INVESTIGATION OF ENHANCED ALUMINUM CASINGS FOR UNDERWATER EXPLOSIVES AND DEVELOPMENT OF SPECTROSCOPIC TECHNIQUES FOR MEASURING TEMPERATURE IN ENVIRONMENTS RELEVANT TO UNDERWATER ORDNANCE

BY

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DISSENYATION

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Mechanical Engineering in the Graduate College of the University of Illinois at Urbana-Champaign, 2013

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Enhanced aluminum casings for high explosives were examined both experimentally and theoretically. The experimental analysis utilized aluminum cylinders with linear shaped charges embedded on the surface. The cavities produced jets which outperformed the regions on the cylinder without cavities in terms of enhanced radial bubble growth. It was also shown that cavities with sharp angles at the apex performed better at increasing the bubble volume as opposed to linear cavities with rounded geometries. The theoretical work analyzed the enhancement of aluminum spheres with conical cavities. The radial position of the gas bubble exhibited similar trends to the experimental data for regions with and without cavities based on the penetration of a shaped charge into water. When the cavity liners were designed with the standard guidelines of shaped charge design, the energy potential associated with the displaced explosive was greater than the energy contained in the aluminum cavity liner. If the design guidelines were neglected, the enhanced casings were feasible both on a velocity/penetration distance analysis and energy basis. The energy requirement could also be satisfied, without modifying the design constraints, by filling the cavities with aluminum powder to increase the mass of aluminum in the system.

Two novel spectroscopic temperature measurements were performed on two different underwater systems. A fiber-bundle-coupled emission spectrometer with the input fiber ends anchored along a thin plate near the source provided access to the internal structure of aluminum powder reacting in an underwater environment. This system was sensitive to alignment of the gauge with the combustion event, the intensity of emission from the combustion bubble, and the location of the emission within the gas bubble. An absorption spectrometer was utilized to determine a time-resolved electronic temperature profile for an iron gas bubble created by an underwater electrical wire explosion. Accounting for the refractive properties of the
gas bubble was a critical aspect in transmitting the absorption light source through the bubble and then collecting and focusing the light into the spectrometer. The fitted temperatures for a time period of 200-700 $\mu s$ after the trigger were 3350-3580 K with an uncertainty of $\pm$ 500 K. Additional work should investigate applying this technique to a high explosive underwater.
Dedicated to my parents, Michael and Dawn Kingston.
Thank you for your love and support and ALWAYS answering the question: WHY?
And to Mr. Richard McCleary for being a truly inspirational teacher.
ACKNOWLEDGMENTS

I would like to thank Prof. Nick Glumac and Prof. Emeritus Herman Krier for not only their support over the years, but also their guidance and expertise which have guided my research. Without your support and encouragement, I may have never chosen this path. I would like to thank Prof. D. Scott Stewart and Prof. Joanna Austin for serving on my doctoral committee. And I would also like to thank Dr. Joel Carney for his guidance and support at NSWC-IH.

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Thank you to all of my family and friends who have supported me during this process. During all of the ups and downs, you have provided constant encouragement, which I will forever be grateful. There are several people
who will never fully know their influence in this process, but I am forever thankful for their support, regardless of how brief it may have been.
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<td>AR</td>
<td>Aspect Ratio</td>
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<tr>
<td>BCC</td>
<td>Body-Centered-Cubic</td>
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<tr>
<td>CD</td>
<td>Charge Diameter</td>
</tr>
<tr>
<td>CEA</td>
<td>Chemical Equilibrium with Applications</td>
</tr>
<tr>
<td>DETA</td>
<td>Diethylenetriamine</td>
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<tr>
<td>EDM</td>
<td>Electrical Discharge Machine</td>
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<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
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<tr>
<td>HE</td>
<td>High Explosive</td>
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<tr>
<td>HMX</td>
<td>Cyclotetramethylene Tetranitramine</td>
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<tr>
<td>HSFC</td>
<td>High Speed Framing Camera</td>
</tr>
<tr>
<td>HWHM</td>
<td>Half Width Half Maximum</td>
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<tr>
<td>HTPB</td>
<td>Hydroxyl-Terminated Polybutadiene</td>
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<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
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<tr>
<td>LIBS</td>
<td>Laser-Induced Breakdown Spectroscopy</td>
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<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
<tr>
<td>NM</td>
<td>Nitromethane</td>
</tr>
<tr>
<td>NWSC-IH</td>
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</tr>
<tr>
<td>PETN</td>
<td>Pentaerythritol Tetranitrate</td>
</tr>
<tr>
<td>RDX</td>
<td>Cyclotrimethylene Trinitramine</td>
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RSS  Residual Sum of Squares
TATB  2,4,6-triamino-1,3,5-trinitrobenzene
TNT   2,4,6-trinitrotoluene
UEWE  Underwater Electrical Wire Explosion
UIUC  University of Illinois at Urbana-Champaign
UV    Ultra-Violet

Nomenclature

\( \alpha \)  Half Apex Angle
\( \alpha_G \)  Gaussian HWHM
\( \alpha_L \)  Lorentzian HWHM
\( \beta \)  Collapse Angle
\( \gamma \)  Square Root of Ratio of Target and Jet Densities
\( \Delta \nu_C \)  Collisional FWHM
\( \Delta \nu_D \)  Doppler FWHM
\( \Delta \nu_I \)  Instrumental FWHM
\( \zeta_o \)  Non-dimensional Distance from Virtual Origin to Target
\( \eta_l \)  Lower Energy Level
\( \theta \)  Angle of Enhanced Conical Region
\( \lambda \)  Wavelength
\( \Lambda \)  Fitting Parameter
\( \nu \)  Frequency
\( \nu_o \)  Central Frequency
\( \rho_{HE} \)  High Explosive Density
\( \rho_j \)  Jet Density
\( \rho_o \)  Density of Water at Detonation Depth
\( \rho_t \) Target Density
\( \sigma \) Hard Sphere Diameter
\( \tau \) Non-dimensional Time
\( \tau_o \) Non-dimensional Time of Travel from Virtual Origin to Target
\( A_{ul} \) Spontaneous Emission Einstein Coefficient
\( B_{lu} \) Stimulated Absorption Einstein Coefficient
\( c \) Speed of Light
\( E_B \) Bubble Energy
\( E_l \) Lower Energy Level
\( E_u \) Upper Energy Level
\( g_l \) Lower Energy Degeneracy
\( g_u \) Upper Energy Degeneracy
\( h \) Height of Spherical Cap or Planck Constant
\( H \) Cone Height
\( I_\nu (L) \) Intensity of Light Passing through a Gas Cloud
\( I_\nu (0) \) Incoming Intensity
\( J \) Empirical Constant or Total Angular Momentum Quantum Number
\( J_l \) Lower Level Total Angular Momentum Quantum Number
\( J_u \) Upper Level Total Angular Momentum Quantum Number
\( k \) Boltzmann Constant
\( k_\nu \) Spectral Absorption Coefficient
\( l \) Jet Length
\( L \) Absorption Path Length
\( m \) Liner Mass or Molecular Weight in Atomic Mass Units
\( m_j \) Jet Mass
\( m_s \) Slug Mass

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<td>Total Number of Gas Particles</td>
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<tr>
<td>$n_{Fe}$</td>
<td>Number Density of Iron</td>
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<tr>
<td>$n_l$</td>
<td>Lower Energy Number Density</td>
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<td>$P$</td>
<td>Penetration Distance or Pressure</td>
</tr>
<tr>
<td>$P_o$</td>
<td>Total Hydrostatic Pressure</td>
</tr>
<tr>
<td>$R$</td>
<td>Bubble Radius or Sphere Radius</td>
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<td>$R_H$</td>
<td>Horizontal Bubble Radius</td>
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<tr>
<td>$R_m$</td>
<td>Maximum Bubble Radius</td>
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<tr>
<td>$R_V$</td>
<td>Vertical Bubble Radius</td>
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<tr>
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<td>Travel Time of Jet from the Virtual Origin to Target</td>
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<td>Velocity of Jet Upon Impact or Volume</td>
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<td>$V_{r,ed}$</td>
<td>Reduced Volume for each Conical Cavity</td>
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<td>Slug Velocity</td>
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<td>$V(x,y)$</td>
<td>Voigt Profile</td>
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<td>TNT Equivalent Charge Weight</td>
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<tr>
<td>$x$</td>
<td>Voigt Parameter</td>
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<tr>
<td>$y$</td>
<td>Voigt Parameter</td>
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<tr>
<td>$Y(\nu)$</td>
<td>Overall Lineshape</td>
</tr>
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</table>
\begin{itemize}
  \item \( Y_C (\nu) \) Collisional Broadening Lineshape
  \item \( Y_D (\nu) \) Doppler Broadening Lineshape
  \item \( Y_I (\nu) \) Instrumental Broadening Lineshape
  \item \( z_o \) Distance from Virtual Origin to Target
  \item \( Z^* \) Collisional Frequency
  \item \( Z_{el} \) Electronic Partition Function
  \item \( Z_o \) Hydrostatic Head at Depth of Explosion
\end{itemize}
CHAPTER 1
INTRODUCTION

This dissertation covers two distinct and separate topics concerning underwater explosives: Enhanced Aluminized Casings and Advanced Temperature Diagnostics. There are obvious connections between the two topics, but the connections are not the focus of this dissertation. The enhanced aluminized casings portion focuses on the geometric design of an explosive casing with the purpose of propelling aluminum ahead of the primary gas bubble formed by the explosive and reacting with the surrounding water. Experiments and theoretical models will be discussed to examine the feasibility of such designs.

The diagnostic portion of this project will look at developing techniques to measure the temperature of species within a bubble during underwater combustion. The design of newly developed temperature measurement techniques for underwater combustion will be discussed along with the limitations associated with each design. Some combustion events used in the diagnostic portion involve aluminum, but other metals such as iron and magnesium were also used as the primary metal. Throughout this document the distinction between the two topics will be maintained, although some overlap may exist based on experimental setups and materials tested.

1.1 Motivation

1.1.1 Enhanced Aluminum Casings for Underwater Explosives
The formation of a shock and pulsating gas bubble from an underwater explosive has been extensively studied since World War II. While there are civilian applications for underwater explosives, such as mining, drilling, and construction, the primary application has been for military purposes.
an underwater explosive is detonated, two main phenomena are observed: a shock wave and an oscillating gas bubble. Initially, a majority of work was focused on understanding these two physical phenomena and how they corresponded to the damage observed on underwater structures. From this, four main types of damage mechanisms were determined to be associated with an underwater explosive [1]:

1. Shock wave impact on a structure

2. Structural oscillations (whipping) induced by the pressure field generated by the oscillating bubble

3. Impulse delivered by the pulsating gas bubble

4. Impact force by a re-entrant jet when the bubble is sufficiently close to a structure

The shock wave impact is primarily correlated to the almost instantaneous energy released upon detonation of the underwater explosive. The structural oscillations, or whipping, are dependent on matching the natural frequencies and bending moment of the structure with nearby bubble pulsations. This relationship is related to the period of the explosive bubble and the keel shock factor, both of which are dependent on the charge weight and depth of explosive [2, 3]. The impulse created from a collapsing bubble is similar in magnitude to the impulse created from the shock wave. This impulse is proportional to the bubble energy, which is a function of the maximum bubble radius. In order for a re-entrant jet to form, a structure must be within the maximum bubble radius [4]. Damage mechanisms 3 and 4 are both dependent on the overall bubble radius, while the other mechanisms are not explicitly dependent. In order to increase the bubble impulse or the likelihood of creating a re-entrant jet, the bubble radius needs to be increased, which is one of the main goals of this project. A simple illustration of the shock and bubble dynamics is shown in Figure 1.1, and the formation of a re-entrant jet is illustrated in Figure 1.2.

Increasing the bubble radius of an explosive can be accomplished by increasing the mass of the high explosive. However, this option is not always viable due to volume limitations and safety concerns. Previous work to increase the maximum radius, without increasing the high explosive mass, had
Figure 1.1: A high explosive is detonated near an underwater target. Upon detonation, a shock wave is formed and a bubble is formed from the detonation gases. After the bubble has reached a maximum radius, the hydrostatic pressure causes the bubble to collapse to a minimum radius. When the bubble reaches a minimum volume, a secondary pressure pulse is formed due to the internal shock waves and pressures inside the bubble.
Figure 1.2: When a high explosive is detonated and the bubble contacts a surface (target), a re-entrant jet is formed. The bubble has a higher collapse rate on the side opposite the surface, which causes the bubble to collapse through itself. A high velocity water jet is created during this process, capable of causing highly localized damage to the surface.
focused on the addition of aluminum powder to the explosive formulation. Other metals such as beryllium, boron, and lithium have even greater energy densities than aluminum, but these are toxic, difficult to ignite, or pyrophoric, respectively [5]. For these reasons, as well as the availability and safety concerns, aluminum is typically used as an energetic additive.

The reaction rate of aluminum is much slower than the detonation rate of a high explosive, so the aluminum can act as a dilutant initially and reduce performance [6]. However, it has also been shown that the addition of aluminum can increase the shock and bubble energies by 20% and 60% [6, 7]. The additional energy is released by the aluminum reacting with the detonation products, e.g. H$_2$O, CO$_2$, CO, N$_2$, NO, and NO$_2$. These reactions are shown in Eqs. (1.1)-(1.6).

\[
\begin{align*}
\text{Al}(s) + \frac{3}{2} \text{H}_2\text{O}(g) &\rightarrow \frac{1}{2} \text{Al}_2\text{O}_3(s) + \frac{3}{2} \text{H}_2(g) + 433kJ \quad (1.1) \\
\text{Al}(s) + \frac{3}{2} \text{CO}_2(g) &\rightarrow \frac{1}{2} \text{Al}_2\text{O}_3(s) + \frac{3}{2} \text{CO}(g) + 370.5kJ \quad (1.2) \\
\text{Al}(s) + \frac{3}{2} \text{CO}(g) &\rightarrow \frac{1}{2} \text{Al}_2\text{O}_3(s) + \frac{3}{2} \text{C}(s) + 625.5kJ \quad (1.3) \\
\text{Al}(s) + \frac{1}{2} \text{N}_2(g) &\rightarrow \text{AlN}_3(s) + 173kJ \quad (1.4) \\
\text{Al}(s) + \frac{3}{2} \text{NO}(g) &\rightarrow \frac{1}{2} \text{Al}_2\text{O}_3(s) + \frac{3}{2} \text{N}_2(g) + 885kJ \quad (1.5) \\
\text{Al}(s) + \frac{3}{2} \text{NO}_2(g) &\rightarrow \frac{1}{2} \text{Al}_2\text{O}_3(s) + \frac{3}{4} \text{N}_2(g) + 862kJ \quad (1.6)
\end{align*}
\]

When compared on a mass basis, Eqs. (1.1)-(1.6) release 16.0, 13.2, 23.2, 6.4, 32.8, and 31.9 kJ/gram of aluminum, respectively [8, 9]. The energy released is more than the typical energy released by common explosives such as RDX and PETN, which have enthalpies of detonation of 5.0 kJ/gram and 5.8 kJ/gram. As suggested by Strahle, the reaction of Eq. (1.1) could be exploited if the aluminum was able to react with the surrounding water like a steam explosion, where hot aluminum not only creates a large amount of steam, but also chemically reacts with the water to release significant energy [1]. By reacting with the surrounding water, the aluminum does
not need to compete for a source of oxygen in the typically oxygen-deficient
detonation products. The main obstacle in exploiting the aluminum water
reaction is getting the aluminum outside of the gas bubble produced by the
high explosive (HE), since a typical explosive casing is not accelerated fast
enough by the detonation to escape the gas bubble. The proposed solution
to this problem is shown in Figure 1.3. This concept is similar to a multi-
shaped charge warhead used to produce multiple high speed fragments in an
air blast [10].

Figure 1.3: A) Schematic of a high explosive contained in a reactive casing
with several dimples, B) when detonated the dimples will behave as shaped
charges and create hypersonic jets. The jets carry hot aluminum outside of
the main bubble to react with the surrounding water and release additional
energy to the system while forming protruding cavities.

The schematic shows a high explosive encased in an aluminum liner with
dimples covering the surface. The dimples might act as shaped charges to
create hypersonic jets capable of carrying hot aluminum to the water out in
front of the main bubble. The hot aluminum jets generate steam and react
with the water to release additional energy and produce hydrogen, creating
protruding cavities from the gas bubble, which create a larger overall bubble
and increase the impulse. This enhancement technique proposes to increase
the effectiveness of an underwater explosive on a target.

1.1.2 Temperature Diagnostics

Measuring the temperatures of explosive produced gases is a difficult process.
Due to the violent nature of the explosion, a simple thermocouple, commonly
used in fluid dynamic experiments, will be destroyed very easily, specifically
underwater. If a probe is used to gain access to the temperature profile of
an underwater explosive, it needs to be very rigid and minimally intrusive.
Unlike an air blast, which only expands outward, an underwater explosion will both expand and contract. Since the gas bubble expands and contracts, any object in the path of the gas bubble will interfere with the overall bubble dynamics. Most successful temperature measurement techniques involve observing the explosion and subsequent bubble from a distance and recording the emission of light produced by the explosion. Two typical techniques used to measure the temperature of underwater blasts and underwater electrical wire explosions are pyrometry and emission spectroscopy [11].

For pyrometry, a series of detectors collect emitted light from a combustion event and compare the intensities of two or three different wavelengths to obtain a temperature according to Wien’s radiation relationship, assuming knowledge of the emissivities for the given wavelengths. In emission spectroscopy, a spectrometer detects the emitted intensities for a range of wavelengths. A blackbody curve can be fit to the continuum portion of the spectrum to determine a condensed phase temperature. If at least two emission transition lines are observed, an electronic temperature can be determined by comparing the intensities of the two lines [12]. Both of these methods protect the collection lenses and detectors from the blast by being removed from the actual explosion. As a result of being at a safe distance from the explosion, the measurements may be biased towards the water/gas interface if the gas bubble is optically thick and not represent the overall temperature of the gas bubble.

Lynch et al. performed air blast experiments to examine the temperature distribution inside the combustion of an explosive charge by placing fiber optics in the path of the blast [13]. This setup revealed that the temperature observed by a fiber outside of the blast was greater than the temperatures observed inside the blast. The temperature difference implies that the external temperature measurement, while not always greater, may not be a fair representation of the overall combustion event. Though Lynch et al. focused on air blasts, a temperature distribution may exist for underwater combustion and detonation as well. For this reason, a temperature probe needs to be developed to gain access to the spatial and temporal temperatures of an underwater combustion event.

Temperature measurements of underwater explosions are needed to understand the chemistry and physics happening during the combustion and bubble expansion and contraction. Large scale underwater experiments are
costly to perform, so simulations are usually performed instead. These sim-
ulations predict the temperatures and pressures occurring in the gas bubble
based on the known reaction chemistry of a particular explosive. To jus-
tify the accuracy of the simulations, small scale validation experiments are
performed to measure the pressure and temperature of the gas bubble. For
instance, by knowing the temperature and pressure of the gas bubble, the
combustion physics of aluminum with water may be determined. At pres-
sures above 2 atm, the adiabatic flame temperature of aluminum and liquid
water is lower than the aluminum vaporization temperature, which would
suggest that combustion must start as a heterogeneous reaction [14].

One of the big problems of using emission spectroscopy or pyrometry to
obtain a temperature measurement is their reliance on combustion products
to be strong emitters. The products of metal combustion do not always pro-
duce strong emission signals or emission signals for the entire event. Previous
research has shown that regions with strong light emission are limited and
short lived when compared to the time scale of the combustion event [15].
One solution to this problem is to use absorption spectroscopy to determine
the temperature. Absorption spectroscopy uses a known light source which
transmits light through the combustion bubble. The products in the com-
bustion bubble will be excited to higher energy levels by absorbing specific
wavelengths. By comparing the amount of absorption for each transition, a
temperature can be determined.

1.2 Previous Research & Literature Review

1.2.1 Enhanced Aluminum Casings

Explosives are usually classified into two categories, ideal and non-ideal. Ideal
explosives only contain high explosives such as TNT, RDX, and HMX. The
shock to detonation transition is very quick, and the reaction rate is on
the microsecond time scales. The detonation for ideal explosives follows the
Chapman-Jouget theory which implies that the reaction-rate effects on the
detonation can be neglected [16]. The shock and bubble energies for these
explosives can easily be predicted to first order and scaled by equations to be
discussed in Section 1.2.2. The shock and pressure histories are also capable of being predicted by common program-burn models.

Non-ideal explosives, for the purposes of this document, are composed of ideal explosives and added metals, generally aluminum due to its large energy density as mentioned earlier. The addition of aluminum to the explosive invalidates the program-burn models based on the Chapman-Jouget theory, since the shock to detonation is much slower and the reaction-rates can no longer be ignored because the reactions occur behind the sonic points. The slow reactions affect the shock to detonation transition and extend the reaction zones lengths to $O(10 \text{ mm})$, which is significantly greater than $O(0.2 \text{ mm})$ for ideal explosives [17].

Since the reaction zones are extremely small, the addition of aluminum may increase or decrease the performance of the explosive. Shock and bubble energies have been shown to decrease for any addition of aluminum with a particle size of 350 $\mu\text{m}$, which is attributed to the aluminum acting as a dilutant because of the slower burn times associated with the large particles. Smaller particle sizes (5, 31 and 108 $\mu\text{m}$) gave increases in shock and bubble energies until a critical mass fraction was reached depending on the base explosive, at which point additional Al decreased the performance [18]. Since the Al only reacts with the detonation products and not the surrounding water, the amount of oxygen is limited, causing any excess Al to act as inert particles in the oxygen-deficient environment.

A study by Brousseau et al. focused on the particle size effects of aluminum in TNT (TNT/Al 80/20). They compared nano-aluminum (100-200 nm) and micron sized aluminum (17 $\mu\text{m}$) in an underwater environment [19]. Based on the light emission observed by streak and framing camera images, the nano-aluminum reacted faster than the micron sized particles. The gas bubble expanded faster for the nano-aluminum, which correlated well with the faster reaction time. This effect was more pronounced when the charge diameter was near the critical diameter of the explosive, where the critical diameter is the minimum diameter required to sustain a detonation.

A similar study was conducted by Bates which compared the enhancement effects of nano-aluminum (80-100 nm) to micron sized aluminum (1-3 $\mu\text{m}$) for different explosives with varying reaction zone lengths [20]. Bates theorized that for an explosive with a relatively long reaction zone, nano-aluminum should outperform the micron sized particles. The longer reaction
zone would provide enough time for the nano-aluminum to completely combust and release all of its energy as opposed to the much larger micron sized particles. But surprisingly, the micron particles outperformed the nano sized particles for peak pressure and reduced time constant (indication of shock wave) when combined with nitromethane which has a reaction zone length of 0.01 mm. When RDX, which has a reaction zone length of 0.12 mm, was used as the high explosive, the peak pressure was 8% higher for the nano-sized particles than the micron sized and the reduced time constant was 14-20% shorter. These improvements were associated with the kinetics and reaction zone length and not overall energy content of the nano-aluminum, since nano-aluminum contains approximately 75% active aluminum as compared to roughly 99% for the micron sized particles.

The particle size dependence on the shock energy and bubble energy is important for understanding how the aluminum combusts during the explosion. It should be noted that in the studies above, the aluminum was primarily reacting with the detonation products of the high explosive and not the surrounding water. There is no open literature that reports aluminized explosives reacting with the surrounding water. The inability to gain access to the free field water as an oxidizer limits the total amount of energy that can be released.

One study used an aluminum cylinder to encase an RDX based explosive, in an attempt to have the surrounding water react with the aluminum. The aluminum liner increased the bubble energy over the output of the bare RDX charge. However, the bubble energy of the aluminum lined charge was significantly lower than the energy output of the same amount of aluminum powder (5-150 µm) homogenously mixed with the RDX based explosive [21]. This result may indicate that the aluminum casing did not break up early enough to react with the detonation products before they cooled off, and that the casing may not have been propelled ahead of the detonation gases to react with the surrounding water.

1.2.2 Bubble Dynamics

When an underwater explosive is detonated, the high explosive (generally solid, but possibly liquid) is converted to gaseous detonation products. The
detonation happens at such a rapid rate, that the gases are contained within an extremely small volume with very high pressures. Due to the detonation and sudden creation of high pressure gases, a strong pressure wave is created, producing a shock wave. As previously mentioned, the shock wave is the first damage mechanism produced by an underwater explosive. Roughly 40-60% of the energy available from the high explosive is carried away in the shock wave, where the difference in energy partition to the shock wave is dependent on the type and packing density of the high explosive [22–27].

The remaining energy, \( E_B \), is contained in the gaseous bubble, formed from the detonation products, as potential energy. The bubble energy, in Joules, can be determined by the following equation [26]:

\[
E_B = \frac{4}{3} \pi R_m^3 P_o
\]

where \( R_m \) is the maximum bubble radius (m) and \( P_o \) is the total hydrostatic pressure (Pa). A majority of this energy is released during the collapse of the bubble at the end of the first oscillation phase. Initially, the trapped detonation gases can be at a pressure on the order of 5 GPa, which is much higher than the hydrostatic pressure of the surrounding water (even at water depths of 4 km the hydrostatic pressure is only 39 MPa). This pressure differential drives the gases to expand against the water in order to equilibrate with the surrounding pressure [27]. As the bubble expands, it passes the point of equilibrium with the ambient water pressure and is unable to stagnate, due to the inertia of the outflow of gas and water. The bubble eventually stops expanding and reaches a maximum radius with an internal pressure sufficiently lower than the ambient pressure due to overexpansion. As a result of the over expansion, the bubble collapses from the force of the water. The inertial effects drive the bubble past the equilibrium point as before, and the limits of the compressibility of the detonation gases cause the bubble to stop collapsing at a minimum radius.

Near the point of minimum volume, a secondary pressure pulse is released due to the interaction of internal shock waves converging at the bubble center [28]. The peak pressure of this pulse is less than the initial shock wave, but the pressure event extends for a longer period of time resulting in an impulse that is similar in magnitude to the original shock impulse. Once again, the internal gas pressure is greater than the external water pressure,
which leads to another expansion and collapse. This cycle continues until the
gas bubble has dissipated its energy through pressure pulses, viscous effects,
instabilities at the gas/water interface, condensation and gas cooling [24]. A
small scale experiment previously conducted at the UIUC [29] illustrates an
eexample of the bubble dynamics and is shown in Figure 1.4. The figure is
an image sequence of an RP-80 detonator exploding underwater, where an
RP-80 detonator is composed of 80 mg of PETN and 123 mg of RDX.

Figure 1.4: An RP-80 detonator, containing 203 mg of explosive, suspended
underwater and detonated about 8 inches below the surface. The gases from
the detonation products create a high pressure bubble which expands to reduce
its internal pressure. Due to overexpansion, the bubble collapses in an attempt
to equilibrate with the surrounding water. This process occurs for 3 distinct
expansion and collapse phases before oscillating around an equilibrium radius
and pressure. These images were recorded using a Vision Research Phantom
v7.0 camera at a rate of 26143 fps and 10 µs exposure.

The previous description of an oscillating bubble is only valid in free field
conditions. If the explosive is near the free surface or the floor of the body of
water, or nearby a structure in the water, the oscillation is disrupted. If the
bubble is near a structure, or another surface, the bubble has the potential
to form a water jet. The dynamics associated with the formation of a jet
are described in terms of an interference on the side of the bubble by a solid
structure. During the expansion phase, the movement of the water is impeded
on the side of the bubble near the structure, which causes the bubble to be
displaced away from the structure. As the gas bubble begins to collapse,
the side opposite the structure is able to accelerate inward faster than the
side near the structure because of the ease of movement of the water. The
inwardly accelerated water causes the bubble to collapse from the far side
and through the center of the bubble to the side near the structure causing
localized damage to the structure by the fast moving water jet [4,27].

When the bubble is near the water surface, a downward jet will be formed
since the free surface provides less resistance to the bubble motion than the
open water. Beyond the free surface scenario, a jet will be formed towards a
rigid surface whether it’s above or below the explosive. However, the effects
of buoyancy and gravity will cause the jet to have either a sharp or broad
geometry compared to a jet going to a structure on the side of the bubble.
In order for a re-entrant jet to be formed, the high explosive needs to be
detonated within the maximum bubble radius to the structure [4]. However,
if the high explosive is placed below the structure, the distance can be slightly
larger than the maximum bubble radius since buoyancy will cause the bubble
to migrate upwards slightly towards the structure.

The simplest theory for the dynamics of a collapsing cavity in water was
first proposed by Rayleigh in 1917 and is known as the Rayleigh-Plesset
equation [30]. The solution to this problem was applied to the dynamics
associated with an oscillating gas bubble created by an underwater explosive
given a few assumptions, which are (a) incompressible fluid, (b) instantaneous
detonation, (c) adiabatic gas bubble, (d) negligible internal energy, (e) perfect
sphericity, (f) radial motion only, (g) negligible gravity and buoyancy effects,
and (h) negligible surface tension and viscous effects.

By applying these assumptions to the equations of motion, the time at a
location of a specific bubble radius, $R$, is given by [27,31].

\[
t = \left( \frac{3\rho_o}{2P_o} \right)^2 \int_{R_o}^{R} \frac{dR}{\left[ \left( \frac{R_m}{R} \right)^3 - 1 \right]^{1/2}}
\]

where $\rho_o$ is the density of the water. The maximum radius, $R_m$, during
the first expansion phase is determined by a similarity solution formulated
by [26], i.e.,
\[ R_m = J \left( \frac{W}{Z_o} \right)^{1/3} \]  \hspace{1cm} (1.9)

where \( W \) is the TNT equivalent charge weight (kg) and \( Z_o \) is the hydrostatic head (m) at the depth of the explosion. \( J \) is an empirical constant which was determined to be 3.38 \( m^{4/3}/kg^{1/3} \) for TNT [30, 32, 33]. These equations are applicable in the free field, but are invalid if the high explosive is within 10 bubble radii of a structure or water surface [7]. By taking these two equations, the bubble radius as a function of time for the RP-80 previously shown in Figure 1.4 is plotted in Figure 1.5, with the velocity as a function of time shown in Figure 1.6. In order to use the previous two equations, the explosive mass of the RP-80, which contains PETN and RDX, was converted to a TNT equivalent mass. The detonator was only 2 bubble radii away from the water surface, which causes some of the assumptions in the calculation to be invalid.

![Figure 1.5: Radial position versus time for an RP-80 detonated underwater. The mass fit, implies that the maximum radius used in the Rayleigh-Plesset equation was determined from the equivalent TNT mass of the detonator. The maximum radius fit used the experimentally measured maximum radius for the Rayleigh-Plesset equation. Because of the assumptions, specifically no energy losses, both theoretical fits overshoot the experimental curve.](image)

The radius versus time calculation was plotted for two different cases. The first case took the mass of the detonator and used that along with the depth
to determine the maximum radius. The other condition used the measured maximum radius from the experimental images as the maximum radius for Eq. (1.8). The second maximum and first and second minimum were measured from the experimental data and used for both cases. The Rayleigh-Plesset equation predicts a longer bubble period than shown experimentally, which is expected based on the many ideal assumptions. The actual bubble is non-adiabatic and also loses energy through viscous effects. If heat loss was accounted for, the predicted maximum radius would be less and the period would be shorter [34]. This effect would also cause the time of expansion to be greater than the time of contraction, making the above equations more reliable for the first expansion phase, as compared to the other contraction or expansion phases [26]. The velocity profile shows that the radial velocity is relatively slow for most of the oscillation, except for the initial detonation and collapse. This trend is to be expected, since the detonation is not actually instantaneous at the initial expansion, and the gas bubble is non-uniform and has internal energy, especially near the minimum [28].

While these simple analytical equations have been modified to account for heat losses, gravity, and buoyancy effects throughout the years, they are limited when it comes to complex interactions between a gas bubble and a surface or multiple surfaces. Thus the theoretical work on underwater
explosives has shifted to using computer models which can perform the more complex two and three dimensional simulations by using programs such as AUTODYN, ALE, DYNA3D, DYSMAS/Gemini, or other proprietary codes [22, 35–38]. The accuracy of the simulations using these programs can be verified by comparison with experimental data.

1.2.3 Shaped Charge Dynamics

As noted above, a proposed idea for enhancing underwater explosives casings is to propel aluminum outside the main detonation to allow the aluminum fragments to react with the surrounding water. One method that is capable of propelling aluminum or other materials outside the main detonation is a shaped charge. The shaped charge is a device used to directionally focus explosive energy and has typically been used as a device to penetrate dense materials such as steel, concrete, and rock [39]. Since this project is focused on underwater explosives, the target mentioned throughout will be water.

Shaped charges are typically described based on a cylindrical geometry with a conical liner for ease of explanation and will be done so here, although there exist other charge and liner geometries. A cylindrical shaped charge, shown in Figure 1.7, contains four main components: a casing, a detonator, a high explosive, and a liner. The casing is the container upon which all of the other components are assembled. The main energy is provided by the high explosive in the center of the charge, which is initiated by the detonator at the top of the charge. The high explosive has a hollow cavity on the end opposite the detonator that is typically lined with a metallic liner. When the detonator is triggered, a detonation wave is created which propagates through the high explosive. As the wave beginnings to come into contact with the liner, the liner will start to collapse due to the intense pressures (up to 200 GPa) forming into a high velocity jet. The jet typically contains 20% or less of the liner mass, where the remaining mass is contained in a slow moving segment called the slug. The formation of the jet creates a velocity gradient within the jet with a jet tip velocity capable of reaching 10 km/s and slug velocity of 1 km/s [39].

The liner of the charge can have several different geometries, other than conical, depending on the application. Linear shaped charges are commonly
Figure 1.7: Sketch of a cylindrical casing containing a detonator, high explosive, and a lined cavity, known as a shaped charge. The standoff distance is the distance between the base of the charge and the surface of the target, the standoff distance is occupied by air or some other gas. The charge diameter (CD) is the diameter of the explosive charge, which is not always the diameter of the liner. Additional shaped charge configurations can be found in Walters [39].
used in demolition to create straight cuts through structural supports of a building. Conical designs with apex angles less than 60 degrees are typically used in applications that require a high jet tip velocity for penetration. Trumpet, tulip, and biconic liners are typically used to customize the jet velocity with the ability to create a continuous jet or even two distinct jets, which is common in warheads, in order to remove the guidance system that is in the front of the warhead and have the second jet actually impact the target [39]. Hemispherical liners have a jet tip velocity that is approximately 30% slower than a comparable conical liner. However, the hemispherical liner produces a jet that contains roughly 50% of the liner mass, while a conical liner’s jet only contains upwards of 27% of the liner mass [40]. This difference in jet speed and mass makes hemisphere liners more favorable for soft targets (i.e. water) where generation of larger craters and not deeper penetration is more important.

The thickness of the liner is an important parameter in shaped charge design. The thickness should be roughly 1-4% of the charge diameter (CD), which is the outer diameter of the high explosive fill [39]. The charge diameter may be equal to or larger than the liner diameter. If the liner walls are too thick, energy will be lost to internal friction and heating of the liner walls during collapse. However, if the liner walls are too thin, the structure of the liner may not be maintained, and the liner may not collapse properly. Another important parameter required for the proper development of a jet is the standoff distance. The standoff distance is the distance of air (or gas) between the base of the liner and the target, and ideally this distance should be between 2-5 charge diameters. If the standoff is too short, the jet will not fully develop, but if the standoff is too long, the jet will stretch out and break-up before reaching the target [39].

The liner in most applications is made from copper because of its ductility and density which allows it to form a fast and deep penetrating jet. It has been shown that if the liner is made of aluminum and shot into water, the jet will not only penetrate and create a cavity in the water, but it will also react with the water creating a larger cavity than observed by a copper liner. Bill et al. experimented with firing aluminum and copper shaped charges into water. This study saw significant light emission from the aluminum liner when fired into water, indicating an aluminum/water reaction, while the only light observed during the copper tests was from the initial detonation [41].
In order to quantify the amount of reaction, Fant et al. fired aluminum liners into spindle oil, water, and a 27% $H_2O_2$ solution to represent an anaerobic, normal, and oxygen-rich environment. They found that 16% of the liner mass reacts with the detonation products, 19% of the liner reacts with the water, and an additional 40% reacts when placed in an oxygen-rich environment [42]. It should be noted that both of these experiments had a standoff of 2 charge diameters between the liner and the surface of the liquid target.

Modeling of a shaped charge is a complicated process. Typically, a shaped charge model involves starting with the initial geometric configuration and then proceeds to the liner collapse, jet formation, jet coherency and break-up, and penetration. Involving all of these processes into a single model becomes very complicated, which is why most calculations are generally performed by 2-D hydrocodes. Fortunately, these processes can be separated and treated as individual processes described by 1-D equations, which significantly decreases the difficulty associated with modeling a shaped charge. The collapse of the liner and jet formation/velocity are closely linked and will be described as one process. Penetration by a shaped charge will be discussed as this is a major component in the enhanced casing project. The jet coherency and break-up before penetration models will not be described, since the model described in Section 2.1 assumes that the jet is perfectly formed and does not break-up.

Jet Formation

When describing the shaped charge jet formation and the liner collapse, there are two main theories: the Birkhoff et al. theory and the PER theory. Birkhoff et al. [43] were the first ones to formulate a theory for shaped charge formation. They assumed the pressure from the detonation involved in the liner collapse was so extreme that the material strength of the liner was negligible, thus allowing the liner to be treated as an inviscid, incompressible fluid. The simple wedge geometry used to approximate the conical liner is shown in Figure 1.8.

The original geometry of the wedge has an angle of $\alpha$, which is one half of the liner apex angle, before the detonation wave, $U_D$, contacts point O. As the detonation wave passes over the liner, each segment is instantly accelerated...
Figure 1.8: Geometry of the liner collapse described by Birkhoff et al. [43].

to the collapse velocity, $V_0$. This force causes the liner shape to change from $OP$ to $AP$, where the moving liner now has an angle of $\beta$ around the axis, known as the collapse angle. The liner segment at $P$ will be driven at $V_0$ to $B$. Based on this steady state collapse process and geometry the jet, $V_j$, and slug, $V_s$, velocities are given by

$$V_j = V_0 \left\{ \frac{\cos \left[ \left( \beta - \alpha \right) / 2 \right]}{\sin \beta} + \frac{\cos \left[ \left( \beta - \alpha \right) / 2 \right]}{\tan \beta} + \sin \left( \frac{\beta - \alpha}{2} \right) \right\}$$ (1.10)

$$V_s = V_0 \left\{ \frac{\cos \left[ \left( \beta - \alpha \right) / 2 \right]}{\sin \beta} - \frac{\cos \left[ \left( \beta - \alpha \right) / 2 \right]}{\tan \beta} - \sin \left( \frac{\beta - \alpha}{2} \right) \right\}$$ (1.11)

The jet and slug masses, $m_j$ and $m_s$, can be determined by knowing the total mass of the liner, $m$, and solving the horizontal momentum for the collapsing jet to obtain,

$$m_j = \frac{1}{2} m \left( 1 - \cos \beta \right)$$ (1.12)

$$m_s = \frac{1}{2} m \left( 1 + \cos \beta \right)$$ (1.13)

This model assumes a constant cross sectional area, which is true for a wedge, but not a conical liner. In order to account for the cone, a tapered cone would have to be used to maintain a constant cross sectional area. However, a conical liner with constant liner thickness can be approximated by this model without significant error [39].
If the detonation wave travels parallel to the liner axis at constant speed as depicted in Figure 1.8, then \( V_0 \) can be calculated.

\[
\frac{U_D}{\cos \alpha} = \frac{V_0 \cos \left( \frac{(\beta - \alpha) / 2}{\sin (\beta - \alpha)} \right)}{(1.14)}
\]

By using Eq. (1.14) with Eqs. (1.10) and (1.11), a new set of equations for the jet and slug velocities are formed. Now the only unknown value to be determined is \( \beta \).

\[
V_j = \frac{U_D}{\cos \alpha} \sin (\beta - \alpha) \left[ \csc \beta + \cot \beta + \tan \left( \frac{\beta - \alpha}{2} \right) \right] \quad (1.15)
\]

\[
V_s = \frac{U_D}{\cos \alpha} \sin (\beta - \alpha) \left[ \csc \beta - \cot \beta - \tan \left( \frac{\beta - \alpha}{2} \right) \right] \quad (1.16)
\]

Since the entire process is assumed to be at steady state, the detonation velocity and collapse velocity are constant. The jet and slug velocities as well as the jet and slug masses also remain constant. This model slightly over predicts the jet velocities. Also, the model predicts a constant length jet which is equivalent to the slant height of the cone, even though the jet has a velocity gradient and continues to stretch after collapse. Even with these slight inaccuracies to actual shaped charges, the model is extremely useful, due to its simplicity. The model only requires the knowledge of two variables, \( V_0 \) and \( \beta \), where \( V_0 \) can be calculated if the detonation wave travels parallel to the charge axis.

The PER theory developed by Pugh, Eichelberger, and Rostoker [44] use a similar liner geometry as in the theory by Birkhoff et al. with a few modifications as shown in Figure 1.9. The PER theory involves a variable collapse velocity along the liner which decreases from the apex to the base of the cone. This modification makes sense, since there is a larger amount of HE behind the liner near the apex as compared to the amount of HE near the base of the cone or wedge. The variable collapse velocity causes \( \beta \) to vary as shown by the difference in angles between \( PA \) with the axis and \( QJ \) with the axis. By introducing a non-steady velocity, the previous steady-state equations for jet and slug velocities as well as masses are replaced by the following equations

\[
V_j = V_0 \csc \frac{\beta}{2} \cos \left( \alpha + \delta - \frac{\beta}{2} \right) \quad (1.17)
\]
As the liner collapses, the angle of $V_0$ with respect to the normal of the original position on the liner varies and is defined as $\delta$, which is sometimes referred to as the plate bending angle or the Taylor angle. Due to the varying velocity $V_0$, angles $\beta$ and $\delta$ vary along the distance of the liner. If $V_0$ is held constant, these equations reduce to the previous ones described by Birkhoff et al. While the PER theory is more accurate than the steady-state collapse model, there are more unknown variables than equations. In general, these variables are solved by empirical relationships, which means that the equations are limited to geometries and explosives which have previously been experimentally tested. Even with that limitation, the majority of shaped charge jet formation modeling is based on the PER theory.

Penetration Model

When measuring the performance of a shaped charge, the depth of penetration is generally a key component. Penetration only refers to the distance
that the jet has traveled in a target and does not include the distance associated with the standoff. A simple penetration model was also developed by Birkhoff et al. [43] based on the steady state assumption of a shaped charge.

Consider a jet of known length, $l$, with a velocity of $V$ and density of $\rho_j$ penetrating a target with a density of $\rho_t$. When this jet impacts the target, the jet is decelerated and has a penetration velocity of $U$, which is less than $V$. When this system is viewed from a moving coordinate system attached to the front of the jet, as shown in Figure 1.10, the jet has a velocity of $V - U$ and the target now moves in the opposite direction of the jet with a velocity of $U$. From this condition, the pressure on each side of the jet target interface is the same. Now this system is at steady state, which allows for Bernoulli’s equation to be used, resulting in the following equation,

$$\frac{1}{2} \rho_j (V - U)^2 = \frac{1}{2} \rho_t U^2 \quad (1.22)$$

As the jet penetrates the target, the jet is eroded. Assuming the penetration ends when the rear of the jet strikes the target, then the total penetration distance, $P$, can be calculated. The total time of penetration can be calculated by dividing the total length of the jet with the jet velocity, where Birkhoff et al. assumed that the jet length was equivalent to the slant height of the cone. The time can then be multiplied by the target velocity to obtain the distance, $P$. If Eq. (1.22) is rearranged and substituted for the velocity components, the total penetration can be described in terms of jet length and densities only.

$$P = U \frac{l}{V - U} = l \sqrt{\frac{\rho_j}{\rho_t}} \quad (1.23)$$
This rather simple approximation assumes several things. First, the jet velocity is constant and uniform, which prevents the jet from stretching. Also, it assumes that the jet does not break-up, although other versions of this equation account for particulation by a correction factor. Beyond those assumptions, one of the major limitations of this relationship is that it does not depend on the distance from the target. It has been shown, that as the standoff increases from zero, the penetration increases which is attributed to the elongation of the jet since there is a velocity gradient. As the standoff distance continues to increase, the penetration distance increases to a maximum and then decreases. The decrease in penetration is associated with particulation of the jet, which results in a shorter effective jet.

Since actual jets have a velocity gradient and stretch with time, a better model was developed to account for these shortcomings. Allison and Vitali developed a penetration model that was time dependent and accounted for the standoff distance [45]. It was assumed that the jet velocity gradient was linear, which according to Abrahamson and Goodier [46] produces a penetration of 85% of the ideal penetration, and higher order velocity functions provided little improvement to offset their added complexity to penetration models. The ideal penetration can never be realized in reality since the ideal velocity gradient is concentrated in the rear of the jet.

By assuming a linear velocity profile for the jet, a virtual origin must exist. Since each particle in the jet travels at a constant speed, all particles originate from the same virtual origin on the distance-time plane. The virtual origin can be approximated as three-fourths the liner height based on flash radiograph measurements of shaped charges [47]. As in previous models, the material strength of the jet and target is neglected. With this assumption, a minimum penetration velocity must be established to terminate the jet penetration [45]. Compressibility effects were also found to be negligible as long as the compressibilities of the jet and target material were similar [48].

Based on these assumptions, Allison and Vitali developed a generalized penetration equation, Eq. (1.24), for a shaped charge impacting a target with a standoff distance. The generalized equation and time variable, $\tau$, are scaled by the charge diameter. $V_0^*$ is the velocity of the unimpeded foremost tip of the jet. Standoff distance is accounted for by $z_0$, where $z_0$ is the distance from the virtual origin to the target surface. Also, $t_0$ is the time that it takes the jet to travel from the virtual origin to the target. As in other models, the
ratio of target and jet densities is a critical parameter and is included in the variable $\gamma$ for this model. The penetration model is defined by the following,

$$\frac{P(\tau)}{CD} = \tau V_p - \zeta_o$$  \hspace{1cm} (1.24)$$

$$V_p = V_j^o \left( \frac{\tau_o}{\tau} \right)^{\left( \frac{\gamma}{(1+\gamma)} \right)}$$  \hspace{1cm} (1.25)$$

$$\gamma = \left( \frac{\rho_t}{\rho_j} \right)^{1/2}$$  \hspace{1cm} (1.26)$$

$$\tau = \frac{t}{CD} \quad \tau_o = \frac{t_o}{CD} \quad \zeta_o = \frac{z_o}{CD}$$  \hspace{1cm} (1.27)$$

This set of equations produces a penetration distance versus time relationship for a continuous jet. Because the material strengths were neglected, penetration will technically continue indefinitely. Penetration is defined as terminating either when $V_p$ falls below a predefined minimum velocity or the distance-time curve approaches an asymptote.

1.2.4 Previous Underwater Enhancement Research at UIUC

Previous experiments on the enhancement of underwater explosives have been performed at the University of Illinois at Urbana-Champaign (UIUC) [29]. A few of these experiments have previously been reported by the author, and thus the explanations will be brief.

An underwater jetting experiment was performed to test the ability of a shaped charge to create a secondary bubble that was attached to the main underwater bubble. Two modified RP-1 detonators with aluminum shaped charges from Teledyne RISI, Inc. were used for this experiment. The modified detonators contained 530 mg of PETN with a 60° conical cavity lined with aluminum. One charge was sealed with an air cavity that provided approximately one charge diameter standoff. The second charge was prepared with an aluminum flake fill placed in the cavity and zero standoff.

The detonator with a standoff formed an underwater jet that created a secondary unattached bubble from the reacting aluminum jet, where it was
assumed that the light emission (shown in the top row of images in Figure 1.11) was due to reactivity. The other detonator, filled with aluminum flake, formed a jet that carried aluminum away from the main bubble like the other detonator. However, the bubble formed by the reacting aluminum flake and jet was attached to the main explosive bubble produced by the detonator, creating a larger overall bubble as shown in the images on the bottom row of Figure 1.11. In order to enhance an underwater combustion bubble, a precision manufactured shaped charge needed to be impeded by reducing the standoff and increasing the density in the cavity. This experiment showed that adding an energetic powder to the shaped charge cavity still allowed a jet to form while increasing the overall reaction.

Figure 1.11: Top) An aluminum shaped charge with an air cavity fired underwater with a one charge diameter standoff. The charge created a jet that escaped the primary gas bubble and formed a secondary unattached bubble. Bottom) An aluminum shaped charge filled with aluminum flake and zero standoff. A broad jet was formed and expanded the volume of the entire bubble. Intense luminosity for both jets at 0.11 ms and the bottom jet at 0.23 ms indicated a reaction by the aluminum.

Initial testing of explosive casings with shaped charge cavities was performed with aluminum hemispheres instead of spheres due to ease of manufacturing and the loading and detonation of the high explosive [29]. Three different cavity geometries, displayed in Figure 1.12, were compared to a blank hemisphere filled with 2.3 mL of a 99.9/0.1 by volume mixture of nitromethane/diethylenetriamine (NM/DETA). High speed imaging of the different cases are shown in Figure 1.13. The first altered casing had two pressed hemispherical dimples (6.0 mm base diameter) into the casing at 45°
off axis and covered by aluminum tape to provide a zero standoff air cavity. Based on the partially inverted dimples recovered in the residue, this design began to form jets, which were halted once the inverting cavities contacted the water. A second design was tested with two machined $60^\circ$ cone inserts (6.35 mm base diameter), instead of pressed dimples, with an approximate 0.6 CD standoff. This configuration produced two reactive jets, but the jets did not travel orthogonally to the surface of the bubble because the detonation wave did not contact the cones perpendicularly to the central axis. The final hemisphere contained a single $60^\circ$ cone insert (6.35 mm base diameter) aligned perpendicular to the detonation wave with a 0.6 CD standoff. This configuration produced a reactive jet that formed a secondary bubble, which remained attached to the main explosive bubble. The reacting jet escaping the main gas bubble is seen in high resolution at a faster frame rate in Figure 1.14, which actually shows the aluminum jet reacting with the water, based on luminosity.

One key factor that should be noted on the previous study is the thickness of the liner. As mentioned earlier, the ideal thickness should be 1-4% of the base diameter. The thickness of the liner for the dimples and cone inserts was 0.5 mm or 8%. Due to the small scale of the experiments, the liner thickness would have needed to be 0.06-0.25 mm to meet the recommended thickness, and this thickness is extremely difficult to manufacture. Due to the thicker than ideal walls, energy was potentially lost to internal friction and heating of the walls, which reduced the energy available for the liner collapse.
Figure 1.13: High speed image sequences for different casing designs: A) plain hemisphere, B) hemisphere with two dimples, C) hemisphere with two cone inserts, and D) hemisphere with single on-axis cone insert.

Figure 1.14: High speed image sequence of the single on-axis aluminum cone insert casing design. At 0.020 ms, the aluminum from the shaped charge is ahead of the main gas bubble and reacting with the water based on the luminosity.
process [39]. Jet performance was also affected by the angle at which the detonation wave contacted the liner. The ability to create a point initiated detonation wave from the center of the charge was difficult to achieve since the mass of the high explosive in the detonator is on the same order as the main charge.

Additional small scale testing was performed at UIUC based on the previous results. Small cylinders with conical liner cavities placed on the perimeter of cylinders were tested to demonstrate the concept of a completely enhanced casing, as opposed to a single cavity. Also, these cylinders were completely axi-symmetric and placed in open water, instead of being confined to a tamping plate to simulate symmetry. The experimental setup and results are described in detail in Appendix A.

1.2.5 Bubble Formation Techniques

High explosives previously discussed in the formation of underwater bubbles are capable of being scaled down for laboratory testing. This type of testing occurs on a limited basis, due to safety and cost concerns, and the lengthy down-time between testing. Bubbles, which obey the same dynamics as those created from high explosives, can be formed for laboratory testing by other methods.

Bubbles can be created by ultrasonic vibrations which are capable of forming single and multiple cavitations. These cavitations do not oscillate, but rather collapse only once after being formed, and usually result in light emission known as sonoluminescence. These events tend to be quite small and are only present for a few microseconds, so measurement techniques are currently limited with this system.

Spark generated bubbles have been used as laboratory models for underwater explosions. Small bubbles are created by a high energy electrical discharge between two electrodes underwater, which causes the water in the electrode gap to dissociate into $H_2$ and $O_2$. The presence of these non-condensable permanent gases [49] cause the bubble to expand and collapse and obey the Rayleigh-Plesset equation [50]. Bubbles created with this method are visibly transparent since the only products in the bubble are the dissociated gases, which makes visualization easier compared to high explosive experiments.
The optical clarity of bubbles created by a spark generator provide an opportunity to perform absorption spectroscopy. One disadvantage with this technique is the presence of the electrodes, which interfere with the dynamics of the bubble.

Laser-induced plasmas can also be created underwater for the purpose of forming a bubble and measuring the emission and bubble dynamics. A laser is focused on to a small target, typically a small foil of plastic or metal, and the energy of the laser ablates the target forming a small bubble of plasma and hot gases. This process is known as laser-induced breakdown spectroscopy (LIBS). If the focus is small enough and the laser has sufficient power, the water at the focal point of the laser will ionize and form a plasma without a target material [38]. This system works well for creating a bubble, but little can be done in terms of elemental detection because the emission lines from the underwater plasma are strongly broadened by pressure. This system can be improved by using a double pulse laser system instead of a single laser pulse. For the double pulse system, the first pulse ablates the material and creates the bubble, while the second laser pulse is used to probe the gas inside the bubble [51]. A temperature measurement can be made by fitting a blackbody to the emitted spectra, or by comparing the intensities of multiple atomic transitions.

Small bubbles can also be created by placing a small wire between the electrodes underwater and discharging a large amount of energy rapidly through the wire. This process is known as an underwater electrical wire explosion (UEWE). Care must be taken when choosing a wire material to limit a potential metal/water reaction. Nelson used an UEWE to create a pressure pulse to disrupt molten aluminum droplets in water for research related to steam explosions [52]. Aluminum foils and tungsten wires were placed between electrodes separated by 1 cm. For the same electrical discharge energy, the aluminum foil performed significantly better than the tungsten wire because of the chemical energy released from the aluminum/water reaction. The aluminum foils created a bubble five times as large as those formed from tungsten wire and had a peak pressure 12 times greater than those from tungsten.
1.2.6 Temperature Diagnostics

Due to the violent nature of underwater explosives, temperature measurements are taken optically by utilizing either pyrometry or spectroscopy techniques. In order to understand the issues associated the different measurement techniques, a brief description of pyrometry, emission spectroscopy and absorption spectroscopy will be given based on an explosion in air. Pyrometry and emission spectroscopy have a similar experimental setup as shown by the sketch in Figure 1.15. A lens or system of lenses focuses on a volume of gas produced by the explosive. These lenses focus the light to the detector, which is either the pyrometer or the emission spectrometer. The pyrometer typically measures the intensity of 2 or 3 wavelengths, and uses Wein’s radiation law to determine a temperature by comparing the intensities. When the collected emission from the explosion is focused on to the slit of an emission spectrometer, the incoming light is diffracted to produce a range of wavelengths. A blackbody temperature can be fit to the intensities for all wavelengths in the measured range according to Planck’s law. A temperature measured in this fashion corresponds to that of the condensed phase. If atomic or molecular signatures are present, a temperature can be determined based on the specific energy transitions observed.

![Figure 1.15: Sketch of a simplified emission setup in air. The emission from a gas cloud is collected by a lens and focused onto the slit of a spectrometer (detector) for emission spectroscopy experiments. Pyrometry is performed with a similar setup, but the detector only measures emission intensities for a few wavelengths.](image)

Absorption spectroscopy has an experimental setup similar to the sketch shown in Figure 1.16. A light source, continuous or pulsed, goes through a lens to create a collimated beam. This beam passes through the gas cloud from the explosive and specific wavelengths of light are absorbed by atoms and molecules. The light is then focused onto the slit of a spectrometer. The spectrometer diffracts the light into a range of wavelengths just as in the
emission system. The measured signal through the cloud is compared to the intensity observed in the absence of a gas cloud, which is explained in more detail in Section 4.1. Based on the amount of absorption for each energy transition observed, a temperature can be determined.

**Figure 1.16:** Sketch of a simplified absorption setup in air. A light source, continuous or pulsed, is collimated by a lens system and sent through a gas cloud. The gas cloud absorbs part of the collimated beam, which is collected by another lens system and focused on to the slit of a spectrometer (detector).

Substantial work has been performed on measuring the species and temperatures present in air blasts by spectroscopy. Several studies have been conducted with emission spectroscopy measurements of high explosives. As an example, Miller and Pangilian used collection optics with an emission spectrometer to measure the time resolved emission of Al and AlO for different explosives [53]. Due to the extreme environments of the detonation and combustion of 25 mm right cylinders of PBXN-111 and PBXIH-135, the collection optics were located 30° of the charge axis to protect them from the blast. Since this was a line of sight measurement and the explosives gases were optically thick, this method only measured the chemistry of the detonation gases based on the surface of the gas cloud. As a result, no information regarding the internal chemistry of the gases can be determined with this method.

As previously mentioned, Lynch et al. used an array of fibers sheathed in stainless steel capillary tubes with an emission spectrometer to probe the internal temperature of a small scale fireball [13]. Due to the small amount of explosive used, the setup easily survived the blast. This setup would most likely be severely damaged, possibly destroyed, if used to probe the large scale explosive blasts by Miller and Pangilian.

Absorption measurements have also been performed on both small and large scale explosives. Glumac used a broadband dye laser as the light source
for absorption measurements of exploding bridgewires of titanium and aluminum and 4 mg charges of Al/Bi$_2$O$_3$ [54]. This technique demonstrated the ability to detect absorption of atomic and molecular species in optically thick fireballs for both bridgewires and small scale explosives.

Carney et al. developed a technique of measuring the molecular absorbance of water molecules from large scale explosions [55]. Water was chosen as the absorber since it is present in explosive detonation products and thus would not require the explosive to be doped, which would change the explosive formulation. This technique was capable of measuring temperatures based on water absorption, by using a massive probe to prevent misalignment of the optics when impacted by the blast wave. The large disturbance on the expanding blast by their setup is not much of an issue for an air blast, but would be more significant for an underwater blast.

In terms of temperature measurements on underwater explosive systems, a substantial amount of work has been done on underwater electrical wire explosions (UEWE). UEWEs are very small scale explosions which have been primarily used to measure properties of plasmas, since the water surrounding the exploding water provides better confinement of the discharge channel and generation of high pressures as opposed to a plasma created in air or a vacuum [56]. The general setup of an UEWE attaches a small thin wire, typically copper with a diameter of 100 µm or less and a length of 100 mm or less, between to two electrodes. The wire and electrodes are placed underwater and a high current and voltage is passed through the wire. The nanosecond scale deposition of a large amount of energy causes the wire to rapidly heat through Joule heating and the wire material becomes ionized, creating a high pressure plasma confined underwater [57]. At this point the high pressure plasma creates a shockwave and expands like an underwater explosive. Initial pressures have been calculated to range from 3-12 GPa depending on the size of wire, current, and voltage supplied [56, 58–60].

Most experiments of UEWEs focus on the properties of plasma which occur on a nanosecond timescale. As a result, a majority of the data only observes the first few microseconds, but a few studies have data up to about 150 µs. During the early time period (less than 5 µs), the plasma is optically thick and at an extremely high pressure. These factors limit the available diagnostics since significant spectral line broadening is caused by pressure and stark broadening [57]. For this reason, only surface temperature measure-
ments based on a blackbody have been performed even though the continuum spectra do not always resemble a blackbody [56, 58, 59].

Measurements, using a spectrometer, observed temperatures ranging from 1-9 eV for the first 600 ns, where 1 eV is equivalent to 11604.5 K [57, 58]. At 3.5 µs after triggering, the temperatures significantly decrease to roughly 0.5 eV (5800 K) [56]. A pyrometer using 3 wavelengths measured a temperature of 5000 K at 1.4 µs and 25,000 K at 3 µs [11], which is significantly different than the spectrometer measurements. Another technique used by Grinenko et al. [58] recorded the intensities of 11 different wavelengths and fit a blackbody temperature to all the wavelengths. They found a temperature near 0.6 eV at 100 ns. While these temperatures are for different lengths of copper wire and various current and voltage inputs, the range of temperatures is very large due to the blackbody assumption for all of these measurements.

The spectral emission of a copper UEWE was measured by Grinenko et al. for over 130 µs [56]. After the current discharge (approx. 25 µs), light emission was observed for > 100 µs. During this period, absorption lines of Cu I were observed on the background of the severely broadened Cu I emission lines, indicating self-absorption. After 100 µs, the absorption lines disappeared and only the emission spectrum was detected.

Another area of interest for bubble temperature measurements is sonoluminescence. Sonoluminescence is the emission of light from a small collapsing cavity, created by high intensity ultrasonic vibrations in a liquid [61]. Didenko et al. measured the emission from a water/benzene mixture and observed the spectra of C₂. By fitting a theoretical emission curve to the molecular spectra, temperatures were measured to be 4300 ± 200 K.

A similar experiment performed by McNamara et al., looked at the multibubble sonoluminescence from solutions of Fe(CO)₅, Cr(CO)₆, and Mo(CO)₆ under Ar and sonicated at 20 kHz [62]. Fe, Cr, and Mo atomic emission lines were observed for each solution, and a temperature was fit to each spectra. The temperature for Fe was 5100 ± 300 K and Cr and Mo were fitted to temperatures of 4700 ± 300 K and 4800 ± 400 K, respectively. It should be noted that each temperature was the average of several collection periods and no temporal resolution exists, since the emission only occurs once during the bubble collapse.
CHAPTER 2

THEORETICAL METHODS AND EXPERIMENTAL DESIGN OF ENHANCED ALUMINUM EXPLOSIVE CASINGS

The investigation of the performance of enhanced aluminum casings focused on theoretical and experimental work. The theoretical calculations mainly dealt with the one dimensional analytical equations defined in the previous chapter for shaped charges and underwater explosives. An idealized spherical casing with conical shaped charges was the basis for the theoretical work. The experimental portion concentrated on the effects of different linear cavity geometries on the surface of cylindrical casings.

Throughout this document, specifically for sections focused on enhanced casings, the terms liner and casing are used when describing the design of shaped charges or explosive charges that contain shaped charge elements. The term casing refers to the metal surrounding the majority of the high explosive charge. The casing is generally a cylindrical shape that contains the liner. The cavities that protrude into the high explosive are lined with metal, which is referred to as the liner. The liner typically has a conical or hemispherical shape.

2.1 Theoretical Calculations for Enhanced Aluminum Casings

A simple analytical model was developed to study what the effect of covering a sphere with conical cavities would have on the performance of an underwater explosive. In order for the conical cavities to be feasible, they had to initially satisfy geometric constraints, and then velocity and energy balance constraints.

The geometric constraints limit the size of the cones based on the number of cones and the reduced volume percentage of the high explosive that the cones occupied. Additionally, the apex angle of the cones was fixed at 42°,
to reduce the number of variables. The apex angle chosen was based on the geometries tested at NSWC-IH and on the previous shaped charge work by Fant et al. [42]. An apex angle of 42° was selected over a 60° apex angle for the model since a 42° cone will produce a faster jet than a 60° cone. Also, an apex angle of 42° is the apex angle of the standard charge used by several research facilities [63–65]. By fixing the apex angle, the height and diameter of the cone could be determined for any given explosive charge radius as depicted in Figure 2.1, with Eqs. (2.1-2.3), where $V_{\text{red}}$ is the volume of each cone based on the total number of cones and reduction in HE volume.

$$V_{\text{red}} = \frac{2}{3} \pi h R^2 + \frac{1}{3} H R^2 \sin^2 \frac{\theta}{2} - \frac{1}{3} R^3 \cos \frac{\theta}{2} \sin^2 \frac{\theta}{2}$$

(2.1)

$$h = R \left( 1 - \cos \frac{\theta}{2} \right)$$

(2.2)

$$H \tan \alpha = R \sin \frac{\theta}{2}$$

(2.3)

**Figure 2.1:** Cross sectional sketch of a conical cavity on the surface of a sphere. The radius of the sphere, $R$, and the apex angle of the cone, $2\alpha$, are fixed, along with the volume, $V_{\text{red}}$, that the cone must fill based on the number of cones and overall volume reduction of the high explosive. The remaining parameters are adjusted to account for the initial conditions.

After solving for these parameters, only geometries with $\theta < 2\alpha$ were considered. Otherwise the cones would pass through the center of the sphere and interfere with each other, which is not physically possible. Once the base diameter of the shaped charge was determined, the thickness of the liner was
set to 4% of the diameter. This percentage was the maximum thickness that was allowed for optimal jet formation [39], assuming the charge diameter was equal to the base diameter. At this point in the model, two different aspects were considered to determine a successful enhancement: the energy balance of reactive aluminum versus the displaced explosive and the jet penetration versus bubble growth.

Energy Balance

The energy balance examined the energy of the aluminum added to the system compared to the energy removed by the reduction in HE. Five different high explosives were examined in the simulation work and are listed in Table 2.1 along with their explosive properties. The heat of detonation was determined by Akhavan [8] and density and detonation velocity were provided by Cooper [66]. The TNT equivalence ratio was determined from Eq. (2.4) [66], and is multiplied by the weight of the high explosive to get an equivalent weight of TNT. This definition is one of the more common methods used to determine the TNT equivalent weight.

\[
TNT_{\text{Equivalence Ratio}} = \frac{U_2^H (HE)}{U_2^H (TNT)} \tag{2.4}
\]

<table>
<thead>
<tr>
<th>Explosive Name</th>
<th>Density (g/cc)</th>
<th>Heat of Explosion (kJ/kg)</th>
<th>Detonation Velocity (m/s)</th>
<th>TNT Equivalence Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETN</td>
<td>1.78</td>
<td>5794</td>
<td>8590</td>
<td>1.519</td>
</tr>
<tr>
<td>RDX</td>
<td>1.81</td>
<td>5036</td>
<td>8800</td>
<td>1.594</td>
</tr>
<tr>
<td>HMX</td>
<td>1.90</td>
<td>5010</td>
<td>9150</td>
<td>1.723</td>
</tr>
<tr>
<td>TATB</td>
<td>1.94</td>
<td>3496</td>
<td>8000</td>
<td>1.317</td>
</tr>
<tr>
<td>TNT</td>
<td>1.654</td>
<td>4476</td>
<td>6970</td>
<td>1.000</td>
</tr>
</tbody>
</table>

For a fixed sphere radius and reduction in explosive, the total energy of the explosive can easily be determined from the density and heat of detonation of each explosive. The energy of the aluminum liner is calculated from the energy release associated with Eq. (1.1). From this point, the energy
between the removed explosive and the added aluminum can be compared. Additionally, the energy of the aluminum should be adjusted for the amount of aluminum that actually forms into the reactive shaped charge jet, since a majority of the aluminum liner ends up in the slug, which is not very reactive. In addition to accounting for the jet mass, a correction factor should be used to limit the amount of jet mass that reacts. The aluminum in the jet may not completely react with the water, since the jet is constantly slowing down and breaking up as it interacts with the water which limits the amount of reaction. By considering these correction factors, the amount of reactive aluminum is significantly decreased.

Bubble and Jet Dynamics

For the expansion and contraction of a gas bubble, Eq. (1.8) was used. By using this relation, all of the assumptions associated the Rayleigh-Plesset were required. While this equation tends to over predict the time of collapse, the initial expansion phase, where the shaped charge jet and bubble expansion interact, matches well with experimental values as described in Section 1.2.2. In addition to the Rayleigh-Plesset assumptions, it was also assumed that the regions of the explosive sphere without cavities were unaffected by the neighboring cavity regions. Essentially, the surface of the sphere expands based on the mass of a solid explosive sphere. This is a reasonable assumption, since the gases will be expanding together with the gases and shock waves that are driving the shaped charge.

The bubble dynamics, according to the Rayleigh-Plesset equation, are only governed by the maximum radius as described by Eq. (1.9). By using this equation, the bubble dynamics were actually controlled by the depth of the explosion and TNT equivalent weight of the high explosive for a given sphere diameter. The depth was varied between 100 and 2000 m. The shallower depth was set at 100 m to satisfy the 10 bubble radii depth rule, and the deepest limit was set at 2000 m, which is greater than the maximum operational dive depth of most military submarines $O(1000 \text{ m})$.

The shaped charge dynamics use the Birkhoff velocity equations, Eq. (1.15), to determine a jet tip velocity. In order to use this equation, the collapse angle, $\beta$, was set at $37.5^{\circ}$. This angle was chosen based on the work per-
formed by Jones [63], which showed an initial collapse angle between 30° and 45° for the first half of the liner collapse. That study was based on the PER theory, which meant that the collapse angle varied. However, the maximum jet tip velocity is formed by the initial collapse, and the initial jet tip velocity is the primary concern for the penetration model. By using this collapse angle, the jet tip velocities for the various explosives were also similar to the experimental and theoretically calculated velocities which were typically near 7000-8000 m/s [63, 65]. Jones measured a jet tip velocity of 7330 m/s for an explosive with a detonation velocity of 7760 m/s. Also, Mason et al. measured early time jet velocities for aluminum shaped charges driven by liquid nitromethane, which has a detonation velocity of 6320 m/s, near 6000 m/s [67]. The Birkhoff relations for a detonation velocity of 6320 m/s and collapse angle of 37.5° give a jet tip velocity of 5940 m/s, which is similar to the measured velocity.

Figure 2.2 shows the jet tip velocities for the five high explosives used in this current study as a function of collapse angle. At 37.5°, the range of jet tip velocities were roughly 6550-8600 m/s, which is a reasonable range when comparing the detonation velocity to jet tip velocity, as compared to values from previous literature. So by this comparison, a collapse angle of 37.5° was a reasonable assumption.

Shaped charge penetration was determined by using the model developed by Allison and Vitali [45], Eqs. (1.24-1.27), which gives penetration as a function of time. This set of equations assumed that the jet was sufficiently far from the target, so that it had already formed but not yet broken up. Generally this standoff distance is 2-5 charge diameters (CD). For the enhanced charge, the standoff distance was assumed to only be the distance from the base of the cone to the sphere radius, h. In order to use these simple analytical equations, it was assumed that a fully developed jet formed in this very short distance.

The Allison and Vitali model assumed a variable velocity jet, unlike the Bernoulli penetration model, Eq. (1.23), which assumed a constant velocity jet. By using this model, the high explosive used will influence the depth of penetration, whereas the Bernoulli model was only influenced by the densities of the target and jet and the predefined jet length.

The compressibility of water was ignored for the purpose of penetration. The penetration model was based on a ductile material penetrating a hard
Figure 2.2: The jet tip velocities calculated according to Birkhoff et al. for the various explosives as a function of the collapse angle. The jet mass fraction (dashed line) is only a function of the collapse angle and is 10.3% for $\beta = 37.5^\circ$. 
and dense material, such as steel. Therefore, the use of the penetration model might over predict the depth of penetration.

The penetration model required a minimum penetration velocity to stop the penetration. Previous cut-off velocities have been cited as 1000 m/s, 2000 m/s, and 2160 m/s [39, 45, 64]. Based on the work by Mason et al. [67], who fired shaped charges into water with an appropriate standoff distance, the penetration velocity approached an asymptote near 1000 m/s. For the model in question, a more conservative cut-off velocity of 2000 m/s was used. By setting a greater cut-off velocity, the penetration distance will be reduced, which should help to account for the assumption of a perfectly formed jet. This assumption was needed in order to utilize the Allison and Vitali model, but in reality, the standoff distance was extremely small and would not have allowed for a jet to fully form before interacting with the target. If the jet is not perfectly formed, a reduction in penetration distance will be observed. For this reason, the cut-off velocity was set at the upper limit to compensate for the assumption of a fully formed jet and reduce the penetration distance.

In order to combine these two sets of equations, the reference times and positions had to be the same. Since the penetration model assumes a virtual origin, the shaped charge starts moving before the detonation wave actually reaches the surface of the explosive sphere. The penetration time was adjusted to match the time at which the gas bubble was formed and started expanding. The surface of the explosive sphere was chosen as the reference position, which meant that the penetration model was adjusted to have the start of the target match the distance of the sphere.

After the reference times and positions were established, the models were combined. The initial bubble position was based on the position of the shaped charge jet. At the point in time that the penetration velocity fell below the cut-off velocity, the bubble position was governed by the position of a gas bubble at the same point in time as described by the Rayleigh-Plesset equation. This assumption allowed the position-time trajectory of the bubble to match the end position of the jet penetration trajectory. By doing this, it was assumed that the jet and reacting aluminum generated gases, either from the evaporation of water or the generation of hydrogen gas from the reaction, at an equivalent rate to maintain the same pressure observed by an unenhanced exploding sphere over the entire penetration time period. The Matlab code for modeling the dynamics of shaped charges and underwater
explosives is shown in Appendix C.1 and Appendix C.2.

2.2 Experimental Design of Enhanced Aluminum Casings

All experiments dealing with enhanced aluminum casings were performed at the Naval Surface Warfare Center in Indian Head, MD (NSWC-IH) at the Sigmund J. Jacobs Detonation Science Facility under the supervision of Dr. Joel Carney. The facility was operated by Bob Hayes and additional support staff. The facility consisted of a large explosive test chamber, also known as a bombproof. The chamber had 3 foot thick concrete walls reinforced with rebar and the inside walls were lined with half inch steel plates. Optical access was provided by port hole windows located throughout the chamber. The windows consisted of several layers of polycarbonate to provide optical access for camera equipment while still providing protection against the fragmentation and blast pressures from the explosive charges. Smaller access ports located on the walls and ceiling of the chamber provided access for fiber optic cables and the detonation cable.

Underwater explosives with cylindrical aluminum casings containing various geometric linear cavities along the outer perimeter, which would form shaped charges and promote the exothermic aluminum water reaction, were the primary focus of the experiment. All designs were machined from 6061 aluminum by Xact Wire EDM Corp. The outer diameter, depth, and outer wall thickness of the cylinders were kept constant at 2.495”, 1.50” and 0.040”. Every charge had a steel end cap with an outer diameter and thickness of 2.75” and 0.375”, and one side had a 2.50” diameter extrusion with a depth of 0.125”, so that the casing cylinder would snugly fit in the opening. There was a solid end cap on the bottom and an end cap with a 1.00” centered hole on the top of the casing. The hole was filled with a 0.25” thick, 1.00” diameter DETA sheet booster. On top of the DETA sheet and steel end cap was a polyethylene detonator holder, which contained an RP-80 detonator. The steel end caps were epoxied to the aluminum cases and the polyethylene holder, with detonator, was attached to the end cap by grease as the charge was being prepared for firing. Figure 2.3 shows the general assembly of one of the charges.
Figure 2.3: The photo on the left shows the aluminum casing with top and bottom end caps and the polyethylene detonator holder. The image on the right is a cross sectional computer rendering of the charge assembly. The aluminum casing (A) has a bottom steel cap (B) and a steel cap with a hole on the top (C). A polyethylene holder (D) is used to hold the RP-80 detonator (E) in place. The detonator is used to initiate the explosive train which follows with a DETA sheet booster (F) and the PBXN-110 explosive fill (G).

A total of 8 cylinders shown in Figure 2.4 were designed for testing at NSWC-IH. Two of the cylinders contained no cavities and were used as the baseline to compare the effectiveness of the other designs. In order to make a fair comparison between cylinders with different cavities, all other geometries were designed to contain 20% less explosive than the plain cylinders. The choice of 20% was chosen in order to form several cavities of reasonable size on each casing. Designs with less than a 20% volume reduction would limit the size and potentially limit the manufacturability of each casing. Although the casings were all designed with a cavity volume of 20%, the actual design was close to 20% but slightly over, as listed in the last column of Table 2.2. Due to the limited number of tests scheduled, the geometries chosen were divided into two different subsets, wedges and semi-ellipses. The wedge designs compared the difference between an included angle of 42° and 60°, as well as the difference between using 8 or 10 cavities evenly spaced out along the outer perimeter. The semi-ellipse shape had three designs which consisted of 8 cavities per casing. The ratio of the semi-major axis to the semi-minor axis was set at 1.0, 1.5, and 2.0, which varied the cavity depths from shallow with a constant radius of curvature to a deep cavity with a varying radius of curvature which started to approach the wedge shape. A
A complete set of drawings for each casing are in Appendix B.

![Figure 2.4: Eight casings were designed for testing at NSWC-IH.](image)

All of the cavity walls had a thickness of 0.020” with slightly larger thicknesses near the corners where 0.050” radial chamfers were required due to manufacturing limitations. The outer wall of the cavity was also 0.020” due to manufacturing and material limitations, although the thickness would ideally be on the order of 0.001” or less as this wall was designed only to hold back water from filling the cavities.

PBXN-110 was chosen as the primary explosive to fill the aluminum liners since it can easily be poured to fill the entire casing and it contains no aluminum. PBXN-110 consists of HMX and HTPB in a nominal ratio of 88/12. The explosive mixture was prepared and poured into each of the liners by Joe Chang and Phil Thomas of NSWC-IH. The ends of the aluminum liners were sealed by end caps made from A16 steel. The bottom was attached and sealed to each aluminum liner, and then filled with the explosive, as shown in Figure 2.5. Once the high explosive had cured, the top end cap was attached and sealed to the aluminum liner. As mentioned, the modified liners were designed to contain 20% less explosive than the plain cylinder. The design weight percentage and the actual weight percentage of each liner were similar, as listed in Table 2.2, but were slightly different due to minor inaccuracies in manufacturing, such as fillets, tolerances, etc. Because of the time constraints at the facility, two of the charges were not tested: Ellipse AR 1.5 and Baseline 2.
Figure 2.5: The eight aluminum casings with bottom end caps attached and filled with PBXN-110.
Table 2.2: Each liner mass was weighed and recorded and the percentage increase was based on the average of the two baseline casings. The volume of each casing was calculated by the 3D model along with the percentage increase. The HE mass was measured by weighing the difference between each filled and empty casing. Based on the reduction in mass from the baseline casings, a percentage decrease was determined. The calculated percentage difference was based on the reduced design volume of the explosive cavity.

<table>
<thead>
<tr>
<th>Description</th>
<th>Liner</th>
<th>HE Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured Mass</td>
<td>Volume via 3D Model</td>
</tr>
<tr>
<td></td>
<td>(g)</td>
<td>% Diff.</td>
</tr>
<tr>
<td>Baseline 1</td>
<td>20.22</td>
<td>0.00%</td>
</tr>
<tr>
<td>Pyramid 8 42</td>
<td>27.00</td>
<td>33.53%</td>
</tr>
<tr>
<td>Pyramid 8 60</td>
<td>24.85</td>
<td>22.90%</td>
</tr>
<tr>
<td>Pyramid 10 60</td>
<td>25.48</td>
<td>26.01%</td>
</tr>
<tr>
<td>Ellipse AR 1.0</td>
<td>23.49</td>
<td>16.17%</td>
</tr>
<tr>
<td>Ellipse AR 1.5</td>
<td>25.06</td>
<td>23.94%</td>
</tr>
<tr>
<td>Ellipse AR 2.0</td>
<td>26.05</td>
<td>28.83%</td>
</tr>
<tr>
<td>Baseline 2</td>
<td>20.22</td>
<td>0.00%</td>
</tr>
</tbody>
</table>
In order to test the charges in an underwater environment, the charges were suspended in sacrificial acrylic water tanks, manufactured by Precision Plastics. Due to the physical size limitations of the bomb proof access door, the tanks had external dimensions of 33” x 33” x 35”, with a wall thickness of 0.375”. The top of the tank had a 2” piece of acrylic around the perimeter to provide support while still allowing access through the top. For each experiment, the tank was placed on a large steel barbette to support the weight of the tank and align the center of the tank with the camera’s optical access port, as shown in Figure 2.6.

![Figure 2.6: Sketch of experimental setup at NSWC-IH. The blast chamber had optical port holes to protect the flash and camera from the blast. A Fresnel lens mounted in front of the flash collimated the light before passing through the acrylic water tank. The water tank was mounted on a steel barbette and the charge was suspended in the water tank by string.](image)

Each charge was suspended in the water by strings tied around the top and bottom end caps and the four string ends were attached to the four corners of the tank. This rather simple, somewhat crude method allowed the charge to easily be leveled and centered above the fiber optic gauge in the tank and aligned with the camera. The charge was positioned so that the charge axis was parallel to the camera axis. The standoff distances between the charge and the fiber optic gauge, as well as the amount of water above the charge, varied between tests and are listed in Table 2.3. Since the charges are extremely close to the surface of the water in comparison to their maximum
bubble radius, based on their charge weight, the small difference in charge depth is insignificant.

Table 2.3: The depth below the top of the tank for the water surface, charge center, and top of fiber gauge are listed in inches for the six casings tested. The far right column lists the standoff between the top of the fiber gauge and the outer diameter of the charge end cap.

<table>
<thead>
<tr>
<th>Depth from top of tank (inches)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Level</td>
<td>Charge Center</td>
<td>Fiber Gauge</td>
<td>Stand Off</td>
</tr>
<tr>
<td>Baseline 1</td>
<td>5.0</td>
<td>21.750</td>
<td>25.625</td>
<td>2.50</td>
</tr>
<tr>
<td>Pyramid 8 42</td>
<td>5.0</td>
<td>22.750</td>
<td>25.375</td>
<td>1.25</td>
</tr>
<tr>
<td>Pyramid 8 60</td>
<td>5.0</td>
<td>24.000</td>
<td>25.375</td>
<td>0.00</td>
</tr>
<tr>
<td>Pyramid 10 60</td>
<td>5.0</td>
<td>24.000</td>
<td>25.375</td>
<td>0.00</td>
</tr>
<tr>
<td>Ellipse AR 1.0</td>
<td>2.0</td>
<td>23.875</td>
<td>25.250</td>
<td>0.00</td>
</tr>
<tr>
<td>Ellipse AR 2.0</td>
<td>5.0</td>
<td>23.875</td>
<td>25.250</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The primary diagnostic for this experiment was high speed imaging. A Shimadzu PV-2, with an AF Nikor 80-200 mm lens set at a focal length of approximately 170 mm and f/16 was used for this experiment. The camera was set to record 100 images with an interframe time of 4 µs and an exposure time of 0.5 µs. In order to image the event, a Photogenic Powerlight 2500DR flash lamp was used in conjunction with a Fresnel lens to collimate the backlighting. The flash lamp was operated with max intensity by setting the flash power to 1000 W·s. Due to the destructive nature of these experiments, several different Fresnel lenses (focal lengths of 18-24 inches) were used, but unfortunately, the specifications of each were not recorded.

A secondary diagnostic, which was based on the emission spectrometer design concept to be presented in Section 3.1, was a fiber gauge plate system. The fiber gauge was placed directly below the aluminum cylinder with little to no offset based on the outer diameter of the end cap as listed in Table 2.3. The fiber gauge was composed of 2 main parts, a 1/16” x 2” x 2” square plate made from an ABS-like material with grooves sandwiched between two 1/16” x 3” x 3” square stainless steel plates as shown in Figure 2.7. The small square was rapid prototyped with four 0.020” square channels from a resin with ABS-like properties. Fiber optic cables, 390 µm diameter, were placed in the upper two channels. One of the fibers was connected to an Andor SR-303i-A spectrometer and Hamamatsu C4742-98 streak camera and the
other fiber was connected to a SPEX 270M spectrometer and Hamamatsu C4880 streak camera.

![Diagram](image)

**Figure 2.7**: The image on the left is a sketch of a casing detonating with the fiber gauge in its path. The rapid prototyped fiber holder and steel protection plates are shown in the photo on the right.

Initial observations detected the light signal from the flash up to the time of detonation, at which point no signal was recorded. It is not certain whether the detonator and booster charge disrupted the fibers before the PBXN-110 was detonated, or if the shaped charges themselves impacted the gauge and destroyed it. Since no spectral information was obtained from this setup, there will be no further discussion of this setup.

It should be mentioned that the size of the tank is quite small compared with the amount of HE. There were larger water test facilities available at NSWC-IH, but they had significantly smaller HE limits than the blast chambers, since they were designed to withstand the detonation after each test. The limitation on the amount of HE prevented the use of these facilities with the designed casings in this experiment. Larger testing facilities outside of NSWC-IH have large ponds that are designed for significantly larger charges than the ones used in this experiment, but the operation costs to run a single test were considerably outside of the operating budget.

The high speed images were the primary diagnostic of the investigation. A computer program was written using Matlab to track the shock wave and
the bubble growth generated by each explosive, as presented in Appendix C.3 and Appendix C.4, respectively. Both methods used built-in edge detection functions to track the edge of the shock wave and bubble. Due to the orientation of the charge with the camera and flash, all measurements were based on a radial shock wave and bubble expansion.

When the shock wave interacted with the acrylic tank walls, small cavitation bubbles were formed and completely obstructed the camera view of the bubble. Because of this obstruction, only the first 250 $\mu$s of each image sequence was available for determining the bubble dynamics.

In order to resolve the shock wave, the background features in the images were first removed by defining a region of interest around the charge in the first image of each image sequence. By defining the region of interest, the program detected the charge centroid, the charge diameter, and the pixel calibration. Based on the charge origin, the program was able to use built-in edge detection methods to determine the radial position of the shock wave at several different pixel locations. For each image, there were several pixels that met the edge detection criteria, but some of the detected edges were of items in the background of the image, such as support structures and detonation wires or the edge of the bubble, as seen in the bottom left image of Figure 2.8. In order to clarify the shock wave position, the farthest outliers were removed until the mean and median of the radial shock wave position for all pixels in a single image were within half a standard deviation. The final shock wave with outliers removed is shown in the bottom left image of Figure 2.8 and the detected shock wave is overlaid in yellow on the actual image in Figure 2.9. This procedure was performed for every image in a given image sequence until the shock wave exited the field of view.

The gas bubble was tracked in a similar manner as the shock wave. Every image was initially passed through a gray scale threshold function to detect the bubble and any other optically thick features. As the bubble expanded outward, the bubble edge was determined by detecting the first edge radially outward from the charge center. Unlike the shock wave detection code, the bubble code only tracked the bubble growth of a single section, or pie-slice, of the bubble since non-uniform lighting and the support structure of the fiber gauge caused interferences with the edge detection. Each bubble was divided into sections encompassing one or two shaped charges. Generally a section in the bottom right corner of each image sequence was selected due a greater
Figure 2.8: The original image of Shot 2 image 5 (top left) shows the shock wave along with the bubble and support structure for the fiber gauge. The code used edge detection in a region of interest (top right) to find all possible edges (lower left). After the outliers from the edge of the bubble and supports were removed, only the pixels detecting the shock wave remained (lower right).
Figure 2.9: The original image of Shot 2 image 5 has the detected shock wave overlaid in yellow. This visual confirmation confirmed the accurate detection of the shock wave for multiple pixels.
and more uniform backlight, the absence of support structures, and a larger viewing area before the bubble would expand out of frame. After the area of the bubble in each section was determined, the sectioned area was multiplied by the number of sections and pixel calibration factor to determine an overall radial bubble area.

The edge detection of the bubble was also utilized to track the pixels on the edge and determine the maximum and minimum radius for each image. The minimum radius was assumed to be the radial position of the bubble expanding and the maximum radius was the foremost position of the jet. These positions were used to illustrate the overall trends of enhanced aluminum casings as compared to the trends observed in the theoretical calculations.

There was a concern that the bubble did not expand symmetrically, so several different sections were processed for a single shot. Images from three different sections are shown for Shot 4 in Figure 2.10 and the overall radial bubble size is plotted in Figure 2.11. The radial areas match well for all sections until the end of the viewable image sequence since light levels were reduced and parts of the bubble were at the edge of the frame. The standard deviation from the mean of the bubble area for the three different sections was less than 3.8% for every frame measured. If the variations at the end of the image sequence are neglected, there is no noticeable difference between the various sectioning methods when calculating the radial bubble area.

![Figure 2.10](image)

**Figure 2.10:** Three different sections were evaluated to determine the consistency of measuring the radial bubble area when using different sections. The image on the left is referred to as Left 1/5, the middle image is Right 1/5, and the right image is Right 1/10, where the fraction refers to the radial fraction of the bubble area.
Figure 2.11: Three different sections were evaluated to determine the consistency of determining bubble area when using different sections.
CHAPTER 3

EXPERIMENTAL DESIGNS FOR SPECTROSCOPIC TEMPERATURE DIAGNOSTICS

This chapter is focused on the development of spectroscopic techniques for determining the temperature of underwater combustion events. An emission spectrometer was constructed to primarily measure the internal temperature of an underwater reactive aluminum particle cloud. The absorption spectrometer, after several iterations, was designed to measure temperatures inside the gas bubble formed by an exploding iron wire.

3.1 Emission Spectrometer

The emission spectrometer experiments were designed to measure the light emission from aluminum particles reacting with water. These experiments had four main components: a water tank, an explosive charge, a gauge, and a spectrometer. In addition to the emission measurement taken for each test, several different high speed imaging systems were used to record the event. The remainder of this section details the experimental setup as well as the settings and variations of each experimental set.

3.1.1 Water Tank

All experiments were conducted in the Mechanical Engineering Laboratory at the University of Illinois at Urbana-Champaign. Emission tests were performed in a water tank housed in a blast enclosure. The enclosure served to reduce the noise from the detonation of high explosives, and provide an additional layer of protection from potential high speed fragments produced from the explosion. The water tank shown in Figure 3.1 was constructed from 1/4” stainless steel. The tank had nominal dimensions of 24” x 24” x 36”, which gave a volume of 0.34 cubic meters or roughly 90 gallons. Addi-
tional information on the basic construction and drawings of the water tank are described in detail in [29].

Figure 3.1: Image of the water tank used for the emission experiments. The stainless steel plate on top is used for mounting the explosive charge.

Further modifications were made to the water tank beyond the basic construction presented in [29]. The original mounting bars were constructed out of uni-strut to provide flexibility in mounting positions. However, after several experiments were performed, the flexibility of the uni-strut system created problems with rigidity and thus repeatability of test results. The uni-strut was replaced with more rigid and permanent 1.50” square stainless steel tubing. The square tubing provided a rigid structure to attach diagnostics and experimental apparatuses. The rigidity also decreased the shot to shot variation in alignment and positioning that was previously an issue.

3.1.2 Fiber Gauge

The primary component of the underwater emission experiments was a thin, moderately non-intrusive fiber gauge. Eight 1 mm plastic core fibers designed for optical light emission in the visible spectrum, obtained from Edmund Optics, were used to collect the light emission from the combustion event. Initially, the fibers were placed inside stainless steel capillary tubes mounted to an aluminum rod similar to the air blast experiments performed by Lynch.
et al. [13]. Due to the violent nature of underwater explosions, the capillary tube design catastrophically failed, as can be seen in Figure 3.2.

**Figure 3.2:** A before and after image of the fiber gauge design involving stainless steel capillary tubes. Unlike in air, the fibers and the capillary tubes were significantly damaged during the underwater explosion.

In order to properly protect the fibers, each of the fibers was placed in a 1 mm square channel on the side of an aluminum plate. The channels on the plate not only provided protection for the fibers, but also ensured repeatable positioning between tests. The gauge holder was designed with a slim profile to minimize the interference between the underwater combustion event and the gauge itself. The fiber gauge measured 3” wide by 4” tall with a thickness of 0.120”. The channels were covered by aluminum tape to protect the exposed side of the fibers and keep each fiber fixed inside the channel. The fibers were recessed from the leading edge of the plate such that an f/3 cone was allowed into the end of the fiber in order to match the inlet to the spectrometer. Figure 3.3 shows images of the fiber gauge before and after a test, with an end on view to illustrate the slenderness of the gauge and the position of the fibers.

The positions of the eight fibers were determined by examining high speed images from previous underwater tests. Based on these images, the first fiber was placed 0.40” from the base of the charge as depicted in Figure 3.4. The following three fibers were then positioned 0.25” below the first and separated by 0.25”. The remaining four fibers were positioned 0.50” below the fourth fiber and individually spaced apart by 0.50”. Since the bubble growth rate is faster at the start of an underwater explosion than at any other time [27], the first four fibers were positioned closer together to have several fibers within the initial bubble formation. The increased spacing of the last four
fibers allowed for the collection of additional data from a larger portion of the bubble during late time bubble growth. The fiber gauge was mounted from the side of the stainless steel water tank with the leading edge of the gauge aligned with the vertical axis of the charge, but offset by 0.25”. The offset was required to protect the gauge from the initial blast and to reduce the interference with the charge, since the top of the gauge was aligned with the bottom of the charge.

Figure 3.4: Fiber gauge schematic depicts the position of the individual fibers in relation to the charge. The fibers were recessed to create an f/3 entrance cone. The fibers have varied spacing to ensure several fibers capture early and late emission from the underwater reaction.

The fibers for this test were approximately 15 ft long at the beginning of
the experimental set. Long fibers were required in order to reach from the spectrometer, located outside the blast chamber, through the walls of the blast chamber and into the water tank and fiber gauge. While the distance between the spectrometer and the fiber gauge was shorter than 15 ft, the fiber was constantly shortened between tests for several reasons. Before each test, every fiber was cleaved with a razor blade to provide a flat end face, which removed no more than one inch from each fiber. The largest loss of fiber was caused by the experiment itself. A section of the fiber in the channel was fractured on every test which resulted in loss up to 3” of fiber per test. On rare occasions, a fragment from the casing would impact a fiber, and reduce the fiber length by 1-2 ft. In order to protect the fiber from the majority of fragments, the fibers were routed behind small metal plates mounted along the edge of the water tank.

3.1.3 HSFC Spectrometer

The light emission collected by the fibers from the combustion bubble was sent to a custom imaging spectrometer designed and constructed by Glumac and Lynch [13]. The spectrometer is shown in Figure 3.5. The fibers were aligned vertically on a 100 micron slit at the focal plane of a 135 mm f/2.8 camera lens which served as a collimator. The collimator generated a collimated beam of light from the fibers and directed it onto a diffraction grating. The diffraction grating was a reflection grating with 1800 gr/mm. The light was dispersed by the grating and sent to a 50 mm f/1.3 camera lens used as a focusing optic and the input optic for the High Speed Framing Camera (HSFC) from Cooke Corp. All of the optics were covered by a blackout box to prevent stray room light from entering the system.

The HSFC split the incoming light among four intensified CCD cameras with pixel resolution of 1280 x 1024. Each CCD camera acts independently of the other three CCD cameras in terms of delay and exposure timing. Additionally, each CCD can be operated in a double shutter mode, which allows for one image to be taken and a second image to be taken within a minimum of 500 ns after the first shutter sequence. Thus, the entire system can operate with a framing rate of greater than 1 million frames per second but can only capture eight images. Due to the independent nature of each
Figure 3.5: HSFC Spectrometer - Fibers enter through a 100 µm slit and go through a collimating lens. The collimated light then diffracts off of the diffraction grating and enters a focusing lens. The focusing lens directs the light into the detector, the HSFC [13].
CCD, the timing for recording the spectral response of the bubble was able to vary significantly.

The initial bubble growth, which was very fast and provided significant emission, required several frames with very short exposures within the first 30 $\mu$s. While the later bubble growth was slower and produced less light emission, so longer exposure times were used for the remaining frames over a period of 150 $\mu$s. The initial timing and exposures were predicted based upon the high speed photography used earlier to determine the fiber spacing.

Before each experiment, the four CCDs of the HSFC had to be calibrated for both wavelength and intensity, for each individual fiber. Calibration was necessary before every test, since the fibers were damaged during each test and had to be cleaved between experiments.

The first step in calibration was to determine the specific rows that corresponded to a given fiber, since the fibers were spread over multiple rows. The region of rows for each fiber on each frame was determined by a simple algorithm based on the measured intensity and number of illuminated pixels per row. Once each fiber had a defined number of rows, the values of each pixel in a column were summed. These collimated sums will now be referred to as the pixel value; essentially each fiber now has a single row of pixels.

Wavelength calibration was performed with a mercury lamp by using the emission lines at 546.0735, 576.9598, and 579.0663 nm to calibrate pixel position to wavelength. By finding the peaks of the emission lines in terms of pixel number, a second order polynomial was fit for all pixels. The dispersion was 0.23 nm/pixel with a 4.05 pixel resolution (FWHM) to give a spectral resolution of 0.93 nm for a range of 230 nm centered at 545 nm.

After the wavelength calibration, the spectral efficiency of each pixel had to be calibrated. Each fiber was exposed to a tungsten lamp with a known temperature of 2810 K. By comparing the detector signal levels and the predicted values based on a blackbody fit, a correction factor was determined for each pixel. After all of the calibrations had been performed, the spectrum from each fiber was fit to a blackbody curve to determine a temperature history for every fiber location.
3.1.4 High Speed Imaging

High speed imaging was used throughout the experimental data set to image the combustion events underwater. Two different imaging systems were used to record the experiments, either one of two Vision Research cameras or the HSFC system by Cooke Corp. Two similar cameras by Vision Research, a Phantom v7.0 CMOS and a Phantom v5.2 CMOS, were used to record the overall event. The Phantom v7.0 CMOS is slightly faster and more sensitive than the Phantom v5.2 CMOS, but for the purposes of recording the overall event the only criteria for choosing a certain camera was instrumental availability. These cameras were capable of recording the entire event from the detonation of the HE charge through the gas bubble dissipating to the water and atmosphere which lasted approximately 8-10 ms with an interframe time of 19-40 $\mu$s. These cameras captured the entire event, even though the main focus was only during the emission phase of the gas bubble which was generally the first 300 $\mu$s after detonation.

In order to record at a high framing rate, a second HSFC, identical to the one previously described, was used. By using the HSFC, instead of the Phantom cameras, the time and exposure of each image could be exactly matched to the settings of the HSFC used for spectroscopy. By comparing the images to the spectroscopic data, changes in emission for each fiber could be validated by the position of the emission observed in the corresponding image. This approach also helped to determine if the emitting portion of the combustion bubble was aligned with the edge of the fiber gauge if no spectral signal was detected.

3.1.5 Explosive Charge Configuration

The charge used for the underwater emission experiments consisted of a casing, an explosive, a shaped charge, and a powder fill. A rendering of the charge along with the overall experimental setup is shown in Figure 3.6. The charge was mounted to the base steel base plate and held in place by a polyethylene spacer.

The casing was made from 1018 steel which housed the other components of the charge. A complete drawing of the casing can be seen in Figure 3.7. At the top of the slender portion of the casing was a recessed area which
Figure 3.6: On the left is a rendering of the charge mounted with the fiber gauge directly below. A steel confinement tube was used to capture steel fragments from the blast and prevent water from interfering with the charge. The charge is shown on the right with all of the individual components labeled.

Figure 3.7: Drawing of the steel casing used for holding the detonator, high explosive, shaped charge and fill powder.

The high explosive chosen for this experiment was liquid nitromethane (NM) sensitized with diethylentriamine (DETA). The ratio of NM to DETA
was 99/1 by volume. The explosive mixture was detonated by a standard RP-80 detonator from Teledyne RISI, Inc. which contained 80 mg of PETN and 123 mg of RDX.

The shaped charge, used to propel the powder fill into the water ahead of the gas bubble, was an aluminum cone manufactured by Wagner Machine Co. The cone was made from 6061 aluminum with an apex angle of 60°. The outer diameter of the cone base measured 0.512” with a wall thickness of 0.010”. The base of the cone was sealed with cellophane tape to prevent water from filling the cavity.

A few tests were conducted with an air filled cavity, which created a very fast and bright jet of aluminum. To increase the emission of aluminum and residence time of the jet in the line of sight of the fiber gauge, the cavity was filled with nano-aluminum powder. The nano-aluminum was defined as having a particle size less than 80 nm, but the size distribution was unknown. During the filling process, the powder was placed inside the cavity and the entire casing was gently tapped to level the powder. The cavity was completely filled and then sealed with cellophane tape as previously mentioned. The mass of the powder varied between 80-95 mg for all nano-aluminum tests.

One test was conducted with 290.4 mg of magnesium powder. The magnesium was procured from Alfa Aesar with a mesh size of -325 (particles less than 24 µm). Magnesium was chosen since it was known to burn with a very intense emission, which would easily be detected by the emission spectrometer.

The entire casing was mounted to a polyethylene spacer which fit inside the steel mounting plate and was attached to the support bars. A 4” diameter steel cylinder was placed around the slender portion of the casing on the top of the steel plate. A rubber gasket and liberal amount of grease was used to create a water proof seal between the steel plate and cylinder. The cylinder prevented water from reaching the NM/DETA, which is not waterproof, and it confined the steel shrapnel from the casing created during detonation. Water was filled to within one inch of the top of the cylinder to maximize the hydrostatic pressure on the charge.
3.2 Absorption Spectrometer

The absorption spectrometer experiment was constructed to determine the temperature of an underwater explosion during the absence of an emission signal. The initial experimental design focused on using an actual explosive underwater and conducting absorption spectroscopy on the gases trapped in the bubble. After a few preliminary tests, the idea of using an explosive was abandoned and replaced with an underwater electric wire explosion, UEWE. The following section discusses the development of the current absorption system capable of measuring temperatures from UEWEs.

3.2.1 Absorber Material Selection

An RP-80 detonator was initially investigated for use in this experiment since it was previously shown (in Figure 1.4) to produce an oscillating bubble on a laboratory scale. An RP-80 contains 123 mg of RDX and 80 mg of PETN, which primarily produces CO, N₂, H₂O, CO₂, H₂, OH, H, O₂, O, NO, HO₂, and N according to the NASA Lewis Research Center’s computer program Chemical Equilibrium with Applications (CEA) based on the known bubble radii and HE properties. A majority of these detonation gases do not have strong transitions in the near UV or visible spectrum, and if they did, they did not have a large enough concentration to produce a usable signal. To circumvent this problem, the initial approach was to seed an RP-80 with a nonreactive metal powder that had strong atomic transitions in the near UV or visible spectrum. Additionally, by using the combustion code in CEA, which utilizes the density and known internal energy of the reactants, a temperature was determined for every measured bubble radius as shown in Figure 3.8. Based on these temperatures, an absorber would need to be sensitive to temperatures in this range. Beyond satisfying the temperature criteria, an element would also need to have several atomic transitions (4 or more) within a window of 5 nm and have a distribution of ground states in the range of 0-9000 cm⁻¹ between 350 nm and 600 nm.

The absorber element needed to have several transitions in a small wavelength range, so that a high resolution spectrometer could detect and resolve the absorption lines and fit a temperature to them. The criterion of a low ground state was required to ensure that the element would easily be excited...
The temperature was calculated using the CEA combustion program that takes the internal energy of the HE and the specific volume of the detonation gases. It was assumed that the mass of the gas was the same as the initial HE mass and the volume was calculated by measuring the bubble radius in high speed images.

to an upper state during combustion. Ideally, the transitions needed to be between 350 nm and 600 nm, since this is where ground state electronic transitions are known to occur and several detectors are designed to operate in this region.

After applying the criteria for atomic transitions to almost every element on the periodic table, only a handful of elements remained, Al, Ti, Cr, Fe, Nb, Ru, Pr, Nd, Sm, Gd, Ho, and Er. From this small set of elements, theoretical absorption curves were calculated for temperatures ranging from 3000 K to 4000 K to determine their temperature sensitivity. In order to be considered sensitive, the relative absorption between two transitions needed to change by 5% or more for a temperature increase of 100 K. This needed to occur for several transition pairs in order to be considered for use as an absorber, which narrowed the list to Fe, Pr, Nd, Ho, and Er. Figures 3.9-3.12 present the temperature sensitivity for Ti and Fe at temperatures below 1000 K, where Ti is sensitive, and temperatures from 1500 K to 5000 K, where Ti is not sensitive but Fe is sensitive.

Based on the small list of eligible elements, iron was chosen for several rea-
Figure 3.9: Ti absorption lines below 1000 K. 15 transitions with a ground state below 9000 cm$^{-1}$ are plotted for temperatures of 300, 500 and 1000 K. Significant differences in relative absorption near 396 and 400 nm can be observed as the temperature changes.
Figure 3.10: Ti absorption lines above 1000 K. 15 transitions with a ground state below 9000 cm$^{-1}$ are plotted for temperatures of 1500, 3000 and 5000 K. There is no significant change in relative absorption between multiple transitions at different temperatures.
Figure 3.11: Fe absorption lines below 1000 K. 14 transitions with a ground state below 9000 cm$^{-1}$ are plotted for temperatures of 300, 500 and 1000 K. There is no significant change in relative absorption between multiple transitions at different temperatures. Several transitions are not even excited at these temperatures.
Figure 3.12: Fe absorption lines above 1000 K. 14 transitions with a ground state below 9000 cm$^{-1}$ are plotted for temperatures of 1500, 3000 and 5000 K. Significant differences in relative absorption near 373.5, 375, and 376 nm can be observed as the temperature changes.
sons. Iron had 14 transitions between 371.5 nm and 377 nm with ground energy states of 0.000, 415.932, 704.004, 888.129, 978.072, 6928.266, 7376.760, 7728.056, 7985.780, and 8154.710 cm$^{-1}$. Various forms of iron powder and wire were easily accessible and economically affordable compared to other elements such as holmium or neodymium. Furthermore, there were few health concerns associated with iron.

The initial experimental design focused on using an actual explosive underwater seeded with an element and conducting absorption spectroscopy on the gases trapped in the bubble. After a few preliminary tests involving iron powder and an RP-2 detonator (32 mg of PETN and 18 mg of RDX), the idea of using a high explosive was bypassed and replaced with an experiment which utilized an exploding wire underwater, UEWE. The explosive method was abandoned for several reasons. First, the very nature of using an explosive raised concerns for safety and required a certified explosive handler to perform the experiments. Tests involving underwater explosives also required a large amount of preparation time beforehand and clean up afterward. Since the preliminary experiments used to test the setup initially showed very little promise, it was determined that this project would require a large number of experiments to develop and refine the technique. The amount of testing required would be quite expensive and time consuming if high explosives were used for every trial. By using UEWEs, the time required to setup, experiment, and clean up would be significantly reduced. Since UEWEs only require a short piece of wire and a capacitor to operate, the safety concerns were significantly reduced. The use of UEWEs was a better choice overall when considering safety, cost, and turnaround time between experiments.

The bubble behavior of an UEWE was similar to that of a high explosive, except on a much smaller scale. This small scale allowed for the experiment to be performed on a laboratory bench top, enabling the diagnostic equipment to remain stationary between experiments, unlike experiments using explosives. The ability to have stationary diagnostics enabled differences in absorption signals from multiple experimental runs to be attributed to a single variable with certainty, unlike experiments involving underwater explosives. Experiments involving explosives normally required realignment of the entire optical train after each test since they were disrupted by the explosive, which lead to interpreting differences in absorption signals as a function of changing a variable, when the difference was actually caused by a slight
misalignment of optics.

The bubble behavior was also extremely repeatable, since the position of the wire and the energy deposited on the wire could accurately be controlled. The repeatability of experiments was a significant advantage over underwater explosives. While explosives are also extremely repeatable, positioning of diagnostics around them varied between and during experiments due to the violent nature of explosives.

The primary wire for the UEWE test was an almost pure iron wire from Alfa Aesar. The wire had a diameter of 0.003” and a purity of 99.995%. A small diameter wire was required due to the limited energy available by the capacitor system. If the wire diameter was too large, 0.010” or greater, it would not explode with the discharge unit that was employed.

3.2.2 Light Source

Finding a lighting source to provide the baseline for the absorption signal was not a simple task. The light source had to have a strong, constant emission signal in the near ultra-violet (UV) since iron was the chosen element. By looking in the near-UV, a detector could be chosen from several easily accessible detectors currently in the laboratory.

Several different types of light sources were vetted before settling on a specific source. Continuous broadband visible light sources typically operate in the visible (400-700 nm) and then suddenly drop off in intensity around 380-390 nm. Other continuous UV sources, such as a deuterium lamp, have bands of strong intensities below 350 nm. There were some light sources that had a constant signal over the 370-380 nm range, but when operated as a continuous light source, they were too weak to provide a sufficient signal for absorption measurements.

UV-LEDs were considered as a light source for this experiment. When the LED was connected to a power source at the recommended voltage, the signal was too weak to operate as an absorption light source. Since the relationship between the current and light intensity output to voltage in an LED is non-linear, if the input voltage was doubled the light intensity increased by ten times. This technique was only possible if the LED was operated by a short voltage pulse, otherwise the LED would instantly overheat and burnout. A
simple pulsating circuit was constructed to create a short pulse width (less than 100 ms) with a high input voltage relative to the baseline signal to power an LED. Beyond the timing issues associated with a pulsating LED, creating a collimated beam from an LED was difficult. This technique was used in the preliminary explosive testing phase, but it was also abandoned at the same time that the explosive testing was converted to the UEWE experiments.

Argon flash bombs were investigated as a source of a single, high intensity, short pulse of UV light. An argon flash bomb, in the simplest explanation, is a tube filled with argon that has an explosive at one end of the tube and a window at the other end. When the explosive is detonated, the shock wave travels down the length of the tube towards the window. The shock wave heats up the argon through compression heating and ionizes the gas, which is accompanied by a very intense continuum emission in the UV spectrum [68]. Since argon is a monatomic gas, the energy from the shock wave can only be used to ionize the gas unlike a molecular gas which uses some of the energy to dissociate.

One advantage in using an argon flash is that the duration of the flash can be set by adjusting the length of the tube. However, this method includes the use of an explosive for every test which would require an explosive handler. A few proof of concept experiments investigated the light intensity and feasibility of using an argon flash. The results proved that the amount of variables and safety involved with an argon flash were not outweighed by the performance, so this lighting source option was not chosen.

Other noble gases, such as krypton and xenon, can also be used to create high intensity light, and are commonly used in flash bulbs. Xenon flash bulbs were investigated to determine the intensity dependence on wavelength and time. The Powerlight 2500DR by Photogenic Professional Lighting had a xenon flash bulb with variable power settings to adjust the intensity of the flash. While the Powerlight 2500DR had a stronger signal in the visible spectrum, the signal strength in the near UV was more intense than the previous lighting sources. A sample intensity temporal profile of the flash is shown in Figure 3.13. The flash had a delay of approximately 200 µs from the trigger until a substantial signal was observed. After this delay a fairly constant signal was observed for nearly 250 µs before decaying.

Since the Powerlight flash is primarily used in the photography industry,
there was already a built-in triggering mechanism that could be synchronized with the triggering system. The triggering mechanism in the flash required a switching circuit instead of 5 V pulse like many of the instruments used in the experimental setup. A triggering circuit described in [29] was used to convert the 5 V pulse from the pulse generator to close the circuit in the flash triggering system.

3.2.3 Testing Apparatus

As the development of the absorption measurement transitioned from detecting the temperature of a gas bubble formed from high explosives to a small gas bubble created by an UEWE, the testing facility transitioned from a large 340 liter water tank to a small 0.5 liter water chamber. By using a small chamber, the experiment could be performed on a table top next to the spectrometer and optics, instead of using fiber optics to connect the sensitive spectrometer and optics to the experiment inside a blast chamber.

The water tank, as seen in Figure 3.14, is a 4” aluminum cube with chamfered corners. The chamber was created by milling 2” diameter holes through
all faces of the cube. The bottom face and two side faces were covered with 1/8” thick steel plates and sealed with a size 229 O-ring. Optical access was provided on two of the faces by window flanges made from 6061 Al. Each window flange held a Borofloat window with a diameter of 75 mm and thickness of 6.5 mm from Edmund Optics. Vertical positioning and leveling of the tank were achieved by four optical posts attached to the base plate. The tank was filled with distilled water to within 1 cm of the top of the tank for every test. Distilled water was used instead of tap water in order to remove the unknown materials present in tap water, which improved the optical clarity.

![Water tank](image)

**Figure 3.14:** Water tank used to conduct UEWE tests. The bottom plate was attached to four optical posts to provide vertical adjustment and a system for rigidly mounting tank to the optical table.

The wire was held between two copper micro-alligator clips. The clips were soldered to 5” lengths of 1/8” diameter copper rods which were spaced apart by 6 mm. The rods were mounted to a 1” x 4” x 1/8” acrylic plate, which insulated the wire and clips from the aluminum tank. The wire clip assembly is shown in Figure 3.15. A small piece of electrical tape was wrapped around one of the wire clips to prevent an accidental short circuit. Before every test, needle nose pliers were used to flatten the ends since they were normally deformed after each test. Then the mating surfaces of the clips were sanded with 400 grit or finer sandpaper to remove any surface roughness or remaining sections of wire that bonded to the clips from previous tests. The wire being tested was cut to a length of 10-15 mm and placed in the clips, approximately
2 mm from the ends of the clips. The wire and clip holder mount was then placed inside the water chamber with the wire oriented perpendicular to the light path shown in Figure 3.16.

Figure 3.15: A) Copper wire clips soldered to 1/8” copper rods and mounted on an acrylic plate. B) The clips were separated by a spacing of roughly 6 mm. C) The UEWE bent and deformed the clips every test. D) The clip ends were flattened and straightened by pliers after every test. E) Every wire was placed within 2 mm from the ends of the clips.

The electrodes were connected to a custom made fireset, used to provide the electrical discharge for the UEWE, displayed in Figure 3.17. The discharge unit contained a 1 µF capacitor capable of storing an electrical charge up to 5000 V. For this experiment, the unit was discharged when the capacitor had been charged to 4250-4400 V, which would give an energy output of 9.03-9.68 J. The fireset was operated at this lower voltage range to prevent damage to the internal circuitry.
Figure 3.16: The image on the left shows the wire clip mount positioned in the water tank with power supply leads connected to the copper rods. The mount was centered on the tank and held in place by electrical tape. A view through the window port shows the wire and wire clips in the image on the right.

Figure 3.17: The custom fireset provided the required electrical discharge to create a UEWE. The fireset contained a $1\mu$F capacitor rated for 5000 V with a potential discharge maximum energy of 12.5 J. For safety concerns, the unit was operated with a voltage between 4250 V and 4400 V to provide an energy output of 9.03-9.68 J.
3.2.4 Light Path

In typical absorption systems, refraction is neglected in the design of the optical light path. As the light moves through media with different indices of refraction, the direction of light is altered. Typically, this effect is neglected since the index of refraction of air is similar to that of the gas cloud being measured, and the setup resembles the simple schematic shown in Figure 1.16. It was assumed that a small collimated beam would be able to pass through the center of the bubble with limited refraction based on previous high speed imaging. High speed imaging showed an iron UEWE form a bubble with an optically clear center with minor distortions as seen by the image of the calibration grid present in the bubble in Figure 3.18. The initial experimental setup was based on this design as seen in Figure 3.19. This setup used the Powerlight 2500 DR with a pinhole to create point light source. A 12.7 mm f/4 lens collimated the light and passed it through the water tank and combustion bubble created by the exploding wire. The light was then collected by a 25 mm f/4 lens and focused on the slit of the spectrometer. A shutter, placed in front of the slit, prevented early emission from the wire from entering the spectrometer, so only the collimated light was detected.

![Image showing the optical clarity of a bubble created from a UEWE. The image of the calibration grid was easily transmitted through the bubble and it appeared as though the only distortion was a function of magnification. Each line on the calibration grid in the background was separated by 0.5".](image)

Figure 3.18: Image showing the optical clarity of a bubble created from a UEWE. The image of the calibration grid was easily transmitted through the bubble and it appeared as though the only distortion was a function of magnification. Each line on the calibration grid in the background was separated by 0.5".
Unfortunately, after several tests of varying the wire orientation, position, length, and shutter timing, no absorption signal was observed. The only spectral signals observed were from the emission created by the plasma within the first 200 µs of the explosion. The original assumption that refraction of the light would be minimal if the beam was focused on the center of the bubble was not valid. A simple experiment was setup to confirm that a collimated beam would be refracted and not transmitted directly through the UEWE bubble. The Phantom v7.0 high speed camera was setup to image a UEWE with a small 405 nm laser beam centered just below the wire. A neutral density filter was placed in front of the camera to reduce the intensity of the laser and protect the camera. The image sequence for the iron UEWE with a laser is shown in Figure 3.20. Once the bubble expanded into the path of the laser, the laser was no longer observed until the bubble collapsed near 3.42 ms.

Since refraction cannot be neglected for underwater bubbles, a ray tracing program, OSLO EDU Edition 6.4.6, was used to determine the path of light
for an idealized situation. The gas bubble was modeled as a 1” diameter spherical air cavity, since it was assumed that the index of refraction of air would be similar to that of a UEWE bubble. This model only accounts for the light path once the UEWE had transitioned from a small high pressure plasma to a gaseous bubble. Additionally, the actual bubble transitions from an elliptical shaped bubble with its major axis parallel to the bench top to an elliptical bubble with its major axis perpendicular to the bench top. It can be assumed that this model is accurate for two dimensional cross sections of the bubble that are approximately circular.

Figure 3.21 shows the calculated effects of a collimated beam transmitted through a Borofloat window, water, air cavity, water and Borofloat window again. The windows on the chamber ends are 2” in diameter since this is the maximum viewable diameter for the window ports. For this idealized situation, the light exited the water chamber as a rapidly diverging set of rays. By placing a large lens with a low f-number in front of the collimated beam, the divergence of the exiting beam was significantly reduced as shown in Figure 3.22. Beyond a few rays at the edge of the initial lens, which rapidly diverge, a majority of the initial beam can be collected with another lens and focused onto a detector. The results of the ray tracing were verified by comparing them to a simplified version of light only passing through an air bubble in water [69].

Based on the ray tracing, a new setup was designed to account for the refraction of light. A sketch of the setup is shown in Figure 3.23. A blackout board with a 2.75” diameter hole was placed in front of the flash to prevent stray light from entering the optics. The light proceeded through a 2.375” diameter aperture, in an effort to promote a loosely collimated beam of light. The beam then contacted a 75 mm f/1.33 plano-convex lens, which focused the light to the center of the water chamber. The light exited the chamber and was collected by a 50 mm f/2 double convex lens that focused the light onto a 25 µm entrance slit on the spectrometer.

The complete optical train can be seen in the left image of Figure 3.24. The middle and right images show the blackout panel and the aperture used to loosely collimate the flash. The large focusing lens is shown on the right of the water tank in Figure 3.25, and the double convex lens is shown on the left. The double convex lens was used instead of a plano-convex lens, since the light coming from the bubble was divergent and not collimated,
Figure 3.21: A collimated beam of light transmitted through the experimental water chamber with an idealized spherical air bubble representing the gas bubble from an UEWE. The light exited the chamber as a set of fast divergent rays.

Figure 3.22: A collimated beam of light passed through a large lens with a focal length of 100 mm. The light was then focused through the water chamber and onto the center of the air cavity. Besides for a few rays on the edge of the initial lens, the light exited the air cavity as a slowly diverging set of rays which can could be collected and focused to a detector.
Figure 3.23: The flash passed through a 2.75” aperture on a blackout panel to reduce the amount of stray light. Then a 2.375” diameter aperture was used to promote nearly collimated light through the system. A large 75 mm f/1.33 lens focused the light into the chamber and the center of the bubble. The exiting light was collected by a 50 mm f/2 lens and focused on the entrance slit of the spectrometer. Approximate distances are listed as a reference for spatial constraints.

and double convex lenses are better at focusing diverging rays of light than plano-convex lenses.

In order to accurately focus the light from the lamp through the system and onto the slit of the spectrometer, a technique was developed to simulate the refractive properties of a gas cavity during alignment. A substitute for the gas bubble required a permanent and fixed cavity with an optically transparent envelope in the near UV. Based on this requirement, an S-8 light bulb was used to simulate the gas bubble. The S-8 light bulb was chosen because the shape resembled the vertically elongated ellipse observed in high speed images and the bulb had a maximum horizontal diameter of one inch. The bulb, displayed in Figure 3.26, had the filament carefully removed, so that only the glass envelope and brass base remained. The bulb was attached to a 1/4-20 bolt, that was threaded to a thin aluminum plate, which provided vertical adjustment.

When the bulb was centered in the middle of the tank filled with water, the light exited the water tank as a slowly diverging beam of light similar to the predictions made in OSLO. The collection lens was able to accurately
**Figure 3.24:** The image on the left shows the complete optical setup. The aperture is shown in the middle image and the blackout panel with flash is shown on the right.

**Figure 3.25:** Image of the focusing lens on the right side of the water tank and the collection lens on the left side of the tank.
Figure 3.26: Left) An S-8 light bulb without the filament is attached to a 1/4-20 bolt, which is threaded into an aluminum plate. Aluminum tape was used to level the aluminum plate, since the threaded hole was not true with the vertical axis of the bulb. Right) The bulb, placed in the water, was used to focus the light from the flash and f/1.33 lens into a slowly diverging beam.

focus the light down to a small spot size on the slit of the spectrometer. Without this method, alignment of optics with the spectrometer were nearly impossible and only achieved by trial and error with several UEWEs.

3.2.5 Spectrometer and Detector

The light from the system was focused onto the slit of the spectrometer. The Jobin Yvon SPEX HR-460 spectrograph was used in this experiment with a 25 $\mu$m slit and a 2400 gr/mm reflection grating. The CCD detector used with the spectrograph was an Andor model DV420-UV-FK. The detector was operated in fast kinetics mode (FK mode), where only a single row of pixels was used to detect the signal. The pixel readout is shifted downward onto the unused portion of the chip on the order of a few microseconds, enabling the detector to give microsecond time resolution.

The detector was designed to operate in FK mode with exposure times of 1, 2, 4, and 16 $\mu$s. When these exposure times were used, the signal levels detected were too low to be used for absorption measurements. The detector was capable of operating with longer exposure times in the FK mode, but the inputted exposure time was not the actual exposure. It was desired to have exposures times of 100 $\mu$s, which required an inputted exposure time of 103 $\mu$s for 30 frames. This was determined by monitoring the signal from the Fire channel on the I/O box and measuring the time interval between
successive rise times which indicated the detector was actively detecting a signal. A sample plot of the signal recorded by the Fire channel is shown in Figure 3.27. It is unknown as to whether the detector was exposed to the light signal during the down phase of each period. For that reason, the measurements are reported purely as the time period over which the measurement occurred and not an absolute exposure time.

The spectrometer and detector were calibrated for wavelength by using an iron hollow cathode lamp. The iron hollow cathode lamp was a convenient choice for a calibration source, since the primary element investigated in the absorption experiment was iron. The pixel locations of the peaks for six iron transition lines were used to determine the wavelength calibration. The dispersion was 0.0196 nm/pixel with a 2.36 pixel resolution (FWHM) to give a spectral resolution of 0.0463 nm for a range of 5.5 nm centered at 374.25 nm.

Figure 3.27: The Andor detector was triggered at 0.0 ms. The Fire signal corresponds to the time period when the detector is active. An exposure time of 103 µs in the detector software gave a period of 100 µs between successive voltage rise times.
All experiments used a PicoScope 3424 oscilloscope to record the output timing signal from the Andor detector, the flash intensity, trigger from the pulse generator and the pulse received by the fireset from the pulse generator. The oscilloscope trace of each signal confirmed the timing relationships between the fireset, flash, and detector. These traces were primarily used to track the time periods exposed to the greatest intensity by the flash. In order to get appropriate intensity levels for various time periods of the bubble expansion, the flash was delayed to shift the timing of the peak intensity.

3.2.6 Background Signal

The background signal in most absorption systems is observed by recording the intensity without the medium of interest, i.e. an explosive, flame, or gas cloud, in the light path. In other systems the light source is split, such as a pulsed laser light source, with one section going through the medium of interest and the other routed around the event, going directly to the detector. Both of these techniques are fairly straightforward when operating in air with a collimated light source. But a problem arises when performing absorption on an underwater oscillating gas bubble. In order to have an appropriate reference signal, the light reference needs to experience the same conditions, specifically the refraction of light by the water/gas and gas/water interfaces, as the experimental light path without the absorptive medium. In order to accomplish this, a dynamic gas bubble, similar to the one created by the iron wire, without atomic absorption lines in the region of interest needed to be created.

Copper was chosen as the background wire, since it does not have ground state transitions in the 370 - 378 nm region of interest. A 40 AWG copper wire, diameter of 0.0031”, was chosen to create a non-absorptive oscillating gas bubble. High speed images were taken of iron and copper wires exploding underwater to compare the dynamics of the each. The wires were observed in two different orientations: parallel and perpendicular to the optical path. A partial image sequence of the parallel configuration is shown in Figure 3.28 and the perpendicular configuration is shown in Figure 3.29 for each wire.

From the high speed images, three different bubble radii were measured. The vertical radius was measured for each wire and configuration and plotted
Figure 3.28: Image sequence of Fe (top) and Cu (bottom) exploding wires parallel to the light path. The spacing between the gridlines was 0.5".

Figure 3.29: Image sequence of Fe (top) and Cu (bottom) exploding wires perpendicular to the light path. The spacing between the gridlines was 0.5".
in Figure 3.30a. The vertical radii were extremely similar for the copper and iron wires regardless of the orientation. The horizontal radii, plotted in Figure 3.30b, showed two different expansion rates which were due to the orientation of the wires. For wires in the parallel configuration, the bubble radii observed was a result of the wire expanding radially outward from its axis. In the perpendicular orientation, the bubble radii initially observed the 5 mm long wire and the axial expansion of the bubble. For both orientations, the copper and iron wires had almost the same growth rates. An approximate volume was calculated by \( \frac{4}{3} \pi R_V R_H^2 \), based on the vertical radius, \( R_V \), and the square of the horizontal radius, \( R_H \), for each image sequence. As shown in Figure 3.30c, the copper and iron wires have the same values for volumetric expansion. The actual volume based on the vertical radius and the horizontal radii of the parallel and perpendicular orientations was not determined due to differences in timing for the image sequence, but the actual volume growth rate does lie between the parallel and perpendicular orientations.
Figure 3.30: A) Vertical bubble radii, B) horizontal bubble radii, and C) the bubble volumes for copper (square) and iron (diamond) wires with a length of approx. 5 mm and positioned either parallel (closed) or perpendicular (open) to the light path.
CHAPTER 4
THEORETICAL ATOMIC ABSORPTION

This chapter describes the equations and methods required to create theoretical atomic absorption traces and the process of fitting the theoretical traces to experimental data. The first section defines the fundamental equations used to create the theoretical absorption traces. The equations and notation utilized in this section are primarily based on equations by Laurendeau [12]. The other section of this chapter describes the computational techniques and methods used to efficiently calculate and fit the theoretical absorption traces to the experimental data signals to determine a temperature, pressure, and iron number density for a given test condition.

4.1 Theoretical Absorption

The fundamental equation used to determine absorption or the amount of attenuation is known as the Beer-Lambert attenuation law:

\[ I_\nu(L) = I_\nu(0) e^{-k_\nu L} \] (4.1)

\( I_\nu(L) \) is the intensity for a given wavelength passing through a gas cloud, or gas bubble, with a path length of \( L \). \( I_\nu(0) \) is the incoming intensity for a given wavelength that has not passed through the gas. The remaining term, \( k_\nu \), is the spectral absorption coefficient, which typically defines the shape of an absorption signal since the path length is generally predetermined. Absorption signals are normally expressed as the percentage of incoming irradiance absorbed, which can be seen by rearranging Eq. (4.1).

\[ \frac{I_\nu(L)}{I_\nu(0)} = e^{-k_\nu L} \] (4.2)
Because of the dynamic nature of the bubble and the multiple light paths through the gas bubble, the path length cannot easily be determined and fixed as in normal absorption experiments. The path length will be treated as an unknown variable and will be fitted to the experimental data. The remaining unknown variable is the spectral absorption coefficient, $k_\nu$, which is defined by

$$k_\nu = (h\nu/c) B_{lu} n_l Y(\nu) \quad (4.3)$$

Planck's constant and the speed of light, $h$ and $c$ respectively, are known constants unlike the remaining terms. The remaining terms, $B_{lu}$, $n_l$, and $Y(\nu)$, are defined for each individual electronic transition and are referred to as the stimulated absorption Einstein coefficient, lower energy number density, and lineshape, respectively. In order to calculate these terms, several other spectral constants are required. $B_{lu}$ will be described first, followed by the term $n_l$, and finally the most complex calculation, $Y(\nu)$, the lineshape.

$B_{lu}$ is related to the spontaneous emission Einstein coefficient, known as $A_{ul}$, by Eq. (4.4). $A_{ul}$ is a measured constant for each transition and is available for most electronic transitions in online databases such as NIST and Kurucz [70,71]. Since the transitions are only electronic, the upper and lower degeneracies of the transition, $g_u$ and $g_l$, are obtained by the simple relationship to the total angular momentum quantum number as shown in Eq. (4.5). $A_{ul}$ and other values for the 14 atomic iron transitions examined in this experiment are listed in Table 4.1.

$$B_{lu} = \frac{g_u}{g_l} \frac{c^3}{8\pi h\nu^3} A_{ul} \quad (4.4)$$

$$g = 2J + 1 \quad (4.5)$$

The second unknown variable required to solve for $k_\nu$ is the lower number density for each transition, $n_l$, as defined by Eq. (4.6). The upper fraction in the exponential is written in the traditional format using $\epsilon_l$ with units of Joules, and the second version simply shows the conversion needed to convert $E_l$ from $cm^{-1}$ to Joules. The total number density of iron is $n_{Fe}$, which could be determined based on the total number of iron atoms in the system. The numerical calculation is relatively straightforward, but extremely difficult to
calculate in practice, since the amount of iron that was transformed from a solid into a gaseous state is usually very difficult to determine. For this reason, \( n_{Fe} \) is one of the variables which is fitted to the data.

\[
n_l = \frac{g_l n_{Fe}}{Z_{el}} \exp \left( -\frac{\epsilon_l}{kT} \right)
= \frac{g_l n_{Fe}}{Z_{el}} \exp \left( -\frac{E_l \cdot h \cdot c \cdot 100}{kT} \right)
\] (4.6)

\( Z_{el} \) is the electronic partition function and is defined in Eq. (4.7), where \( \epsilon_j \) is the energy associated with the \( j^{th} \) energy level and the corresponding degeneracy is \( g_j \), where \( g \) can be calculated from \( J \) using Eq. (4.5). For moderate temperatures (\( \leq 7000 \) K), the partition function is generally only calculated for the first 20 energy levels, since these energy levels account for \( \geq 90\% \) of the partition function. Due to the computational efficiency of Matlab and for completeness, all 148 energy levels for iron based on the NIST database were used to determine \( Z_{el} \) for the theoretical calculations and are shown in Table 4.2.

\[
Z_{el} = \sum_j g_j e^{(-\epsilon_j/kT)}
\] (4.7)

The final parameter needed to determine \( k_\nu \) is the lineshape, \( Y(\nu) \). The lineshape of an atomic transition is affected by several parameters which lead to line broadening. The main causes associated with line broadening for this experiment are Doppler, pressure, and instrumental broadening. The various types of broadening will be described along with their fundamental equations, and the overall approach to modeling these effects as one lineshape.

Doppler broadening is caused by the random motion of gas particles. As is the case in classical physics, the gas particles can be moving toward or away from the observer (detector), which causes a Doppler shift. The Doppler shift creates a distribution of frequencies around the central wavelength, which has a Gaussian profile described by Eq. (4.8). The full-width at half-maximum (FWHM), \( \Delta \nu_D \), is defined in Eq. (4.9), where \( \nu_o \) is the central frequency and \( m \) is the molecular weight in atomic mass units. As previously mentioned, the equations and notation in this chapter are based on the work by Laurendeau [12] unless stated otherwise. It can be observed that the only ex-
Table 4.1: Calculated and measured variables for iron transitions. $\lambda$ is the central wavelength of each transition, $A_{ul}$ is the spontaneous emission Einstein coefficient, $E_l$ and $E_u$ are the lower and upper energy levels in $cm^{-1}$, respectively, and $J_l$ and $J_u$ are the lower and upper total angular momentum quantum numbers. $g_l$ and $g_u$ are the lower and upper degeneracies and $B_{lu}$ is the stimulated absorption Einstein coefficient. $\lambda$, $A_{ul}$, $E_l$, $E_u$, $J_l$, and $J_u$ were obtained from the Kurucz database [71], while $g_l$, $g_u$, and $B_{lu}$ were calculated from the previous terms.

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Table 4.2: Iron energy levels in \( cm^{-1} \) and corresponding angular momentum quantum numbers from NIST [70].

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<td>1</td>
<td>100</td>
<td>33946.931</td>
<td>2</td>
</tr>
</tbody>
</table>
ternal influence on this lineshape is the temperature, $T$, which is the primary parameter being fitted in this experiment.

$$Y_D(\nu) = \frac{2}{\Delta \nu_D} \sqrt{\frac{\ln 2}{\pi}} \exp \left[-4 \ln 2 \frac{(\nu - \nu_o)^2}{\Delta \nu_D^2}\right]$$ (4.8)

$$\Delta \nu_D = \frac{2\nu_o}{c} \sqrt{2 \ln 2 \frac{kT}{m}}$$ (4.9)

Pressure broadening is a result of the collision rate between the gases. As the pressure increases within a system, the gas collisions increase, which causes a broadening of the signal. This broadening, which has a Lorentzian shape, is described by Eq. (4.10) where $\Delta \nu_C$ is the collisional FWHM.

$$Y_C(\nu) = \frac{\Delta \nu_C}{2\pi} \frac{1}{(\nu - \nu_o)^2 + (\Delta \nu_C/2)^2}$$ (4.10)

$$\Delta \nu_C = \frac{2Z^*}{\pi}$$ (4.11)

were, $Z^*$, the collisional frequency for a pure gas, as defined in Eq. (4.12).

$$Z^* = 4n\sigma^2 \left(\frac{\pi kT}{m}\right)^2$$ (4.12)

In Eq. (4.12), $\sigma$ is the hard sphere diameter of iron, which is 248 pm [72]. This diameter is based on the atomic radius measurement of solid iron in a Body-Centered-Cubic (BCC) crystal structure. Also, $n$ is defined as the total number of gas particles, which is different than the total number of iron gas particle, $n_{Fe}$.

$$n = \frac{P}{kT}$$ (4.13)

For this experiment, it is assumed that the only gas within the bubble was iron vapor. This is probably not true, since the iron wire, while 99.995% pure, has some minute impurities, and the water surrounding the wire is most likely converted to water vapor or dissociated to hydrogen and oxygen gases during the UEWE. However, since the pressure dependence, as shown in Section 6.2.2, is very minimal, the error in assuming a pure gas is very small compared to the other sources of error in this experiment.
Both the \( Y_D(\nu) \) and \( Y_C(\nu) \) are defined by the internal parameters of the experiment, temperature and pressure. Since both of these lineshapes are important, they must be combined by convolution to produce a third lineshape type, known as a Voigt profile. The convolution of a Gaussian and a Lorentzian profile produces a Voigt profile and is a fairly complex calculation, [73], as shown below.

\[
V(x, y) = \frac{y}{\pi} \int_{-\infty}^{\infty} \frac{\exp(-u^2)}{y^2 + (x - u)^2} du 
\]

\[
y = \sqrt{\ln 2} \frac{\alpha_L}{\alpha_G} 
\]

\[
x = \sqrt{\ln 2} \frac{(\nu - \nu_o)}{\alpha_G} 
\]

where \( u \) is a dummy variable for the integral and \( \alpha_G \) and \( \alpha_L \) are the half-width at half-maximums (HWHM) for Gaussian and Lorentzian profiles, respectively. The Voigt profile is very computationally intensive, and while it can be numerically calculated, a simpler analytical semi-Voigt equation can be used instead to decrease the computational time, as described in Section 4.2.3.

Once the Voigt lineshape, or semi-Voigt lineshape, has been calculated, the final influence on lineshape to be determined is the instrumental broadening. When discussing instrumental broadening associated with a spectrometer, there are several parameters which influence signal broadening. The primary influences of broadening are the slit width, diffracting grating, and pixel size.

The lineshape of the instrument broadening, \( Y_I(\nu) \), was determined by examining the shape of the calibration lines from the iron hollow cathode lamp. By fitting Gaussian, Lorentzian, and Voigt line profiles to each calibration line, it was possible to see which one had the best fit with the smallest residual. These results are shown in Table 4.3, along with two sets of averages for the errors, FWHM, and R-squared values for each lineshape. One of the averages included values for all six wavelengths used for calibration, but a second average was taken that removed the 374.55613 nm line, since there is also a 374.58994 nm transition line. While the 374.55613 nm line is a stronger transition than the 374.58994 nm line, this weaker line skews the shape of the transition. From the table, the best fit for the calibration lines
was achieved with a Gaussian fit, which resulted in a FWHM of 2.36 pixels. The pixel is a meaningless unit and is converted to units of frequency (1/s) after wavelength calibrations have been performed to give the instrumental FWHM, ∆ν_I. The difference in FWHM between the two averages is minimal, and essentially either of the two values will give the same end result as explained in Section 6.2.2.

In order to incorporate the instrumental broadening effects, a Gaussian line profile based on Eq. (4.8) is convolved with the previously defined Voigt profile for each transition to produce an overall line profile Y(ν) for each transition. Now k_ν can be calculated for each transition for a given T, P, and n_{Fe} by using Eq. (4.3). A plot showing the individual k_ν values for each transition are shown in Figure 4.1 for a given T, P, and n_{Fe} of 3700 K, 25 MPa, and 2x10^{10} atoms/m^3, as well as the overall absorption coefficient.

![Figure 4.1](image)

**Figure 4.1:** Individual absorption coefficients with respect to wavelength for 4 iron transitions are shown and the overall absorption coefficient (black) when all transitions are combined into a single trace for T=3700 K, P=25 MPa, and n_{Fe}=2x10^{10} atoms/m^3.

When all of the equations are combined together, the simple expression for absorption, Eq. 4.2, becomes Eq. (4.17). The unknowns in this equation are Z_{el}, T, Y(ν), n_{Fe}, and L. The first three terms are functions of temperature and pressure, while n_{Fe} and L are independent of temperature and pressure. When an experimental absorption signal is fitted to a theoretical absorption
Table 4.3: Comparison of Potential Instrument Line Profiles and FWHMs.

<table>
<thead>
<tr>
<th>Lineshape</th>
<th>Wavelength (nm)</th>
<th>Center (pixel)</th>
<th>Error (pixel)</th>
<th>FWHM (pixel)</th>
<th>Error (pixel)</th>
<th>Adjusted $R^2$ Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voigt</td>
<td>374.4854</td>
<td>326.78758</td>
<td>0.16081</td>
<td>2.63112</td>
<td>0.48963</td>
<td>0.94242</td>
</tr>
<tr>
<td></td>
<td>374.82622</td>
<td>333.25471</td>
<td>0.06141</td>
<td>2.76395</td>
<td>0.33163</td>
<td>0.99144</td>
</tr>
<tr>
<td></td>
<td>374.55613</td>
<td>346.54245</td>
<td>0.16320</td>
<td>2.95507</td>
<td>0.47026</td>
<td>0.94385</td>
</tr>
<tr>
<td></td>
<td>373.71316</td>
<td>389.88060</td>
<td>0.13276</td>
<td>2.31874</td>
<td>0.20495</td>
<td>0.96726</td>
</tr>
<tr>
<td></td>
<td>373.48638</td>
<td>401.42569</td>
<td>0.11009</td>
<td>2.12106</td>
<td>0.16749</td>
<td>0.98026</td>
</tr>
<tr>
<td></td>
<td>371.99348</td>
<td>477.38980</td>
<td>0.06978</td>
<td>2.17934</td>
<td>0.08032</td>
<td>0.99431</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.11634</td>
<td>2.49488</td>
<td>0.29071</td>
<td>0.96992</td>
</tr>
<tr>
<td>Average w/o 374.55613 nm</td>
<td></td>
<td></td>
<td>0.10697</td>
<td>2.40284</td>
<td>0.25480</td>
<td>0.97514</td>
</tr>
<tr>
<td>Gaussian</td>
<td>374.4854</td>
<td>326.77590</td>
<td>0.08893</td>
<td>2.61889</td>
<td>0.28946</td>
<td>0.95699</td>
</tr>
<tr>
<td></td>
<td>374.82622</td>
<td>333.23755</td>
<td>0.03763</td>
<td>2.55689</td>
<td>0.13623</td>
<td>0.99205</td>
</tr>
<tr>
<td></td>
<td>374.55613</td>
<td>346.62184</td>
<td>0.08581</td>
<td>2.80994</td>
<td>0.26857</td>
<td>0.96193</td>
</tr>
<tr>
<td></td>
<td>373.71316</td>
<td>389.98090</td>
<td>0.04612</td>
<td>2.31852</td>
<td>0.12231</td>
<td>0.98415</td>
</tr>
<tr>
<td></td>
<td>373.48638</td>
<td>401.43147</td>
<td>0.04565</td>
<td>2.13877</td>
<td>0.12781</td>
<td>0.98328</td>
</tr>
<tr>
<td></td>
<td>371.99348</td>
<td>477.43826</td>
<td>0.01472</td>
<td>2.17208</td>
<td>0.04113</td>
<td>0.99829</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.05314</td>
<td>2.43585</td>
<td>0.16425</td>
<td>0.97945</td>
</tr>
<tr>
<td>Average w/o 374.55613 nm</td>
<td></td>
<td></td>
<td>0.04661</td>
<td>2.36103</td>
<td>0.14339</td>
<td>0.98295</td>
</tr>
<tr>
<td>Lorentzian</td>
<td>374.4854</td>
<td>326.73783</td>
<td>0.10269</td>
<td>2.97753</td>
<td>0.62313</td>
<td>0.94357</td>
</tr>
<tr>
<td></td>
<td>374.82622</td>
<td>333.24969</td>
<td>0.03602</td>
<td>2.94774</td>
<td>0.24376</td>
<td>0.99272</td>
</tr>
<tr>
<td></td>
<td>374.55613</td>
<td>346.62609</td>
<td>0.09147</td>
<td>2.91253</td>
<td>0.51963</td>
<td>0.95339</td>
</tr>
<tr>
<td></td>
<td>373.71316</td>
<td>389.97578</td>
<td>0.09263</td>
<td>2.34353</td>
<td>0.31324</td>
<td>0.94955</td>
</tr>
<tr>
<td></td>
<td>373.48638</td>
<td>401.43466</td>
<td>0.03669</td>
<td>1.73671</td>
<td>0.25844</td>
<td>0.98110</td>
</tr>
<tr>
<td></td>
<td>371.99348</td>
<td>477.46029</td>
<td>0.02331</td>
<td>1.80195</td>
<td>0.16629</td>
<td>0.99235</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.06380</td>
<td>2.45333</td>
<td>0.35408</td>
<td>0.96878</td>
</tr>
<tr>
<td>Average w/o 374.55613 nm</td>
<td></td>
<td></td>
<td>0.05827</td>
<td>2.36149</td>
<td>0.32097</td>
<td>0.97186</td>
</tr>
</tbody>
</table>
signal, only the product of the iron number density and path length can be fitted to the signal and not the individual variables. As a result of this, a fitting parameter, Λ, was fit to each experimental absorption curve along with temperature and pressure, where Λ is the product of the iron number density, \( n_{Fe} \), and path length, \( L \), with units of \( \text{atoms/m}^2 \).

\[
\frac{I_\nu(L)}{I_\nu(0)} = e^{\exp \left[ -\frac{\hbar \nu g_i}{c Z_{el}} \exp \left( -\frac{\epsilon_i}{kT} \right) B_{lu} n_{Fe} L Y(\nu) \right]} \tag{4.17}
\]

For a given \( T, P, \) and \( n_{Fe} \), \( k_\nu \) can be found and input into Eq. 4.2 to produce a theoretical absorption signal. This process is illustrated in Figure 4.2 by using the information from Figure 4.1 and a path length of 0.015 m. In Figure 4.1 it can be seen that for the given conditions, the transitions at 374.5561 nm and 374.5899 nm appear as a single transition in the overall absorption coefficient. This effect also leads to the appearance of only 13 transitions in Figure 4.2 instead of 14 troughs associated with each of the fitted transitions.

![Figure 4.2](image)

**Figure 4.2:** Theoretical absorption curve for iron at \( T=3700 \text{ K}, P=25 \text{ MPa}, n_{Fe}=2\times10^{10} \text{ atoms/m}^3 \), and \( L=0.015 \text{ m} \).
4.2 Absorption Coding Techniques

The previous section described the equations and variables needed to calculate a theoretical absorption signal. This section will describe the techniques required to fit the experimental absorption signals to the theoretical signals, in order to determine a temperature, pressure, and fitting parameter. Several procedures are required to justifiably fit the theoretical signals to the raw data.

4.2.1 Calibration

The detector records data as intensity per pixel, which is essentially meaningless data unless the pixels are calibrated to a known wavelength distribution. Before any testing was performed, a wavelength calibration was performed with an iron hollow cathode lamp. Since iron has several transitions in the region of interest compared to other calibration sources (i.e. nickel, mercury, and thorium) and is the same element being used in the experiment, it was an easy choice to use as a calibration source.

Unlike the experiment, there is no temporal dependence on the wavelength calibration, so the spectrometer was set to record a single shot with an exposure of 21 ms. Figure 4.3 shows the intensity from the hollow cathode lamp for the region of interest on the detector versus pixels and wavelength. While the detector does have 1024 pixels across its face, only the pixels of interest were used for the wavelength calibration. The exact center for each peak was determined by using the fitting algorithms in OriginPro 8.6.0. The lineshape of the transitions were determined to be Gaussian as previously discussed and the peak centers are listed in the Table 4.3. A second order polynomial was fit between the known wavelength transitions and the calculated pixel centers. By applying the polynomial fit to each pixel, a central wavelength was determined for each pixel.

The 374.55613 nm transition was ignored when determining the second order polynomial, as was done previously when determining the correct line shape for the instrumental broadening. When the coefficients of the polynomial were calculated with and without this line, there was actually no difference in their values. This essentially means that while the weaker 374.5899 nm line skews the wings and overall shape, the center of the lineshape was
dominated by the 374.55613 nm line. Additionally, the relationship between pixel and wavelength was almost completely linear, so the small change in peak center essentially goes undetected.

![Image](image-url)

**Figure 4.3:** (Above) Intensity versus pixel from the detector showing the transition lines from an iron hollow cathode lamp. (Below) Intensity versus wavelength (nm) after the pixels have been correlated to a wavelength. Even though the detector has 1024 pixels, only the pixels of interest are shown and involved in the wavelength calibration.

### 4.2.2 Convolution

In section 4.1, the process mentioned for calculating the overall lineshape involved the convolution of the lineshapes from Doppler, pressure, and instrumental broadening. The procedure was described in the order that broadening is expected to occur. Broadening first occurs in the actual experiment (Doppler and pressure), and then in the instrument. The convolution of lineshapes becomes very complex, if the convolution is done in this order. The first step would involve a Gaussian and a Lorentzian, which produces a Voigt profile. This convolution is complicated, but not as difficult as the next step involving the Gaussian from the instrumental broadening. The convolution of a Voigt with a Gaussian may be straightforward in theory, but this is extremely difficult in terms of coding.
Luckily, convolution is both commutative and associative. This allows the two Gaussian lineshapes to be convolved together, first, and then convolved with the Lorentzian profile as expressed by Eq. (4.18). By changing the order, the first convolution becomes a simple identity. The convolution of two Gaussians results in a Gaussian with a FWHM, $\Delta \nu_G$, defined by Eq. (4.19). Once the new Gaussian is formed, it is convolved with the Lorentzian lineshape from pressure broadening to produce a Voigt profile as previously mentioned.

\[
Y(\nu) = Y_D(\nu) \ast Y_C(\nu) \ast Y_I(\nu) \equiv (Y_D(\nu) \ast Y_I(\nu)) \ast Y_C(\nu) \quad (4.18)
\]

\[
\Delta \nu_G = \sqrt{\Delta \nu_D^2 + \Delta \nu_I^2} \quad (4.19)
\]

### 4.2.3 Voigt vs Semi-Voigt

The Voigt profile described in Section 4.1, Eqs. (4.14-4.16), is the convolution of a Gaussian profile with a Lorentzian profile. When this set of equations is solved numerically (see Appendix C.7), the integral requires a unit spacing (U) between the limits. As a side note, the Voigt profile was calculated with limits of $\pm 6$ instead of $\pm \infty$ without any loss in accuracy as was shown in [74]. As this unit spacing is reduced in size, the resolution and accuracy of the profile increases but the computational time required to solve the equation drastically increases. As an example, for a single transition at 373.0 nm with the Gaussian and Lorentzian HWHMs both set at $1 \times 10^{10}$ 1/s and a wavelength range from 372 nm to 374 nm with 0.002 nm increments and unit spacing set at 1e-3, the total computational time for Matlab was 0.419 sec. When the Voigt code was calculated for unit spacings of 1e-4, 1e-5, and 1e-6, the computational time was 3.028 sec, 50.329 sec, and 452.071 sec, respectively. Regardless of the accuracy for the computational times, the higher resolution Voigt profiles drastically increase the computational time and do not provide any noticeable improvement in accuracy as depicted in Figure 4.4.

The computational time for some of the unit spacings may be acceptable when only a single transition is being calculated over a small range, but the theoretical absorption signals need to be calculated for the Voigt function.
of every transition over large ranges as the HWHMs increase in size, which would require an unrealistic amount of computational time if implemented.

In order to improve the computational time, a Voigt approximation was utilized. An analytical approximation to the Voigt function, Eqs. (4.20) & (4.21), was developed by Abrarov [75]. The approximation takes Eq. (4.14) and applies a Fourier expansion to the exponential and adjusts the limits of integration to create the following set of equations where \( x \) and \( y \) are previously defined by Eqs. (4.15) & (4.16). The error associated with this approximation in comparison to a Voigt function with unit spacing of 1e-6 is shown in Figure 4.4. The approximation has an error on the same order of magnitude as the other Voigt functions and has a computational time of 0.060 sec, which is an order of magnitude faster than even the coarsest Voigt approximation.

\[
V(x, y) \approx \frac{1}{2\sqrt{\pi}} \sum_{n=0}^{N} a_n \left[ \frac{(in\pi\tau_m \pm \tau_m^2 y)(1-e^{-(in\pi \pm \tau_m y)\cos(\tau_m x)})+e^{-(in\pi \pm \tau_m y)\tau_m^2 x \sin(\tau_m x)}}{\tau_m^2 x^2 - (n\pi - i\tau_m y)^2} \right. \\
- \left. \left( \frac{(in\pi\tau_m - \tau_m^2 y)(1-e^{(in\pi - \tau_m y)\cos(\tau_m x)})-e^{(in\pi - \tau_m y)\tau_m^2 x \sin(\tau_m x)}}{\tau_m^2 x^2 - (n\pi + i\tau_m y)^2} \right) \right] \\
- a_0 \left[ y - e^{-\tau_m y}(y \cos(\tau_m x) - x \sin(\tau_m x)) \right] \\
\frac{2\sqrt{\pi}}{2\sqrt{x^2+y^2}}
\]  
(4.20)

\[
a_n \approx \frac{2\sqrt{\pi}}{\tau_m} \exp\left(-\frac{n^2 \pi^2}{\tau_m^2}\right), \quad n \leq \left\lfloor \frac{\tau_m^2}{2\pi} \right\rfloor
\]  
(4.21)
Figure 4.4: The error between the Voigt function operating with a unit spacing of 1e-6 is shown for U = 1e-3, 1e-4, and 1e-5 as well as the difference when the Semi-Voigt function developed by Abrarov was used.
4.2.4 Sub-Pixel

During an experiment, a continuous spectrum was dispersed across the detector and thus each pixel. For the calibration process, it was assumed that each pixel corresponded to a single wavelength, instead of a range of wavelengths. Assigning a single wavelength value for each pixel was acceptable during calibration; however, the intensity recorded by each pixel was not the intensity of that single wavelength. During the experiment, each pixel detected the intensities of a range of wavelengths and output a single value corresponding to the overall integrated intensity detected. Essentially, the intensity observed was the integral value of the intensity of all the wavelengths impinging on the pixel.

The theoretical calculations outlined in Section 4.1, are wavelength dependent, or more accurately frequency dependent. In order to fit the raw data, an absorption signal was calculated for each pixel based on its central wavelength. This allowed for a fairly easy comparison between the theoretical and experimental intensities for each pixel. The absorption signal that was calculated for each central wavelength was actually the integration of several wavelengths. This procedure, shown in Appendix C.5, mimicked what the detector observed and outputted for each pixel. From the wavelength calibration, a central wavelength was assigned to each pixel. The difference between the central wavelength of two adjacent pixels was divided into 10 even increments, and each increment was assigned to a sub-pixel. A simplified version of this process is illustrated in Figure 4.5.

![Figure 4.5: Simplified model of pixelation scheme shows how each pixel was subdivided into sub-pixels that were equally divided between adjacent pixels. Actual pixels were divided by approx. 0.02 nm and subdivided into increments of 0.002 nm when performed with a pixelation value of 10.](image)

Once the pixels were subdivided, the wavelengths were processed by the code shown in Appendix C.9 to produce an absorption signal. After the in-
tensity for each sub-pixel was calculated, each group of sub-pixels intensities were numerically integrated (Riemann sum) to produce a final value which was assigned to the original pixel as shown in Figure 4.6. This figure shows an absorption signal for a given $T$, $P$, and $\Lambda$ of 3700 K, 25 MPa, and $3 \times 10^8$ atoms/m$^2$ over a small wavelength range of 373.4-373.6 nm. The signal was plotted in three different ways, with the first being a single point calculated for the central wavelength of the pixel. The second version has the value of 10 sub-pixels plotted and then integrated to produce a single value for the central wavelength. And the third version of the signal has 100 sub-pixels and subsequent integrated value for every central wavelength. Based on the integration method, it can be seen that every pixel in the trough is slightly elevated, while pixels on the wings of the transitions observe a slightly lower value. The difference between values calculated with 10 sub-pixels and 100 sub-pixels is minimal, but the computational time is proportional to the pixelation value. Due to the computational time, a pixelation value of 10 was used for all theoretical data.

4.2.5 Background Adjustment

An absorption signal, as defined in Eq. (4.2), is the ratio of the intensity of a light source passing through a gaseous cloud to the intensity of the light source traveling through the same path without the absorptive gaseous cloud. As described in Section 3.2.6, the common approach to obtain the incoming irradiance signal, $I_o$, was not possible in this setup because interfaces between the water and gas bubble significantly impacted the path of the signal. For this reason, copper wire was used as a substitution for creating similar sized bubbles as those formed by iron wire. Because of this substitution, the transmission loss through the bubble in regions of non-absorbance, i.e. no atomic absorption lines, was different for the iron and copper wires. As a result, when the iron signal, $I$, was divided by the copper signal, $I_o$, the non-absorbance regions were not at unity or linear, as can been seen in Figure 4.7.

In order to adjust the background to unity, a third order wavelength dependent polynomial was fit to the intensities of the non-absorbing regions. A third order fit was chosen since a constant or linear correction factor would simply shift the signal and not correct for the curvature observed during most
Figure 4.6: Absorption signal for $T$, $P$, and $\Lambda$ of 3700 K, 25 MPa, and $3 \times 10^8$ atoms/m$^2$, zoomed in on a small wavelength range. The black diamonds show what would be plotted if a single value was used for each pixel. The red diamond shows the integrated value assigned to the central wavelength based on the 10 sub-pixels and the blue diamond shows the integrated value assigned based on 100 sub-pixels.
Figure 4.7: The upper plot shows the experimental absorbance for iron compared to copper. The shaded boxes indicate the regions used for determining a 3rd order polynomial (black line). The bottom plot shows the original signal (red) and the signal (black) adjusted by the polynomial curve. The data shown corresponds to a time period of 100-200 $\mu$s after the explosion of the wires.
test conditions. When a $4^{th}$, $5^{th}$, or $6^{th}$ order fit was used, it introduced additional curvatures between the non-absorbing regions which were unrealistic. A third order fit was chosen over a second order fit, since a third order fit was shown to have a lower residual sum of squares between the fitted line and experimental signal.

Once the polynomial fit was determined for the non-absorbing regions, the polynomial was used to calculate the percentage of absorbed irradiance for the entire wavelength region of interest. Then the experimental signal was divided by the polynomial calculated signal. This process adjusted the entire signal such that the non-absorbing regions were essentially set at unity, not accounting for noise. This adjustment then allowed for a direct comparison between experimental and theoretical absorption traces, which ultimately lead to determining temperatures for each experimental trace. The Matlab code for this adjustment can be found in the first portion of the code presented in Appendix C.6.

4.2.6 Fitting Algorithm

The previous sections have discussed the techniques and equations used to develop a theoretical atomic absorption trace for iron, which has been used to build a database of traces for varying temperatures, pressures, and fitting parameters (iron number densities and path lengths). Additionally, the experimental data has now been adjusted to account for using a copper wire in determining the background signal instead of an iron wire. The final portion of coding for theoretical and experimental absorption is fitting the experimental data to a theoretical trace, which is shown in Appendix C.6.

The Matlab code in Appendix C.9 was used to produce an extremely large database of absorption traces for a matrix of temperatures, pressures, and fitting parameters. This database was used to fit each experimental absorption signal to a specific $T$, $P$, and $\Lambda$. The process for fitting each experimental trace to a theoretical trace was based on determining the lowest residual sum of squares for all variations.

During the sub-pixel portion of the code, all integrated values were assigned to the central wavelength of the pixel for which they were calculated. The observed value in the experimental trace was subtracted from this the-
oretical value for each pixel and then squared. The sum of these squared differences is known as the residual sum of squares (RSS). Only the pixels in the wavelength range of interest (370.5-378.0nm) were involved in this calculation. Additionally, the fitting procedure could be performed on only specific portions of the absorption spectra to isolate specific transitions, or the procedure could also ignore the noise in the baseline signal as will be discussed in Section 6.2.1. Once the RSS was determined for every combination of $T$, $P$, and $\Lambda$, the minimum RSS was taken as the best fit. The error associated with this fitting method is described in Section 6.2.2.
CHAPTER 5

THEORETICAL AND EXPERIMENTAL RESULTS OF ENHANCED ALUMINUM CASINGS

5.1 Theoretical Analysis of Enhanced Spherical Casings

Initial theoretical work was concerned with simulating the geometries in Section 2.2 using ALE3D. ALE3D is an arbitrary-Lagrangian-Eulerian code, which is capable of modeling hydrodynamic problems in two or three dimensional environments. While this program is capable of modeling shaped charges and underwater explosives separately, problems arose when the two concepts were combined for the enhanced casing geometries. The time scales are extremely different for a shaped charge, $O(200 \, \mu s)$, and the expansion and contraction of a gas bubble underwater, $O(20 \, \text{ms})$. In order to accurately model the detonation and shaped charge formation, very small time scales are required, which then consumed large amounts of computational power to maintain the time scale for the bubble dynamics. If a coarser and longer time scale was used to alleviate the computational power problem, then the detonation physics and shaped charge dynamics either failed or had to be significantly simplified, rendering the effect of the shaped charge on the bubble dynamics to be unknown. For this reason, use of ALE3D was abandoned, and a simpler analytical approach was taken, as previously described in Section 2.1.

5.1.1 Geometric Constraints

The first part of the analytical approach determined the size of conical cavities on the surface of a explosive sphere based on a fixed cavity apex angle of 42° while varying the number of cavities and percentage of high explosive removed from the sphere. Figure 5.1 illustrates the ratio of the cone base
diameter to the spherical charge diameter. This ratio increased as the percentage of high explosive removed was increased. The volumetric reduction of high explosives created a minimum number of cones required to satisfy the geometric constraints. This constraint was observed when comparing the minimum number of cavities for each explosive reduction. The minimum number of cones for a HE reduction of 5% or 10% was 4, but a minimum of 8 cones was required for a HE reduction of 25% as shown in the inset of Figure 5.1.

Figure 5.1: The ratio of the conical cavity base diameter to the spherical charge diameter plotted versus the number of cones implemented. This ratio increased as the reduction in high explosive was increased. The minimum number of cones was governed by the geometric constraints and the volumetric reduction of high explosives.

From the geometric and explosive volume constraints, the base diameter of each cavity was fixed for a given number of cones and a set spherical diameter. Based on the design recommendations for shaped charges, the wall thickness of each cone was set at the maximum recommended thickness of 4% of the base diameter [39]. As the number of cones was increased and the sphere diameter was decreased, the wall thickness decreased, which approached the
limits of manufacturing, $O(1 \text{ mm})$. Figures 5.2 and 5.3 illustrate the effect that the number of cones and sphere diameter have on the wall thickness and the difference for each condition as the percentage of HE was increased from 5% to 25%. As the reduction in HE was decreased, the wall thickness also decreased for a given condition.

**Figure 5.2:** Wall thickness of conical cavities for a 5% reduction in HE with a varying number of cones and sphere diameters. The manufacturing limit is about 1 mm, which covers a large portion of the available conditions as represented by the pure yellow region.
Figure 5.3: Wall thickness of conical cavities for a 25% reduction in HE with a varying number of cones and sphere diameters. The manufacturing limit is about 1 mm, which covers a limited portion of the conditions for small sphere diameters with a large number of cones as represented by the pure yellow region.
5.1.2 Energy Constraints

Based on the geometric constraints, an energy balance was performed on the enhanced casings. The energy balance determined the difference between the energy associated with the aluminum liner reacting with water based on Eq. (1.1) and the energy from the displaced high explosive. In order for the design to be feasible on an energy basis, the available energy from the aluminum liner must be equal or greater than the energy available from the displaced explosive. Under the best circumstances, this is a very difficult condition to satisfy, since the volume of the aluminum liner is a very small fraction of the displaced volume of high explosive, as illustrated in Figure 5.4.

![Figure 5.4](image)

**Figure 5.4:** A cross sectional view of the displaced conical volume of high explosive on the left and a cross sectional view of the conical aluminum liner which replaces the high explosive. For this concept to be feasible, the energy balance from the small aluminum volume must be equal to or greater than the energy of the displaced high explosive.

With the geometric constraints and a wall thickness of 4% of the liner base diameter, there was no combination of conditions, for any of the five explosives examined, which resulted in a positive gain in energy with the enhanced casings, even with the entire liner reacting. Only by increasing the liner thickness from 4% to a minimum of 12% of the liner diameter was there a net energy gain by using the enhanced aluminum casings with the lowest permitted number of cones. The advantage of using aluminum cavities was only observed with TATB, due to its low heat of explosion (3496 kJ/kg), and only when the explosive volume was reduced by 15-30%. As the liner thickness was increased to 15%, the enhanced casings had an energy gain for several configurations for TATB and TNT, which also has a relatively low heat of explosion (4476 kJ/kg), although no gain was observed for PETN, RDX, or HMX. Figure 5.5 presents the net energy gain for a 20 cm diameter sphere of TATB where 25% of the HE was replaced by conical cavities as a percentage of the energy of an unenhanced 20 cm sphere of TATB.
Figure 5.5: Based on a 25% reduction in TATB for a 20 cm diameter sphere, the minimum number of cavities allowed was 8. As the liner thickness is increased from 11% to 15% the amount of energy gained by the enhanced casing increases for each configuration. This energy gain assumes the entire liner is consumed in the aluminum-water reaction. The energy gain is presented as a percentage of the energy of an unenhanced 20cm sphere of TATB.
The surface map in Figure 5.6 illustrates the energy increase associated with various combinations of cones and explosive reductions for a 20 cm sphere of TATB with a constant wall thickness of 15%. While not every combination of HE reduction and number of cavities was geometrically allowed, there were several combinations that were capable of producing the same net energy gain. For example, a HE reduction of 17.5% with 7 cones had an energy gain of 2.292% when compared to the unenhanced 20 cm sphere of TATB and an energy increase of 2.284% was observed for a sphere with 23 cones and a 45% reduction in HE. The scenario with 23 cones will have a more uniform pattern of jetting than the conditions with 7 cones. While the uniform jetting pattern is important, the reduction in HE is the more significant one. By reducing the amount of HE for a given volume without reducing the energy output, an explosive magazine is capable of holding more munitions without exceeding the HE limits of the magazine or maintaining the same amount of munitions for more restrictive magazine HE limits.

While a reduction in the explosive of 90% produces the largest net energy gain based on geometrical constraints, this analysis does not account for the required amount of HE to successfully form a shaped charge from a cavity. For this reason, only the conditions which cover less than half the surface of the sphere are considered as practical conditions to ensure that the cavities are surrounded by more than just a sliver of high explosive. By applying this condition, only configurations with an explosive volume reduction of less than 50% were possible, as shown in Figure 5.7.

Unlike the previous analysis, which assumes the entire aluminum liner was reacting, the actual amount of aluminum that reacts is actually closer to only 35% or less of the total liner mass [42]. When this assumption was included, a net energy gain was only observed when the liner thickness approached 100%, i.e. a solid aluminum cone, which would completely prevent a jet from forming. Based on the energy balance, the only feasible use of an enhanced aluminum casing would be with an explosive that had a very small heat of explosion (<500 kJ/kg). As the explosive heat of formation is decreased, the validity of utilizing an enhanced aluminum casing is increased. In terms of the energy constraints, there are no geometric conditions or combination of high explosives which would create an enhanced casing which would outperform an unenhanced casing.
Figure 5.6: Positive energy gain for a 20 cm sphere of TATB with a constant wall thickness of 15% of the cavity base diameter. The surface plot shows that the same net energy gain can be achieved for several different combinations of HE reduction and number of cavities. The energy gain is presented as a percentage of the energy of an unenhanced 20cm sphere of TATB. The energy gains assume the entire liner is consumed in the aluminum-water reaction.
Figure 5.7: Positive energy gain for a 20 cm sphere of TATB with a constant wall thickness of 15% of the cavity base diameter. Only the combinations which cover less than 50% of the sphere surface are shown, as combinations covering more than 50% of the surface may not have enough HE to properly initiate the formation of shaped charges. The energy gain is presented as a percentage of the energy of an unenhanced 20cm sphere of TATB. The energy gains assume the entire liner is consumed in the aluminum-water reaction.
5.1.3 Velocity Constraints

The velocity constraints on the performance of an enhanced aluminum casing are separate from the energy constraints. The velocity constraints are based on the geometry of the casing, the depth of detonation below the water surface, and the high explosive.

Before the results of the enhanced casings can be reported, the trends of a normal sphere of explosive need to be examined. The depth of the explosion is a critical factor in determining the maximum bubble radius as previously stated in Eq. (1.9). As the depth of the explosion increases, the maximum radius and time period for the first expansion and contraction phase decreases, as shown in Figure 5.8, which illustrates the effects of water depth on a 20 cm diameter sphere of RDX. As the water depth increases, the hydrostatic pressure also increases, which limits the expansion of the high pressure detonation gases.

![Figure 5.8: Radial position of a bubble for a 20 cm diameter sphere of RDX detonated at multiple depths. As the depth of the explosion increases, the maximum radius and time period decrease.](image)

When the depth of the explosive was fixed, the only influence on the maximum bubble radius was the high explosive. The bubble dynamics for 20 cm diameter spheres filled with different high explosives (PETN, RDX, HMX, TATB, and TNT) are plotted in the Figure 5.9. Based on the the maximum bubble radius from Eq. (1.9) and the TNT Equivalence Ratio from Eq. (2.4),
the maximum bubble radius at a given depth is a function of the density and the detonation velocity as given by Eq. (5.1) for a fixed volume, $V$. This relationship indicates that a 10% increase in density will yield a 3.23% increase in the maximum radius, while a 10% increase in the detonation velocity of a high explosive will yield a 6.56% increase. This relationship explains why PETN outperforms TATB, even though for the same geometry, the mass of TATB is greater than the mass of PETN.

$$R_m = J \left( \frac{U_{D(HE)}^2 \rho_{HE} V}{U_{D(TNT)}^2 \rho_{TNT} V} \right)^{1/3}$$ (5.1)

Figure 5.9: A 20 cm diameter sphere of various high explosives detonated at 500 m. HMX produced the largest bubble since it had the greatest detonation velocity and density.

The analytical penetration model described in Section 2.1 was combined with the bubble dynamics model and applied to a sphere with a 30% volumetric reduction in high explosive. A 30% volumetric reduction will be maintained for all enhanced casings throughout this section unless specified otherwise.

The analytical results of an enhanced casing with 12 conical cavities and a plain casing are plotted in Figure 5.10 for water depths of 500 and 1500 m. The enhanced casings have a greater bubble radius than the plain spheres for the regions on the sphere which have a conical cavity. Water was assumed to
be incompressible and thus the density was constant over all depths. Since the density of water was fixed, the penetration model produced the same penetration distance regardless of the water depth. As a result, the absolute difference in maximum bubble radius was constant and unaffected by the depth, but the relative difference between the enhanced and unenhanced bubble radii increased with depth. The enhanced bubble radius is a result of the shaped charge penetrating the water until the jet velocity falls below the minimum penetration velocity of 2000 m/s, at which point the radial bubble position transitions to the bubble model. The penetration time is only a small fraction of the total expansion phase as displayed in Figure 5.11, which features the transition time period for a 20 cm sphere with 12 cones at 500 m.

![Figure 5.10: A 20 cm diameter sphere of RDX with 12 cones detonated at 500 m and 1500 m. The absolute increase in bubble radius was the same for all depths, but the relative change in bubble radius increased with depth.](image)

Since the collapse phase of the each bubbles was not corrected for the increased maximum radius, the bubble collapsed to an artificial minimum that had been offset by the penetration distance of the jets. Because the collapse phase is not the focus of the current analysis, only the trends associated with the expansion phase and maximum bubble radius will be examined. The primary term used to describe the effects of enhanced casings was the enhancement ratio, which is defined as the maximum radius of an enhanced casing divided by the maximum bubble radius of a plain explosive sphere.
Figure 5.11: A 20 cm diameter sphere of RDX with 12 cones detonated at 500 m. At early times, the enhanced radial position was a function of the shaped charge penetration model until the velocity dropped below 2000 m/s. When the minimum penetration velocity was reached, the radial position transitioned from being governed by the penetration model to the bubble expansion according to the Rayleigh-Plesset relations.
The enhancement ratio was based on other methods used to normalize unenhanced bubble dynamics by dividing radial distances by the maximum bubble radius.

As previously demonstrated, the depth, and high explosive both influenced the enhancement effect of a casing. The number of cavities also affected the performance of an enhanced casing. When examining the parameters that affect the enhancement ratio, the diameter of the sphere was found to have no influence since the maximum unenhanced bubble radius and the geometries of the cavities both scaled with the sphere diameter. Figure 5.12 illustrates that the enhancement ratio is independent of sphere diameter. The enhancement ratio was only dependent on the number of cavities, the water depth and the high explosive.

Based on the premise that water was incompressible, the density of water was held constant. As the water depth of detonation increases, the hydrostatic pressure increases, which decreases the expansion of the detonation gases. Since the penetration distance is only a function of the density, which is constant, and not water depth, the increased ambient pressure only affects the maximum attainable bubble radius of an unenhanced explosive casing and not the penetration distance of the shaped charge into the water. For this reason, as shown in Figure 5.13, regardless of the HE fill, the enhancement ratio was greater at deeper water levels. This result indicated that a
greater benefit would be achieved if enhanced casings were utilized in deep sea applications instead of shallow water operations.

Figure 5.13: The enhancement ratio was plotted for 20 cm diameter spheres with 12 cones filled with five different high explosives detonated at various depths. As the water depth increased, the enhancement ratio increased regardless of the high explosive.

While the water depth had a significant effect on the relative performance of enhanced casings, the number cavities also had a significant role. The geometric design constraints controlled the base diameter of each cone based on a fixed volumetric reduction of high explosive and the number of cones. When the enhanced casings were designed for only a few cavities (<10), the base diameter was a significant fraction of the sphere diameter. Since the penetration distance scaled with the base cone diameter, a large diameter will create a greater penetration distance and a greater enhancement ratio than a system designed around 100 cones as illustrated by Figure 5.14. The increase in bubble radius was only observed along the radial location of the cones, which means that a system with only a few cones will produce a “star burst” pattern with most of the bubble being unaffected by the cavities. However, as
the number of cones increases, the penetration distance decreases but a more uniform pattern of enhancement will be observed for the entire expanding bubble and not just a few localized positions.

Figure 5.14: The enhancement ratio was plotted for 20 cm diameter spheres filled with five different high explosives detonated at 500 m below the surface of the water with various numbers of cavities. As the number of cones increased, the enhancement ratio decreased regardless of the high explosive.

The previous examples all produced the same pattern with HMX outperforming all other high explosives and TNT providing the least amount of enhancement. By examining actual high explosives, the effects of the detonation velocity and the density cannot be separated. In order to separate these effects, a set of theoretical explosives was examined. A theoretical explosive with a detonation velocity of 8000 m/s and density of 1.8 g/cc was used to evaluate the individual performance effects of density and detonation velocity, by varying the density and detonation by ±5% and ±10%. The performance effect was measured by the ratio of the maximum radius of the modified theoretical explosive to the baseline theoretical explosive with a constant detonation velocity of 8000 m/s and density of 1.8 g/cc.
The effects of varying the HE density and detonation velocity are shown in Figure 5.15 for a 20 cm diameter enhanced casing with various numbers of cavities at a fixed detonation depth of 500 m. When the detonation velocity was increased by 10%, the maximum radius increased by 10% for 4 cones, and then slowly dropped to just below 8% for enhanced casings containing upwards of 100 cones. However, when the density was increased by 10%, the maximum radius with 4 cones started at 2.2% and slowly increased to just under 3% for 100 cones as the number cavities increased. Changes in the HE density should have little effect because the HE density is only used to calculate the maximum bubble radius of an unenhanced casing, and the maximum radius is only influenced by the cube root of the density. On the other hand, the detonation velocity is raised to two thirds power in the maximum bubble radius relationship to account for the TNT equivalence and the detonation velocity is proportional to the jet tip velocity and thus the penetration distance.

The effects of varying the density and detonation velocity for a 20 cm sphere with 12 cones detonated at varying depths is shown in Figure 5.16. The enhancement for an increase in detonation velocity increases slowly with depth, while the enhancement decreases slowly with detonation depth for an increase in density. The detonation velocity has a greater influence on the enhancement, regardless of the water depth or number of cavities, than the high explosive density. As a rule of thumb, when comparing two high explosives for use in an enhanced casing, the one with the greater detonation velocity should be chosen, regardless of the density, assuming the high explosive requirements for storage and operation are met.
Figure 5.15: The effect of the (A) detonation velocity and the (B) density on the performance of a theoretical high explosive detonated at 500 m for various numbers of cavities.
Figure 5.16: The effect of the (A) detonation velocity and the (B) density on the performance a theoretical high explosive with 12 cones detonated at various depths.
5.2 Experimental Results of Enhanced Aluminum Cylindrical Casings

While the theoretical calculations were designed for a spherical explosive, the experimental work was centered on cylindrical casings due to manufacturing and testing limitations. Since the experiments were conducted on cylinders and the axis was parallel to the high speed camera line of sight, it was assumed that all images of shock wave and bubble growth were purely radial observations.

On every underwater test, the casing’s axis was assumed to be perfectly parallel to the line of sight of the camera. It was assumed that the dimensions of the shock wave and bubble in and out of the viewing plane were similar for all charges, since the axial dimension was the same for all charges. Based on this assumption, all measurements were considered to be an effect of radial expansion and not axial growth. A reduced image sequence of all six casings tested is shown in Figure 5.17. Initial observations demonstrate that the enhanced casings produce a cylindrical bubble with noticeable protrusions, which are aligned with the position of the cavities.

The baseline case produced a cylindrically symmetric bubble for the first 50 $\mu$s and then an almost periodic protrusion pattern emerged from the surface of the bubble. Initially, the explosive blast expanded outward and hydrodynamically expanded the casing, which explains the initial uniform expansion. After 50 $\mu$s, the casing completely fails and fragments due to the stresses imparted by high pressure detonation gases. The fragments are propelled ahead of the bubble, and create an almost periodic pattern, as shown in the later images of the sequence. It is not possible to explain the spacing of these protrusions with a definitive answer, but the casing most likely failed uniformly with small surface defects promoting crack growth. This failure is similar to the case fragmentation of an RP-80 detonator as shown in the bottom row of images in Figure 5.18 [29]. The enhanced casings do not exhibit these protrusions, since the formation of the shaped charges provide a path of least resistance for the expansion of the high pressure detonation gases.

The temporal resolution was limited by the camera to 4 $\mu$s. For this reason, the initial detonation time of the high explosive and not the detonator, may vary slightly between tests. Also, the initial calibration assumed a perfect
Figure 5.17: Abbreviated image sequences of all six cylindrical casings tested at NSWC. All images were recorded with a Shimadzu PV-2 at 250,000 fps with an exposure of 0.5 µs.
parallel alignment between the charge axis and the camera axis, such that the 2-D projection of the charge was a perfect circle representing the end cap. If this alignment was slightly off, the 2-D image of the charge before detonation would be larger than the surface area of the end cap and cause an error in the calibration. Additionally, the tracking procedure of the shock wave position was only accurate to ±1 pixel for all radial shock positions, and then the average of all detected positions was used as the shock wave position, which had a maximum standard deviation of 0.017 pixels. The bubble position used an edge detection system, which was accurate to within ±1 pixel, and then subjected to the calibration error to provide the position and area of the bubble.

The shock wave tracker program was applied to all casing image sequences to track the radial position of the shock wave in relation to the center of the charge. There was no noticeable difference in the shock wave position between the casings, as shown in Figure 5.19, as expected. While the baseline casing has 25% more high explosive than the enhanced casings, the shock wave position is governed by the cube root of the mass, which implies that the baseline position should only be greater by 7%. This difference is still significant, but not when considering the temporal and spatial errors associated with the detection of the shock wave. It is difficult to see on the plot, but the baseline shock wave (black line) outperforms all of the casings except the casing with eight 60° cavities (red line).

The primary goal of this experiment was to examine the effects of cav-
Figure 5.19: The radial shock wave position plotted versus time for all casings. All of the casings have a similar shock wave history, which is expected since the enhanced casings have the same amount of high explosive.
ity geometries on the formation and expansion of the gas bubble. For a fair comparison between an enhanced and unenhanced charge, the baseline charge should have contained the same explosive weight as the enhanced charges. Instead, the baseline charge maintained the same overall geometry as the enhanced casing and thus contained 20% more explosive, which easily outperformed the enhanced casings as shown by the plotted bubble area in Figure 5.20. Due to the presence of the shock wave near the bubble surface, the exact position of the bubble was difficult to determine for the first 28 µs.

![Figure 5.20: The radial bubble area plotted versus time for casings. The plain casing bubble expands faster than the enhanced casings since it contains 20% more high explosive. The pyramidal cavities have a slightly larger bubble area than the semi-ellipsoidal cavities for the first 250 µs.](image)

Since all of the charges were identical along the charge axis, in and out of the focal plane, the differences in bubble area were attributed to cavity geometry only. Base on this premise, the cavities with a pyramidal geometry outperformed the geometries with semi-ellipsoidal geometries in total bubble area. This observation was supported by visual observations of the image sequences.
For geometries with included angles of 42° or 60°, noticeable luminosity was observed in the initial frames at the cavity locations. The luminosity would suggest reactivity between the aluminum and water, based on previous shaped charge experiments in water. The image sequences for enhanced casings with semi-ellipsoidal cavities did not produce luminosity at the cavity locations. From these observations, enhanced casings with pyramidal cavities perform better than casings with semi-ellipsoidal cavities.

The usable portion of each image sequences was limited to the first 250 µs because of the interactions of the shock wave with the acrylic tank and the subsequent structural failure of the acrylic tank. Based on the high explosive mass of each charge, the theoretical time for a maximum bubble radius to be achieved for the enhanced casings was $O(80 \text{ ms})$. Due to the significant difference between the observed expansion phase time period and theoretical time period, only a weak comparison between cavity geometries and performance was possible based on the luminosity and bubble area.

As was shown in the theoretical analysis, the regions near a cavity will experience a greater radial bubble position than regions without cavities. This effect was shown for a spherical explosive in Figure 5.11, but the premise still applies to cylindrically enhanced casings. The bubble tracker program was used to detect the edge of the bubble and determine the maximum and minimum radial position for each frame. The maximum radial position was located along the radius with the protrusion formed by each cavity and the minimum position was associated with the regions of the bubble without a cavity. The radial positions of the jet/protrusion and the bubble are shown in Figure 5.21.

Each radial position was normalized by the measured radius of the charge before detonation. Due to the periodic nature of the baseline, only the minimum radius was plotted, which represents the actual gas bubble expansion. The jet position from the enhanced casings has the same general shape as the bubble position, but offset due to the penetration distance by the initial shaped charge. This pattern is similar to Figure 5.11, where the initial bubble surface is governed by the penetration model until the radial velocity decays to a minimum penetration velocity. Then the radial position expands according to the Rayleigh-Plesset relations for cylindrical casings. As with the theoretical model, the penetration time is only a very small fraction of the actual expansion phase.
Figure 5.21: The jet position for each enhanced casing was plotted as a solid line, and the bubble position of the non-enhanced portion of the casing was plotted as a dashed line. Due to shock wave interactions around the cavities, the position of the bubble for the first 32 µs was not determined except for the plain casing. The jet position at later times primarily follows the trends of the unenhanced bubble regions with an offset due to the initial shaped charge penetration distance.
Based on the experimental work, the enhanced casings were proven to be capable of forming protrusions along the surface of a detonation gas bubble. Due to the relatively short observable time period, a definitive comparison between the different cavity geometries was very limited. By comparing the position of the protrusion to the radial position of an unenhanced region of the bubble, the trends of enhanced casing mentioned in the theoretical analysis seem appropriate, although no noticeable difference between the casings could be determined. The bubble area measurements along with the observed luminosity, suggest that the pyramidal cavities perform better than the semi-ellipsoidal cavities, although this is only speculation due to the small fraction of the observed expansion.
CHAPTER 6

RESULTS AND DISCUSSION OF SPECTROSCOPIC TEMPERATURE MEASUREMENTS

6.1 Emission Spectroscopy for Underwater Metal Combustion

During the emission experiments a high speed spectrometer was used to detect the emission of metal combustion underwater. Along with the spectra observed, high speed imaging observed the entire combustion event and not just the emitting portion. In this section, raw and processed spectra will be shown for selected experiments along with the extracted condensed phase temperature measurements. High speed images will also be shown to illustrate the importance of the jet alignment with the fiber gauge, as well as the limitations of the fiber gauge.

6.1.1 Primary Emission Results

The spectral results of the experiment varied among tests, specifically when the charge was misaligned with the fiber gauge. The image sequence shown in Figure 6.1, displays the first four uncorrected frames from the HSFC detector for a charge containing 90.2 mg of nano-aluminum. The images are displayed in a pseudo-color based on intensity for easier viewing than a gray-scale color scheme. The wavelengths displayed are an approximation to illustrate the region of interest, since the actual wavelength calibration is unique to each individual frame and fiber position. The image sequence shows the spatial and temporal progression of the emitting portion of the bubble as would be expected for a shaped charge pointing downward.

After the images were calibrated for wavelength and intensity, as previously described in Section 3.1.3, an intensity versus wavelength plot was produced for every fiber and time frame. The intensity plot for fiber 3 at 30 µs is shown
Figure 6.1: First four emission spectral images from HSFC after detonation of nitromethane above a cavity containing 90.2 mg of nano-aluminum powder with varying time scales. The pseudo-color represents the intensity observed by each pixel, as the actual image is seen in gray scale. The wavelength scale is an approximation.

in Figure 6.2, along with a blackbody temperature curve fit to the data. Some of the data become noisy at the edges of the trace due to vignetting, where the edges of the lens reduce the light throughput. This effect causes the intensity correction factors to be larger for the edges compared to the light passing through the center of the lens. As a result, a small amount of noise gets amplified on the edges of the signal. These portions of the signal were therefore ignored during the blackbody fitting procedure.

A blackbody temperature was fit to almost every spectrum for each fiber. Some of the fibers detected little to no signal or they were saturated, which caused the blackbody to either converge on an unrealistic temperature with an extremely high residual or not converge at all. A contour plot of the fitted temperatures for the previously shown images along with the other 4 frames of the test sequence are shown in the Figure 6.3. This figure was created by taking into account the exposure time and the physical spacing of the fibers.

The initial time is listed as occurring at 20 $\mu$s after the initial detonation. This time delay was due to the time required for the detonation to propagate from the detonator through the NM/DETA to contact the aluminum shaped
Figure 6.2: Intensity plot of fiber 3 at 30 µs. A blackbody temperature was fit to the experimental data to give a temperature of 3160 K.

Figure 6.3: Contour of emission temperatures from an aluminum shaped charge filled with 90.2 mg of nano-aluminum. The region of emission, based on the visual observation of emission in the high speed imaging, is outlined by the dashed line.
charge and propel the aluminum jet and powder into the water surrounding the fiber gauge. This timing scheme allowed for a few fibers to be exposed to the combustion bubble at the initial formation.

As illustrated in the temperature profile, the combustion bubble emission moves significantly in the first 20 $\mu$s of formation according to the light received by the fibers. After this initial movement has occurred, the position of the luminous portion of combustion stayed relatively constant for approximately 100-150 $\mu$s. After this time, there is insufficient emission to resolve any usable spectrum. Due to a slight error in setting up the HSFC, the actual time period was not continuous. There are a few 1-10 $\mu$s gaps in the later time periods, which is essentially a negligible error at those late times.

Temperatures measured at 20 $\mu$s and 23 $\mu$s after detonation were between 3400 K and 3900 K, which is well above 2900 K, the predicted adiabatic flame temperature of aluminum in a stoichiometric mixture of liquid water [14]. However, the minimum detonation temperature of nitromethane is 3600 K [76], which implies that the early temperatures are not strictly a measure of aluminum reacting with water. The other temperatures listed are within a reasonable range for the combustion of aluminum with water.

The temperature profile corresponds surprisingly well with luminosity of the high speed image sequence for the same experimental run as shown in Figure 6.4. The image sequence depicts the luminous portion of the bubble initially moving downward and then stopping, as shown by the temperature profile. The image sequence is not perfectly aligned in time with the temperature profile, since the accuracy of determining the zero point for the image sequence is considered to be the first frame before any detonation is observed. For this reason, the region of emission depicted in the temperature contour plots is purely shown as a guide to where temperature measurements might be observable.
Figure 6.4: High speed image sequence of a charge with 90.2 mg of aluminum. The position of luminosity tracks well with the contour plot of measurable temperatures. The images were recorded with the Phantom v5.2 with an exposure of 3 µs.

6.1.2 Limitations

The previous section showed the results for a single experiment since it was the most complete test with the fewest amount of problems. The word, problems, is used loosely, since most of the other tests showed the limitations of this measurement technique. The main limitations are jet alignment, emission intensity, and the location of the emission.

The first limitation, which is very specific to this experimental setup, is the alignment of the shaped charge with the fiber gauge. In order to observe the aluminum water reaction, a shaped charge was used to propel an aluminum jet and/or powder into the surrounding water. If the jet was fired slightly off-axis in either position or angle, in relation to the alignment of the fiber gauge, the fiber gauge was unable to detect the emission. An experiment with 92.2 mg of nano-aluminum was fired 1.75” away from the fiber gauge. The aluminum jet and powder fired very true in relation to the gauge, as can be seen in Figure 6.5. However, due to the distance between the combustion and the edge of the gauge, very little emission was detected, and a temperature fit was not possible for any time period or fiber position. As a result, this gauge is only useful when the ends of the fibers are in engulfed in the combustion event. Additionally, after the first 100 µs, only the side facing away from the gauge was emitting light, which significantly limited the ability to detect
emission by the gauge.

Figure 6.5: High speed image sequence of an aluminum shaped charge with 92.2 mg of aluminum. The aluminum reacted well with the water. However, the 1.75” offset between the charge gauge prevented any type of spectroscopic detection. The images were recorded with the Phantom v5.2 with an exposure of 3 $\mu$s.

The second limitation of the emission fiber gauge was the need for significant emission. This effect was observed when a plain aluminum cone without any fill powder was used as the sole source of aluminum. The jet created by the shaped charge traveled through the water at nearly the same velocity as a charge filled with powder, as shown in Figure 6.6. However, the jet only burned bright enough for the spectrometer to detect a signal during the first 40-50 $\mu$s. Due to the limited luminosity, the temperature profile of the aluminum cone with an air filled cavity was only known for a small portion of time, as shown in Figure 6.7, as compared to the temperature profile of an aluminum cone with a nano-aluminum fill, as previously seen in Figure 6.3.

The addition of aluminum powder to increase the emission signal should not be considered a reasonable solution to the weakly emitting aluminum jet without powder. These are two different conditions, since the nano-aluminum not only increases the aluminum in the system, but the particle size of the powder greatly increases the ability of the aluminum to react. As a result, even though the intensity of emission increases, the actual experiment has been changed from what was initially being tested. This comparison merely shows an example of when the emission spectrometer has the ability to easily
Figure 6.6: High speed image sequence of a charge with an aluminum cone filled with air only. The aluminum jet reacts with the water, but the detectable luminosity of the event by the spectrometer only occurs for the first few frames. The images were recorded with the Phantom v5.2 with an exposure of 3 μs.

Figure 6.7: Contour temperature of an aluminum cone only filled with air. The region of emission, based on the visual observation of emission in the high speed imaging, is outlined by the dashed line. The time of detectable emission was significantly less than when the cone was filled with nano-aluminum powder, as was presented in Figure 6.3.
detect a signal and a similar experiment where the spectrometer is not as effective.

As far as the limitations associated with the fiber gauge, the alignment and positioning of the charge in relation to the gauge is critical, but easily controlled by carefully aligning the experiment and placing the gauge in the path of the reacting metal. A lack of intensive emission cannot be easily controlled, unless the experiment is modified to include metal powders which are known to be intense emitters. Assuming these previous limitations were accounted for in the experiment by using a system with very intense emitters and properly aligning the gauge with the path of the reaction, there would still remain one critical limitation to overcome. Determining the location of the emission from an underwater combustion event is perhaps the biggest limitation, without a simple solution.

The vertical location of the emission is not a factor in this type of diagnostic, since the gauge can be raised or lowered to accommodate various heights. The radial location of emission is the critical limitation when using this diagnostic. The fiber gauge has a fixed position which limits the viewing angle of combustion. This problem was previously observed in Figure 6.5, which showed the emitting portion of the bubble on the side set away from the gauge.

A better example of this can be seen in Figure 6.8 for a charge filled with 290.4 mg of magnesium powder, with a particle size ≤44 µm. Magnesium was chosen as a fill powder to increase the intensity and duration of emission. The reaction of magnesium with water, as compared to nano-aluminum and water, was much more intense and had a longer duration of emission, based on the high speed images and pixel counts. The magnesium reaction was observed for well over 400 µs. The late time images appeared to be blurred, which is an effect of the interaction between the shock wave from the detonation and the polycarbonate windows.

The location of the emission from the magnesium seemed to favor the side set away from the gauge. Due to the non-uniformity of the still intense emission as seen in frames marked at 0.169 ms and 0.206 ms, only one fiber was able detect a usable temperature near this time period. Figure 6.9 depicts the temperature contour of magnesium reacting with water. Based on the level of emission observed in the high speed images, several more fibers should have detected a temperature during the later times.
Figure 6.8: High speed image sequence of a charge with an aluminum cone filled with 290.4 mg of magnesium only. The reaction of magnesium and water has a very intense emission and long duration. The late time images were blurred due to the interaction of the shock wave and polycarbonate windows. The images were recorded with the Phantom v5.2 with an exposure of 3 µs.

Figure 6.9: Contour temperature of an aluminum cone filled with 290.4 mg of magnesium. The region of emission, based on the visual observation of emission in the high speed imaging, is outlined by the dashed line.
The variability in the location of the emitting region in the bubble made this type of diagnostic difficult. One potential explanation for the variation in emission location could be from a slight misalignment of the aluminum shaped charge in the casing. The jet may veer slightly off the main axis, which would help to increase the reaction (emission) in one particular region. Additionally, the powder fill in the cavities interferes with the liner collapse, which could also create jet veering. Also, the fiber gauge itself could be interfering with the reaction of powders and water. When the shaped charge propels the powder downward into the water, the fiber gauge may interfere with the dispersal of the powder into the water. As a result, the side away from the gauge is unaffected and the powders can easily react with water. Due to the limited amount of testing, it was difficult to definitively explain all the causes of the observable differences. Precautions can be taken to account for the other limitations, but the location of the emission is difficult to predict without a firm understanding of the causation.

6.2 Absorption Spectroscopy of an UEWE Gas Bubble

The key to obtaining absorption spectra of an underwater bubble was the inclusion of the refractive index of the gas bubble in determining the light path. Once this aspect of the light path was accounted for by using a fast (small f-number) lens to focus collimated light into the center of the bubble, the only other key to this setup was using a glass envelope to simulate the refractive properties of the gas bubble during alignment. By using both of these techniques with a time resolved spectrometer, several absorption spectra were recorded.

6.2.1 Primary Absorption Results with an Iron Wire

For every iron absorption measurement taken with the flash setup, an identical emission experiment was performed without the flash. The emission signal was subtracted from the absorption signal to remove background noise and the emission produced by the plasma created during the formation of the bubble. This process was also performed on a set of copper wires in the same experimental configuration for every absorption experiment, since the
reference signal for the iron gas bubble was a copper gas bubble as previously described in Section 3.2.6. The background corrected iron signal was divided by the background corrected copper reference to produce the common $I_{\nu}/I_{\nu}(0)$ signal versus wavelength. This signal was then corrected to account for the non-unity values of the non-absorbing regions of the signal by the process described in Section 4.2.5.

Figure 6.10 shows a series of time resolved adjusted spectra for an iron wire detonated at time zero. Each spectrum shown corresponds to a time period of 100 $\mu$s as indicated by the periodic signal of the Andor FK, as displayed in Figure 6.11. As time progresses, the absolute strength of the absorption signal and the relative strength of absorption between electronic transitions gradually change. For this set of spectra the flash was triggered at time zero, but due to internal delays in the electric discharge of the flash, the full intensity of the flash was not observed until 200 $\mu$s, as shown in Figure 6.11.

Since the flash was not at full power until 200 $\mu$s, the absorption observed for the first 200 $\mu$s is actually not pure absorption. The detected spectrum for this time period is a result of light emission from the plasma formed by the UEWE. The saturated absorption signal is a result of self-absorption, where the intensity of the light emission from the plasma is reabsorbed by the surrounding iron gas creating an absorption signal. This phenomenon has previously been observed with UEWEs by Grinenko et al. For a copper UEWE, they observed emission and self-absorption for more than 100 $\mu$s [56].

To account for the emission time of the iron wire, the Andor FK CCD was set to record with 40 $\mu$s exposures. An iron wire was detonated, without a flash, at 0, 10, 20 and 30 $\mu$s after the Andor began recording. By noting the time periods with a signal level above the background noise, the emission time was determined to be a maximum of 160 $\mu$s. The 40 $\mu$s exposure time allowed the CCD to detect upwards of a few hundred counts above the ambient noise, which is suitable for determining the presence of emission, but not a sufficient count level to properly perform absorption measurements. Because of the emission signal by the UEWE, the first two 100 $\mu$s time periods are ignored throughout the remainder of this experiment.

As time increases, the strength of the absorption traces in Figure 6.10 are reduced until only faint levels of absorption can be detected around 500 $\mu$s and no measurable absorption signals at 600 $\mu$s. Since the light source was
Figure 6.10: Time-resolved spectra for an iron wire detonated at \( t = 0 \) ms. The Andor detector recorded a spectrum every 100 \( \mu s \). These spectra have been adjusted for background emission and adjusted to unity. The flash signal only maintained a useful intensity from 200-600 \( \mu s \) when triggered at \( t = 0 \) ms.
Figure 6.11: The voltage history traces for the detonation signal of the fireset, the recording periods of the Andor FK CCD, and the intensity of the flash when triggered with the detonation of the wire at $t = 0$ ms.

A flash lamp, there was only a limited time period ($\sim 300 \mu s$) with a high intensity light emission capable of producing usable absorption traces. The delay of the flash was varied to shift the temporal location of the maximum flash intensity as shown in Figure 6.12. The signal was only shifted to cover the first millisecond of the gas bubble formation and expansion, since no signal was detected after 700 $\mu s$.

Each one of the spectra in Figure 6.10 was fit to a temperature, pressure, and fitting parameter according to the fitting procedure described in Section 4.2.6. Figure 6.13 illustrates the best fit theoretical absorption spectrum to an experimental spectrum taken 300 $\mu s$ after the flash and fireset were triggered. The best fit for this specific spectrum corresponded to a temperature, pressure, and fitting parameter of 3250 K, 10 MPa, and $1.5 \times 10^8$ atoms/m$^2$, respectively. A narrower view of the transitions between 373.1 nm and 375.1 nm is shown in Figure 6.14. The red diamonds are the actual intensity value recorded by the Andor FK, which represent the intensity of the small wavelength range covering the pixel. Each black square represents the calculated intensity value for the small wavelength region corresponding to each pixel. The theoretical absorption trace plotted represents the best
Figure 6.12: The intensity vs time traces for the Photogenic Flash are shown for several different delays. By adjusting the delay of the flash, the temporal location of the maximum intensity was shifted to different time periods of interest.

By shifting the delay of the flash, several temporal absorption sequences, similar to Figure 6.10, were created. Each absorption signal was processed and fit to a temperature, pressure, and fitting parameter. The average temperature, pressure, and iron number density along with the corresponding standard deviation for all time periods is listed in Table 6.1. As the bubble expanded, the temperature decreased, as expected. The pressure in the bubble was initially 20 MPa at 200-300 µs after the trigger and decreased to 7.5 MPa at 600-700 µs. This is a significant decrease in pressure from the initial measured pressures of 3-12 GPa for the plasma during the first microsecond [56, 58–60]. The decrease in pressure is reasonable based on the volume of the initial wire/plasma system compared to the volume of the expanding gas bubble.

The fitting procedure used to match the experimental absorption spectra to the theoretical spectra, fit every pixel value between 370.5 nm and 378 nm. By using the entire wavelength range, the wings of the transition lineshapes, produced by the broadening, would be accounted for specifically in regions fit between all of the red diamonds and black squares between 370.5 nm and 378.0 nm.
**Figure 6.13:** The experimental absorption trace, red diamond, detected 300 \( \mu \)s after the wire and flash were triggered. The black line represents the best theoretical fit, which corresponds to a temperature, pressure, and fitting parameter of 3250 K, 10 MPa, and 1.5x10^8 atoms/m^2, respectively.

**Table 6.1:** Fitted temperatures, pressures, and fitting parameters for an iron UEWE. The number of usable signals refers to the number of spectra that had an absorption signal above the background noise. (There was only one acceptable absorption signal for the 600-700 \( \mu \)s time period.)

<table>
<thead>
<tr>
<th>Time Period (( \mu )s)</th>
<th>200-300</th>
<th>300-400</th>
<th>400-500</th>
<th>500-600</th>
<th>600-700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usable Traces</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Temp. (K)</td>
<td>Mean</td>
<td>3530</td>
<td>3580</td>
<td>3540</td>
<td>3490</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>294</td>
<td>241</td>
<td>147</td>
<td>378</td>
</tr>
<tr>
<td>Press. (MPa)</td>
<td>Mean</td>
<td>20.00</td>
<td>15.00</td>
<td>13.75</td>
<td>9.88</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>7.07</td>
<td>7.07</td>
<td>6.50</td>
<td>8.95</td>
</tr>
<tr>
<td>( \Lambda ) (atoms/m^2)</td>
<td>Mean</td>
<td>3.25E8</td>
<td>1.45E8</td>
<td>6.75E7</td>
<td>3.38E7</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>1.03E8</td>
<td>1.12E7</td>
<td>7.50E6</td>
<td>6.50E6</td>
</tr>
</tbody>
</table>
Figure 6.14: The red diamonds are the actual pixel values for a signal detected 300 µs after the wire and flash were triggered. The black squares are the calculated intensity values for the wavelength regions corresponding to each pixel which were compared to the experimental values to determine a best fit. The black line represents the best theoretical fit with a temperature, pressure, and fitting parameter of 3250 K, 10 MPa, and $1.5 \times 10^8$ atoms/m$^2$, respectively.
with no transitions. The fitting procedure could easily be modified to fit the theoretical traces to the experimental data based on specific transitions. This method may be useful for neglecting specific transitions, which are insensitive to certain temperature ranges. Additionally, since there is significant noise generated in the system by using a copper wire for the reference signal and adjusting the baseline signal, the fitting procedure may be set to only fit the transitions and neglect the baseline signal, which contains a significant amount of noise. This method would neglect the effects of the transition wings and only use the central peak regions of the transitions, which may be a more effective technique since the transitions only represent a small portion of the spectra, which could be influenced by the much larger non-absorbing regions.

6.2.2 Variable Dependence

The temperature, pressure, iron number density fits were based on the set of conditions which produced the lowest residual sum of squares (RSS). For the spectra plotted in Figure 6.13, the RSS values for all possible temperatures and iron number densities for the fitted pressure of 10 MPa are shown in Figure 6.15. Based on this figure, there is an obvious region of low RSS values which are in the expected temperature region. When only the minimum RSS values are plotted, a small region of temperatures and iron number densities produce similar RSS values, as shown in Figure 6.16. The lowest RSS value was 1.445829, but there were several combinations of temperatures and fitting parameters for this fixed pressure with RSS values below 1.70. A similar surface plot, Figure 6.17, was observed when the RSS values are compared for pressure and temperature with a fitting parameter of $1.5 \times 10^8$ atoms/m$^2$. Because of the similarities in the RSS values, the sensitivity of absorption to changes in temperature, pressure, and fitting parameter will be evaluated based on the conditions of Figure 6.13.

The sensitivity or more appropriately, the error, associated with temperature for the best fit was determined by fixing the pressure and fitting parameter at 10 MPa and $1.5 \times 10^8$ atoms/m$^2$, respectively, while varying the temperature, initially at 3250 K, by ±200 K and ±500 K. The results are shown for a narrow wavelength range, which includes the atomic transitions
**Figure 6.15:** The residual sum of squares used to determine the best theoretical fit to the experimental absorption data. The surface plot displays the RSS values for various temperatures and iron number densities for a fixed pressure of 10 MPa. RSS values correspond to the difference between the theoretical spectrum and the experimental spectrum recorded from 300-400 µs when the flash and fireset were triggered at $t = 0$ ms.
Figure 6.16: A close up of the minimum RSS values. The surface plot displays the RSS values for various temperatures and iron number densities for a fixed pressure of 10 MPa. RSS values correspond to the difference between the theoretical spectrum and the experimental spectrum recorded from 300-400 µs when the flash and fireset were triggered at t = 0 ms.
Figure 6.17: A close up of the minimum RSS values. The surface plot displays the RSS values for various temperatures and pressures for a fixed fitting parameter of $1.5 \times 10^8 \text{ atoms/m}^2$. RSS values correspond to the difference between the theoretical spectrum and the experimental spectrum recorded from 300-400 $\mu s$ when the flash and fireset were triggered at $t = 0$ ms.
with ground states of 415.932 cm\(^{-1}\), 888.129 cm\(^{-1}\), and 6928.266 cm\(^{-1}\) in Figure 6.18. Due to the high temperatures, only the transitions with ground states energies of at least 1000 cm\(^{-1}\) exhibited significant changes in absorption. Based on the change in absorption for the transition at 373.4864 nm, the temperature values reported are conservatively within ±500 K.

**Figure 6.18:** The best fit theoretical absorption wavelength trace is plotted and compared to the experimental data. While holding the pressure and fitting parameter constant at 10 MPa and 1.5x10\(^8\) atoms/m\(^2\), respectively, theoretical traces created for a temperature, initially at 3250K, adjusted by ±200 K and ±500 K are plotted. Low energy ground states are unaffected by the temperature change at these elevated temperatures.

The error associated with Λ, initially at 1.5x10\(^8\) atoms/m\(^2\), was determined by varying the fitting parameter by ±15% and ±30% while the temperature and pressure were held constant at 3250 K and 10 MPa as shown in Figure 6.19. Unlike temperature, the fitting parameter is not dependent on the ground state energy of the transition. When the fitting parameter is varied, the absorption levels change exponentially. Based on the plot and the RSS plot earlier, the fitting parameter can confidently be stated to be within 15% of the best fit Λ.
Figure 6.19: The best fit theoretical absorption trace is plotted against the experimental data. While holding the temperature and pressure constant at 3250 K and 10 MPa, theoretical traces created for a fitting parameter, initially at $1.5 \times 10^8 \text{ atoms/m}^2$, adjusted by $\pm 15\%$ and $\pm 30\%$ are plotted. Small changes in the fitting parameter dramatically affect the absorption traces, since the intensity is exponentially related to the fitting parameter.
The sensitivity procedure was performed on the pressure, initially at 10 MPa, by holding the temperature and fitting parameter constant at 3250 K and 1.5x10^8 atoms/m^2 while varying the pressure. The results are plotted in Figure 6.20. For the range of data shown, the experimental data is less than the 5 times the fitted pressure. For other regions and time periods, the pressure data was shown to be within a ±5 fold range of the fitted pressure, which is supported by the pressure range of lowest RSS values in Figure 6.17. Based on this wide pressure range, the fitted absorption lines are weakly dependent on pressure. Since the absorption signal has little dependence on the pressure, the pure gas assumption used in developing the pressure broadening effects has very little effect on the overall absorption lineshape.

Figure 6.20: The best fit theoretical absorption trace is plotted against the experimental data. While holding the temperature and fitting parameter constant at 3250 K and 1.5x10^8 atoms/m^2, theoretical traces were created by varying the pressure around an initial value of 10 MPa. The absorption signal has a minor dependence on pressure.

In the development of the theoretical absorption traces, the FWHM of the instrument was determined, in Section 4.1, to be 2.36 pixels. While care was taken to determine this value by examining different lines shapes.
and excluding FWHMs from transitions with overlapping lineshapes, the difference between using 2.36 and 2.43 has a minor effect of the absorption, as shown in Figure 6.21, specifically in the inset. As the FWHM increases, the absorption troughs become slightly bigger, but the overall lineshape is maintained.

![Figure 6.21](image)

**Figure 6.21:** For the previously used absorption signal with a temperature, pressure, and fitting parameter of 3250 K, 10 MPa, and $1.5 \times 10^8$ atoms/m$^2$ respectively, the instrumental FWHM was varied between 2 and 3 pixels. The FWHM only deepens the absorption troughs as it is increased, but does not affect the overall absorption lineshape.

### 6.2.3 Non-Iron Absorption Techniques

Iron wire was the primary metal used in the absorption experiments, and the most successful, but other materials were tested as possible absorbers. This section is presented only as a brief overview of attempts at absorption measurements with other absorbers. The materials tested were not wires, but were either powder or foils. All materials were tested with the same
fireset and optical setup as previously described for absorption with an iron wire.

In order to use powders in an UEWE, a copper wire was used as the primary structure to hold the powder and create the electrical connection to the fireset. The powder was applied to a copper wire by either lightly coating the wire with vacuum grease and dipping the wire in the powder or the powder was premixed with the grease and then the wire was coated with the powder-grease mixture. The powders used in this experiment were Mg, Mn, and Fe.

The powder-grease systems never provided any absorption signals. Since the powder was on the surface of the wire, or even separated from the surface by grease, the electric discharge most likely only passed through the copper wire. As a result, the powder never turned into gas or plasma, which would have been able to absorb the light source.

Unlike the powders, thin strips of aluminum were capable of creating absorption signals. The aluminum foil was standard cooking aluminum foil cut into 2-3 mm wide strips and placed between the electrodes. Aluminum has two main atomic transitions at 394.4006 and 396.1520 nm with ground state energies of 0 cm$^{-1}$ and 112.061 cm$^{-1}$. The background corrected signals for aluminum are shown in Figure 6.22. Only the late time absorption is shown, since the aluminum foil had an emission signal for the first 450 $\mu$s.

Since the aluminum transitions have almost the same ground state energy levels, the absorption signal is similar for both lines. As previously stated, in order to accurately fit a temperature to an absorption signal, a significant difference in lineshapes is required between transitions. While aluminum is not a useful element for this absorption experiment, it may be useful in other applications or with a lower energy output from the fireset.
Figure 6.22: The late time spectra for an aluminum foil strip detonated at $t = 0.050$ ms. The Andor detector recorded a spectra every 100 $\mu$s. The flash signal was triggered at $t = 0$ ms. The spectra shown have only been adjusted for the emission from the aluminum foil.
CHAPTER 7

CONCLUSIONS & RECOMMENDATIONS

7.1 Conclusions

7.1.1 Enhanced Aluminum Casings

The first part of the enhanced casing project examined the combination of one dimensional shaped charge penetration models and underwater gas bubble expansion models. The model examined spherical aluminum casings with conical cavities containing an apex angle of 42°. Only 5 types of high explosives were examined in this study, but it was shown that the energy content of the aluminum liner which replaced a portion of the high explosive was less than the energy content of the replaced high explosive. Only when the aluminum liner thickness was increased to at least 12% of the liner diameter and the entire liner mass reacted with the water did the enhanced liner outperform the low energy explosive, TATB, in terms of energy content. The increased thickness could be allowed since the actual liner thickness design is based on a percentage of the charge diameter, which was unknown for a spherical system with several charges.

When the model was analyzed based on the velocity criteria for shaped charge penetration only, all allowable geometries exhibited an increased bubble radius. For a given explosive reduction, the diameter and the radial enhancement increased as the number of cavities was decreased. As the number of cavities increased, the overall enhancement of the bubble decreased, but the enhancement became more uniform.

The enhanced casing experiment was based on aluminum cylinders with linear shaped charge cavities of various geometries. During the initial detonation of the casings, luminosity, which suggests reaction, was observed near the cavities with pyramidal cavities and not the semi-ellipsoidal cavities.
The performance of the pyramidal cavities had a slight advantage over the semi-ellipsoidal geometries for overall bubble volume area when viewed as an axisymmetric expansion. The radial bubble position trends determined by the velocity criteria of the analytical model for the enhanced regions versus the unenhanced regions were similar to the radial positions of the jets from the enhanced regions of the cylinders compared to the unenhanced bubble expansion regions. A conservative analysis would suggest that the pyramidal cavities are better than semi-ellipsoidal cavities; however, only a small fraction of the bubble expansion was observed.

From the experimental work, enhanced casings were capable of forming aluminum jets from shaped charges and these jets form protrusions, which locally increase the bubble radius near the radial axis of the cavity. However, the energy balance from the theoretical model indicated that the maximum amount of aluminum available for reaction with the surrounding water had less energy content than the displaced high explosive.

While the energy analysis would indicate that there is very little promise in utilizing conical cavities to enhance the performance of an underwater explosive, the energy analysis does not account for the energy release rate of the explosive or the aluminum. The primary goal of the enhanced casings was to increase the maximum bubble radius to improve the impulse from the collapsing bubble or improve the likelihood of creating a reentrant jet. Based on the experimental work, the shockwave velocity, which is related to the shock energy of the explosion, experienced a minor reduction (if any) for the enhanced casings. Also, the enhanced portions of the casings outperformed the baseline in radial growth, which would suggest a larger maximum bubble radius would be observed for the enhanced casings. Regardless of the energy analysis, the bubble radius appears to be increased in both experiments and theoretical calculations, which was the primary goal of enhancement technique.

7.1.2 Spectroscopic Temperature Measurements

The emission spectrometer system was designed with a slender fiber gauge to minimize interference between the combustion bubble and gauge, while providing internal spatial resolution. By using a high speed framing camera
as the detector for the spectrograph, high resolution temporal spectra were capable of being recorded. This system was capable of obtaining spatial and temporally resolved condensed phase temperature measurements for strongly emitting underwater combustion events.

There were several limitations associated with this emission system. The emitting portion of the combustion event had to engulf the fiber gauge, in order to detect an emission signal. Also, this diagnostic system could only be utilized for systems with strong emitters.

In order to measure temperatures in non-emitting or weakly emitting systems, an absorption spectrometer was constructed for an iron UEWE system. Due to the oscillating gas bubble, the refraction of light by the bubble had to be accounted for in the underwater system, unlike typical air combustion systems. A collimated light beam from a xenon flash lamp was focused to the center of the gas bubble, which refracted the light into a slowly diverging beam of light. This light beam was collected and focused into a temporally resolved spectrometer.

A reference signal was created by using a copper wire to replicate the bubble dynamics created by an iron wire, but without transitions in the spectral region of interest. Since a copper wire was used as the reference signal, a significant amount of noise was introduced to the system when the iron signal was divided by the copper signal and adjusted to unity. Each experimental spectrum was fit to a theoretical absorption signal to determine a temperature and pressure. The fitted temperature for each spectrum had a conservative error of 500 K and the pressure was fit to within 30%.

The emission and absorption techniques for measuring temperature were developed under controlled laboratory conditions. The emission system was designed for only a small portion of the leading edge to be engulfed by the combustion underwater. If this technique is to be used for underwater explosives, several requirements must be met. In order to limit interference, a small gauge plate in terms of the bubble radius would need to be used. This would limit the observation to a small portion of the gas bubble near the edge of the bubble expansion, or regions within the bubble which would most likely only be able to detect a signal as the bubble passes over the gauge. Once the gauge is engulfed by the bubble, the likelihood of the fibers withstanding the extreme pressures, temperatures or movements are slim. Beyond the survivability of the gauge, the explosive must also contain detonation prod-
ucts with intense and sustained emission to detect a signal and interpret a temperature. This technique is not applicable for large scale explosives (> 1 kg), but it should be able to be adapted for underwater explosives with a maximum weight of 10 grams or slightly higher if experiments are conducted at depth.

The absorption technique developed for measuring temperatures of UEWEs cannot directly be applied to an underwater explosive system. A bench top system allowed for precise alignment of the optics and light source which would be difficult on a large scale system, but possible if several light sources are used as described in the next section. The primary difficulty in measuring a temperature by absorption spectroscopy is attaining an appropriate reference signal. If the detonation products have a sufficient concentration of a strong absorber, the reference will need to be calculated separately without a gas bubble. If the explosive is seeded with a non-reacting absorber instead, then a reference signal can be attained by performing a second experiment with a high explosive without a seeded absorber. Not only would this be expensive, but the absence of the absorber may change the temperature of the high explosive and thus the dynamics of the bubble and reference signal. This would be similar to the UEWE experiments which used an iron wire with a copper wire as the reference signal.

7.2 Recommendations

7.2.1 Enhanced Aluminum Casings

In this study, the theoretical feasibility of enhanced casings was only performed on conical cavities with 42° apex angles, since the open literature contained values of the collapse angle and jet velocities for shaped charges with 42° apex angles. The main limitation in using enhanced aluminum casings is the energy balance between the added aluminum and the displaced high explosive.

Further work should be performed to include cavities with different geometries, such as hemispheres, trumpets, biconics, or truncated cones just to name a few. These different liner geometries may contain a larger volume of aluminum than pure conical cavities for the same amount of displaced
high explosive. These geometries may also allow for a greater liner thickness, which would also increase the aluminum mass available to react with water. The goal would be to find a geometry which would increase the aluminum mass enough to compensate for the energy lost from the high explosive, and still properly function to create a high speed jet. A computer model would need to be employed to determine the collapse and jetting properties of the various shaped charge geometries, since most geometries do not have simple one-dimensional governing equations like the conical cavities.

Additional work should also examine the effects of filling the cavities of an enhanced casing with powdered aluminum or other reactive metal powders. It was shown during the emission spectroscopy experiments and early underwater shaped charge work, that aluminum powder placed within a shaped charge reduces the penetration of a shaped charge, but increased the overall amount of aluminum reaction. This would help compensate for the energy content of the high explosive displaced by the aluminum lined cavities.

Since it was shown, both experimentally and theoretically, that the period of jetting occurred for a relatively small portion of the expansion phase of a gas bubble, computational modeling may be useful to determine the characteristics of enhancement for various geometries. The small time period of jetting in relation to the bubble expansion would allow the use of ALE3D to model different shaped charge geometries and examine the jetting characteristics during the formation of the shaped charge jet. By incorporating a chemistry modeling software, the energy output of the aluminum shaped charge could be modeled and compared to an unenhanced charge for effectiveness. By incorporating the kinetics of aluminum combustion and detonation, the energy release rate could be evaluated for each casing. This modeling would also verify how much of the cavity liner reacts with the water.

7.2.2 Spectroscopic Temperature Measurements

The current absorption technique for measuring temperatures was limited to a temporal resolution of 100 $\mu$s because of the intensity of the light source. Now that the technique has been developed to account for the refraction of light in the bubble, a stronger light source should be employed to increase the temporal resolution. By using several UV-LEDs and pulsing them with 2 or
3 times the recommended voltage, a sufficient light signal could be produced capable of attaining a temporal resolution of 1 μs. The increased temporal resolution would also decrease the noise of the signal, since the change in temperature would be less over a 1 μs period than a 100μs period.

The absorption technique was designed to measure the temperature of a small UEWE on a laboratory bench top. Because of the small scale, a large lens, used to focus the light source to the center of the bubble, was placed just outside of the small water tank. In a larger scale setup, where an explosive is suspended in a large water tank or pond, there would be no practical way to place a focusing lens near the explosive. In order to circumvent this problem, a single lens and light source could be replaced by a set of beams without a lens.

The light path created by a collimated beam and a focusing lens could be replicated by placing several collimated beams of light in an arc pattern and directing them at the high explosive, at predetermined angles from ray tracing software, to produce a collimated exit beam of light as shown in Figure 7.1. In order to test the feasibility of this proposed setup, a small scale experiment could be setup with a single collimated beam of light at a predetermined angle.

![Figure 7.1: Top-down view of proposed experimental setup to make absorption measurements on a large scale explosive test without the ability to use a focusing lens. Multiple collimated beams of light simulate the light path entering a gas bubble from a focusing lens and produce a collimated beam of light to be collected and focused onto a spectrometer.](image-url)
If the radial history of the bubble is well characterized, a single collimated beam of light could be flashed at a specific time for a given bubble size to produce a collimated exit beam. Since the angle of optimal transmission through the bubble would change as the bubble expands and contracts, a single pulsed beam of light would only provide information for a limited period of the bubble lifetime. This procedure could be replicated with several single pulsed flashes at various angles to account for the changing bubble size.

Assuming the reflection and refraction of light at the bubble/water interfaces could be predetermined to account for losses, the reference signal for this method could be taken by the collimated light source. By using the original light source as the reference, there would no longer be a requirement to seed a high explosive with a non-reacting absorbing species, and then perform a second high explosive test with a non-seeded high explosive to get a reference signal. An absorption measurement could potentially be performed on a single explosive test, instead of requiring multiple detonations for a single data point.
APPENDIX A

SMALL ALUMINUM CYLINDER PROOF OF CONCEPT FOR ENHANCED CASING PROJECT

A.1 Introduction

Previous work was performed with aluminum hemispheres of various sizes to look at the effects of placing shaped charge cavities on the surface of hemispherical aluminum explosive casings [29]. These experiments provided little information in regards to demonstrating the ability to create reactive aluminum jets escaping the primary gas bubble from an underwater explosion. However, these experiments demonstrated the importance of creating a planar or spherical detonation wave, which is perpendicular to the primary axis of a shaped charge. A small scale cylindrical experiment was developed to serve as a proof of concept for creating reactive aluminum jets from the casing of an underwater explosive.

The primary goal of this test sequence was to prove that small cavities lining an explosive casing are capable of creating small reactive jets. The previous hemisphere tests showed the importance of creating a uniform and centralized initiation point, which is easier to achieve with a cylinder than a hemisphere. A hemisphere requires a point initiated detonation to achieve a three dimensional spherical wave, where as a cylinder only requires symmetry in two dimensions to create a radially propagating detonation wave. Since this test was used as a proof of concept, only two test conditions were examined: a plain aluminum cylinder casing and a cylindrical aluminum casing with conical shaped charges on the edges.
A.2 Experimental Setup

The cylinder tests were conducted at the Engineering Student Projects Laboratory located on the UIUC campus. This facility was used for experiments that required a larger water tank than the tank in the Mechanical Engineering Laboratory. The steel water tank at this facility had nominal dimensions of 91.4 cm x 91.4 cm x 106.7 cm. The tank had optical access on two sides via polycarbonate windows, which allowed for high speed imaging of the underwater events with a high speed camera from Vision Research, the Phantom v7.0 CMOS. High speed imaging was recorded at a frame rate of 78.4k fps with an exposure of 2 µs. The images were backlighted to provide a contrast between the surrounding water and the explosive bubble. The primary purpose of the high speed imaging was to observe the early time events of the initial jetting or lack of jetting from the indentations on the casings and the late time events of bubble oscillation.

Pressure measurements were made using three W138A26 Tourmaline ICP underwater blast transducers from PCB Piezotronics. These gauges were placed at 28.1, 32.0 and 34.7 cm from the charge. A schematic of the tank with a suspended charge is shown in Figure A.1 along with a top-down image of the pressure transducers in the water tank without the charge.

![Figure A.1: The image on the left is a model of the water tank with a cylindrical charge suspended in the center of the tank. The image on the right is a top down image of the water tank with pressure transducers installed.](image)

The cylindrical charge was designed to have a central initiation and have a larger number of symmetric reactive dimples as compared to the hemisphere experiments. A schematic of the charge configuration without dimpling is

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shown in Figure A.2. Approximately 5 grams of NM/DETA were used as the main charge, and the radial dimension was designed such that the run-to-detonation distance was smaller than the distance from the detonator to the charge wall. In addition, an RP-81 detonator containing 80 mg of PETN and 450 mg of RDX, the largest detonator in the UIUC inventory, was used to initiate the NM/DETA. The baseline charge was comprised of a standard Al cylindrical wall with a wall thickness of 0.89 mm and heavy steel end caps, 6.35 mm thick, such that the blast was primarily directed radially outward.

**Figure A.2:** A schematic of the aluminum cylindrical charge. An RP-81 detonator is placed in the center of the cylinder and used as the source of detonation for the NM/DETA. This detonation sequence directs the blast radially outward, which is key in developing reactive jets from shaped charges attached to the cylindrical casing, not shown in this schematic.

The control charge used for this experiment was just the plain cylinder described above and shown in the schematic of Figure A.2. The enhanced reactive casing charge was created by adding six 60° aluminum cones with a base diameter of 6.35 mm and a wall thickness of 0.30 mm that were filled with nano-aluminum powder (≤ 80 nm). The addition of nano-aluminum powder was used to increase the aluminum water reaction. The added cones decreased the explosive charge mass by 4%. The control and reactive charges are shown in Figure A.3. Each charge was suspended 58.4 cm below the surface of the water in order to mitigate surface effects. The cones of the reactive casing were aligned such that one cone fired straight up and another fired straight down.
A.3 Results & Discussion

The primary goal of this setup was to determine if several small jets of reactive material could make it outside of the combustion bubble - thereby using ambient water as an oxidizer and energy enhancer - and whether the bubble dynamics were affected by the jetting. Figure A.4 displays the imaging sequences for the two tests. For the control case, a uniform bubble was formed with no jetting as expected. For the enhanced casing, the effects of the jets are clearly visible as compared to the plain casing. At early times, the jets do indeed penetrate outside the bubble and show evidence of reaction, indicated by the regions of strong luminosity. This reaction and jet formation does disrupt the formation of the bubble, and the disruptions on the bubble’s surface are evident at least as late as 280 µs after detonation. After approximately 400 µs, the video sequence becomes dark because of the interactions between the shock wave and the polycarbonate windows. The interference goes away around 2 ms and the bubble expansion was visible until approximately 11 ms, at which point the remaining portion of the video sequence was obstructed by the bubble. Due to the limited size of the water tank, there was no observable bubble collapse, and thus the jetting effects on bubble dynamics beyond early time expansion are unknown from this experiment.

Pressure traces showed no significant differences in the peak pressure and impulse for the two charges, despite the reduced HE in the second test. Pressure traces for the initial pressure peaks for all transducers are shown in Figure A.5. When the pressure traces for each individual transducer are
Figure A.4: The upper row of images shows the results from the plain cylinder test. A symmetrical gas bubble was formed from the plain cylinder. The bottom row of images shows the results from the enhanced casing test for the same time period as the plain test. The white arrows in the first two frames point toward regions containing jets and intense luminosity, indicating reactivity. The lingering effects on the gas bubble from the jets can be seen in the remaining images when compared to the gas bubble produced by the plain cylinder.

adjusted for timing between the two tests, the traces are very similar in shape. Also, the cumulative pressure impulse was essentially the same for both test conditions, as should be expected. No enhancement in the initial blast was observed or expected from these tests, since the initial blast wave is created from the fast reacting high explosive and not the slow reacting case fragments.
Figure A.5: The three graphs depict the pressure (solid line) and cumulative impulse (dashed line) for the pressure transducers. All graphs have the same scaling with the pressure traces corresponding to the y-axis on the left and the cumulative impulse traces corresponding to the y-axis on the right. There is no discernible difference between the plain casing (black) and the enhanced casing (red) for either the pressure traces or the cumulative impulses.

A.4 Conclusions

The small scale cylinder experiments were performed as a proof of concept, since the smaller experiments involving hemispheres provided little information regarding the feasibility of creating aluminum jets from the cavities in the side of an explosive casing. The enhanced cylinder casing created small protruding jets from the main gas bubble as shown by the high speed images. These images showed that after the initial detonation and formation of jets, the gas bubble had noticeable surface protrusions when compared with the gas bubble of the plain cylinder casing.

Based on the pressure traces and the impulse signals, there was no significant difference between the plain and the enhanced cylinder casings. This result was not surprising since the size of the tank prevented the collapse of either of the gas bubbles, which is where a difference in pressure should be noticeable.

These small scale cylinder tests proved the concept of producing aluminum jets from cavities on the surface of explosive casings. These jets were observed to escape the main bubble and react with the surrounding water based on the luminosity observed with high speed imaging during the early phases of bubble expansion. The bubble geometry was permanently altered by the addition of these cavities when compared to the plain cylinder. Based on this
test sequence, additional experiments with larger cylindrical charges were conducted to determine the effect various cavity geometries have on the formation and sustainability of aluminum jets.
APPENDIX B

DRAWINGS FOR ENHANCED ALUMINUM CASINGS TESTED AT THE NSWC-IH
Figure B.1: Baseline cylinder at NSWC-IH.
Figure B.2: Pyramid 8-42 cylinder at NSWC-IH.
Figure B.3: Pyramid 8 60 cylinder at NSWC-IH.
Figure B.4: Pyramid 10 60 cylinder at NSWC-IH.
Figure B.5: Ellipse AR 1.0 cylinder at NSWC-IH.
Figure B.6: Ellipse AR 1.5 cylinder at NSWC-IH. Not Tested.
Figure B.7: Ellipse AR 2.0 cylinder at NSWC-IH.
APPENDIX C
MATLAB CODE

C.1 Theoretical Shaped Charge and Underwater Explosive Model

% Shaped Charge on Surface of Underwater Explosive Model
% Tracks the radial position of a shaped charge on the surface of a
% spherical explosive charge underwater and compares it to the position of
% an unenhanced region on the sphere.
% Created by Lance Kingston
% Date Created: September 7, 2012
% Last Updated: November 29, 2012
% Parameters

global Redvol alpha

D = [.100 .120 .140 .160 .180 .200 .300 .400 .500 .600 .800 1.00]’;
% Charge Diameter (m)
Cnum = [4 6 8 10 12 14 16 18 20 25 30 40 50 60 70 80 90 100];
% number of cones
Depth = [100 250 500 1000 1500 2000]’;
% Depth of charge (m)
step = .0001;
% Increment of radius for numerical integration in Bubble Dynamic(m)
Red = .20;
% Reduction in Volume from cavities (0−1)
Angle = 42;
% Apex Angle (degree)
Jetper = 1;
% Percent of liner that becomes the jet (0−1)
Reactper = 1;
% Percent of jet mass that reacts (0−1)
BETA = 37.5;
% Collapse angle Birkhoff (deg)
alpha = pi * Angle / 180;
%(radians)
Vmin = 2000;
% Penetration Velocity Cutoff (m/s)
%Atmospheric Pressure (Pa)
Patm=101325;

%Gravity (m/s^2)
g=9.81;

%Density of Water (g/cc)
rhoH2O=1;

%Density of Aluminum (g/cc)
rhoAl=2.7;

%Density of Jet
rhoj=rhoAl;

%Density of Target
rhot=rhoH2O;

%Energy released when Al reacts with water (kJ/g)
E_release=16.0;

%% Geometry of Cones
%Preallocates space for required variables
RedVol=zeros(size(D,1),size(Cnum,2));
theta=zeros(size(D,1),size(Cnum,2));
h=zeros(size(D,1),size(Cnum,2));
H=zeros(size(D,1),size(Cnum,2));
CavVol=zeros(size(D,1),size(Cnum,2));
TotalAngle=zeros(size(D,1),size(Cnum,2));
Check=zeros(size(D,1),size(Cnum,2));
Dia=zeros(size(D,1),size(Cnum,2));
SCRatio=zeros(size(D,1),size(Cnum,2));
t=zeros(size(D,1),size(Cnum,2));
Liner=zeros(size(D,1),size(Cnum,2));
DiffVol=zeros(size(D,1),size(Cnum,2));
JetVol=zeros(size(D,1),size(Cnum,2));
ReactVol=zeros(size(D,1),size(Cnum,2));
JetMass=zeros(size(D,1),size(Cnum,2));
E_Al=zeros(size(D,1),size(Cnum,2));
Energy_Al=zeros(size(D,1),size(Cnum,2));

for j=1:size(Cnum,2)
    for i=1:size(D,1)
        %Find the cone geometry associated with each Charge Dia and # of Cones
        Volume(i,1)=(4*pi/3)*(D(i,1)/2)^3; %Volume (m^3)
        SA(i,1)=4*pi*(D(i,1)/2)^2; %Surface area (m^2)
        Ratio(i,1)=SA(i,1)/Volume(i,1); %Ratio of Surface Area to Volume
        RedVol(i,j)=Red*Volume(i,1)/Cnum(1,j); %Volume of Cones Combined (m^3)
        R=D(i,1)/2; %Radius for solver
    end
end

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redvol=RedVol(i,j);  %Reduced Volume per cone for Solver (m^3)
x0=[pi/4,.01,.05];  %Initial guesses for solver, x
(1)=theta (radians), x(2) = height of cap (m), x(3)=
height of cone (m)
options=optimset('Display','off');
[x,Fval,exitflag] = fsolve(@VolSolve,x0,options);
theta(i,j)=x(1);  %Central angle (radians)
h(i,j)=x(2);  %Height above chord (m)
H(i,j)=x(3);  %Height of cone from base to apex (m)
CavVol(i,j)=((2/3)*pi*h(i,j)*(D(i,1)/2)^2+(1/3)*H(i,j)*(
D(i,1)/2)*sin(theta(i,j)/2))^-2-(1/3)*D(i,1)/2)^3*cos
(theta(i,j)/2)*(sin(theta(i,j)/2))^2;  %Volume of
cavity removed per cone (m^3)
SolidAngle=2*pi*(1-cos(theta(i,j)/2));  %Solid Angle
per cone (Steradians)
TotalAngle(i,j) = SolidAngle*Cnum(1,j);  %Total Solid
Angle (Steradians)

% Prevents overlapping cones
if TotalAngle(i,j) < 2*pi && (H(i,j)+h(i,j))< D(i,1)/2
&& theta(i,j) < alpha
    Check(i,j)=1;
else
    Check(i,j)=NaN;
end

%Cone properties
Dia(i,j)=2*H(i,j)*tan(alpha/2);  %Diameter of Cone
base (m)
SCRatio(i,j)=(Dia(i,j)/D(i,1))*Check(i,j);  %Ratio
of Cone Dia to Charge Dia (m)
thick_per=.15;  %Percent of Dia for
liner thickness (1-4%)
t(i,j)=thick_per*Dia(i,j);  %Liner thickness (m)
Liner(i,j)=(1/3)*H(i,j)*(Dia(i,j)/2)^2-(1/3)*((Dia(i,j)
/2)-t(i,j))^3)/tan(alpha/2);  %Volume of single liner
(m^3)
DiffVol(i,j)=CavVol(i,j)-Liner(i,j);  %Difference in
Volume of cavity and volume of liner(m^3)
JetVol(i,j)=Jetper*Liner(i,j);  %Single Jet Volume
(m^3)
ReactVol(i,j)=Reactper*JetVol(i,j); % Volume that reacts per liner (m$^3$)

JetMass(i,j)=Cnum(1,j)*rhoAl*ReactVol(i,j)*((100^3)/1000); % Total Aluminum mass reacting (kg)

E_{_Al}(i,j)=JetMass(i,j)*E_{_release}*1000; % Energy total (kJ)

Energy_{_Al}(i,j)=Check(i,j)*E_{_Al}(i,j); % Energy Total including Geometry Satisfied (kJ)

end
end

%%% Explosive Properties

% ExpProp={'PETN',1.77,5794,8590,1.519;
% 'RDX',1.82,5036,8800,1.594;
% 'HMX',1.96,5010,9150,1.723;
% 'TATB',1.93,3496,8000,1.317;
% 'TNT',1.654,4476,6970,1.00}; % Name, Density (g/cc), Heat of Explosion (kJ/kg), Detonation Velocity (m/s), Relative Effectiveness (Wikipedia)

ExpProp={'PETN',1.8,5794,7200,1.067;
'RDX',1.8,5036,7600,1.189;
'HMX',1.8,5010,8000,1.317;
'TATB',1.8,3496,8400,1.452;
'TNT',1.8,4476,8800,1.594};

% Name, Density (g/cc), Heat of Explosion (kJ/kg), Detonation Velocity % (m/s), TNT Equivalency based on Detonation Velocity

ExpEnergy={ExpProp{1,1},Volume*ExpProp{1,2}*(1000)*ExpProp{1,3};
ExpProp{2,1},Volume*ExpProp{2,2}*(1000)*ExpProp{2,3};
ExpProp{3,1},Volume*ExpProp{3,2}*(1000)*ExpProp{3,3};
ExpProp{4,1},Volume*ExpProp{4,2}*(1000)*ExpProp{4,3};
ExpProp{5,1},Volume*ExpProp{5,2}*(1000)*ExpProp{5,3}; % Name, Energy (kJ)

%%% Positive Energy Gain Based on Geometry
% What combinations of charge radius and # of cones does the energy balance
% actually say that more energy is in the reactive aluminum liner than in

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% the removed HE?

```matlab
count = 0;
for i = 1:size(ExpProp,1)
    ExpRedEnergy{i,1} = ExpEnergy{i,2} * Red;
    for j = 1:size(Cnum,2)
        for k = 1:size(D,1)
            Diff{i,1}{(k,j)} = Energy_Al(k,j) - ExpRedEnergy{i,1}{(k,1)};
            % Difference from Al to Explosive (kJ)
            if Diff{i,1}{(k,j)} < 0
                DiffPos{i,1}{(k,j)} = 0;
            else
                DiffPos{i,1}{(k,j)} = Diff{i,1}{(k,j)};
                if DiffPos{i,1}{(k,j)} > 0
                    count = count + 1;
                end
            end
        end
    end
end
sprintf('Number of conditions with a positive energy: %d', count)
```

%% Shaped Charge Velocity

% Birkhoff Theory of Shaped Charge Collapse
% Constant Velocity and masses, as well as jet length

```matlab
beta = (BETA) * pi / 180; % Angle of collapsing liner (radians)

for i = 1:size(ExpProp,1)
    Ud = ExpProp{i,4}; % m/s
    Vj{i,1} = (Ud / cos((alpha/2))) * sin(beta - (alpha/2)) * ((1 / sin(beta)) + (1 / tan(beta)) + tan((beta - (alpha/2)) / 2)); % Jet Tip Velocity (m/s)
    Vs{i,1} = (Ud / cos((alpha/2))) * sin(beta - (alpha/2)) * ((1 / sin(beta)) - (1 / tan(beta)) - tan((beta - (alpha/2)) / 2)); % Slug Velocity (m/s)
    Vo{i,1} = (Ud / cos((alpha/2))) * (sin(beta - (alpha/2)) / cos((beta - (alpha/2)) / 2)); % Stagnation Velocity (m/s)
    mj{i,1} = 0.5 * (1 - cos(beta)); % Mass percent of Jet (%)
    ms{i,1} = 0.5 * (1 + cos(beta)); % Mass percent of Slug (%)
end
```

```matlab
for j = 1:size(Cnum,2)
end
```
for i=1:size(D,1)
  jl(i,j)=H(i,j)/cos(alpha/2)*Check(i,j);  % length of jet (m)
  PenBirk(i,j)=jl(i,j)*((rhoj/rhot)^(1/2));  % Penetration Length (m)
end
end
toc

% Bubble Dynamics

display('Bubble Dynamics')
Po=g*rhoH2O.*Depth*1000+Patm;  % Hydostatic Pressure (Pa)
W=zeros(size(D,1),size(ExpProp,1));
for i=1:size(D,1)
  for j=1:size(ExpProp,1)
    W(i,j)=Volume(i,1)*ExpProp{j,2}*ExpProp{j,5}*1000;  % Explosive weight (kg)
  end
end

Ro=D./2;
for k=1:size(ExpProp,1)
  for j=1:size(Po,1)
    for i=1:size(Ro,1)
      Rmax(i,j,k)=3.38*(W(i,k)/(Po(j,1)/(rhoH2O*1000*g)))^(1/3);  % Maximum radius (m^3) Swift and Decius
      B(i,j,k)=((3*rhoH2O*1000)/(2*Po(j,1)))^(1/2);  % Constant in integration (s/m)
      A{i,j,k}=[Ro(i,1):step:Rmax(i,j,k)'];  % Numerical increments for integration (m)
      BubEnergy(i,j,k)=(4*pi/3)*Rmax(i,j,k)^3*Po(j,1)/1000;  % (kJ)
    end
  end
end

% Calculate the time for the progression of the bubble
Rad=cell(size(Ro,1),size(Po,1),size(ExpProp,1));
Ti=cell(size(Ro,1),size(Po,1),size(ExpProp,1));
T=cell(size(Ro,1),size(Po,1),size(ExpProp,1));

for k=1:size(ExpProp,1)
  for j=1:size(Po,1)
for i=1:size(Ro,1)
    Rad{i,j,k}=zeros((size(A{i,j,k},1)*2-1),1);
    T1{i,j,k}=zeros((size(A{i,j,k},1)*2-1),1);
    Arev=flipud(A{i,j,k});
    Rad{i,j,k}(1:size(A{i,j,k},1),1)=A{i,j,k};
    Rad{i,j,k}((size(A{i,j,k},1)+1):end,1)=Arev(2:end,1);
    for m=1:size(Rad{i,j,k},1)
        T1{i,j,k}(m,1)=B(i,j,k)/(((Rmax(i,j,k)/Rad{i,j,k}(m,1))^3-1)^(1/2));
    end
    T{i,j,k}=zeros(size(Rad{i,j,k},1),1);
    T{i,j,k}=cumtrapz(T1{i,j,k})*step; %Time of bubble expansion and collapse (s)
end
end
clear A Arev T1 %Removes large variables to help with memory constraints

% Penetration Model
% Target is located at the boundary of the original sphere

display('Penetration Model')
gamma = (rhot/rhoj)^(1/2);

Timestop=zeros(size(Ro,1),size(Po,1),size(ExpProp,1));
for k=1:size(ExpProp,1)
    for i=1:size(Ro,1)
        for g=1:size(Po,1)
            Timestop(i,g,k)=find(T{i,g,k} < .001,1,'last'); % Cutoff time of matching bubble to reduce computational time
        end
    end
end

% Preallocate memory
Zo=zeros(size(Ro,1),size(Cnum,2));
zetao=zeros(size(Ro,1),size(Cnum,2));
tau0=zeros(size(Ro,1),size(Cnum,2),size(ExpProp,1));
to=zeros(size(Ro,1),size(Cnum,2),size(ExpProp,1));
start=zeros(size(Ro,1),size(Cnum,2),size(Po,1),size(ExpProp,1));
stop=zeros(size(Ro,1),size(Cnum,2),size(Po,1),size(ExpProp,1));
Pstop=zeros(size(Ro,1),size(Cnum,2),size(Po,1),size(ExpProp,1));
tstop=zeros(size(Ro,1),size(Cnum,2),size(Po,1),size(ExpProp,1));
tau1=cell(size(Ro,1),size(Cnum,2),size(ExpProp,1));
T2=cell(size(Ro,1),size(Cnum,2),size(Po,1),size(ExpProp,1));
Pd=cell(size(Ro,1),size(Cnum,2),size(Po,1),size(ExpProp,1));
Pen=cell(size(Ro,1),size(Cnum,2),size(Po,1),size(ExpProp,1));
V=cell(size(Ro,1),size(Cnum,2),size(Po,1),size(ExpProp,1));
T3=cell(size(Ro,1),size(Cnum,2),size(Po,1),size(ExpProp,1));

for k=1:size(ExpProp,1)
    for j=1:size(Cnum,2)
        for i=1:size(Ro,1)
            for g=1:size(Po,1)
                Zo(i,j)=(3/4)*H(i,j)+h(i,j); %Virtual Origin position, rule of thumb (m)
zetao(i,j)=Zo(i,j)/Dia(i,j); %Scaled Virtual Origin (m/m)
tau0(i,j,k)=zetao(i,j)/Vj(k,1); %Scaled time of target impact from virtual origin (m)
tau1{i,j,k}=[0:0.000005:tau0(i,j,k)]'; %Scaled time up to target (s/m)
to(i,j,k)=Zo(i,j)/ExpProp{k,4}; %Time to target (s) time before bubble expands
                ab=find(tau1{i,j,k}(1:1)<to(i,j,k),1,'last'); %Index of time before bubble starts
                T2{i,j,g,k}=[tau1{i,j,k}(1:ab,1)*Dia(i,1);T{i,g,k}(1:Timestop{i,g,k},1)+to(i,j,k)]; %Time sequence for data, to compensate for bubble (s)
                tau2=T2{i,j,g,k}/Dia(i,j); %Scaled time (s/m)
                Vstag=Vj(k,1)*(tau0(i,j,k)./tau2).^((gamma/(1+gamma))); %Velocity at stagnation point (m/s)
Pd{i,j,g,k}=tau2.*Vstag-zetao(i,j); %Scaled Penetration (m/m)
Pen{i,j,g,k}=Pd{i,j,g,k}*Dia(i,j); %Penetration (m)
                for q=1:size(Pen{i,j,g,k},1)
                    V{i,j,g,k}(q,1)=(Pen{i,j,g,k}(q,1,1)-Pen{i,j,g,k(q,1,1)}./(T2{i,j,g,k}(q,1,1)-T2{i,j,g,k}(q+1,1))); %Velocity (m/s)
            end
        end
    end
end
T3{\textit{i}, \textit{j}, \textit{g}, \textit{k}}(\textit{q}, 1) = (T2{\textit{i}, \textit{j}, \textit{g}, \textit{k}}(\textit{q} + 1, 1) + T2{\textit{i}, \textit{j}, \textit{g}, \textit{k}}(\textit{q}, 1))/2; \%Time for Velocity (s)

\textbf{end}

\textbf{start}(\textit{i}, \textit{j}, \textit{g}, \textit{k}) = \textbf{find}(\text{Pen}\{\textit{i}, \textit{j}, \textit{g}, \textit{k}\}(\textit{:, 1}) < 0, 1, \text{'last'}) + 1;

\textbf{stop}(\textit{i}, \textit{j}, \textit{g}, \textit{k}) = \textbf{find}(\text{V}\{\textit{i}, \textit{j}, \textit{g}, \textit{k}\}(\textit{:, 1}) < \text{Vmin}, 1, \text{'first'})

\textbf{Pstop}(\textit{i}, \textit{j}, \textit{g}, \textit{k}) = \text{Pen}\{\textit{i}, \textit{j}, \textit{g}, \textit{k}\}(\text{stop}(\textit{i}, \textit{j}, \textit{g}, \textit{k}), 1);

\textbf{tstop}(\textit{i}, \textit{j}, \textit{g}, \textit{k}) = \text{T2}\{\textit{i}, \textit{j}, \textit{g}, \textit{k}\}(\text{stop}(\textit{i}, \textit{j}, \textit{g}, \textit{k}), 1);

\textbf{end}

\textbf{end}

\textbf{end}

\textbf{end}

\% \% Combine effects of Bubble Dynamics and Penetration
\% * next to a variable for time indicates that the time listed is not absolute, it is a time on one of the timescales that has not been fully corrected

\textbf{display(‘Combine’)}

\textbf{Dist} = \text{cell} (\text{size}(\text{Ro}, 1), \text{size}(\text{Cnum}, 2), \text{size}(\text{Po}, 1), \text{size}(\text{ExpProp}, 1));

\textbf{T5} = \text{cell} (\text{size}(\text{Ro}, 1), \text{size}(\text{Cnum}, 2), \text{size}(\text{Po}, 1), \text{size}(\text{ExpProp}, 1));

\textbf{for} \textit{g} = 1: \text{size}(\text{Po}, 1)
\textbf{for} \textit{k} = 1: \text{size}(\text{ExpProp}, 1)
\textbf{for} \textit{j} = 1: \text{size}(\text{Cnum}, 2)
\textbf{for} \textit{i} = 1: \text{size}(\text{Ro}, 1)

\textbf{PenD} = \text{Pen}\{\textit{i}, \textit{j}, \textit{k}\} + \text{D}(\textit{i}, 1)/2; \%Penetration adjusted to start at the surface of the charge (m)

\textbf{T4} = \text{T}\{\textit{i}, \textit{j}, \textit{g}, \textit{k}\} + \text{to}(\textit{i}, \textit{j}, \textit{k}); \%Bubble time shift to account for the travel of the jet from the virtual origin (s)

\textbf{Tp} = \text{T2}\{\textit{i}, \textit{j}, \textit{g}, \textit{k}\}(\text{start}(\textit{i}, \textit{j}, \textit{g}, \textit{k}); \text{stop}(\textit{i}, \textit{j}, \textit{g}, \textit{k}), 1) - \text{to}(\textit{i}, \textit{j}, \textit{k}); \%Time of Penetration by Jet (s)

\textbf{Tswitch} = \text{T2}\{\textit{i}, \textit{j}, \textit{g}, \textit{k}\}(\text{stop}(\textit{i}, \textit{j}, \textit{g}, \textit{k}), 1); \%Time for switching from jet to bubble (s)

\textbf{change} = \textbf{find}(\text{T4} < \text{Tswitch}, 1, \text{'last'}) + 2; \%index for matching the timescales
inc=stop(i,j,g,k)-start(i,j,g,k)+1; \text{ %Number of points used in penetration}

Bubdist=Rad\{i,g,k\}(\text{change: end,1})+Pstop(i,j,g,k)+D(i,1)/2-Rad\{i,g,k\}(\text{change: -1,1}); \text{ %Distance of Bubble adjusted for penetration distance (m)}

Bubtime=T4(\text{change: end,1})-to(i,j,k); \text{ %Time associated with bubble expansion (s)}

Pentravel=PenD(start(i,j,g,k):stop(i,j,g,k),1); \text{ %Penetration Distance (m)}

Dist\{i,j,g,k\}=zeros((\text{size(Bubdist,1)}+\text{size(Pentravel,1)}),1); \text{ %Distance of bubble and jet combined (m)}

T5\{i,j,g,k\}=zeros(\text{size(Dist\{i,j,g,k\},1)},1); \text{ %Time of bubble and jet travel (s)}

\text{for} b=1:\text{size(Dist\{i,j,g,k\},1)}
\\quad \text{if} b<=\text{inc}
\quad \quad \text{Dist\{i,j,g,k\}(b,1)=Pentravel(b,1);}
\quad \quad \text{T5\{i,j,g,k\}(b,1)=Tp(b,1);}
\quad \text{else}
\quad \quad \text{Dist\{i,j,g,k\}(b,1)=Bubdist((b-\text{inc}),1);}
\quad \quad \text{T5\{i,j,g,k\}(b,1)=Bubtime((b-\text{inc}),1);}
\text{end}
\text{end}
\text{end}
\text{end}
\text{end}
\text{clear Bubdist Bubtime T4} \text{ %Removes large variables to help with memory constraints}

\% Calculate the Bubble Enhancement and Radial Gain

MaxTotal=zeros(\text{size(Ro,1)},\text{size(Cnum,2)},\text{size(Po,1)},\text{size(ExpProp,1)});
RadGain=zeros(\text{size(Ro,1)},\text{size(Cnum,2)},\text{size(Po,1)},\text{size(ExpProp,1)});
\text{for} g=1:\text{size(Po,1)}
\text{for} k=1:\text{size(ExpProp,1)}
\text{for} j=1:\text{size(Cnum,2)}
\text{for} i=1:\text{size(Ro,1)}
\quad \text{MaxTotal}(i,j,g,k)=\max(\text{Dist\{i,j,g,k\}});
\quad \text{RadGain}(i,j,g,k)=\text{MaxTotal}(i,j,g,k)-\text{Rmax}(i,g,k);
\text{end}
\text{end}
\text{end}
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\[
\text{MaxRatio}(i, j, g, k) = \frac{\text{MaxTotal}(i, j, g, k)}{R_{\text{max}}(i, g, k)};
\]
end
end
end
end
C.2 Cone Geometry Solver

% Solves the three equations needed to determine the geometries of the cones on the surface of spherical explosive
% Created by Lance Kingston
% Date Created: September 7, 2012
% Last Updated: November 29, 2012

function V = VolSolve(x)

global R redvol alpha

V = [ redvol − (2/3)∗pi∗x(2)∗R^2 − (1/3)∗x(3)∗(R∗sin(x(1)/2))ˆ2 + (1/3)∗R^3∗cos(x(1)/2)∗(sin(x(1)/2))ˆ2;
    x(2)−R*(1−cos(x(1)/2));
    x(3)∗tan(alpha/2)−R∗sin(x(1)/2) ];
C.3 NSCW-IH Shock Wave Tracker

% Program designed to track edges of shockwave created by an underwater blast and then calculate the shock position and velocity.

% The Shockwave detection cell is designed to be run several times by itself while slowly adjusting the last edge detection line between sobel and roberts, (roberts is better in general) and lowering the threshold value from 0.05 to 0.0005 at the extremely low end for only a few really dark frames.

% Created by Lance Kingston
% Created: Sept. 1, 2010
% Last updated: Sept. 9, 2010

shot= '06';
global Xcenter;
global Ycenter;
global time;
interval=4; %micro-seconds
first=1; %First frame
last=102; %Last frame of sequence
lastshock=30; %Last frame of Shock
prefix=sprintf('Shot %s IHUW_Shot%s.Dat \IHUW_Shot%s.tif
IHUW_Shot%s',shot,shot,shot,shot);

%%% Centroid Calculation
file = sprintf('%s%03.0f.tif',prefix,1);
A=imread(file); %Original image
level= graythresh(A); %Thresholds the image
B=im2double(im2bw(A,level)); %Makes binary image
C=-(B-ones(size(B))); %Inverts image
D=bwareaopen(C,200,4); %Removes small lines and background defects
figure(1) %Shows the progression of edge detection
subplot(2,2,1)
imshow(A)
title('Original')
subplot(2,2,2)
imshow(B)

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```matlab
title('Binary')
subplot(2,2,3)
imshow(C)
title('Inverted')
subplot(2,2,4)
imshow(D)
title('Clean')
pause

close all

Mask1=roipoly(D);  
%Draw border around charge

close figure 1

E=Mask1 & D;  
%Shows the rough area of interest

[r,c] = find(E);  
%Narrows the area to look at

limits(1) = min(r)-5;
limits(2) = max(r)+5;
limits(3) = min(c)-10;
limits(4) = max(c)+10;

if limits(1) < 1
    limits(1) = 1;
end

if limits(2) > 260
    limits(2) = 260;
end

if limits(3) < 1
    limits(3) = 1;
end

if limits(4) > 312
    limits(4) = 312;
end

clear r

clear c

for j = limits(3):limits(4)
    for i = limits(1):limits(2)
        Overlay(i+1-limits(1),j+1-limits(3)) = D(i,j);  
        %Zooms in on the area of interest
    end
end

figure

Mask2 = roipoly(Overlay);  
%Zoomed in view to draw border and remove non-charge objects

close figure 1
```
for j = limits(3):limits(4)
    for i = limits(1):limits(2)
        E(i,j) = E(i,j) & Mask2(i+1-limits(1),j+1-limits(3));
        %Resets size of previous zoomed in area
    end
end

F=E;
figure(2)
title('Charge Only!!')
imshow(F)
pause

close figure 2
Stat=regionprops(im2double(F), 'Centroid', 'FilledArea', 'Extrema');
Xcenter=Stat.Centroid(1) % X-coordinate Centroid
Ycenter=Stat.Centroid(2) % Y-coordinate Centroid
filename1=sprintf('Center%s', shot);
save(filename1, 'Xcenter', 'Ycenter');

% Finds Calibration based on Diameter and Radius
P=zeros(size(A));
MM=edge(im2double(F), 'sobel');

for m = -1:1
    P(floor(Ycenter)+m, floor(Xcenter)+m) = 1;
    P(floor(Ycenter)+m, floor(Xcenter)-m) = 1;
end

figure (3)
imshow(MM+P) %Shows the edges and center of charge
pause

close figure 3

for k=1:4
    diameter(k) = sqrt((Stat.Extrema(k,1)-Stat.Extrema(k+4,1))^2+(Stat.Extrema(k,2)-Stat.Extrema(k+4,2))^2);
end

CalD(1)=mean(diameter)/2.75; %Pixel/inch Based on four extreme sets of points, diameter
CalD(2)=std(diameter)/2.75; %Pixel/inch Based on four extreme sets of points, diameter

z=0;
for i = 1:260
    for j = 1:312
        if MM(i,j) == 1
            z = z + 1;
            distances(z) = ((j-Xcenter)^2 + (i-Ycenter)^2)^0.5;
        end
    end
end
CalR(1) = mean(distances)/1.375; % Pixel/inch Based on distance from edge to centroid, radius
CalR(2) = std(distances)/1.375; % Pixel/inch Based on distance from edge to centroid, radius

%% Initial Conditions Shock Wave
firstframe = 1;
lastframe = 30;
Quality = 2*ones(lastframe,1);

%% Track the shock wave
for j = firstframe : lastframe

    file = sprintf('%s%03.0f.tif', prefix, j); % loads file
    AA(:,:,j) = imread(file);
    if Quality(j)==2
        if j==1 | j==2 | j==3 | j==4 | j==5
            % Adjust the threshold or remove for the first few images
            Edges(:,:,j) = edge(AA(:,:,j),'roberts',0.01);
            % Edge detection sobel ignores the rod, roberts detects the rod
        else
            Adjust(:,:,j) = adapthisteq(im2double(AA(:,:,j)));
            Edges(:,:,j) = edge(Adjust(:,:,j),'sobel');
        end
    elseif Quality(j)==1
        % Adjust the threshold (lower in general) and change from sobel to
        % roberts and vice versa until nice lines are shown
        Edges(:,:,j) = edge(AA(:,:,j),'sobel',0.025);
    else
        continue
    end

end
\begin{verbatim}
Edge_Fill(:, :, j) = bwareaopen(Edges(:, :, j), 20, 8);
    \%Removes small speckles

for g=249:260
    for h=256:312
        Edge_Fill(g, h, j) = 0;
    end
end
theta = 0:0.001:(2*pi);
if j==1
    CircleVector_Inner(:, :, j) = [round(Ycenter+(CalR(1)*1.357-5)*sin(theta));
        round(Xcenter+(CalR(1)*1.375-5)*cos(theta))];
    CircleVector_Outer(:, :, j) = [round(Ycenter+(CalR(1)*1.357+25)*sin(theta));
        round(Xcenter+(CalR(1)*1.375+25)*cos(theta))];
else
    CircleVector_Inner(:, :, j) = [round(Ycenter+(ShockStat(j-1,2)-2)*sin(theta));
        round(Xcenter+(ShockStat(j-1,2)-2)*cos(theta))];
    CircleVector_Outer(:, :, j) = [round(Ycenter+(ShockStat(j-1,2)+15)*sin(theta));
        round(Xcenter+(ShockStat(j-1,2)+15)*cos(theta))];
end
Inner_Edge(:, :, j) = zeros(size(AA(:, :, j))); \%Eventually becomes the inner circle of interest
Outer_Edge(:, :, j) = zeros(size(AA(:, :, j))); \%Eventually becomes the outer circle of interest
for k=1:length(CircleVector_Inner(:, :, j))
    g=CircleVector_Inner(1, k, j); \%Inner row
    h=CircleVector_Inner(2, k, j); \%Inner column
    if g>0 & h>0 & g<261 & h<313
        Inner_Edge(g, h, j) = 1;
    elseif g<1 & h>0 & h<313
        Inner_Edge(1, h, j) = 1;
    elseif g>260 & h>0 & h<313
        Inner_Edge(260, h, j) = 1;
    elseif h<1 & g>0 & g<261
        Inner_Edge(g, 1, j) = 1;
    elseif h>312 & g>0 & g<261
        Inner_Edge(g, 312, j) = 1;
    end
m=CircleVector_Outer(1, k, j); \%Outer row
\end{verbatim}
n = CircleVector.Outer(2, k, j); % Outer column
if m > 0 & n > 0 & m < 261 & n < 313
   Outer.Edge(m, n, j) = 1;
elseif m < 1 & n > 0 & n < 313
   Outer.Edge(1, n, j) = 1;
elseif m > 260 & n > 0 & n < 313
   Outer.Edge(260, n, j) = 1;
elseif n < 1 & m > 0 & m < 261
   Outer.Edge(m, 1, j) = 1;
elseif n > 312 & m > 0 & m < 261
   Outer.Edge(m, 312, j) = 1;
end
end
Mask_Inner(:, :, j) = imfill(Inner.Edge(:, :, j), 'holes'); % Inner Area of Interest
Mask_Outer(:, :, j) = imfill(Outer.Edge(:, :, j), 'holes'); % Outer Area of Interest
Mask_Ring(:, :, j) = Mask_Outer(:, :, j) - Mask_Inner(:, :, j); % Ring of Interest
Edge.Fill.R(:, :, j) = zeros(length(Edge.Fill(:, 1, j)), length(Edge.Fill(1, :, j)));
Edge.Fill.Ring(:, :, j) = Edge.Fill.R(:, :, j);
AA.Ring(:, :, j) = AA(:, :, j);
for g = 1:260
    for h = 1:312
        if Mask_Ring(g, h, j) == 1
            AA.Ring(g, h, j) = AA(g, h, j);
            Edge.Fill.Ring(g, h, j) = Edge.Fill(g, h, j);
        else
            AA.Ring(g, h, j) = 0;
        end
    end
end
for g = 1:260
    for h = 1:312
        if Edge.Fill.Ring(g, h, j) == 1
            rad(g, h, j) = sqrt((h - Xcenter)^2 + (g - Ycenter)^2);
            % Finds all radii from center to every active pixel
        else
            rad(g, h, j) = NaN;
        end
    end
end
% Replaces all off pixels with NaN
end
end
end

ShockStat(j,1)=nanmedian(nanmedian(rad(:,:,j)));  
  %Shock Median
ShockStat(j,2)=nanmean(nanmean(rad(:,:,j)));  
  %Shock Mean
ShockStat(j,3)=nanstd(nanstd(rad(:,:,j)))  
   %Shock Std

% The while loop tries to recursively remove points until
% the median and mean are within 0.5 standard deviations
while ShockStat(j,3)>.5*(ShockStat(j,2)>(ShockStat(j,1)+.25*ShockStat(j,3))  
        | ShockStat(j,2)<(ShockStat(j,1)-.25*ShockStat(j,3)))  
        %Standard Deviation less than 1
    if (ShockStat(j,2)<(ShockStat(j,1)+.1) & ShockStat(j,2)  
        >(ShockStat(j,1)-.1))
        break
    end
for g=1:260
    for h=1:312
        if rad(g,h,j)<(ShockStat(j,1)+.25*ShockStat(j,3))  
            & rad(g,h,j)>(ShockStat(j,1)-.25*ShockStat(j,3))  
            %use .25 std
            rad(g,h,j)=rad(g,h,j);
        else
            rad(g,h,j)=NaN;
        end
    end
end
ShockStat(j,1)=nanmedian(nanmedian(rad(:,:,j)));  
  %Shock Median
ShockStat(j,2)=nanmean(nanmean(rad(:,:,j)));  
  %Shock Mean
ShockStat(j,3)=nanstd(nanstd(rad(:,:,j)))  
   %Shock Std
end
ShockPosition(j)=ShockStat(j,2)/CalR(1)*25.4;  
    %Shock Radius mm
Srad(:, :, j) = -(isnan(rad(:, :, j)) - 1);  % Binary Matrix of Pixels used to determine shock

figure(4)
subplot(2, 2, 1)
imshow(im2double(AA(:, :, j)))
title(['Original Frame ', num2str(j)])
subplot(2, 2, 2)
imshow(im2double(AA.Ring(:, :, j)))
showaxes('on')
title('Region of Interest')
subplot(2, 2, 3)
imshow(Edge.Fill.Ring(:, :, j))
title('Cleaned up')
subplot(2, 2, 4)
imshow(Srad(:, :, j))
title('ShockWave')
pause
close figure 4

Srad_Single(:, :) = Srad(:, :, j);  % Converts to a single matrix

AA_Single(:, :) = AA(:, :, j);  % Converts to a single matrix

AA.Shock_red = im2double(AA_Single);  % Converts to RGB
AA.Shock_green = im2double(AA_Single);
AA.Shock_blue = im2double(AA_Single);

% Makes the edge of the ShockWave Yellow
for g = 1:260
    for h = 1:312
        if Srad_Single(g, h) == 1
            AA.Shock_red(g, h) = 255;  % Red
            AA.Shock_blue(g, h) = 255;  % Green
            AA.Shock_green(g, h) = 0;  % Blue
        end
    end
end

AA.Shock.RGB(:, :, 1) = AA.Shock_red(:, :);
AA.Shock.RGB(:, :, 2) = AA.Shock_blue(:, :);
AA.Shock.RGB(:, :, 3) = AA.Shock.green(:, :);
Data\{j\}\{AA\_Shock\_RGB\};

figure (5)
imshow\(\text{AA\_Shock\_RGB}\)

% Quality list

ts\{sw\} = input\('Is this any good?\n1=Yes 2=No 3=No Shock'\)

if (s\{sw\}==1)
    Quality\(j\) =0;
    ShockMedian=ShockStat (:,1) *25.4/CalR(1);
    %Median mm
    ShockStd=ShockStat (:,3) *25.4/CalR(1);
    %Standard Deviation mm
end
if (s\{sw\}==2),
    Quality\(j\)=1;
end
if (s\{sw\}==3)
    Quality\(j\)=0;
    ShockPosition\(j\)=NaN;
    ShockMedian\(j\)=NaN;
    ShockStd\(j\)=NaN;
end

close figure 5
end

Mistakes=sum\(\text{Quality}\)
RedoFrames=find\(\text{Quality}\)

pause
filename2=sprintf\('ImageSequence\_%s',\text{shot}\);
save\(\text{filename2},\ 'Data'\);

% Shock Velocity
% This is done after all of the frames have been approved
if Mistakes==0
    for j=firstframe: lastframe
        if j==1
        else
\text{ShockVelocity}(j-1) = \frac{(\text{ShockStat}(j,2) - \text{ShockStat}(j-1,2))}{\text{interval}} / \text{CalR}(1) * 25.4; \quad \% \text{Velocity mm/ms}

\text{end}
\text{time}(j) = (j-1) * \text{interval};
\text{end}
\text{end}

% Output to excel
\text{tab} = \text{sprintf('Shot_%s',shot)};
\text{CalHeaders} = \{ 'Calibration (based on radius)', 'Calibration Std' \};
\text{CalUnits} = \{ 'pixel/mm', 'pixel/mm' \};

\text{Headers} = \{ 'Time', 'Shock Position', 'Shock Median', 'Shock Std.', 'Shock Velocity' \};
\text{Units} = \{ 'usec', 'mm', 'mm', 'mm', 'mm/usec' \};
\text{xlswrite('ShockData.xls', CalHeaders, tab, 'A1');}
\text{xlswrite('ShockData.xls', CalUnits, tab, 'A2');}
\text{xlswrite('ShockData.xls', [CalR(1), CalR(2)], tab, 'A3');}
\text{xlswrite('ShockData.xls', Headers, tab, 'A5');}
\text{xlswrite('ShockData.xls', Units, tab, 'A6');}
\text{xlswrite('ShockData.xls', [time(:), ShockPosition(:), ShockMedian(:), ShockStd(:)], tab, 'A7');}
\text{xlswrite('ShockData.xls', [ShockVelocity(:)], tab, 'E7');}
C.4 NSCW-IH Bubble Area Tracker

% This code is designed to ignore the shockwave produced by the underwater explosive and instead track the underwater bubble formed by the detonation products.

% Created by Lance Kingston
% Created: Sept. 10, 2010
% Last updated: Sept. 16, 2010

% Load Data and Initial Conditions
clear all
close all

shot = '06';
global Xcenter;
global Ycenter;
global time;
interval = 4; % microseconds
first = 1; % First frame
last = 102; % Last frame of sequence
lastbubble = 75; % Last frame of bubble
prefix = sprintf('Shot %s\IHUW_Shot%s.Dat\IHUW_Shot%s.tif\IHUW_Shot%s', shot, shot, shot, shot);
filename1 = sprintf('Center%s', shot);
load (filename1);
load ('Calibration'); % All six shots: 1st column is Calibration (pixel/mm), 2nd stand. dev. (pixel/mm)
Quality = ones(lastbubble, 1);

% Track the Bubble size by pie slices
ltheta = -3*pi/8; % The bottom of the pie slice
rtheta = -1*pi/8; % The top of the pie slice

for j = 1: lastbubble
    if Quality(j) == 1
        file = sprintf('%s%03.0f.tif', prefix, j); % Loads file
        AA(:,:,j) = imread(file);
        Orig(:,:,j) = im2double(AA(:,:,j));
        Thresh(:,:,j) = im2double(AA(:,:,j));
        for g = 1:260
            for h = 1:312
                % Further processing...
            end
        end
    end
end
if Orig(g,h,j) > .24
    \%This determines
    the thresholding, may need to be adjusted
    Thresh(g,h,j) = 1;
else
    Thresh(g,h,j) = 0;
end
end
end
end

Sect_Thresh(:, :, j) = zeros(size(Thresh(:, :, j))); \%Sectional Image
b1 = Ycenter - tan(-ltheta)*Xcenter;
b2 = Ycenter - tan(-rtheta)*Xcenter;

for a = 1:260
    for b = 1:312
        if Thresh(a,b,j) == 0
            if tan(-ltheta)*b + b1 > a  \%May need to flip >
                and < to change where you look
                if tan(-rtheta)*b + b2 < a
                    Sect_Thresh(a,b,j) = 1;
                end
            end
        end
    end
end

Bub(:, :, j) = bwselect(Sect_Thresh(:, :, j), Xcenter + 5, Ycenter + 5, 8); \%Add or Subtract from Xcenter, Ycenter to place point in region you want to select.
Bubble(:, :, j) = imfill(Bub(:, :, j), 'holes');

figure(1)
subplot(2,2,1)
imshow(Orig(:, :, j))
title(['Original Frame ', num2str(j)])
showaxes('on')
subplot(2,2,2)
imshow(Thresh(:, :, j))
title('Threshold')
showaxes('on')
subplot(2,2,3)
imshow(Sect_Thresh(:, :, j))

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title('Slice of Interest')
showaxes('on')
subplot(2,2,4)
imshow(Bubble(:, :, j))
title('Complete Bubble Section')
showaxes('on')
pause

Bubble_Single(:, :) = Bubble(:, :, j); % Converts to a single matrix

AA_Single(:, :) = AA(:, :, j); % Converts to a single matrix

Bubble_red = im2double(AA_Single); % Converts to RGB
Bubble_green = im2double(AA_Single);
Bubble_blue = im2double(AA_Single);

%Makes the Bubble Section Yellow
for g = 1:260
    for h = 1:312
        if Bubble_Single(g, h) == 1
            Bubble_red(g, h) = 255; % Red
            Bubble_blue(g, h) = 255; % Green
            Bubble_green(g, h) = 0; % Blue
        end
    end
end

Bubble_RGB(:, :, 1) = Bubble_red(:, :);
Bubble_RGB(:, :, 2) = Bubble_blue(:, :);
Bubble_RGB(:, :, 3) = Bubble_green(:, :);

figure(2)
imshow(Bubble_RGB)
title(['Frame ', num2str(j)])

BubblePixel(j) = (sum(sum(Bubble_Single)) * ((2*pi)/(rtheta - ltheta)); % Number of pixels in bubble
BubbleArea(j) = (BubblePixel(j) * (Calibration(str2num(shot), 1)^2); % Area in mm^2

BubbleData{j} = {Bubble_RGB};
ssw = input ( 'Is this any good?
1=Yes 2=No 3=No Bubble/Image
' )
if (ssw==1)
    Quality(j)=0;
end
if (ssw==2)
    Quality(j)=1;
    BubblePixel(j)=NaN;
    BubbleArea(j)=NaN;
end
if (ssw==3)
    Quality(j)=0;
    BubblePixel(j)=NaN;
    BubbleArea(j)=NaN;
end

close figure 1
close figure 2
end
end

Mistakes=sum(Quality)
RedoFrames=find(Quality)

\% % Bubble Growth Rate
if Mistakes==0 \% This is done after all of the frames have been approved
    for j=1:lastbubble
        if j==1
            else
                BubbleGrowth(j-1)=((BubbleArea(j)-BubbleArea(j-1))/interval); \%Growth Rate mm^2/ms
        end
        time(j)=(j-1)*interval;
        end
    for j=1:length(BubbleGrowth)
        time2(j)=time(j)+interval/2;
        end
end

\% % Save Data
filename3=sprintf ( 'BubbleSequence_%s' , shot);
save(filename3, 'BubbleData');
filename4=sprintf('BubblePixel%s', shot);
save(filename4, 'BubblePixel');
filename5=sprintf('BubbleArea%s', shot);
save(filename5, 'BubbleArea');
filename6=sprintf('BubbleGrowth%s', shot);
save(filename6, 'BubbleGrowth');

%% Save Data to Excel

tab = sprintf('Shot%s', shot);
Headers = {'Time', 'Pixels', 'Bubble Area', 'Time (rate)', 'Growth Rate'};
Units = {'usec', 'pixels', 'mm^2', 'usec', 'mm^2/usec'};
xlswrite('BubbleData.xls', Headers, tab, 'A5');
xlswrite('BubbleData.xls', Units, tab, 'A6');
xlswrite('BubbleData.xls', [time(:,), BubblePixel(:,), BubbleArea(:,)], tab, 'A7');
xlswrite('BubbleData.xls', [time2(:,), BubbleGrowth( : )], tab, 'D7');
C.5 Theoretical Absorption Signal Database

% Generates Theoretical Absorption Signals Database

% This code is specifically designed to create theoretical absorption signals for iron in the UV, 370–380 nm, based on a calibrated wavelength vector. This should be used to create a set of absorption curves for various temperatures, pressures, and number densities which can be fit to an experimental signal at another point in time. The wavelength vector must go from high to low in nanometers.

% The section marked "Variables to change" is the only section that should be adjusted for basic operation of this code. The section "Matrix Parameters" will need to updated based on experimental conditions and when a new element is used.

% Use this code in conjunction with Temperature_Fit.m to attain a best fit of temperature, pressure, and number density for individual absorption signals.

% Created by Lance Kingston
% Date Created: May 1, 2012
% Last Updated: June 29, 2012

% Variables to change
filename1=sprintf('Data_Flash150_120405.xlsx'); %Filename containing calibrated wavelength vector as the first column
filename2=sprintf('Parameters120405_8.mat'); %Filename that the Parameter data will be saved as
filename3=sprintf('Intensity120405_8.mat'); %Filename that the Subpixel Intensity data will be saved as
sf = 2;  %Enter as 1 to save Parameters and Intensity, any other # to not save
Begin = 379.9;  %Upper bounds in nm, at least 3nm greater than upper transition line, based on limits set in Intensity.m
Stop = 368.8;  %Lower bounds in nm, at least 3nm less than lower transition line, based on limits set in Intensity.m
pixelate = 10;  %MUST BE EVEN, Divides primary pixel into subpixels
FWHMpix= 2.36;  %Number of pixels for FWHM from OriginPro Fit, based on average of all calibration lines
vfit = 2;  %Determines which voigt profile to use, 1 =
Voigt fit, 2 = Abrarov analytical approximation and is 6–7
times faster basically the same accuracy as Voigt when \( U = 1e^{-3} \)

%%% Matrix Parameters
pl = 0.015;  % Absorption Pathlength (m)
P, T, and nfe are row vectors
P = [40000, 60000, 80000, 100000, 200000, 300000, 400000, 500000, 700000, 800000, 900000, 1000000, 2000000, 3000000, 4000000, 5000000, 7500000, 10000000, 25000000, 50000000, 75000000, 100000000];  %Pressure (Pa)
T = [1000:100:1900, 2000:50:5000, 5100:100:6000, 7000, 8000, 9000, 10000];  %Temperature (K)
nfe = [1e6:1e6:9e6, 1e7:1e7:9e7, 1e8:1e8:9e8, 1e9:1e9:9e9, 1e10:1e10:9e10, 1e11:1e11:9e11, 1e12:1e12:1e13];  %Number Density (particles/m^3)
lambda = pl * nfe;  % Fitting parameter, product of pathlength and iron number density (atoms/m^2)
Para = {P, T, nfe};  %Cell structure to store the Parameters for future use

if sf == 1  %Determines if the file is saved
    save (filename2, 'Para');  %Saves Parameters as a mat file for future recall
end

%%% Constants
c = 2.9979e8;  %Speed of light (m/s)

%%% Load Experimental Data
% The excel file must contain data in columns with no headers.
The first column corresponds to the wavelength (nm), going from high to low, and then remaining columns correspond to the absorption intensities for varying time periods.
[num] = xlsread (filename1);
wave = num(:, 1);  %Loads the wavelength vector, wavelength is assumed to be the central wavelength on each pixel

%%% Expand Initial Data
% The wavelength is determined by fitting the intensity of each pixel to the calibration lines. Since each pixel has a finite width, it sees more than a single wavelength. The wavelength assigned to each pixel is then assumed to be the
average wavelength that is projected onto each pixel. To account for this, each pixel is pixelated so that several intensities can then be calculated and assigned to subpixels.

Lar=zeros(pixelate,1); % Place holder matrix for each subdivide pixel

for i=1:length(wave)
    if i
        expand=(wave(i,1)-wave(i+1,1))/(pixelate); % Divides the distance between the current pixel and the one in front of it evenly
    else
        expand=(wave(i-1,1)-wave(i,1))/(pixelate); % For the last pixel, same as above except for the current pixel and the one before it
    end
    for k=1:pixelate
        Lar(k,1)=wave(i,1)+((pixelate/2)-k)*expand; % Assigns a wavelength to each subpixel, half minus 1 before and half after the central wavelength
    end
    finewave((i-1)*pixelate+1:i*pixelate,1)=Lar; % Assigns each subdivide set of pixel wavelengths to a new vector to accommodate the larger set of subpixels
end

ios=find(wave>Begin,1,'last'); % Finds the pixel associated with the upper region of interest in the initial data
rios=find(finewave>wave(ios,1),1,'last')-(pixelate/2)+2; % Finds the subpixel associated with the upper region of interest for the pixelated wavelength vector
ioe=find(wave<Stop,1,'first'); % Finds the pixel associated with the lower region of interest in the initial data
rioe=find(finewave<wave(ioe,1),1,'first')+(pixelate/2)-1; % Finds the subpixel associated with the lower region of interest for the pixelated wavelength vector
dif=0;

for i=rios:rioe
    diff=finewave(i,1)-finewave(i+1,1);
    dif=dif+diff; % Sums the difference in wavelength between adjacent subpixels
dpix = dif / (rioe - rios + 1); % Average difference in wavelength between adjacent subpixels (nm)
FWM = FWHMpix * pixelate * dpix; % FWHM of instrument, average (nm)

%% Intensity calculations based on experimental wavelength calibrations
display(’Intensity’)
II = cell(length(T), length(nfe), length(P)); % Preallocate space for intensity calculations for every combination of the above parameters

for r = 1:length(P)
    for s = 1:length(T)
        for t = 1:length(nfe)
            II{s, t, r} = Intensity(T(s), P(r), nfe(t), pl, finewave(rios:rioe, 1), dpix, FWHM, vfit); % Indexes Intensity to a cell for future recall
        end
    end
end

display(’Completed’)

if sf == 1 % Determines if the file is saved
    save(filename3, ’II’); % Saves Intensity as a mat file for future reference
end

%% Pixelate Intensity
% Since each individual pixel is exposed to the intensities of a range of wavelengths and not the intensity of a single wavelength, the intensity recorded is an average of the intensities based on the range of wavelengths. To account for this averaging, the intensities of the previously subdivided pixels will now be recombined and assigned to the original central wavelength.

display(’Recombine Pixels’)
I = cell(length(T), length(nfe), length(P)); % Preallocates space for intensity traces for every combination of the above parameters
for r=1:length(P)
    for s=1:length(T)
        for t = 1:length(nfe)
            Int=II{s,t,r};          %Calls the subpixel intensity calculation
            Int3=zeros(size(wave,1),1);  %Assigns a value of 1 for every pixel
            for i=ios:ioe
                aa=find(finewave>wave(i,1),1,'last')-(pixelate/2)+2;  %Finds the position of the first subpixel for each pixel
                dInt=0;
                for j=1:pixelate
                    Int2=Int(1,j+aa–rios);  
                    dInt=dInt+Int2;           %Sums the intensities of each subpixel for a given pixel
                end
                Int3(i,1)=dInt/pixelate;  %Divides summation by pixelation number to produce an average intensity and assigns it to a single pixel
            end
            I{s,t,r}=Int3';             %Assigns intensity trace to a cell array for future recall in Temperature_Fit.m
        end
    end
end

display('Completed')
C.6 Absorption Fitting Procedure

% Prior to operating this code, Theoretical Absorption Signals must be run. Theoretical Absorption Signals provides the database for fitting temperatures and pressure to the raw data. If this is a new session, but Iron_Fitv1.m has previously been run and the Parameter[<var date>].mat and Intensity [<var date>].mat have been saved, then portions of Theoretical Absorption Signals will need to be run in order to load all of the appropriate variables. The wavelength vector must be in nanometers and go from red to blue.

% The section marked “Variables to change” is the only section that should be adjusted for basic operation of this code. If this is used for other elements and wavelength ranges, then ConstantsFe will have to be replaced with a new constants file and the wavelength ranges for fitting and plotting will need to be adjusted.

% This code is designed to scale absorption data with a background signal that is not unity to unity and then fit a temperature, pressure, and number density to the data. There are a series of graphs at the end of the code which label the transitions with their ground state and plot a range of temperatures to show the accuracy of the fit if the pressure and number density are held constant.

% Created by Lance Kingston
% Date Created: June 7, 2012
% Last Updated: June 29, 2012

%% Variables to change
filename1 = sprintf('Data_Flash200_120405.xlsx'); %Filename containing calibrated wavelength vector as the first column
data1 = 4; %Adjust to look at different time periods in the data file, must be greater than or equal to 2, since first data column is the wavelength
data2 = 4; %Last column to look at in the data series
vfit = 2; %Determines which voigt profile to use, 1 = Voigt fit, 2 = Abrarov analytical approximation and is 6–7 times faster basically the same accuracy as Voigt when U = 1e–3
%% Load Constants
ConstantsFe;

%% Load Experimental Data
% The excel file must contain data in columns with no headers.
% The first column corresponds to the wavelength (nm) and then
% remaining columns correspond to the absorption intensities
% for varying time periods.

[num]=xlsread(filename1);
wave=num(:,1); %Wavelength in nm from
begin = find(wave>378.0,1,'last'); %Upper bounds of
wavelengths of interest for fitting
stop = find(wave<370.5,1,'first'); %Lower bounds of
wavelengths of interest for fitting

%% Curve Fitting
for i=data1:data2; %Adjust to look at different time
    %periods in the data file, must be greater than or equal to 2,
    %since first data column is the wavelength
evalcol=i; %Determines which set of data is
    %processed from the input file.

%% Define regions without absorption lines for curve fitting the
background
pix1 = find(wave>378.0,1,'last')+1;
pix2 = find(wave<377.2,1,'first')-1;
pix3 = find(wave>375.6,1,'last')+1;
pix4 = find(wave<375.25,1,'first')-1;
pix5 = find(wave>374.2,1,'last')+1;
pix6 = find(wave<373.95,1,'first')-1;
pix7 = find(wave>373.15,1,'last')+1;
pix8 = find(wave<372.9,1,'first')-1;
pix9 = find(wave>372.6,1,'last')+1;
pix10 = find(wave<372.4,1,'first')-1;
pix11 = find(wave>371.5,1,'last')+1;
pix12 = find(wave<371.1,1,'first')-1;

xpix=[pix1:pix2, pix3:pix4, pix5:pix6, pix7:pix8, pix9:pix10, pix11:pix12]; %Combined set of fitting pixels
xwave=wave(xpix,1);  %Wavelengths used in the fitting processes
yint=num(xpix,evalcol);  %Intensities corresponding to the wavelengths fit

Order = 3;  %Order of polynomial to fit
p=polyfit(xwave,yint,Order);  %Polynomial fit
f=polyval(p,wave);  %Polynomial evaluated for all wavelengths
fx=polyval(p,xwave);  %Polynomial evaluated for fitted wavelengths

maxyint=max(num([begin:stop],evalcol));  %Calculates maximum intensity for scaling graphs
maxint=ceil(maxyint*4)/4;  %Rounds the maximum intensity to the nearest fourth

yerr=yint-fx;  %Error for each fitted point
xres=sum(yerr.^2);  %Residual of fit

maxyerr=max(yerr);
minyerr=min(yerr);
maxerr=ceil(maxyerr*10)/10;
minerr=floor(minyerr*10)/10;

scaleres = sprintf('Sum of Squares of Residual of Background Fit = %f, (Less than 1 = Great, Over 20 = Bad Fit)',xres);
error = sprintf('Error: Residual = %f', xres);

yfit=num(:,evalcol)./f;  %Intensity scaled by polynomial fit based on wavelength

bkgd=ones(length(xwave),1);  %Indicates regions used for fitting background

maxyfit=max(yfit([begin:stop],1));  %Calculates maximum fitted intensity for region of interest to scale graphs
maxfit=ceil(maxyfit*10)/10;  %Rounds the maximum fitted intensity to the nearest tenth
maxboth=max(maxint,maxfit);  %Determines the largest maximum needed for the comparison graph

% Figure show the polynomial fit, the error for each fit data point, the scaled version of the signal, and a comparison of
the original data to the scaled data

figure ('Name', 'Subplots', 'units', 'normalized', 'OuterPosition'
        ,[0,0,1,1])

subplot(2,2,1)
plot(wave, num(:, evalcol), '-r.'); hold on;
plot(wave, f, 'k'); plot(xwave, bkgd*maxint/2, 'k.');
title('Polynomial Fit')
axis([371, 378, 0, maxint])

subplot(2,2,2)
plot(xwave, yerr, 'b.');
title('error')
axis([371, 378, minerr, maxerr])

subplot(2,2,3)
plot(wave, yfit, 'k'); hold on
plot(xwave, bkgd, 'ro');
title('Scaled')
axis([371, 378, 0, maxfit])

subplot(2,2,4)
plot(wave, num(:, evalcol), '-r.'); hold on
plot(wave, yfit, '-b.');
title('Comparison of Raw Data and Scaled Version')
axis([371, 378, 0, maxboth])

%% Fitting — Sum of Squares of the Residuals
display('Residual Calculations')
Res=zeros(length(T), length(nfe), length(P));
MinC=zeros(size(P,2), size(nfe,2));

%Regions of interest for fitting data, looks at the absorption
 lines of interest and ignores the baseline
d1=find(wave>377.5,1,'last');
d2=find(wave<371.5,1,'first');
fit=[d1:d2];

for r=1:length(P)
    for s=1:length(T)
        for t = 1:length(nfe)
            Res(s,t,r)=sum((1{s,t,r}(1,fit)-yfit(fit,1)).^2);
        end
    end
end
\begin{verbatim}
end
MinC(r,:) = min(Res(:,r));
end

% Searches for the minimum of the residuals over all pressures, temperatures, and number densities
MinR = min(MinC);
MinTot = min(MinR);
[pre, den] = find(MinR == MinTot);
[tem] = find(Res(:, den, pre) == MinTot);
Temp = T(tem);
Density = nfe(den);
Pressure = P(pre);
display('Completed')

result = sprintf('Temp = %d K, Press = %d Pa, Density = %#G
', Temp, Pressure, Density);
disp(scaleres)  % Outputs residual of baseline fitting
disp(result)  % Outputs best fit for temperature, pressure and number density

% Plots
wav = linspace(380,368,8000);  % Finely spaced wavelengths
Intfit = Intensity(Temp, Pressure, Density, wav, dpix, FWHM, vfit);
    % Calculates a finer resolution plot based on the best fit
figure('Name', 'Best Fit', 'units', 'normalized', 'OuterPosition', [0,0,1,1])
plot(wav, Intfit, '-b', 'DisplayName', 'Best fit line')  % Plots a fine resolution best fit line
hold on
plot(wave, I{tem, den, pre}, '-k', 'DisplayName', 'Actual Best Fit')
    % Plots a coarse resolution best fit based on averaging intensities over small regions of wavelengths
plot(wave, yfit, ':r', 'DisplayName', 'Original Data')
    % Plots the original data

title(result)
axis([371, 378, 0, 1.2])
xlabel('Wavelength (nm)')
ylabel('I/I_o')
legend('show')
\end{verbatim}
for  r=1:length(P)
    for  s=1:length(T)
        Resn(s,r)=Res(s,den,r);
    end
end

figure ('Name', 'Pressure', 'units', 'normalized', 'OuterPosition', [0,0,1,1]);
mesh(log10(nfe),T,Res(:,:,pre));
hold on
mesh(log10(nfe),T,Res(:,:,pre-1));
mesh(log10(nfe),T,Res(:,:,pre+1));
figure ('Name', 'Residual', 'units', 'normalized', 'OuterPosition', [0,0,1,1]);
mesh(log10(nfe),log10(P),MinC);
figure ('Name', 'Constant Num. Density', 'units', 'normalized', 'OuterPosition', [0,0,1,1]);
mesh(P,T,Resn(:,:));
end
C.7 Voigt Lineshape

% This function calculates the true Voigt Profile.

% It has 3 inputs:
% x = sqrt(log(2)) * (nu - nu0) / alphaD
% y = sqrt(log(2)) * alphaL / alphaD
% U = the unit spacing for the integral (at least 1e-3)
% alphaD and alphaL are the HWHM in frequency units (1/s) for
the doppler and the lorentzian functions, respectively.
% nu = frequency (1/s)
% nu0 = central frequency (1/s)

% The accuracy of the function is very dependent on the unit
spacing, U. The larger the spacing the worse the function
becomes, but the computational time will decrease
significantly. Maintaining a U value near 1e-3 will provide
accurate results with an acceptable amount of computational
time.

% Created By Lance Kingston
% Date Created: April 27, 2012
% Last Updated: April 27, 2012

function [W]=Voigt(x,y,U)

u=-6:U:6;
W=zeros(size(x)); %Preallocate Space for Output Variable

for i=1:length(x)
    W(i)=(y/pi)*trapz((exp(-(u.^2)))./(y.^2+(x(i)-u).^2))*abs(u(1)-u(2));
end
C.8 Voigt Lineshape Approximation

% This function calculates an analytical approximation of the Voigt profile
% This is an approximation of the Voigt function within the Humlicek regions 3 and 4. The approximation is given by S.M. Abrarov et al. "High-accuracy approximation of the complex probability function by Fourier expansion of exponential multiplier" (2010).
% x = sqrt(ln(2))*(nu - nu0)/alphaD
% y = sqrt(ln(2))*alphaL/alphaD
% where 'ln' denotes the natural log, nu is the wavenumber, nu0 is the center wavenumber, alphaD and alphaL are the Doppler and Lorentzian half-width at half-maximum.
% Suggested values for N & tau are 23 and 12 respectively.

% Original Code by Alfredo Tuesta on December 3, 2010
% Modified by Lance Kingston April 26, 2012

function K = Abrarov2010CPC(x,y,tau,N)
    if nargin == 2
        tau = 12;
        N = 23;
    end
    K = zeros(size(x));
    a = zeros(1,N);
    n=0:N;
    a(n+1) = 2*sqrt(pi)/tau*exp(-n*pi/tau)^2);
    for c = 1:length(x)
        summation = 0;
        for n = 0:N
            first = ((1i*n*pi*tau+tau^2*y)*(1-exp(-(1i*n*pi+tau*y)))*
                      cos(tau*x(c)) + exp(-(1i*n*pi+tau*y)))*tau^2*x(c)*sin
                      (tau*x(c))/(tau^2*x(c)^2 - (n*pi - 1i*tau*y)^2);
            second = ((1i*n*pi*tau-tau^2*y)*(1-exp(1i*n*pi-tau*y))*)
                      cos(tau*x(c)) - exp(1i*n*pi-tau*y)*tau^2*x(c)*sin
                      (tau*x(c))/(tau^2*x(c)^2 - (n*pi + 1i*tau*y)^2);
            summation = summation + a(n+1)*(first - second);
        end
    end
third = (y - \exp(-\tau y)) \times (y \cos(\tau x(c)) - x(c) \sin(\tau x(c))
\times \cos(\tau x(c))) / (2 \times \sqrt{\pi} \times (x(c)^2 + y^2));
K(c) = \text{summation} / (2 \times \sqrt{\pi}) - a(1) \times \text{third};
end
C.9 Theoretical Absorption Signal

% This code will calculate an absorption line profile for a
% given set of parameters. This code was initially designed
% for iron absorption.

% T = A single temperature (K)
% P = A single pressure (Pa)
% lambda = A number density of iron (atoms/m^3)
% wavedata = Column vector of wavelength data (nm) from high to
% low
% dpix = Difference in wavelength between pixels (nm)
% FWHM = Full−Width at Half−Maximum of the instrument based on
% the average
% FWHM of calibration lines (nm)
% vfit = Determines which voigt profile to use, 1 = Voigt fit, 2
% = Abrarov analytical approximation and is 6−7 times faster
% and basically has the same accuracy as Voigt when U = 1e−3

% If this code is used with a different element or wavelength
% range, the ConstantsFe file will need to be updated or
% replaced.

% Created by Lance Kingston
% Date Created: April 27, 2012
% Last Updated: July 23, 2012

function [I]=Intensity(T,P,nfe,pl,wavedata,dpix,FWHM,vfit)

%% Constants
ConstantsFe %Loads variables that are needed for this
portion of the code
U=1e−3; %Parameter for Voigt Accuracy, needs to be
atleast 1e−3, but more accurate for smaller numbers, i.e. 1e
−6, but much longer computational time.

%% Partion Function
Z=zeros(size(EG,1),1); %All energy levels

for i = 1:size(EG,1)
    Z(i,1) = EG(i,2)*exp(−EG(i,1)/(k*T));
end
The electronic parton function, for atomic species this is the only term in the parton function

% Wavelength Vector
wave=wavedata*1e-9; %Wavelength (m)
u=ν/c./wave; %Frequency (1/s)
del=3; %Distance to vary from central wavelength during lineshape calculations (nm)
wave0=zeros(size(T2,1),1); %Preallocate space for central wavelength vector
nu0=zeros(size(T2,1),1); %Preallocate space for central frequency vector
start=zeros(size(T2,1),1); %Preallocate space for starting pixel wavelength/frequency
last=zeros(size(T2,1),1); %Preallocate space for ending pixel wavelength/frequency

for i=1:size(T2,1)
    wave0(i,1)=(T1(i,1))*1e-9; %Define central wavelength (m) from constants
    nu0(i,1)=c./(wave0(i,1)); %Central wavelength converted to frequency (1/s)
    low=T1(i,1)-del; %Low wavelength range cutoff (nm)
    high=T1(i,1)+del; %High wavelength range cutoff (nm)
    start(i,1)=find(wavedata(:,1)<low,1,'first'); %Starting pixel for lineshape calculation
    last(i,1)=find(wavedata(:,1)>high,1,'last'); %Ending pixel for lineshape calculation
end

% HWHM for Doppler and Collisional Broadening
alphaD=zeros(size(nu0,1),1); %Preallocate space for HWHM for doppler broadening

for i=1:length(nu0)
    alphaD(i,1) = 2*(nu0(i,1)/c)*sqrt((2*k*T*log(2))/(m)); %FWM for doppler(gaussian) broadening (1/s)
end

n=P/(k*T); %Total number density (particles/m^-3)
Zstar=4*n*(sig^2)*(((pi*k*T)/m)^(1/2)); %Collision rate for a pure gas (collisions/sec)
alphaL = Zstar/pi; %HWHM for collisional broadening (1/s)

%% Instrumental Line Broadening
% Assumes a single FWHM for all instrument broadening, and applies it to the center wavelength for the entire wavelength range to reduce error between the wavelength extremes.

midwave=(T1(1,1)+T1(size(T1,1),1))/2; %Middle wavelength of interest (nm)
FWHMfreq=c*(FWHM*1e-9)/((midwave*1e-9)^2); %FWHM Frequency of middle wavelength (1/s)
dfreq=(c/(midwave*1e-9))*(dfpix/midwave); %Change in frequency between subpixels (1/s)
delta=[-5e11:dfreq:5e11]; %Frequency range to cover instrument broadening (1/s)
Instru=(2/(FWHMfreq))*(sqrt(log(2)/pi)*exp(-4*log(2)*delta^2/(FWHMfreq^2)); %Lineshape of Gaussian Instrument Broadening (s)

%% Gaussian HWHM
% This consolidates the effects from doppler and instrumental broadening

for i=1:length(nu0)
    alphaG(i,1)=sqrt(alphaD(i,1)^2+FWHMfreq^2)/2; %HWHM of the Gaussian Line Shape (1/s)
end

%% Voigt Profile
X=zeros(size(nu0,1),size(wavedata,1)); %Preallocate Voigt Parameter
Y=zeros(size(nu0,1),1); %Preallocate Voigt Parameter
Yv=zeros(size(nu0,1),size(wavedata,1)); %Preallocate Voigt Lineshape

for i=1:length(nu0)
    X(i,:) = sqrt(log(2)).*(nu - nu0(i,1))./alphaG(i,1); %Parameter for Voigt Profile
    Y(i,1) = sqrt(log(2)).*alphaL./alphaG(i,1); %Parameter for Voigt Profile
end

if vfit == 1
Yv(i,:) = Voigt(X(i,:),Y(i,1),U);

%Voigt Profile (s)
elseif vfit == 2
Yv(i,:) = Abrarov2010CPC(X(i,:),Y(i,1),12,23);
%Voigt Approximation (s)
end
end

% Parameters for the absorption coefficient
nl=zeros(size(nu0,1),1);  %Preallocate space for lower
number density
Blu=zeros(size(nu0,1),1);  %Preallocate space for
Stimulated Absorption Einstein Coefficient

for i=1:length(nu0)
    nl(i,1)=nfe.*(T2(i,4)./Zel).*exp(-(T1(i,3).*h.*c.*100)./(k.*T))%Lower number density (particles/m³)
    Blu(i,1) = T2(i,6);  %Einstein
    %coefficient for stimulated absorption (m³/(J s⁻²))
end

% Absorption Coefficient Calculations
kv=zeros(length(nu0),length(wavedata));  %Preallocate for
spectral absorption coefficient
range=zeros(size(nu0,1),1);  %Preallocate for
lineshape region

for i=1:length(nu0)
    range(i,1)=start(i,1)-last(i,1)+1;  %Significant
    %region to include the wings of the lineshape
    for j=1:range(i,1)
        kv(i,1)=kv(i,1)+j-1 = (h/c).*Blu(i,1).*nl(i,1).*nu(last(i,1)+j-1,1).*Yv(i,last(i,1)+j-1);  %Absorption
    
    end
end

Kv=sum(kv);  %Spectral Absorption Coefficient (1/m)

% I/Io Profile – Output Variable
I= exp(-Kv*p1);  %I/Io as a function of wavelength (dimensionless)
REFERENCES


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