sample during loading. Its square cross section enabled the use of flat windows to reduce lensing effects associated with curved windows. The test section design also offers versatility in sample and sensor mounting as well as easy access to this section.

The concerns about non-planar shock fronts due to the presence of transient waves created by the transition section needed to expand from a 4-in. driver to a 9-in. square driven section were explored. A 1.625-in. (4.13 cm) cylindrical sensor column, which fits between the tube walls and hosts pressure sensors evenly spaced from the tube center out to near the wall, aligned and secured flush with the column surface, and
oriented to face the direction of wave propagation, was utilized in the study. The planarity of the shock front was examined by comparing its arrival times at these sensors. It was found that the deviation from planarity was less than 0.6 mm with an uncertainty of ±0.2 mm associated with sensor placement and sampling rate. This indicates that the front of shock wave generated by the 9-in. square tube is sufficiently planar for the blast wave experiments of interest.

The effects of internal reflections (the waves diffracted from a sample and then reflected from the shock tube walls) were also studied with the same sensor column with the pressure sensing surfaces oriented in various directions away from that of wave propagation. The reflections were found to be noticeable only in small regions facing the tube walls. Furthermore, the magnitude of this secondary loading was found to be insignificant compared with that of the primary loading associated with the passage of the shock wave over the sample. The 9-in. square shock device appears to be an adequate device for samples of 2 in. or less in characteristic dimension.

The unique design features incorporated into the shock wave generation facility make it a world class blast wave research laboratory. Well-controlled blast wave experiments with accurate, repeatable and measureable loading conditions are essential for helping to understand how explosive-induced blast waves are affecting soldiers. The laboratory will be used for investigations of physical and biological mechanisms of bTBI and validations of bTBI-related theories and model simulations. Ultimately it will be used in the development and testing of protective gear for soldiers to mitigate the prevalence of bTBI in the near future.
6.2. RECOMMENDED FUTURE STUDIES

As with any research, there are more questions than answers. There are a few areas of particular importance that attention should be directed towards in the near future. These areas are already the general direction in which this research is headed even if it is not specifically mentioned.

6.2.1 Shock Tube Characterization with Helium

The 4-in. and 9-in. shock tubes have been characterized using nitrogen. This is an inexpensive driver gas which can be used to generate lower peak overpressures for simulating far-field blast waves. Using nitrogen as the driving gas limits the peak overpressure obtainable with this set-up and gives relatively long positive pressure durations in the test section. If higher overpressures and shorter durations are desired, the shock tube should be characterized using gas with a lower molecular weight, e.g. helium. The speed-of-sound in helium is over three times faster than nitrogen, enabling it to expand much faster after membrane rupture. This gives the shock wave shorter positive duration with a greater peak overpressure. This is more representative of a near-field blast shock wave.

6.2.2 More Refined End Effects

The current reflector plate configuration was a proof of concept in shaping the negative portion of the shock wave. A negative artifact of using the reflector plate is the second shock wave experienced in the test section. If modifications were made to the reflector plate, such that a less planar surface is presented to the shock front, the second
shock may become less significant. Accurate pressure history during the negative phase of the shock wave may prove crucial for animal studies due to the possibility of cavitation in the brain.

6.2.3 Catch Tank

Shock wave generation by its very nature is an event involving high noise and rapid energy release. Ideally, the noise generated during experiments would be reduced to an acceptable level where patrons in nearby labs would not become frightened. A catch tank should be developed that assists in reducing the noise and containing some of the energy associated with blast simulation. The catch tank will have to be easily removable for adjustments of the reflector plate. It would ideally be large enough to allow the gas to expand sufficiently so there is little back pressure experienced in the test section. Also, the catch tank would have to be securely fastened to the floor or shock tube to prevent its acceleration during dynamic loading.

6.2.4 28-in. Tube Development

The 9-in. square tube is of sufficient size for testing of small samples such as rats. As observed in the internal reflection tests, the small size creates limitations on sample size if multiple internal reflections are not desired. Development of a 28-in. shock tube would decrease the effects of internal reflections on small samples and enable the possibility of testing larger samples in the future. The increase in size will reinforce the need for the aforementioned catch tank.
6.2.5 Sensor Selection

Many limitations have been observed with the current sensors being used in the blast lab. The Dytran 2300V1 sensors have proven to be time-consuming to calibrate because of their large variations from the factory calibrations. They are also too large for typical pressure measurements inside of the shock tube. Their presence will disrupt the shock waveform.

The PCB 134A24 sensors have proven to have acceptable factory calibration factors with an excellent signal-to-noise ratio. But they are extremely expensive and even larger than the Dytran sensors.

The FISO sensors not previously mentioned are small in size and have been used extensively in previous shock tube / animal studies. They have given non-repeatable results in experiments comparing them with the results from PCB sensors as a reference.

More research needs to be performed in finding sensors that are small, reliable and repeatable. This may be the impossible task, but the situation must be given more attention since accurate measurements are one of the keystones of any experiment.

6.2.6 Blast Induced Traumatic Brain Injury Research in General

The shock tube facility has been developed for the sole purpose of helping the army prevent bTBI in soldiers. Now that the groundwork has been completed, experiments need to be designed and performed to help understand various aspects of the blast wave interaction with the human head. Simplified geometric samples can be used to help validate FEA models. Animal models can be used in this shock facility to help
understand the pathology of mTBI in living tissue. Cadavers could be used to understand how the shock wave propagates through the skull into the human head.

There is a great deal of work to be done and a noble cause to support.
REFERENCES


