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## ABSTRACT

# EFFECT OF ENDPLATE ON THE BLAST WAVE PROFILE IN A COMPRESSED GAS SHOCK TUBE

# by Sudeepto Kahali

Blast related brain injuries are commonly encountered in the recent wars of Iraq and Afghanistan increased use of improvised explosive devices (IEDs). An estimated 20% of veterans returning from these operations have suffered traumatic brain injuries (TBI). The mechanisms and long-term effects of the injury are not fully understood, and extensive research effort is being focused toward identifying the mechanisms of primary blast injury. When a pure shock-blast wave encounters a subject, in the absence of shrapnel, casing or gaseous products, the loading is termed as primary blast loading, and its effects can be studied using shock tubes.

The wave profile of the shock-blast wave produced by the shock tube is characterized by blast overpressure, positive time duration, and impulse. Evolution of the blast wave profiles along the length of the compression driven gas shock tube is studied using experiments and numerical simulations. It is important to identify Shock-blast wave parameters (SWPs), and understand the relationships between the shock tube adjustable parameters (SAPs) and SWPs, in order to control blast wave profiles.

In this thesis work, the position of the end plate is the SAP that is specifically studied. Since the shock tube has an open-ended configuration, in order to contain the shock-blast wave and obtain an acceptable Friedlander curve, an endplate was attached to the open end, as a design concept. It was found that the endplate to shock tube end distance affected the shock wave profile. In this research work, the endplate distances were varied and the evolution of shock profile was measured. It was found that at 4 inches distance from the open end, in the current configuration of the shock tube, the desired Friedlander curve was achieved. At other distances, secondary reflection effects were noticed.

# EFFECT OF ENDPLATE ON THE BLAST WAVE PROFILE IN A COMPRESSED GAS SHOCK TUBE

by Sudeepto Kahali

A Dissertation Submitted to the Faculty of New Jersey Institute of Technology in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

**Department of Mechanical and Industrial Engineering** 

August 2015

# APPROVAL PAGE

# EFFECT OF ENDPLATE ON THE BLAST WAVE PROFILE IN A COMPRESSED GAS SHOCK TUBE

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Dedicated to my younger brother.

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#### **CHAPTER 1**

# **INTRODUCTION**

## 1.1 Background

Traumatic brain injury (TBI) has emerged as the signature injury of the wars in Afghanistan and Iraq. Blast-related injury was the most common cause, with improvised explosive devices (IEDs) being the major source of the blast injuries (1). Explosive capacities of common IEDs are shown in Table 1.1. In a study conducted by the RAND Corporation, it was estimated that 320,000 service members, or 19.5% of the deployed force (total 1.64 million) potentially suffer from TBI (including primary, secondary, tertiary and quaternary injuries) (2). Most of these injuries are categorized as uncomplicated "mild" or "concussive" traumatic brain injury based on clinical criteria and the absence of the intracranial abnormalities on the computed topography (CT) or conventional magnetic resonance imaging (MRI) (3). Mild TBI (mTBI) as defined by the American Congress of Rehabilitation Medicine is a head injury resulting in at least one of: loss of consciousness for at most 30 minutes; post-traumatic amnesia for less than 24 hours; any alteration in the mental state immediately following the incident; or focal neurological deficit(s) that may or may not be transient (4).

However, little is known about the nature of these "mild" injuries, and the relationship between traumatic brain injury and outcomes remain controversial (5). This points to one of the limitations to the current state of blast-induced TBI i.e., the scarcity of information on the pathophysiology of blast-induced neurotrauma (6). This has led to

an increase in research toward the understanding of the mechanism of primary blast injury. Blast wave transmission through cranium, thoracic pressure surge, skull deflection and cavitation are suggested to be the major mechanisms of blast injury (7-10). Fieldtesting and shock tubes are the main methods used in blast injury research. While fieldtesting would be the closest to real world blast conditions, there are some key drawbacks: (i) expensive and unsafe; (ii) time consuming; (iii) repeatability with similar environmental conditions is difficult to achieve (11). A review article on the recent major studies in primary blast injury shows that, out of 49 cases, only 8 used field testing. Among the 36 shock tube users, 33 were using compressed gas shock tubes (12).

Threat	Explosive Capacity	Reference
	(TNT equivalent in kg)	
Pipe Bomb	2.26	(19)
(IED)		
Suicide Bomber	9	
Briefcase Bomb	22.70	
AP fragmentation device	0.55	(20)
AV blast landmine	6-10	

Table 1.1	Explosive	Capacities	of IEDs.
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#### **1.2 Characteristics of Field Explosion**

In the case of an idealized mid-air explosion, the gas products and the fireball expand in a spherical manner and compress the surrounding air. This expanding air continues to increase in velocity at the outer edge and at certain point; the velocity of the envelope just equals the velocity of sound, i.e., M = 1. When this happens, a shock front is formed. The shock front is extremely small of the order a few molecular diameter in width. Across this front, there is a sudden change of pressure from atmospheric of the undisturbed medium to a high pressure. There is a sudden change in pressure, velocity, density across this narrow thickness. Behind the shock front, there is the blast wind where the particles move at very high velocities. This shock front-blast wind continues to expand outwards. However, since the expanding gas occupies an increasing volume (spherical radius r), the shock velocity slowly reduces and eventually becomes the same as the sonic velocity of the medium at which point shock wave dies leaving behind a low velocity blast wind. The strength of the shock wave is measured in terms of over-pressure, termed as blast over-pressure (BOP).

BOP for air shocks can be expressed as:

$$BOP = \frac{7(M^2 - 1)}{6} \text{ bars} \tag{1.1}$$

where, M is the Mach number. In order to simulate a blast wave, it is essential to establish shock wave parameters (SWPs) that can be measured and controlled.



**Figure 1.1** (A) Evolution of shockwave as a function of distance (blast over-pressure higher than 1000 kPa is near range, further away are mid and far range. (B) Profile generated from explosion of 1.814 kg of  $C_4$ , at a distance of 2.8 m. (C) Typical Friedlander wave equation.

Source: A. Sundaramurthy, Namas Chandra, A parametric approach to shape field-relevant blast wave profiles in compressed-gas-driven shock tube, Frontiers in Neurology, volume 5, Article 253. Acute Pathophysiology of Blast Injury-From Biomechanics to Experiments and Computations: Implications on Head and Polytrauma, Namas Chandra and Aravind Sundaramurthy, page 196-251, Brain Neurotrauma: Molecular, Neuropsychological and Rehabilitation Aspects, Ed. Firas. H. Kobeissy, Frontiers in Neuroengineering Series.

The region close to the source of the blast, where objects are exposed to incident pressure of 1000 kPa or higher is known as the near field. The flow conditions in the near field are very complex due to interaction with casing/shrapnel and high temperatures. It can be seen that devising a procedure for simulating such conditions would be very difficult. Regions further away from the blast are classified as mid field and far field (13). These regions are away from the fireball and the blast wave profile for them is similar to one in near field, albeit the reduced amplitude and longer time durations. The shock wave

velocity decreases with increase in radius and at a point it degenerates into a sound wave (Figure 1.1A) (14).

Figure 1.1B shows, pressure-time profile measured using a PCB press type pencil gauge by a free-field explosion of 1.814 kg of  $C_4$  at a distance of 2.8 m from the epicenter of the blast. It can be seen from the profile, the sudden rise in pressure represents the shock front (blast over-pressure), followed by exponential decay. This profile takes the form of a Friedlander wave, which is expressed by the following equation:

$$p(t) = p_o\left(1 - \frac{t}{t_d}\right)e^{\left(\frac{-t}{\alpha}\right)}$$
(1.2)

where  $p_o$  represents the blast over-pressure,  $t_d$  represents the positive time duration (PTD), and  $\alpha$  represents the time delay constant (15). A typical Friedlander wave can be seen in Figure 1.1C (16). Attaining a Friedlander curve in the lab, however does not assure a realistic shock profile, since in an actual explosion the *p*-*t* curve could be more complex due to reflections from the ground, surrounding building structures, and shrapnel discharge. In addition, there may be variations in shape, size, and type of explosion, distance, and direction of the wave, environmental parameters (temperature, wind, dust, and humidity).

Another important feature of free-field blast waves is that in intermediate or far ranges, the size of wave front is much larger than that of the human body. In this case, an effectively edgeless wave front interacts with the body. This characteristic represents a planar wave and has to be recreated in the lab to effectively simulate field blast loading. Since a spherical wave in the near field becomes more planar at farther ranges, a field wave in the intermediate to far range can be approximated with a Friedlander wave, within ranges of  $p^*$ ,  $t^*$ ,  $I^*$  shown in Figure 1.1C (16).

## 1.3 Types of Shock Tubes

# 1.3.1 Detonation Shock Tube

A detonation shock tube consists of a tube with one end open and the other end closed. A chemical explosive is placed in the closed end of the shock tube and detonated to produce a shock blast wave (17).

## **1.3.2** Combustion Shock Tube

In a combustion shock tube, a mixture of oxygen and acetylene is filled in the driver section and sealed using a polymer membrane. This mixture is then ignited using an electric match from a safe location. The fuel undergoes combustion and produces carbon dioxide, water vapor, and heat energy. Expanding gases that come from the driver compresses the air in the driven section and initiates a shock wave (18).

# 1.3.3 Compressed Gas Shock Tube

The most popular type of shock tube, working mechanism is essentially same as the combustion shock tube, except, in this case the sudden release of the compressed gas is used for generating the shock wave (12).



Figure 1.2 Evolution of shock wave in a generic shock tube (compressed, gas driven).

A typical compressed gas driven shock tube consists of a driver section of compressed gas and a driven section of air at atmospheric pressure, which are separated by a set of membranes. When the membranes burst, the gases in the driver section expand rapidly, compressing the air in the driven section, which propagates as a shock wave. The driver gas expansion generates a multitude of rarefaction waves, which travel toward and are reflected from the closed end and now move towards the open end. The sequential arrival of these waves generates the profile of nonlinear decay (Figure 1.2).

At  $x = x^*$ , where the shock front intensity is eroded the least by rarefaction waves, the fastest rarefaction wave (faster than shock front) catches the shock front, leading the wave profile to evolve with propagation distance, resembling the Friedlander wave (curve c of Figure 1.2). Before the initial catch-up,  $x < x^*$  (curves a, b of Figure 1.2) the blast wave assumes a flattop shape as the rarefaction wave reflected from the closed end has

Source: Acute Pathophysiology of Blast Injury-From Biomechanics to Experiments and Computations: Implications on Head and Polytrauma, Namas Chandra and Aravind Sundaramurthy, page 196-251, Brain Neurotrauma: Molecular, Neuropsychological and Rehabilitation Aspects, Ed. Firas. H. Kobeissy, Frontiers in Neuroengineering Series.

not reached yet. Duration of the flattop is given by the difference between the arrival times of shock front and the fastest rarefaction wave. For the range  $x^* < x < 0$ , where x = 0 represents the end of the shock tube, larger numbers of rarefaction waves catch up to the shock front decreasing the  $p^*$  and increasing  $t^*$  with increasing x. The p-t profile near the exit is shown by curve d of Figure 1.2.

The configuration of several shock tube design parameters can be used to alter the observed peak over-pressures and shock velocities generated in the shock tube, which allows users to model a wide range of field-relevant blasts of varied explosive weights and standoff distances.

One such design parameter is the presence of an end-reflector plate at the end of the shock tube. Many groups opt to have an open-ended tube, perhaps unaware of the resulting under-pressure wave that is generated as the compressed gas leaves the mouth of the shock tube, which travels back along the tube, possibly loading the test subject with an under-pressure wave unaccounted for. However, positioning the plate too close to the end of the shock tube can reflect shock wave back along the tube and impart another shock wave exposure on the subject inside the shock tube. This study investigates the propagation of a shock wave through the shock tube and the consequences of altering of the position of the end-reflector plate at the mouth of the shock tube on under pressure waves and the reflected shock waves.

#### **CHAPTER 2**

# **EXPERIMENTAL METHOD AND MATERIALS**

This section consists of an overview of the experimental setup.

#### 2.1 General Features of the Compressed Gas Shock Tube

The main components of the shock tube are the driver section or breech, transition, driven section or straight section, and the catch (or expansion) tank. The test section is in the straight section. The driver contains pressurized gas, which is separated from the transition by several frangible membranes. The pressurized gas ruptures the membranes due to mechanical stress resulting in a shock wave, which expands through the transition and develops in the straight section. Subjects are placed in the test section, which is strategically placed to produce a desired shock wave profile. Finally, the shock wave exits the shock tube and enters the catch tank, which reduces the noise intensity. Each of the components is described below.

# 2.1.1 Driver Section

The compressed gas (e.g., air, Helium, Nitrogen) is contained in the driver section, which is used in the generation of the shock blast wave. It is a cylindrical tube, where one end is permanently sealed and the other end is sealed with frangible membranes such as Mylar. Thin sheets of metals (aluminum or steel) have been used in some designs. It is critical to strictly control the repeatability of burst characteristics, by controlling the material and manufacturing processes of the membranes. The compressed gas (driver gas) is filled into the driver section, pressurized, and allowed to burst depending on the membrane material and its thickness. Once the pressure reaches the burst pressure, the membranes rupture releasing the high-pressured gas into the transition.

## 2.1.2 Transition

Transition is a design element used to change the cross-section of the tube from a circular cylinder (driver section) to a square (driven sections). The transition was designed with a gradual expansion to minimize flow separation and turbulence associated (reflections from the sidewalls) with abrupt changes in cross sectional area. If the sections of the driver and the driven remain the same, there is no need for the transition. However, in order to produce an effective shock front the driven is usually larger and longer than the driver.

# 2.1.3 Driven Section

The driven section or the expansion section is the square section where the fully formed shock blast wave is generated. In the experimental design, a square driven section is used. The use of square cross section as opposed to other geometric other sections serves two purposes: (i) uniform expansion from the breech, which is vital to have a planar wave and (ii) to observe and record events in the test section with high speed camera (where having circular section may cause image distortion) (21). The test section is located within this part. It is vital to note that the test section should be neither too close to the breech nor to the exit.

# 2.1.4 Catch Tank

Depending on the strength of the shock-blast wave produced by the shock tube, the catch tank may or may not be included in a particular design (not needed in current design, Figure 2.1). Its main purpose is to contain and release the large volume of expanded gas generated from a shot, minimizing blast loading of lab structures and reducing noise level. Further, the expansion waves from the open end will change the shape of the pressure pulse at the test section. The use of a suddenly changing cross sectional area was studied and found to successfully mitigate energy (22). The inside of the catch tank is lined with sound absorbing material for reducing the noise.



**Figure 2.1** Schematics of the 9-inch square cross section shock tube with the pressure sensor locations. Typically sensors B1, C1, T4, C2, D2 and D4 were used in the experiments to track the shock wave profile evolution along the entire length of the shock tube. For open end experiments a pencil probe was mounted 4 inches away from the exit.

Table 2.1 Sensor distances from the end of the shock tube.

Sensor	Distance from End (inches)
D6	1.5
D5	11.5
D4	21.5
D3	45
D2	65
D2	85
C2	104.5
Τ4	119.5
C1	134.5
B1	158.25

#### **2.2 Current Configuration**

#### 2.2.1 9-inch Square Cross-Section Shock Tube

The shock tube at the Blast Facility at the Center for Injury Biomechanics, Materials and Medicine (CIBM3), New Jersey Institute of Technology consists of a 9-inch cross-section and a modular design. It has the following characteristics: 1) adjustable volume breech, 2) variable length transition section, 3) the 6-meter long test section, equipped with bulletproof glass windows for high-speed video observation of the specimen during the shock wave exposure, and 4) the reflector end plate. The breech is filled with compressed helium or nitrogen which expands until the membranes rupture. The pressure inside of the breech is continuously measured using a WIKA A-10 sensor. To measure the pressure of the incident shock wave and secondary waves a series of pressure sensors are distributed along the shock tube (Fig. 2.1).

#### 2.2.2 Pressure Measurement

Incident over-pressure measured in the test section was recorded using custom LabView program running on in-house built data acquisition system based on National Instruments PXI-6133 32 MS Memory S Series Multifunction DAQ Modules and PXIe-1082 PXI Express Chassis. Pressure sensors used in our experiments were PCB Piezotronics (Depew, NY) model 134A24 (side on pressure inside of the shock tube) and a pencil probe model 137B24B (incident pressure measurements outside of the shock tube). For one sensor (C1), the sensor PCB 102B06 was used to account for sensor drift. All data were recorded at 1.0 MHz sampling frequency and the typical acquisition time was 0.2 seconds.

# 2.2.3 Experimental Design

This study was designed as a two factor experimental design, 4 x 3. Two experimental variables investigated in this study were: 1) the distance between the reflector plate and the end of the shock tube (four levels) and 2) shock wave intensity (three levels). The distance between the reflector plate and the end of the shock tube was adjusted as shown in Figure 2.2. Four different lengths were used: 1) 0.632", 2) 2" and 3) 4", and 4) open end.

The shock wave intensity was controlled by adjusting the thickness of Mylar membranes sandwiched between the breech and expansion section. The thickness was adjusted by stacking individual membranes with thickness of 0.01 inches. In this study three membrane thicknesses (0.02, 0.04, and 0.06 inches) were used, which corresponds to blast over-pressure of approximately 25, 35, and 45 psi measured in the test section of the shock tube (Figure 2.3). All tests were performed using a single fixed breech volume of 6.5 x  $10^{-3}$  m<sup>3</sup>, and were repeated six times for each combination of experimental covariates.

## **2.2.4 Burst Pressure**

Burst pressure is the pressure in the driver section (breech) at the time of the membrane rupture. This highly compressed gas when allowed to expand rapidly compresses the atmospheric air in the transition and driven sections generating a shock front. Burst pressure for different membrane thicknesses and breech lengths are shown in Figure 2.3D. The burst pressure increases with an increase in the membrane thickness. Furthermore, there is no discernible difference in the burst pressure with respect to increase in breech length for any of the three membrane thicknesses studied. This is due to the fact that the membrane rupture is pressure dependent and this critical pressure is not influenced by breech volume i.e., burst pressure that can be achieved at a minimum breech length B1 can also be achieved at C1, T4 or C2 (Figure 2.1). Therefore, quantity of membranes used and its thickness is directly proportional to the burst.

It should be noted that any variation in the burst pressure for identical conditions (e.g., number of membranes, breech volume, and type of gas) will be due to the variations in filling rate of gas in the breech; since Mylar membrane is viscoelastic in nature the rate of deformation depends on the rate of pressurization of the driver section. In general, there is a pronounced rate dependency effect for smaller breech lengths (results not shown for the sake of brevity), compared to larger ones.



**Figure 2.2** Top image: 1. 0.625", 2. 2-inch, 3. 4-inch, and 4. open end. Bottom Image: The representative incident shock wave profiles generated using helium as a driver gas and Mylar membrane with thickness of 1.016 mm; accompanying reflected shock and under-pressure waves are presented. The profile of the secondary wave depends on the gap between the end plate reflector and the exit of the shock tube.



**Figure 2.3** Peak over-pressure inside of the shock tube as a function of sensor location and membrane thickness: A) 0.02", B) 0.04", and C) 0.06". D) Burst pressure corresponding to shock waves generated at respective membrane thicknesses.

## **CHAPTER 3**

# NUMERICAL METHODS

Once the experiment was completed, it was necessary to validate the model. This section describes the methodology for the simulations.

#### **3.1 Numerical Approach**

A computational framework for the blast simulations was created using the Euler-Lagrangian coupling method. In this method, an Eulerian mesh is used to model shock wave propagation inside the shock tube and a Lagrangian mesh for the plate. This computational environment allows accurate concurrent simulations of the formation and propagation of blast wave in air, the fluid-structure interactions between the blast wave and the head models, and the stress wave propagation within the head. Computational framework is shown in Figure 3.1. Shock tube that is used in the modeling is based on the experimental shock tube.

The Eulerian domain (air inside the shock tube) is meshed with 8-noded brick elements, with appropriate mesh refinement near the regions of solid bodies to capture fluid-structure interaction (FSI) effects. Parametric studies on mesh size have been performed and it is found that mesh size of 3 mm is appropriate to capture flow field around the head (i.e. pressures, velocities) and FSI effects. For Eulerian elements, mesh convergence is achieved at this element size; thus element size of 3 mm is used near the regions of solid bodies and along the direction of blast wave propagation. Air is modeled as an ideal gas equation of state (EOS) (see equation 3.5) with following parameters: density- 1.1607 kg/m3, gas Constant- 287.05 J/(kg-K) and temperature 27 °C.,

$$P = (\gamma - 1)\frac{\rho}{\rho_0}e\tag{3.1}$$

where *P* is the pressure,  $\gamma$  is the constant-pressure to constant-volume specific heat ratio (=1.4 for air),  $\rho$  is the initial air mass density, and *e* is the current mass density and *e* is the internal volumetric energy density. The Mach number of the shock front from the experiments is approximately 1.4, and hence the ideal gas EOS assumption is acceptable, as the ratio of specific heats do not change drastically at this Mach number.



Figure 3.1 Shock tube with experimental setup.

#### **3.2 Loading, Interface, Boundary Conditions**

To numerically reproduce primary blast loading, there are two possible techniques to impose the boundary conditions: technique (a) Modeling of the entire shock tube (cross section – 229 x 229 mm), in which driver, transition and extension sections are included in the model so that events of burst, expansion and development of a planar of the blast wave are reproduced; technique (b) Partial model with experimentally measured (*p*-*t*) history is used as the pressure boundary condition, where the numerical model comprises the downstream flow field containing the test specimen. Technique (a) is computationally very expensive. For example, a full scale simulation of 711 mm X 711 mm cross section, 9880 mm long shock tube (excluding catch tank) with cylindrical to square transition requires about 5 million eight-noded brick Eulerian elements and takes about 147 CPU hours on a dedicated 48 processors. These simulations reach the limits of computing power in terms of memory and simulation time (24).

On the other hand, technique (b) requires about 1.26 million elements with 10 CPU hours. The pressure, velocity and temperature profiles obtained using technique (b) match well with the profiles that are obtained using full scale model (technique (a)) at the boundary and downstream locations. Hence technique (b) is capable of capturing the pressure, momentum and energy of the shock wave. Approach similar to technique (b) has been widely used in shock dynamics studies using shock tubes (23).

The model consists of a quadrant of the Eulerian domain: shock tube and accompanying space of the room behind it (Figure 3.2). The room and the tube are constrained to act like a single entity (Figure 3.3). The velocity perpendicular to each face of Eulerian domain (shock tube) is kept zero in order to avoid escaping/leaking of air

through these faces (Figure 3.4). This will maintain a planar shock front traveling in the longitudinal direction with no lateral flow. The end plate is constrained in all six degrees of freedom to avoid rigid body motion (Figure 3.5). An enhanced immersed boundary method is used to provide the coupling between the Eulerian and the Lagrangian domains. Here, the Lagrangian region resides fully or partially within the Eulerian region and provides no-flow boundary conditions to the fluid in the direction normal to the local surface. Further, the Eulerian region provides the pressure boundary conditions to the Lagrangian region.

Thus, a combination of fixed Eulerian mesh and solid-fluid interface modeling through the enhanced immersed boundary method allows for the concurrent simulations of the formation and propagation of a primary blast wave in a fluid medium and accounts for the effects of both fluid-structure interaction and structural deformations once the blast wave encounters a solid. The interactions (contact conditions) between Eulerian (containing air and a propagating blast wave) and Lagrangian regions are defined using 'general contact' feature (card) in Abaqus. In general contact, contact constraints are enforced through the penalty method with finite sliding contact formulation. Various contact property models are available in general contact. In the present work, frictionless tangential sliding with hard contact is used as contact property model (16).



**Figure 3.2** Abaque setup for the shock tube. Input sensor values of C1 are used to generate the shock wave. Mesh size is 3mm for the shock tube area.



Figure 3.3 Displacement and rotation across X, Y and Z planes are disabled.

![](_page_36_Figure_0.jpeg)

Figure 3.4 Same planes across the room and shock tubes are affixed.

![](_page_37_Picture_0.jpeg)

Figure 3.5 Plate is constrained in all six degrees of freedom.

# **3.3 Solution Scheme**

The finite element model is solved using the nonlinear transient dynamic procedure with the Euler-Lagrangian coupling method (Abaqus). In this procedure, the governing partial differential equations for the conservation of momentum, mass and energy (see equations 3.2-4) and the equations defining the initial and boundary conditions are solved simultaneously. Conservation of mass (continuity equation):

$$\rho \frac{\partial v_i}{\partial x_i} + \frac{\partial \rho}{\partial t} + \nu \cdot \nabla \rho = 0$$
(3.2)

Conservation of momentum (equation of motion):

$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho b_i = \rho a_i \tag{3.3}$$

Conservation of energy (energy equation):

$$\rho \frac{\partial e}{\partial t} + \nu \cdot \nabla e = \sigma_{ij} \frac{\partial v_i}{\partial x_j} - \frac{\partial q_i}{\partial x_i} + \rho q_S \tag{3.4}$$

where, is a density, x, v and a are displacement, velocity and acceleration of a particle respectively, is a Cauchy stress, b is a body force, e is an internal energy per unit mass, qis a heat flow per unit area and is a rate of heat input per unit mass by external sources.

In Eulerian-Lagrangian method, the whole model is being solved (i.e. both Eulerian and Lagrangian domains) with the same Lagrangian equations. The notion of a material (solid or fluid) is introduced when specific constitutive assumptions are made. The choice of a constitutive law for a solid or a fluid reduces the equation of motion appropriately (e.g., compressible Navier-Stokes equation, Euler equations etc.). For the Eulerian part/domain in the model the results are simply mapped back to the original mesh with extensions to allow multiple materials and to support the Eulerian transport phase for Eulerian elements. Eulerian framework allows for the modeling of highly dynamic events (e.g. shock) which would otherwise induce heavy mesh distortion.

In Abaque the Eulerian time incrementation algorithm is based on an operator split of the governing equations, resulting in a traditional Lagrangian phase followed by an Eulerian, or transport phase. This formulation is known as "Lagrange-plus-remap." During the Lagrangian phase of the time increment nodes are assumed to be temporarily fixed within the material, and elements deform with the material. During the Eulerian phase of the time increment deformation is suspended, elements with significant deformation are automatically re-meshed, and the corresponding material flow between neighboring elements is computed. As material flows through an Eulerian mesh, state variables are transferred between elements by advection. Second order advection is used in the current analysis. The Lagrangian (solid) body can be a deformable body and can deform based on the forces acting on it and the deformation of the Lagrangian solid influences the Eulerian part/domain.

A typical 3D simulation requires about 7 hours of CPU time on 48 dedicated Opteron parallel processors (processor speed 2.2 GHz, 2 GB memory per processor), for an integration time of 2.5 msec. The simulation time is selected such that the peaks due to stress wave action have been established. A time step of the order of 5 x 10-7 sec is used to resolve and capture wave disturbances of the order of 1 MHz, which increases the overall computational effort for the total simulation time of interest (16).

## **CHAPTER 4**

# **RESULTS AND DISCUSSION**

#### **4.1 Comparison of Blast Wave Profiles**

Peak overpressures for different membrane thicknesses and back plate conditions are shown in Figure 2.3. Blast over-pressure increases with membrane thickness and shows a direct correlation with burst pressure (the pressure measured in the breech at the time of membrane rupture). Burst pressure remains constant along blasts with same membrane thicknesses regardless of back plate distances. Slight differences in burst pressure can be attributed to micro-variations in filling rate of the breech.

The over-pressure values obtained from the experiment were used as input for running the Abaqus simulations. For this paper, measured data from sensor C1 was used for all the results as the input data. This section consists of comparisons between over-pressure profiles between the experimental values and simulated values obtained from Abaqus. The data is arranged in increasing order of shockwave intensity, which was controlled be adjusting the thickness of Mylar membranes packed between the breech and expansion section. The thickness was adjusted by stacking individual membranes with thickness of 0.01 inches. For the experiments, three membrane thicknesses of 0.02 (2 membranes), 0.04 (4 membranes) and 0.06 inches (6 membranes) were used.

#### 4.1.1 No Plate

Experiment is conducted with an open ended configuration. The comparisons can be seen in Figures 4.1 (2 membrane), Figure 4.2 (4 membrane) and Figure 4.3 (6 membrane). It can be seen that the values match closely for thin membrane but vary more as membrane thickness increases. No plate configuration produces an ideal Friedlander waveform. Since the size of the room is a limitation and the purpose is to eliminate the use of a catch tank, this configuration is not desired due to excess noise caused by this configuration.

# 4.1.2 0.632-Inch Gap Plate

For this configuration, the plate is moved to the lowest denomination possible from the end of the shock tube. Overpressure values from the experiment and Abaqus can be seen in Figures 4.4 (2 membrane), Figure 4.5 (4 membrane) and Figure 4.6 (6 membrane). A reflection is observed for all the sensors, subsequent to C1. The arrival time of the peaks can be seen to match closely, however, peaks for higher membranes have a fair amount of variation. Since this plate configuration greatly distorts the waveform that is anticipated, this setup is also not desired.

# 4.1.3 2-Inch Gap

The plate is moved to a distance of 2 inches. In this case, it is observed that while the intensity of the reflected wave is much lower, reflection still exists. Since the purpose of the experiments is to obtain a Friedlander waveform, this does not fulfil that criteria. The comparisons can be seen in Figures 4.7 (2 membrane), Figure 4.8 (4 membrane) and Figure 4.9 (6 membrane).

#### 4.1.4 4-Inch Gap Plate

Distance between the shock tube and end plate is set to 4". The figures comparing experimental values vs Abaqus simulations can be seen in Figures 4.10 (2 membrane), Figure 4.11 (4 membrane) and Figure 4.12 (6 membrane). No reflections were observed for all membrane thicknesses. The waveform can be seen to resemble the Friedlander waveform (Figure 1.1).

A common observation is that while for two membranes (25 psi), the overpressures for experimental and computational values match, it is not the case for four and six membranes (35 and 45 psi). In the experiment, as the helium expands in the breech, the original shockwave rupture the membrane and travels into the body of the shock tube, the air inside the tube is compressed, and these compressed air molecules are left in the wake of the shockwave. At the same time, helium travels into the shock tube and mixes with the air. The extent of the mixing is dependent on the burst pressure, which is much higher with increase in membranes (Figure 2.3). Thus, the shockwave travels through a medium that is not just air, but a mixture of air and helium, where the velocities of the shockwaves vary with change in medium. In the computational setup, the medium is assumed to be air. To account for the gases in the shock tube as in the experiment, mixing theory would have to be considered in the simulation, which is out of the scope of this thesis. Hence, this is possibly the reason for the variation in the over-pressure peaks (and velocities) for higher membranes.

From the various over-pressure graphs, for sensor locations D2 and D4, it can be seen that the experimental values, as time increases, the difference between the experimental and computational value increases. This was initially detected after comparisons with Abaqus values, and was much higher previously. At C1 (input data for computation), instead of the tourmaline based PCB 134A24 (used in all the remaining sensors), the quartz sensor PCB 102B06 was used. This reduced the baseline drift significantly for the simulation results.

![](_page_43_Figure_1.jpeg)

**Figure 4.1** Comparison between experimental and Abaqus values for no plate configuration with two membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

![](_page_44_Figure_0.jpeg)

**Figure 4.2** Comparison between experimental and Abaqus values for no plate configuration with four membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

![](_page_45_Figure_0.jpeg)

**Figure 4.3** Comparison between experimental and Abaqus values for no plate configuration with six membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

![](_page_46_Figure_0.jpeg)

**Figure 4.4** Comparison between experimental and Abaqus values for 0.632" plate distance with two membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

![](_page_47_Figure_0.jpeg)

**Figure 4.5** Comparison between experimental and Abaqus values for 0.632" plate distance with four membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

![](_page_48_Figure_0.jpeg)

**Figure 4.6** Comparison between experimental and Abaqus values for 0.632" plate distance with six membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

![](_page_49_Figure_0.jpeg)

**Figure 4.7** Comparison between experimental and Abaqus values for 2" plate distance with two membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

![](_page_50_Figure_0.jpeg)

**Figure 4.8.** Comparison between experimental and Abaqus values for 2" plate distance with four membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

![](_page_51_Figure_0.jpeg)

**Figure 4.9.** Comparison between experimental and Abaqus values for 2" plate distance with six membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

![](_page_52_Figure_0.jpeg)

**Figure 4.10.** Comparison between experimental and Abaqus values for 4" plate distance with two membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

![](_page_53_Figure_0.jpeg)

**Figure 4.11** Comparison between experimental and Abaqus values for 4" plate distance with four membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

![](_page_54_Figure_0.jpeg)

**Figure 4.12** Comparison between experimental and Abaqus values for 2" plate distance with six membranes. Values from C1 sensor from the experiment were used to simulate the experiment in Abaqus and generate the values. A baseline drift is seen for sensors D2, D4.

#### 4.2 Shock Wave Velocities

The velocity of the shock front, as it travels along the length of the shock tube is seen in Figure 4.13A. It can be observed that with an increase in membrane thickness, there is a clear increase in shockwave velocity. However, there is no significant difference between the shock velocities for varying back plate conditions. Velocities of the under-pressure waves and reflected waves generated by the back plate position can be seen in Figure 4.15, which noticeably demonstrates the difference in the varying conditions. The green horizontal line denotes the speed of Mach 1, which is a required characteristic of a shock wave. It is evident that none of the generated under-pressure waves were shock waves. Even though the reflected waves experienced significant acceleration and travelled more quickly than the under-pressure waves, the velocity was still much lower than the original shock front. It should be noted that the original shock wave travels in the opposite direction of these reflected waves and under-pressure waves.

The wave velocity values from the experiment were used to predict particle velocity values using equation 4.1.

$$\frac{u_p}{a_x} = \frac{5(M_x^2 - 1)}{6M_x} \tag{4.1}$$

Where  $M_x$  is the Mach number of the blast wind, and  $\frac{u_p}{a_x}$  is the ratio of particle velocity to that of local acoustic velocity front.

Abaqus was also used to calculate the particle velocities from the simulations. The comparison between the values from the experiment and the calculated values from Abaqus can be seen in Figure 4.14. From the figure, it can be seen that when the membrane is thin, the values from the experiment and Abaqus simulation are coincident, however the peak values for higher membrane thickness is more varied. This could be due to sensors having lower sensitivities for higher denominations.

## 4.3 Impulse

The significance of the observed reflection waves and under-pressure waves on the loading of the test subject is more clearly observed in Figure 4.16.Without a back plate, the under-pressure wave that was generated had a peak value between 35-45% of the BOP of the original shock wave in the test section (as measured at T4). This means that the test subject (i.e., animal model) is being loaded with the original shock wave, but also an under-pressure wave, coming from the opposite direction, of a significant magnitude.

Implementing a back plate 4" away from the mouth of the shock tube decreases the under-pressure ratio by about 20% in the test section of our shock tube. Bringing the plate two inches closer completely eliminates the observed under-pressure waves reentering the tube, but introduced another complication – a reflection of the original shock wave, back into the shock tube. At this configuration, the test subject is exposed to the original shock wave plus the additional reflection wave, which is 10-15% of the original shock front, coming from the opposite direction. Bringing the plate even closer, with a gap of only 0.632" separating the end of the tube and the plate, the reflection ratio at the test section balloons to 30-40% of the original shock front BOP.

![](_page_57_Figure_0.jpeg)

**Figure 4.13** Calculated shock wave velocities at different sensor locations as a function of blast intensity: A) 0.02", B) 0.04", and C) 0.06". Individual data points were horizontally shifted for clarity of presentation. The B1 sensor was used as a reference.

![](_page_58_Figure_0.jpeg)

**Figure 4.14** Predicted (abaqus) vs calculated (experiment) shock wave velocities at different sensor locations as a function of blast intensity: 1) 0.02", 2) 0.04", and 3) 0.06". The C1 sensor was used as a reference.

![](_page_59_Figure_0.jpeg)

**Figure 4.15** Velocities of reflected under-pressure (A, B) and over-pressure (C, D) waves generated with: a) open end, B) 4" gap, C) 2" gap and D) 0.625" gap. The straight arrow indicates the direction of the reflected waves' propagation. The red and green horizontal lines indicate sound speed in the air. The velocity of reflected waves increases with the distance from the end of the shock tube, which is caused by increased helium (driver gas) concentration closer to the breech. The D4 sensor was used as reference.

![](_page_60_Figure_0.jpeg)

**Figure 4.16** The ratios of peak over-pressure between incident and reflected shock wave measured at different locations inside of the shock tube as a function of sensor location and blast intensity: A) 0.625" gap, B) 2" gap between end of the shock tube and reflector plate. The ratios between incident peak over-pressure and "peak" reflected under-pressure for blasts generated when the gap between the end of the shock tube and reflector plate was 4" (C) and with open end (D). The data points were horizontally shifted for clarity of presentation.

## 4.4 Velocity Vector Field

Abaqus was used to create vector field plots and to observe direction of the shockwave. Two variations were made. Plots were compared based on their plate distances and shock wave intensities. Plots comparing plate distances are 4.17, 4.18, 4.19, and 4.20. Plots comparing shockwave intensities are 4.20, 4.21, and 4.22.

The reflected waves can be seen for 0.632" and 2" plate distances (Figure 4.18, 4.19). As for 4" plate distance, at all time-intervals, there are no reflected waves, further iterating that at 4", the shockwave follows an ideal Friedlander waveform.

![](_page_61_Figure_3.jpeg)

Figure 4.17 Velocity Vector field plots for No plate, two membranes.

![](_page_62_Figure_0.jpeg)

Figure 4.18 Velocity Vector field plots for 0.632" plate, two membranes.

![](_page_62_Figure_2.jpeg)

Figure 4.19 Velocity Vector field plots for 2" plate, two membranes.

![](_page_63_Figure_0.jpeg)

Figure 4.20 Velocity Vector field plots for 4" plate distance, two membranes.

![](_page_63_Figure_2.jpeg)

Figure 4.21 Velocity Vector field plots for 4" plate distance, four membranes.

![](_page_64_Figure_0.jpeg)

Figure 4.22 Velocity Vector field plots for 4" plate distance, six membranes.

#### CHAPTER 6

# **CONCLUSION AND SUMMARY**

In this research, different configurations of the end plate were explored and its effects on the shockwave profile were noted. End plate distances were systematically varied along with shock wave intensities and results were analyzed for both pulse and particle velocities. As a part of the thesis, a numerical model was constructed for all the configurations and compared with the experimental data.

It was observed that at two membranes (25 psi) the experimental results are validated by the Abaqus model. However, at four and six membranes (35 and 45 psi), variations are observed at peak over-pressures and velocities. This can be possibly attributed to the shockwave entering non-linear regime (strong shockwaves) and mixing of driver gas with the driven gas. Since in our model we only account for the driven gas (due to computational constraints), these effects are not computationally observed. It is suggested in the future work, the entire shock tube including breech should be modelled to account for this discrepancy. Additionally, through the simulation, a sensor drift (especially in D2, D4) was detected and corrected by installation of a new sensor.

In closing, based on the over-pressure graphs and velocity vector plots, it can be concluded that at 4" plate distance, the profile of the shockwave is damped such that, its profile remains the same. Thus with a plate at such distance, the requirement of a catch tank is eliminated due to a Friedlander waveform being observed.

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