Underwater Blast Injuries, and the Sinking Of the Submarine *HL Hunley*

by

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Roger Nightingale

Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Biomedical Engineering in the Graduate School of Duke University

2016
ABSTRACT

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Abstract

Underwater blasts travel further and injury more easily than blasts in air. However, because of a relative lack of data and study dedicated to the subject, the tolerances of personnel in the water to blast exposures have historically been poorly quantified. This dissertation presents an analysis of underwater blast exposures that have resulted in injuries and fatalities. Previously known standards for risk were evaluated and determined to be insufficient. Historical medical reports of exposed divers in the water were then evaluated and reconstructed to form the first known curves to prescribe a quantitative risk of injury or fatality.

The mystery of the submarine *HL Hunley* is an historical underwater blast exposure that has puzzled generations of enthusiasts. The tools for evaluating blast transmission through the water were applied to this puzzle, and it was concluded that sufficient blast transmitted through the hull of the submarine itself to cause fatal or at least injurious levels of air blast trauma to the crew inside.
Dedication

This dissertation is partially dedicated to my parents, Ron and Denise Lance.

Thank you to my dad for giving me his love of history, and to my mom for giving me her love of math, even though I was not always the most willing recipient.

I would also like to dedicate this dissertation to my fiancé, Nicholas Azan. The incredible support, unwavering encouragement, experimental assistance, and bottomless ice cream he has provided have on many days been all that separated me from failure. The words “thank you” can’t even begin to describe my gratitude.

Finally, this dissertation is also dedicated to my grandfather, Earl Lance, one of the original Navy frogmen and underwater explosives experts. I think of him often and wish we could’ve set some charges together.
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1. Introduction

1.1 Statement of the Problem and Hypotheses

The dangerous effects of underwater blasts at a distance have been known at least since the 1820s, following the clearance and salvage of the Royal George in Portsmouth harbor in 1829 (Heinke 1856, Green 1859). This effort revealed that underwater blasts are still dangerous, even at a distance. Underwater blast injuries to humans were first described as the result of accidental depth charge detonations in 1916 during WWI (Mathew 1917), and historical sources state more soldiers were injured by underwater blast than air blast in WWII (Williams 1942). Among the more fascinating cases of underwater blast exposure is the Civil War submarine H.L. Hunley, which mysteriously sank following the detonation of its own torpedo during a successful attack on the USS Housatonic.

This dissertation contains the results of a series of investigations to 1) determine the source and evaluate the validity of previously available guidelines for risk of injury from underwater blasts, 2) create a set of data-based injury risk curves, and 3) investigate the role of underwater blast in causing the fatalities of the crew of the H.L. Hunley. In addition to multiple risk guidelines, hundreds of historical exposures to underwater blasts are documented and available in medical case reports (e.g. (Breden, d’Abreu et al. 1942, Cameron 1943, Cameron 1947, Bebb 1951, Bebb 1954)). These cases
were collected and compiled to form a database of human blast exposures that could not legally or ethically be repeated experimentally. Computational modeling tools, specifically the DYSMAS underwater blast modeling software created by Naval Surface Warfare Center Indian Head Division, were used to reconstruct these cases and approximate the exposures experienced, and these exposures were then compiled to generate preliminary injury risk curves (McKeown, Dengel et al. 2004, Lance, Capehart et al. 2015).

The sinking of the HL Hunley was investigated through two approaches: the two primary known theories were evaluated, and the construction of a physical scale model was used to investigate the role of underwater blast in the mysterious deaths of the crew.

To further our understanding of the injury response to underwater blasts, the research presented herein addressed the following specific aims:

1) Created a comprehensive database of all known underwater blast safety standards, with information about their scientific origins

2) Using historical data, determined the underwater blast exposure levels that cause injury and death

3) Investigated the effect of hypoxia and hypercapnia on the crew of the H.L. Hunley to assess the possibility of asphyxia killing the crew.
4) Investigated the plausibility of the “lucky shot” theory to explain the sinking of the *Hunley*

5) Built a scaled physical model of the submarine *H.L. Hunley* and assessed its response to underwater blasts

These efforts tested the following hypotheses:

1) Current and previous safety standards for risk of injury from underwater blast are insufficiently scientifically founded.

2) Historical underwater blast exposures can be compiled and used to construct injury risk curves.

3) Crew gas exchange, the volume of the vessel, and the final resting positions of the crew make anoxia and the “lucky shot” theories unlikely causes of the death of the *H.L. Hunley*.

4) The crew of the submarine *H.L. Hunley* died from pulmonary/gut blast exposure when the blast of their own charge transmitted through the vessel hull into the vessel airspace.

1.2 Relevance

Underwater blast injuries have consistently appeared in most modern naval military conflicts, and the military and scientific communities have repeatedly called for
a realistic injury guideline. Even as recently as 2001 that need had not been satisfied (Cudahy and Parvin 2001). In contrast to the lack of scientifically based injury guidelines, there has been substantial scientific effort to characterize underwater blast injuries in both the United States and the United Kingdom in the 1940s through 1970s, when hundreds of blast tests were conducted. While one of the known guidelines is the result of these tests, dozens of additional risk guidelines are available in the literature that are wildly inconsistent and seem to have little, if any, scientific justification (Wolf 1970, Cudahy and Parvin 2001, Lance and Bass 2015). One of the most frequently cited guidelines is found in the US Navy Dive Manual; this guideline has no apparent scientific justification and advises military operators that they are safe within injurious exposure levels (USN 2011, Lance and Bass 2015, Lance, Capehart et al. 2015). Military personnel still frequently conduct operations with and near underwater explosives, despite the lack of available information regarding protective measures and safe standoff distances (Tan 2013, Kiddy 2014).

One of the earliest and most fascinating exposures to an underwater blast occurred during the Civil War, when the submarine H.L. Hunley was exposed to the explosion of its own torpedo (Hicks and Kropf 2007). Despite the raising of the submarine in the year 2000 and subsequent archaeological conservation, no cause has yet been found by the conservationists to indicate damage to the hull or provide a
definitive explanation for the submarine’s sinking (Hicks and Kropf 2007, Hunley 2014, Klein 2014). My hypothesis was that the underwater blast transmitted through the hull of the vessel and could have had a lethal effect on the men inside. The experimental data support this hypothesis; therefore the Hunley provides the first demonstrated example of injurious blast transmission through a structure underwater. Modern submarines have far more advanced and complex hull designs, so it is unlikely that modern submariners would suffer the same levels of exposure from an external charge. However, having such an example case proves that such injuries are possible, and solves one of the most enduring mysteries of American history.

1.3 Dissertation Organization

This dissertation is focused around several academic papers both published and in progress as a result of the research performed during my tenure as a PhD student in the Duke Injury Biomechanics Lab. During that time, I have published four papers, with a fifth in progress. The first four papers (Lance and Bass 2015, Lance, Capehart et al. 2015, Lance, Moon et al. 2016, Lance, Warder et al. 2016) are each given independent chapters within this document. The paper relevant to the final chapter, regarding the blast trials and experimental research about the Hunley’s torpedo explosion, is still in progress.
2. Background

Portions of this chapter are modified in part from Refs (Lance and Bass 2015, Lance, Capehart et al. 2015, Lance, Moon et al. 2016, Lance, Warder et al. 2016), with permission.

2.1 Physics of Air Blast

An explosion occurs when a chemical reaction converts the explosive material into a gas. This reaction occurs very rapidly at high temperatures and pressures, and generates a large quantity of heat. These physical disturbances then propagate outward from the center of the explosion. When the chemical reaction occurs quickly enough that the reaction front keeps up with the motion of the physical disturbance, the explosion is a detonation. However, some explosives, such as black powder, react at slower rates and instead deflagrate or burn as the front of the chemical reaction falls behind the outward propagation of the resultant heat, temperature, and pressure (Cooper 1996).

When an ideal, spherical explosion occurs in air, the pressure wave it produces is often described using the Friedlander equation (Equation (1)). This equation is also plotted graphically in Figure 1.

\[
\text{Eq (1) } \quad \frac{\text{Pressure}}{P^*} = e^{\frac{-t}{t^*}} (1 - \frac{t}{t^*})
\]

- \(P^*\) = Peak positive overpressure
- \(t^*\) = Positive phase duration
- \(t\) = Time
A shock wave that has an ideal Friedlander form is typically described using two variables: peak positive overpressure, and positive phase duration. The peak positive overpressure is the maximum pressure reached by the shock wave, while the positive phase duration is how long the pressure level remains positive before it drops below the ambient pressure level and the positive phase is succeeded by the negative phase. The peak positive overpressure is described using either of two pressure measurements: incident or reflected pressure. The incident pressure is the pressure value of the shock wave itself as measured from a perpendicular or side-on direction, independent of any effects of the gauge altering the flow of air. The reflected pressure is measured with gauge elements facing into the direction of propagation of the oncoming shock wave.
The gauge elements therefore reflect the oncoming wave and read a higher pressure value than the incident pressure at the same location. The relationship between incident and reflected pressure values is described by the Rankine-Hugoniot equations (Taylor 1963). The Rankine-Hugoniot equations demonstrate that reflected pressures in air have values two to eight times as high as incident pressures from the same blast. Nearby surface or objects can also reflect the initial pressure and cause a more complex, non-ideal waveform.

A shock wave, by definition, also has a sharp rise time. The rise time is the length of time for the pressure to rise from ambient level to the peak positive overpressure. While some deflagrating explosives can produce pressure waveforms with slower rise times, these pressure waveforms are not considered shock waves and have been shown to be far less injurious (Richmond, Damon et al. 1968). For the purposes of injury biomechanics and this dissertation, a shock wave is defined as a waveform with a rise time of 1 ms or faster (Chiffelle 1966, Richmond, Damon et al. 1968, Bass, Rafaels et al. 2008).

2.2 Physics of Underwater Blasts

The increase in both the density and the speed of sound in water means that when explosions occur underwater, the resulting shock and pressure waves travel more efficiently and further than they do in air (Cole 1948). As a result, explosions in water
have been reported to cause discomfort and injuries up to 3.2 km (2 miles) from the source (Wright 1947). Unlike for air blast, even ideal underwater blasts may not have a waveform that can be described using a Friedlander-like equation. Underwater blast waveforms are affected by numerous parameters including charge depth, bottom depth, gage depth, bottom reflectivity, and gas bubble fluctuations following detonation. The effects of these variables on the shape of the blast waveform has been investigated exhaustively since the early 1940s and some variables are still the subject of active research (Cole 1948, Bebb 1951, Slifko and Farley 1959, CRC 1968, Christian and Gaspin 1974, Ridah 1988, Nakahara, Nagayama et al. 2008). While some literature resources do provide simple equations to describe the peak pressure and initial decay of the shock wave (Cole 1948, Kedrinskii 1972, Rogers 1977), these equations all assume an exponential decay to the waveform. This assumption is only valid for a single time constant of decay, and does not incorporate the subsequent waveform or the actions of the gas bubble. These equations are therefore typically considered sufficient for calculating the expected peak pressures of waveforms, but are not considered sufficient, even by their authors, to fully describe the effects of blast.

Similarly, scaling laws have been developed and validated for moderate-pressure or higher (>65 kPa) ideal blasts underwater (Arons 1954). These scaling laws are discussed in more detail in section 2.2.1. However, underwater blasts can cause
serious injuries and fatalities to unprotected persons even in extremely low pressure ranges (Wright 1947); the limited data that are available to validate these laws in low pressure ranges suggest that the laws overestimate the impulse of exposure in these regions (Blaik 1965).

The definitive text for comprehensive information about additional aspects of underwater blast physics that were determined not to be relevant to this dissertation is Ref (Cole 1948). Though the full details of underwater blast physics are beyond the scope of this dissertation, two main points are important to the studies presented herein: 1) no research group has ever identified a Friedlander-like equation that accurately describes a generalized underwater blast waveform and 2) the surface of the water reflects a tension, or rarefaction, wave back down into the body of water that decreases the pressure of the primary waveform wherever the two intersect. The rarefaction wave that reflects off the surface can result in a dramatic decrease both in peak pressure and in overall impulse for measurement points near the surface of the water. These decreases play an important role in the historical descriptions of the injuries of unprotected personnel because the majority of documented human exposures to underwater blast have occurred at or near the surface of the water. Neither the exponential decay models nor the scaling laws discussed below can account for the negative pressure reflection off the surface. Like air blasts, positive-pressure waves in underwater blasts are reflected
off surfaces with higher densities such as structures or the ocean bottom, but this effect is uncommon in human exposures unless the exposure occurs in shallow water or an enclosed space. Because of these complexities, descriptive parameters like peak pressure and impulse are often difficult to predict without advanced computational modeling. Figure 2 shows two idealized examples of underwater blast waveforms with identification of their various components.
Figure 2a. Idealized pressure-time curve for an underwater blast. Figure adapted with permission from a diagram provided by Greg Harris, Naval Surface Warfare Center Indian Head Division.

Figure 2b. Example pressure-time curve for an underwater blast with surface and bottom reflections. A: ambient pressure. B: peak positive overpressure. C: onset of pressure reduction from surface rarefaction wave. D: secondary peak from bottom reflection.

2.2.1 Scaling of Blasts in Water

The most common method of scaling the effects of explosions is Hopkinson scaling, also known as “cube root scaling” or the principle of similitude (Neuberger,
The most critical behaviors of underwater shock waves follow traditional scaling laws since peak overpressure, duration, and impulse scale predictably with the overall length scale of the experiment (Cole 1948, Kedrinskii 1972). However, it is more informative and convenient to describe the output of the charge via the equations provided by Hopkinson scaling. To apply this scaling method, the cube root of the charge mass is frequently used to adjust other factors such as distance from the charge or time, rather than forming truly dimensionless pi groups. The Hopkinson scaling equations for peak pressure, impulse, and time constant for underwater blast are shown as Equations (2)-(4) (Cole 1948, Arons 1954).

Eq (2)
\[ P_{max} = k_{pressure} \left( \frac{W^{1/3}}{R} \right)^{\alpha_{pressure}} \]

\( k \) = scaling constants  
\( \alpha \) = decay constants  
\( W \) = charge weight  
\( R \) = distance from the center of the charge  
\( P_{max} \) = peak positive overpressure

Eq (3)
\[ Impulse = k_{impulse} W^{1/3} \left( \frac{W^{1/3}}{R} \right)^{\alpha_{impulse}} \]

Eq (4)
\[ \Theta = k W^{1/3} \left( \frac{W^{1/3}}{R} \right)^{\alpha} \]
\( \Theta \) = time constant of initial decay (\( \mu \)sec)

The same constants \( k \) and \( \alpha \) are conventionally used in all three equations but their values are specific to the calculation of each value, and are determined empirically for each explosive type. For example, the values for peak pressure for TNT are \( \alpha = 1.13 \).
and $k = 52,390$ (converted to units of kPa, kg, m) whereas for impulse they are $\alpha = 0.94$ and $k = 6,698$ (converted to units of kPa*ms, kg, m) (Arons 1954). While values for $k$ vary between explosive types, $\alpha$ values for peak pressure tend to be closely similar because they are dictated by the physical laws regarding blast propagation and decay rate of pressures in water rather than being dictated by the properties of each unique explosive. For example, $\alpha = 1.13$ for both TNT and pentolite, but shows a modest change to only 1.15 for both HBX and Torpex even though these aluminized explosives are generally regarded as far more powerful (Arons 1954, Cooper 1994).

The Hopkinson scaling equations and empirical $\alpha$ values agree closely with the established analytical solution for underwater shock wave propagation, called the Kirkwood-Bethe approximation (Kedrinskii 1972). The main limitation to these scaling laws, with respect to the work presented in this dissertation, is that they have conventionally been applied primarily in pressure regions relevant to structural damage, and have therefore not been as well-validated in the comparatively low pressure regions that can still be injurious to unprotected humans ($<65$ kPa). However, the sparse data that do exist are consistent with the analytical theory of weak shock propagation, which concludes that in the low-pressure regions the pressure values decay more quickly than the Kirkwood-Bethe approximation and Hopkinson scaling laws predict (Blackstock 1965, Blaik 1965). Application of Hopkinson scaling laws in low-pressure regions
therefore errs on the side of overestimating the peak pressures actually observed. This error means that any standoff distances prescribed using Hopkinson scaling laws will likely be incorrect, but will be incorrect on the side of overestimation and safety.

Hopkinson scaling does not use proper pi groups and is not truly dimensionless. However, the methodological parallels are evident in the construction of the equations, since charge weight is dependent on volume and therefore the cube root is effectively a length scale. Impulse is the integration of the pressure curve over time, so the addition of an additional $W^{1/3}$ is logical because characteristic time also scales with the characteristic length scale ($L$) of the experiment.

One caveat to scaling of underwater blast experiments is that the actions of the gas bubble, which can contribute additional impulse to the later parts of the blast waveform, cannot be scaled by the same factor as the rest of the experiment. This inability is because the bubble behavior is partly dictated by gravity, which is extremely difficult to scale experimentally, and partly by gas density, which cannot be scaled without altering the explosive type used. The pi groups that dictate the length and time scales of the bubble behavior are shown as Equations (5) & (6) (Cole 1948).

\[
\text{Eq (5)} \quad L_{\text{BUBBLE}} = \left( \frac{Y}{g \rho_0} \right)^{1/4} \quad \text{Y = bubble energy}
\]

\[
\text{Eq (6)} \quad t_{\text{BUBBLE}} = \left( \frac{Y}{g^5 \rho_0} \right)^{1/8} \quad g = \text{gravity} \\
\rho_0 = \text{initial bubble gas density}
\]
Bubble energy ($Y$) is a direct function of charge weight ($W$). Therefore, because charge weight is scaled by the cube of the experimental length scale ($L^3$), the length scale of the bubble is a function of $L^{3/4}$ and the time scale is a function of $L^{3/8}$. Since the shock wave properties scale directly with $L$ and it is not practical to experimentally modify gravity and initial gas density, it is therefore effectively impossible to simultaneously scale both the behavior of the shock wave and of the bubble. However, the experimental methods described in this dissertation only apply scaling methods to the description of the initial shock wave itself. The scaling limitations of the bubble behavior are therefore an important limitation to consider in studies of underwater explosives in general, but are not directly relevant to the experiments described herein.

### 2.2.2 Structural Scaling and Transmission into Structures

Blast interactions with full-sized structures can be complex and expensive to test experimentally, so these tests are often performed both in air and in water by scaling down the size of the experiment according to the relevant dimensionless parameters (Cole 1948, Grujicic, Snipes et al. 2013). These scaled experiments must be performed using geometric similarity; specifically, all dimensions of the structural features must be scaled down by the same length factor so that the structure maintains its original geometric design (Cooper 1996). The material properties must also be the same for both the model and the structure if those properties influence the behavioral response.
Experimental scaling is frequently used to simplify experiments that test the interaction of underwater blasts with ships and has been a standard experimental method for over 70 years (Taylor 1942, 1948). It is a widely used protocol for both the assessment of susceptibility to damage and the analysis of whole-ship motions in response to underwater blasts (Reid 1996, Chen, Tong et al. 2009, Peng, Zhang et al. 2011). For scaled structural tests with underwater blasts, time must also be scaled by the same factor as length (Cole 1948, Cooper 1996).

G.I. Taylor first described the pi groups that dictate the behavior of an underwater blast wave hitting an air-backed structure, primarily in an attempt to predict damage to ships from TNT depth charges (Taylor 1963). His derivations are therefore extremely relevant to the problem of blast interaction with the hull of the Hunley. Taylor’s dimensional analysis as well as subsequent studies by other groups concluded that the amount of momentum transferred into a structure by a blast wave can be scaled by size if the time-relevant parameters of the blast wave are also scaled (Taylor 1963, Kambouchev, Noels et al. 2006, Kambouchev, Noels et al. 2007, Grujicic, Snipes et al. 2013). Dimensionless parameters dictating the amount of momentum transferred are shown as Equations (7) & (8).
\[ \varepsilon = \frac{\rho c}{mn \sin \phi} \]

\( \rho \) = density of medium in front of the structure
\( c \) = speed of sound in medium in front of the structure
\( m \) = areal density of the structure
\( n \) = time constant of decay of the blast wave
\( \phi \) = angle of the structure surface, if conical

\[ \beta_s = \frac{\rho_s U_s t_i}{\rho_p h_p} \]

\( \rho_s \) = mass density of the material in front of the structure
\( U_s \) = propagation speed of the incident blast wave
\( t_i \) = time constant of the incident blast wave
\( \rho_p \) = mass density of the structure
\( h_p \) = structural thickness

*Note: Kambouchev et al refer to this value as the duration of the incident blast wave. However, this pi group appears in other literature sources with variations best suited to the waveforms being described in that set of experiments (Peng, Zhang et al. 2011). Kambouchev et al were examining blasts in air, so a duration value was convenient; however, it is also common to use the time constant of decay of the shock wave as the time-scaling parameter. Since the time constant is more relevant to underwater blasts, the time parameter has been defined as such for the purposes of this dissertation. For the waveforms measured during this testing, the values are extremely similar.

Momentum transfer into a structure produces motion of that structure. This motion away from the initial blast causes a reduction in pressure at the front of the structure, and an increase in pressure behind the structure. This increase in pressure behind the structure then becomes a secondary waveform that propagate off the reverse...
side. This backface blast wave has not been well-studied experimentally, but modern computational studies by Grujici et al. describe the propagation of a true secondary shock wave with sharp rise time behind the solid structure wall itself (Grujicic, Snipes et al. 2013). These simulations show that the backface pressure response is the product of rapid motion of the structure wall in response to the original external blast. Therefore, perfectly rigid structures do not produce such a wave, and the phenomenon is more distinct behind structures that are more flexible. Such a backface wave means that, even if the original blast wave is largely reflected at the front material interface of the structure, it is possible that people behind the structure could still be injured or killed by transmitted shock from a sufficiently large charge at a sufficiently close range even without overt damage to the structure. Indeed, the calculations of both research groups were performed under the assumption that no damage occurred to the structure itself (Taylor 1963, Grujicic, Snipes et al. 2013). The calculations of both research groups were also performed assuming that the blast wave was traveling perpendicular to the face of the structure; however, studies of ship motion have demonstrated that the effects of blasts at angles to the structure can still be quantified using a simple sin correction (Reid 1996).

While it initially may seem that a thicker structure should always provide more physical resistance to and protection from the secondary shock effects of a blast wave, it
is important to remember that these pi groups are only one component of an experiment that must be scaled as a whole. Wall thickness is only one geometric dimension of a model and therefore must be scaled in accordance with the length scale of the rest of the structure, which also dictates the surface area exposed to the blast. Time is also adjusted by the same scale, meaning that if wall thickness is increased by a factor of 10, then the overpressure duration must be increased by the same factor, and the surface area of exposure will be increased by a factor of 100. The creation of the backface shock wave is also dependent on motion of the wall; extremely thick walls will be closer to perfectly rigid and will have extremely small pi group values in both analysis. Thick walls will therefore not absorb as much momentum from the initial shock and will instead reflect the initial shock rather than flexing and creating a backface wave.

Therefore, when taken in the overall context of the whole model, the assertion that the behavior scales properly with plate thickness makes more logical sense.

2.2.3 DYSMAS Modeling Software

The Dynamic System Mechanics Advanced Simulation (DYSMAS) hydrocode is a family of codes designed to model the complex propagation and structural effects of underwater explosions, without any of the simplifications required by scaling laws. The group of codes was developed collaboratively between the German defense firm IABG and the Naval Surface Warfare Center Indian Head Explosive Ordnance Disposal
Technology Division (NSWC IHEODTD), with integration of code packages from Livermore Software Technology Corporation. The code contains three primary components: the ParaDyn Lagrangian solver, the Gemini Eulerian solver, and the Standard Coupler Interface (SCI). This code was used primarily to model underwater blast propagation for the analysis and development of injury risk curves (Chapters 3 and 4). Only the Gemini Eulerian solver was used for the purposes of this dissertation; therefore the background will be limited to this software component.

2.2.3.1 GEMINI Structure and Function

Gemini is a finite difference Eulerian solver. It can be used independently to model blast propagation, or it can couple interactively with the Lagrangian solver ParaDyn. Gemini was designed to accurately model the parameters involved in underwater explosions, specifically complex scenarios such as shockwaves and bubble jetting (Walters 2011). Among its features are the ability to use a wide range of equations of state and to model scenarios relevant to complex blast scenarios, such as partial chemical reactions and user-dictated burn rates. At each time step, Gemini uses a higher order Godunov method algorithm to find a solution for the fluid mesh. The equations of conservation of mass, momentum, and energy are solved in a one-dimensional approach through one principal direction at a time. The mesh size is user-dictated, and can be given higher resolution in areas of interest such as in the vicinity of
the blast, while the time step is dictated by the program, which computes the minimum time required for a stable solution.

2.2.3.2 Software Validation

The DYSMAS hydrocode has been extensively validated and tested. Unfortunately, many of the technical documents published by NSWC Indian Head cannot be directly cited in an unlimited-distribution document such as this dissertation. However, there also exists an extensive, publicly available body of work by external scientists comparing DYSMAS to experimental results. Perhaps the most comprehensive piece of public validation was performed by Turner in 2007, with an examination of the underwater implosion of glass spheres (Turner 2007). This study successfully modeled not only the structural failure of the glass spheres, but the ensuing pressure waveform following the structural collapse, the oscillations of the gas bubble, and the reflections off the walls of the box containing the experimental setup. Additional references have validated the use of DYSMAS for blasts in air, blasts in complex structural environments, and blast exposures of simplified models of human tissue (Bennett, Heard et al. 2006, Bewick and Flood 2010, O’Daniel, Harris et al. 2011, Goeller, Wardlaw et al. 2012).
2.3 **TNT Relative Equivalency**

A wide diversity of explosive types are available worldwide, and it is helpful to have a common yardstick against which the many unique types can be compared to quantitatively describe their destructive power. TNT is conventionally used as this yardstick, and the strengths of other explosive types are typically described by stating their TNT equivalency, also known as relative equivalency (RE) (Cooper 1996). Specifically, an explosive type is assigned a fractional number, its RE, that describes its strength relative to the strength of TNT. The RE is multiplied by the charge weight of the explosive to calculate the estimated required weight of TNT to produce an equivalently powerful charge. This relationship is shown as Equation (7).

\[
W_{TNT} = RE \times W_{\text{other explosive}}
\]  

Eq (9)

Most explosives have RE values in the range 0.8-1.2 (Cooper 1994). However, it is important to note that TNT equivalency can be measured multiple ways, and often the results vary widely between these test methodologies. Tests such as the sand crush test and the Trauzl lead block test are sometimes used to measure RE values, but insufficient standardization of these test methods has led to a wide variation in measured RE values for each explosive type (Cooper 1994, Cooper 1996). Equivalency values can also be calculated by relating the peak pressure and impulse values produced by an explosion to the TNT charge weight that is required to produce those same values at the same.
distances. This type of RE value shows a much stronger relationship to the inherent chemical properties of the explosive substrates rather than variations in experimental methodology and is therefore far more useful than other tests (Cooper 1994). While the peak pressure and impulse equivalencies for a charge type can vary with the scaled distance from the charge, in general they are fairly consistent across a range of distances for ideal non-aluminized charge types. Measurements of the variation for five available charge types show a maximum deviation of 11% from the mean RE value for each charge type along a range of distances (Cooper 1994).

TNT equivalency and Hopkinson scaling can therefore be used to assess the estimated output of black powder charges that could not be constructed experimentally, as long as these techniques are used carefully with awareness of the typical ranges of variation inherent to the measurement types.

2.4 **Blast Injuries**

Explosions in air typically injure through any of four general categories: primary blast from direct effects of the shock wave, secondary blast from energized projectiles, tertiary blast from whole body translation, and quaternary blast from effects of inhaled gases and other sources (Bjørnø and Levin 1976, Hoo Fatt 1997, Bass, Rafael et al. 2008). Shock waves from blasts travel faster than the speed of sound in a given material. The speed of sound and therefore the speed of the shock wave depend on the density of the
medium that the wave is traveling through. Therefore, shock waves transiting material interfaces, especially in the transition from denser to less dense interfaces, may deposit momentum and energy near those interfaces where they are forced to slow as they enter the next material type.

The most vulnerable, easily injured tissues in the human body are those that contain air, such as the lungs, intestinal tract, and the airspaces of the ears (Mellor 1988, NOAA 2016). Since the speed of sound and material density in lung or gas-containing intestinal tract is much less than in the surrounding tissue, shock wave transit may damage sensitive lung or gut tissues. Typically pulmonary injuries occur through spalling, when the alveolar surfaces rupture and bleeding into the lungs occurs. Symptoms of pulmonary injuries can include coughing, difficulty breathing, hemoptysis, and apnea (Ecklund 1943, Chavko, Prusaczyk et al. 2006). Abdominal injuries generally include perforation or tearing as well as hematoma and ecchymosis. These injuries can occur at any point along the large and small intestine, but have a tendency to cluster near the ileocecal junction, where the ileum of the small intestine joins the cecum of the large intestine (Breden, d’Abreu et al. 1942, Cameron 1943, Cameron 1947, Paran, Neufeld et al. 1996). The pulmonary injuries in underwater blast exposures are very similar to those seen in air blast (Cameron 1947, Bowen, Fletcher et al. 1968, Bass, Rafaels et al. 2008). Intestinal injuries are common in underwater blasts
but typically manifest in air blast only if the lungs are shielded in some way, typically by the presence of a bulletproof vest (Cripps and Cooper 1996, Wood, Panzer et al. 2013).

### 2.4.1 Injuries from Air Blast

The overall intensity of a blast exposure, which is responsible for injury severity, depends on more than one physical parameter. For ideal air blasts, the Friedlander waveform allows an indirect but comprehensive description of blast intensity through only two parameters, often peak pressure and positive phase duration. Many currently available air blast injury criteria use these two parameters to describe exposure and therefore injury risk (Bowen, Fletcher et al. 1968, Bass, Rafaels et al. 2008, Rafaels, Bass et al. 2010, Rafaels, Bass et al. 2011, Panzer, Bass et al. 2012, Rafaels, Bass et al. 2012).

For personnel exposed to blast from within the hull of a boat, such as the crew of the *Hunley*, the vessel wall would provide a protective effect from projectiles, so secondary injuries would be unlikely. The predominant injury pattern would likely be primary injuries from the shock wave itself. It is important to note that of the injuries typically produced by the primary effects of air blast (e.g., pulmonary, gastrointestinal, traumatic brain injury, ruptured eardrum), all are damage to the soft tissues and would not be evident from skeletal or highly decomposed remains. Indeed, in Mellor’s database of air blast injuries, all fatalities showed some degree of pulmonary trauma and
17% of those killed by severe air blast exposure showed no postmortem findings beside severe pulmonary trauma alone (NOAA 2016).

### 2.4.2 Injuries from Underwater Blast

Injury risk underwater is less well-described and may be a function of multiple variables of the exposure including peak positive overpressure, duration of overpressure, total energy of the blast, and maximum area under the pressure-time curve. This area, called the impulse, is often equal to the area under the positive phase of the pressure-time curve, but may be further augmented by bottom reflections or bubble action following the initial shock wave. These additional factors typically increase the impulse by at least 25%, and possibly up to 150% over the impulse from the shock alone (Cole 1948). While it is likely that multiple variables are necessary to accurately predict injury risk across the range of reasonable exposures, methods of predicting injury risk from underwater blast have historically used one of three physical criteria to describe exposure: 1) explosive charge weight and range, 2) blast (explosion) impulse, or 3) peak positive overpressure.

Peak positive overpressure and positive phase duration alone cannot be used for the complex waveforms from underwater blasts, unlike air blast, because the entire shape of the curve is much more variable and a positive phase duration value is often difficult to determine. An impulse value is therefore a more comprehensive description
of the overall blast waveform. The difficulty in precisely calculating or predicting impulse has led most researchers to prescribe injury risk guidelines based on range or peak pressure, even though these factors have long been thought to be insufficient (Bebb 1954, Andersen and Løken 1968, Richmond, Yelverton et al. 1973, Christian and Gaspin 1974, Fothergill, Schwaller et al. 2002, Lance and Bass 2015).

2.4.3 Guidelines for Assessing Injury Risk in Air

The first set of comprehensively researched risk curves for injury and fatality from air blast, known as Bowen’s Curves, were developed and published in the 1960s (White 1961, Bowen, Fletcher et al. 1966, Chiffelle 1966, Bowen, Fletcher et al. 1968, Richmond, Damon et al. 1968, Bjørnø and Levin 1976, Hoo Fatt 1997). These curves have been updated and modified by subsequent research groups to include more data and cover a broader diversity of blast exposure types, such as long-duration pressure waves and repeated exposures. (Bass, Rafael et al. 2008, Rafael, Bass et al. 2010, Panzer, Bass et al. 2012). Typically, these curves assume an ideal Friedlander waveform, and can be used to calculate the risk of injury or fatality based on peak pressure and duration. As an example, the pulmonary fatality risk curves prescribed in Ref (Bass, Rafael et al. 2008) are shown as Figure 3.
Humans are not always exposed to blast in the same consistent, uniform position and orientation; therefore many curves exist for a variety of orientations relative to the shock propagation (Bowen, Fletcher et al. 1968, Bass, Rafaels et al. 2008). For example, if a person is lying on the ground with their feet oriented towards the oncoming shock wave (parallel to the direction of propagation), they will be at a much lower risk than someone exposed to the same wave but oriented perpendicular to the direction of propagation (Bowen, Fletcher et al. 1968). Research with blasts in confined spaces have shown that, even with complex waveform types, injury risk is still better predicted by peak overpressure rather than simply distance from the charge (Johnson, Yelverton et al.)
In addition, it is important to select the correct curve based on whether the gauges used measured incident or reflected pressure.

### 2.5 Respiratory Physiology During Exercise

Chapter 5 contains an analysis of the supply of breathing gas available to the crew of the Hunley within the enclosed submarine. To perform this analysis, existing quantitative information was used from the well-developed field of respiratory physiology during exercise conditions. The analysis required calculation of both oxygen consumption and carbon dioxide production, and the effects that varying levels of these gases would have had on the crew.

In clinical research, hand-pedaled arm ergometers are frequently used to measure and control levels of exercise performed by human test subjects; the cranking motion of these ergometers is biomechanically similar to the cranking motion used to propel the Hunley (Åstrand and Rodahl 1977). The primary difference is that the Hunley crew used both arms in synchrony, while ergometers require cranking that alternates between arms. A hand-pedal ergometer is shown in Figure 4.
Figure 4. The author demonstrates use of a hand-pedal ergometer. Hand-pedal ergometers allow the control and measurement of exertion using an arm-powered cranking motion biomechanically similar to the motion used by the Hunley crew.

The duration of oxygen supply within an enclosed space is dependent on how quickly oxygen is being consumed. Rate of oxygen consumption is directly correlated with a person’s level of exertion; for example, a consumption of 1.5 L/min is consistent with mild to moderate exercise, while rates of 2.2-3.2 L/min are consistent with exercise that is moderate to severe, but sustainable over long periods (Åstrand and Rodahl 1977).

In addition to hypoxia, concurrent hypercapnia from increased carbon dioxide (CO₂) levels for personnel rebreathing gas within an enclosed space is also important. Unlike hypoxia, which may not be evident to sufferers, hypercapnia can cause overt and identifiable symptoms such as sensation of choking, shortness of breath, chest pain, tingling, trembling, headache, nausea, and psychological fear and discomfort (Åstrand and Rodahl 1977, Poma, Milleri et al. 2005, Colasanti, Salamon et al. 2008). The amount
of carbon dioxide produced by a person is calculated by multiplying their rate of oxygen consumption by the respiratory exchange ratio (RER). The RER is a fractional ratio describing the rate of CO₂ volume produced per unit of O₂ volume consumed. RER at rest is typically around 0.8; RER often increases during exercise, and can exceed 1.0 during heavy exertion. This ratio is primarily determined by the biochemical processes being used by the body to produce energy at the time of measurement.

2.6 Confederate Submarine HL Hunley

2.6.1 The Attack on the USS Housatonic

The HL Hunley sank the Union ship USS Housatonic and killed 5 Union soldiers by setting off a black powder torpedo against the ship’s hull between 8:45-9:00 pm on the evening of February 17, 1864. The narrow, tapered submarine was 12 m (40 ft) long with a width of only 1.2 m (4 ft) (Murphy, Lenihan et al. 1998). It was hammered out of the wrought iron boiler of a previous ship, and carried a crew of 8 men (Figure 5).
Figure 5. The *HL Hunley* as it would have appeared in attack position on the evening of February 17, 1864. Image courtesy Michael Crisafulli of The Vernian Era website. More renderings and details of the construction of the *Hunley* can be found at [http://www.vernianera.com/Hunley/](http://www.vernianera.com/Hunley/)

The vessel’s commander, Lieutenant George Dixon, could see out the fore conning tower and was responsible for navigation. The remaining crewmen powered the vessel’s propeller from the inside using a hand crank (Kloeppel 1987, FOTH Nov 2, 2001). At the other end of a hinged 16-foot spar was firmly bolted the *Hunley’s* torpedo, a copper torpedo of the common Singer’s design type filled with 61.2 kg (135 lbs) of black powder and fitted with a pressure-sensitive trigger, shown as Figure 6 (Jones 2001).
Figure 6. Archival drawing of the *Hunley's* torpedo. The torpedo would have measured 61 cm (24 in) in length.

A map of the attack is shown as Figure 7. Note that the *Hunley* is found east and south of the *Housatonic*; it therefore traveled further out to sea before settling to the ocean floor.
Figure 7. Map of the entrance to Charleston Harbor. An 1865 bathymetric map of the Harbor entrance (Willenbucher and Krebs 1865). Map is overlaid with relevant positions of both the *Hunley* and *Housatonic*. Stars indicate the bow of each vessel. Note that the historical hand-drawn map location for the *Housatonic* shows some discrepancy compared to modern GPS measurements.
Table 1. Values used to create Figure 7. All magnetic orientations have been adjusted to orientations relative to true north based on the magnetic declination at the location and time of the measurement (NOAA).

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Source</th>
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<tbody>
<tr>
<td>Final location of the wreck of the <strong>Hunley</strong></td>
<td>32.720836, -79.77467</td>
<td>(Hicks 2015)</td>
</tr>
<tr>
<td>Orientation of the wreck of the <strong>Hunley</strong></td>
<td>223.5°</td>
<td>Map pg. 88 (Murphy, Lenihan et al. 1998), also (Hunter 2003)</td>
</tr>
<tr>
<td>Final location of the wreck of the <strong>Housatonic</strong></td>
<td>32.72115, -79.77795</td>
<td>Diagram pg. 54 (Conlin, Bell et al. 2005)</td>
</tr>
<tr>
<td>Orientation of the wreck of the <strong>Housatonic</strong></td>
<td>235°</td>
<td>(Conlin, Bell et al. 2005)</td>
</tr>
<tr>
<td>Orientation of the <strong>Housatonic</strong> during the attack</td>
<td>291.6°</td>
<td>(USN 1874)</td>
</tr>
<tr>
<td>Orientation of the <strong>Hunley</strong> during the attack</td>
<td>111.6°</td>
<td>(USN 1874)</td>
</tr>
<tr>
<td>NOAA Charleston Harbor Fort Sumter Range Buoy 8</td>
<td>32.715, -79.79233</td>
<td>(NOAA)</td>
</tr>
</tbody>
</table>

In making this figure it has been assumed that the distance the crew of the **Housatonic** succeeding in moving the ship during the attack is negligible compared to its final wreck site (USN 1874). There are conflicting accounts regarding the exact angle of the **Hunley** to the keel of the **Housatonic** during the attack, but the accounts most commonly report that the submarine approached the **Housatonic** at a right angle to the keel and across the tidal current (USN 1874).
Before its final disappearance on February 17\textsuperscript{th}, the \textit{Hunley} had sunk twice on training missions, killing a total of 13 crewmen. In light of the previous sinkings of the \textit{Hunley}, the crew was reportedly forbidden from making the submarine negatively buoyant, even on the night of its attack (Beauregard 1878), and was to attack on the surface of the water without fully submerging. This command made the vessel safer to operate and also provides valuable information about its position in the water column because historical drawings are available detailing the attack position (Alexander Sunday June 29, 1902). These drawings and their use are shown and discussed in more detail in Section 5.2.1.

Witnesses onboard the \textit{Housatonic} described seeing the submarine approach on the surface, followed by the explosion of the torpedo. However, all crewmen stated that they did not see what happened to the submarine after the explosion. One sailor stated that much later he saw the Hunley’s planned signal for victory, a blue light, on the water. However, he saw this light long after the attack and while clinging to the rafters of his sunken ship in a cold February ocean (USN 1864). The account should therefore be treated with some degree of skepticism.

\textbf{2.6.2 Features of the Submarine and Archaeological Discoveries}

The \textit{Hunley} was raised from the ocean floor in the year 2000, and conservation efforts have been ongoing since (Oceaneering International 2000, Jacobsen 2005). Over
130 years on the ocean floor left the vessel filled with sediment and caked with a layer of concretion, sufficient to obscure any clues to the cause of sinking. The removal of each layer of concretion has deepened rather than solved the mystery of the submarine’s sinking. Since its raising, several archaeological discoveries have been made regarding the Hunley. Most importantly, when the sediment was excavated from the inside of the Hunley, it was discovered that the remains of all eight crewmembers were still seated at their respective stations within the vessel (Hunley 2001). The Chairman of the Friends of the Hunley at the time, Warren Lasch, was quoted describing the remains: “The crewmembers’ remains being discovered at their stations indicated both a recognition and acceptance of their fate… evidence seems to suggest more and more that the final moments were quick and decisive.” (Hunley 2001) Lieutenant George Dixon, who manned the forward command position below the fore conning tower, was described as “right there in his duty station slumped over to one side with his legs up near the bulkhead, exactly where he would have been if he was on duty.” (Hunley 2001).

Additionally, geological analysis of the sediment and macrofauna showed that there was a “calm period of little to no deposition” following sinking, indicating that the hull was intact when it sank (Sharrer, Darrah et al. 2001, Martin and Case 2011).

The skeletal remains of the crewmembers were not only found seated at their respective stations, but there were also no physical injuries evident from the skeletal
remains or any apparent attempts to escape (Martin and Case 2011, FOTH April 16, 2001, FOTH February 1, 2002). The conning towers, which formed the only path of escape, were closed with the aft tower still securely locked (FOTH 2006). The bilge pumps were not set to pump out water (FOTH 2008). The keel ballast weights, which could be released from within the boat, remained firmly attached (Murphy, Lenihan et al. 1998, Alexander Sunday June 29, 1902). Sedimentary analysis showed that the large holes discovered in the hull did not occur until long after the sinking, and no additional damage was found to the hull beneath the concretion that provided an explanation (FOTH 2009, Lance, Warder et al. 2016, FOTH September 17, 2015).

Additionally, remains of the torpedo that were found during conservation provided critical clues to the analysis of the attack. A “torpedo,” as the word was used in 1864, was simply an underwater charge and did not have a propulsion source like the modern device. The *Hunley*’s torpedo was attached to the vessel hull by a long metal spar, used to stab the side of the enemy ship and theoretically leave the charge itself behind. During conservation, the remnants of the torpedo’s copper casing were found still securely fastened to the submarine’s spar, jagged and peeled back from the explosion (Figure 8).
Figure 8. Illustration of the *Hunley*’s spar after conservation. The spar showed remains of the torpedo’s copper casing, which were displaced and peeled back by the force of the explosion.

This discovery means that the submarine did not back away from the *Housatonic*, but rather was the exact length of its spar and torpedo (spar 16 feet, charge 2 feet) from the ship hull when the charge detonated (Hunley 2013).

### 2.6.3 Previous Theories to Explain the Sinking

Prior to the *Hunley*’s rediscovery, historians had supplied myriad theories to explain its sinking (Kloeppel 1987). However most of these theories, such as the idea that it got sucked under the sinking wreck of the *Housatonic*, were disproved by the location at which it was discovered and the early conservation efforts. Two of the publicly known theories have endured: that the crew suffocated within the enclosed hull, and that a “lucky shot” fired by the crew of the *Housatonic* was sufficient to cause the sinking.
2.6.3.1 Suffocation

Historical accounts describe a bellows and snorkel tubes designed to circulate air within the body of the submarine, and indeed such a system was discovered upon the vessel’s recovery (Hunley 2001, Alexander Sunday June 29, 1902). However, little is known about how well this system functioned, or if it functioned at all. Former Hunley crewman William Alexander wrote that the bellows never functioned properly, and that fresh air was instead obtained by opening the conning tower hatches every 20 minutes (Hicks and Kropf 2007, Alexander Sunday June 29, 1902). Other historical accounts were similarly dismissive of the bellows and snorkel system (Hicks and Kropf 2007). Indeed, the bellows are not included on any known historical drawings or diagrams, perhaps indicating that the draftsmen may have neglected the nonfunctional structure. Aside from the bellows system, the vessel had no means of taking in fresh air other than opening the hatches.

The crew was acutely aware of the risks of hypoxia in a closed environment, and performed tests to determine the duration of their oxygen supply (Alexander Sunday June 29, 1902). The test consisted of holding the vessel submerged, too deep for any possible operation of the bellows, while the crew performed their normal cranking operations with a lighted candle burning. These tests were used to measure the
submarine’s maximum safe time of submergegence, stated to be 25 minutes (Alexander Sunday June 29, 1902).

2.6.3.2 “Lucky Shot” Theory

During the Hunley’s attack, crewmembers on the deck of the Housatonic fired their small arms weaponry in an attempt to sink or at least deter the Hunley. However, the Housatonic crew did not identify the attack of the approaching submarine until it was too close and moving too quickly to train the heavy artillery of their battery at the correct angle, so only personal weapons were fired. Among the weaponry reportedly fired, a rifle was the most powerful and therefore had the most potential to cause ballistic damage (USN 1874). The long-standing “lucky shot” theory of the Hunley’s sinking is that this gunfire damaged the hull of the vessel, either causing it to flood or killing Lieutenant Dixon, the man responsible for the primary controls and steering of the submarine (Kloeppel 1987). When the Hunley was raised, a large hole approximately 214 cm² in area was discovered in the conning tower (Figure 9).
Figure 9. Illustrations of the H.L. Hunley after conservation. Left: the full vessel, including the damaged conning tower, seen from the port bow. Right: Frontal view of the damaged conning tower after conservation. The starboard window shows damage attributed to erosion, while the port window and side of the tower also show the damage hypothesized to have occurred from arms fire (circled).

Analysis of the sediment inside the vessel indicated that a hull breach of unknown size was created in the conning tower during or soon after sinking (Jacobsen, Blouin et al. 2012). This breach could have been from damage to the conning tower but alternatively the same pattern of sediment could have occurred if the fore conning tower was not latched at the time of sinking. It also would have occurred if the damage to the conning tower occurred after the sinking in an unrelated event. The “lucky shot” theory holds that either this large breach in the conning tower or a smaller hole made by a broken window in the tower is responsible for the sinking of the Hunley. The conning tower windows were above the waterline during the attack as reported by the crew of the Housatonic, so if the vessel did not sink immediately from this damage the crew
would have had time either to set the bilge pumps to pump out water or to attempt to escape. Therefore if the “lucky shot” theory is true, the Hunley would have by definition started sinking almost immediately after its attack on the Housatonic.

2.7 Miscellaneous Background

The Hunley portion of this dissertation serves as a comprehensive investigation into the entire set of surroundings, theories, and injuries involved in the sinking of the famous submarine. Therefore, it has required the application of principles from many and varied fields, not all of which fall within the discipline of either blasts or injury biomechanics. Therefore, this section serves as a collection of the additional information from other fields that was necessary to perform these investigations but did not fit properly under other subject headings.

2.7.1 Ballistic Scaling Methods and Historical Tests

To assess the “lucky shot” hypothesis, it was desirable to assess the ballistic performance of small arms of the period against the hull material. However, it is difficult to conclusively ascertain the exact material composition and methods used to manufacture the conning towers of the Hunley, which were cast iron, without taking samples from the historical artifact itself. It was therefore difficult to perform ballistic testing using identical metal targets. However, both the Union and Confederate militaries did an extensive amount of ballistic testing using cast iron plates of varying
thicknesses to investigate the durability of this material for armor on the now-famous ironclad ships used during the war (duPont 1969). No records could be found that described ballistic testing with the 12.7 mm (½”) thickness used to construct the conning towers, but modern ballistic testing is frequently performed using well-validated scaling principles (Dougherty and Eidt 2009, Burns 2012). Scaling can be used to assess the effect of physical dimensions of an experiment. For example, if the thickness of a target is varied by a factor L, then the same depth of penetration of the target will occur for all impacts where the mass of the ballistic projectile used is varied by L^3, because mass is a volumetric measurement (Bliss and Dunn 2000, Dougherty and Eidt 2009, Burns 2012). Projectile velocity remains experimentally constant regardless of size scale.

2.7.2 Bathymetry of Charleston Harbor

Additionally, investigating the motion of the Hunley after the attack is difficult because it is not known how quickly the crew continued to propel the boat, in which direction, or if they continued propelling the boat at all. The bathymetry of Charleston Harbor has changed significantly in the intervening years, limiting the utility of experimentation (Jacobsen, Blouin et al. 2012). Most significantly, multiple efforts have taken place between 1895 and 2002 to widen and deepen the channel entrance. Jetties were also constructed to open the channel entrance. The entrance bar had a naturally controlled depth of approximately 3 m in 1864, but over the intervening years has been
progressively dredged and opened with jetties to a depth of 14.3 m (Simmons and Herrman 1972, Kjerfve 1989, Zimmerman, Jutte et al. 2003). In addition, in 1942 a volumetric 97% of the flow of the Santee River was diverted into the Cooper River; this diversion means that the flow of water into Charleston Harbor from rivers was increased from 10 m$^3$/s total in 1895 to over 425 m$^3$/s from the Cooper River alone (Simmons and Herrman 1972, Woollen 1976, Kjerfve 1989). Analysis of the shorelines near the harbor has additionally shown that where changes have occurred, they have had the effect of enlarging the basin (Hayes and Kana 1976). While a comprehensive analysis of the tidal prism of the harbor is beyond the scope of this dissertation, the increased flow from rivers by a factor of 43, the increased depth of the Harbor channel by a factor of 5, and the landscape of the tidal basin combined strongly indicate that the overall tidal prism has grown since the attack in 1864. A larger modern tidal prism means that the speed of modern tidal currents outside Charleston Harbor represent an extreme upper bound for the speeds of the currents potentially seen by the Hunley.

2.7.3 Tidal Patterns and Currents

A large object that is nearly fully immersed, such as the Hunley, has motion that is almost exclusively dictated by currents. An object of this size would reach the same speed and direction as the surrounding currents within roughly one minute of when it began to drift freely (Daniel, Jan et al. 2002, Breivik, Allen et al. 2011). Therefore,
calculations using modern tidal current levels can provide an upper limit for the potential distance drifted by the *Hunley* after its attack on the *Housatonic*. A map of the attack and wreck sites is provided in Section 2.6.1 as Figure 7, and the values used to create the map are listed in Table 1.

While the eyewitness accounts provided by the crew of the *Housatonic* differ with respect to the level of the tide, the accounts unanimously agree that the attack occurred between 8:45-9:00 pm (USN 1864). The tidal patterns surrounding the attack can therefore be calculated, because Charleston Harbor is a harmonic tidal station. Harmonic stations are stations whose tidal patterns are governed by predictable, consistent time constants (NOAA-CO-OPS 2016). Therefore, at harmonic tidal stations, the tidal level can be calculated accurately for any historical date and time.

### 2.7.4 Black Powder

Black powder is a low explosive, a volatile blend of crushed charcoal, sulfur, and either sodium or potassium nitrate (duPont 1969). It has been used for hundreds of years as gunpowder and as a blasting medium. Unlike high explosives, which have burn rates faster than the speed of sound, black powder deflagrates rather than detonates. The explosive performance of black powder can therefore be even more highly dependent on the burn rate of the material. Variables such as grain size, powder density, and even the type of wood used to make the charcoal can have noticeable effects on the burn rate and

Black powder performance is also highly dependent upon the strength with which it is confined (von Maltitz 2003). When it is spread on the ground and lit in an open, unconfined environment it burns with negligible pressure generation; however, when it is confined the charge casing allows the gradual generation of internal pressure until the point of casing failure (Ermolaev, Belyaev et al. 2010). While it is categorized as a low explosive, the data presented in below sections of this dissertation clearly show that it is capable of generating a shock wave when properly confined.

Tests of modern black powder have shown comparable performance in both burn rate and pressures produced to cannon-grade Union powder from the Civil War (Kosanke, Kosanke et al. 1995). However, a black powder manufacturing plant was constructed by the Confederacy only in response to the start of the Civil War with almost no pre-existing manufacturing capability anywhere in the South (Bragg, Ross et al. 2007). The Confederate Powder Works in Augusta, Georgia was built by George Washington Rains, who had no prior first-hand experience making powder and based the production methods entirely on information read in a pamphlet about the British Waltham Abbey Powder Works (Rains, Rains 1882). Rains also took great pride in drastically increasing the pace of production by eliminating or combining several key
steps in the manufacturing process (Rains 1882). In addition, the Confederacy reported making their black powder using cottonwood charcoal because of wide availability (Rains). The use of cottonwood would have had the effect of slowing the burn rate compared with modern black powders (duPont 1969, Wilson 1995). Historical documentation shows that Charleston was being exclusively supplied by the powder works at Augusta (Rains 1882), so it is therefore reasonable to conclude that the Hunley's torpedo contained Confederate Powder Works black powder (Milgram and Gentieu 1961).
3. Underwater Blast Injury: A Review of Standards

This chapter is adapted from (Lance and Bass 2015), with permission.

3.1 Introduction

This article summarizes the development of the current major guidelines used for underwater blast and illustrates how insufficiently and inconsistently they attempt to predict injury. While injuries from blast in air have been extensively studied and quantified, the level of blast exposure that produces injuries from underwater blast have received far less experimental validation (Bowen, Fletcher et al. 1968, Bass, Rafaels et al. 2008, Rafaels, Bass et al. 2010, Rafaels, Bass et al. 2011, Panzer, Bass et al. 2012, Rafaels, Bass et al. 2012). The first documented cases of underwater blast injury occurred in 1916 during WWI, but even as recently as 2001 underwater blast researchers have acknowledged that there are still no scientifically based criteria for predicting injury or death (Mathew 1917, Cudahy and Parvin 2001). Over 1,500 underwater blast-related casualties were identified in case studies during WWII alone; presumably a far larger number occurred but were not identified in medical publications (Williams 1942). This lack of criteria is certainly not due to lack of scientific effort. Hundreds of papers have been published on the subject, but the resulting injury guidelines have been grossly inconsistent, and often poorly scientifically founded (Wolf 1970, Cudahy and Parvin 2001).
3.2 Methods

3.2.1 Homogenization of Guideline Types

As discussed in the Background, there have historically been three types of guidelines used to describe risk from underwater blast. These three types of guidelines are difficult to compare directly because they measure different physical quantities. To compare the guidelines together, a representative underwater explosion was simulated using the US Navy’s Gemini Solver (Wardlaw, McKeown et al. 1998, Mair 1999, Wardlaw, Luton et al. 2003, Ferencz, DeGroot et al. 2008, O'Daniel, Harris et al. 2011). The Gemini Solver simulates the detonation of explosives underwater, as well as the propagation of the resulting shock wave. The program receives as inputs the variables describing the blast scenario, and computes the complex waveforms produced by explosions in underwater environments. The resulting pressure and impulse values were used to assign theoretical distances from the explosive charge to the values given by those guidelines. Gemini is a computational program designed to simulate underwater explosions, and has been extensively experimentally validated (Wardlaw, Luton et al. 2003, McKeown, Dengel et al. 2004).

To consistently estimate the blast parameters, a representative case simulated the detonation of 136 kg (300 lb) TNT with pressure curves sampled at distances 5-200 m from the center of the charge. Both the explosive charge and the sampled curves were
40 m below the surface of the water, with a free lower boundary condition to simulate deep open water. This case was used to establish example mathematical relationships between range, the distance from the charge center, and peak pressure. Similarly, the relationship was also established between range and impulse. These functions are shown as Equations (1) and (2), and describe predicted range \( R \) as a function of peak pressure \( P_m \) and impulse \( I \) \( (R^2 = 0.997 \) and 0.995, respectively). Equations (Eq (10) and (11) are not the direct output of the Gemini Solver, but rather empirical curvefits to the outputs that the Solver calculated at the sampled locations. These equations are valid only for this representative underwater blast scenario with 136 kg TNT charge mass. They were used only as tools for direct comparison of guideline types and are not valid as generalized descriptions of all underwater blast scenarios.

Eq (10) \[
R(P_m) = 332.8 e^{(-1.62 \times 10^{-5})P_m} + 64.6 e^{(-1.41 \times 10^{-4})P_m} \\
\]
\( R = \) Range (m) \( P_m = \) Peak pressure (kPa)

Eq (11) \[
R(I) = 258.7 e^{(-8.68 \times 10^{-4})I} + 60.5 e^{(-7.58 \times 10^{-5})I} \\
\]
\( I = \) Impulse (kPa*ms)

Using these equations, guidelines that provided peak pressure or impulse values were converted to range values so that they could be directly compared. The guideline types were assigned numerical values of 3 for “safe/deterrent,” 2 for “danger/injury,” or 1 for “lethal” and analyzed. Linear regression analyses were performed to analyze the
consistency of the guidelines. For the regression analyses, the guidelines from Richardson, 1991 were omitted as they were never intended to be applied to humans (Richardson, Greene et al. 1991).

### 3.2.2 Guidelines Based on Peak Pressure

The most common type of guideline for underwater blast injury provides a recommended maximum overpressure. Researchers’ attempts to apply a peak pressure-based guideline originate from the successful use of peak pressure and overpressure duration to predict injury risk from air blast (Bowen, Fletcher et al. 1968, Bass, Rafaels et al. 2008). However, in air blast, the entire blast waveform can often be described using an ideal overpressure (Friedlander) wave and an easily identified duration, while in water there is no such simple formula for prediction of the pressure trace (Cole 1948, Swisdak 1978). The waveform resulting from an underwater blast is substantially affected by variables such as depth of explosion, depth at point of measurement, bottom depth, and bottom composition/topography. There is no single equation that accurately describes a generalized waveform for underwater blasts. The wide variation in the shape of underwater waveforms often makes it difficult to identify the duration of the blast exposure, which is important in the wounding process and in estimating the injury risk and severity. The guidelines based on peak pressure are presented in Table 2, with each recommended maximum peak pressure given in both psi and kPa for consistency. The
ranges at which these recommended maximum peak pressures will occur for the representative 136 kg TNT explosion, as calculated by Eq (10), are also shown in the table. The same guidelines are shown graphically in Figure 10 as a function of the year they were published.

Table 2: Guidelines based on recommended peak pressure of exposure. *Calculated ranges, based on test case. †Reference describes use of experimental data in guideline development.

<table>
<thead>
<tr>
<th>Reference</th>
<th>P_{max} (psi)</th>
<th>P_{max} (kPa)</th>
<th>Range* (m)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Ellis 1944)</td>
<td>25</td>
<td>172</td>
<td>315</td>
<td>‘Safe’ level used in unpublished Chesapeake Bay trials, 1942; no disclosure of original basis</td>
</tr>
<tr>
<td>(Christian and Gaspin 1974)</td>
<td>125</td>
<td>862</td>
<td>139</td>
<td>Based on unscaled, summarised sheep data (no reference provided)</td>
</tr>
<tr>
<td>(USN 2011), Navy Dive Manual Rev. 6</td>
<td>50</td>
<td>345</td>
<td>252</td>
<td>No reference provided; seems to trace back to assertion in Corey^{34}</td>
</tr>
<tr>
<td>(Fothergill, Schwaller et al. 2002)</td>
<td>0.03</td>
<td>0.2</td>
<td>--</td>
<td>High-frequency sound, not blast (omitted from figures, provided for reference only)</td>
</tr>
<tr>
<td>(Ainslie 2008)</td>
<td>0.1</td>
<td>0.7</td>
<td>--</td>
<td>High-frequency sound, not blast (omitted from figures, provided for reference only)</td>
</tr>
<tr>
<td>NATO DMAC (safe)</td>
<td>0.9</td>
<td>6.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NATO DMAC (deterrent)</td>
<td>11.5</td>
<td>79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Corey 1946)†</td>
<td>300</td>
<td>2,068</td>
<td>60</td>
<td>Based on experiments with strips of intestine inside diving dress; attempted to model the human torso surrounding the intestine, but ignored that majority of perforations occur near ileocaecal junction, suggesting a contribution by</td>
</tr>
<tr>
<td>Source</td>
<td>Range</td>
<td>Pressure</td>
<td>Mortality</td>
<td>Notes</td>
</tr>
<tr>
<td>-------------------------------------------------------------</td>
<td>-------</td>
<td>----------</td>
<td>-----------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>(Draeger, Barr et al. 1946)</td>
<td>250</td>
<td>1,724</td>
<td>71</td>
<td>surrounding support structures (which would lower the pressure required).</td>
</tr>
<tr>
<td>(Greaves, Draeger et al. 1943)</td>
<td>500</td>
<td>3,447</td>
<td>41</td>
<td>Quotation of guideline presented by Corey,(^{34}) approximated number based on experiments with beef intestine as well as unreferenced experiments at Fort Pierce</td>
</tr>
<tr>
<td>(USN 2011), Navy Dive Manual Rev. 6</td>
<td>500</td>
<td>3,447</td>
<td>41</td>
<td>Based on plumes of water “shredding” at the surface during a ~500 psi blast wave; no data referenced or presented</td>
</tr>
<tr>
<td>(Williams 1944)</td>
<td>800</td>
<td>5,516</td>
<td>30</td>
<td>No reference provided; seems to trace back to Greaves, 1943</td>
</tr>
<tr>
<td>(Bebb 1951)</td>
<td>650</td>
<td>4,482</td>
<td>35</td>
<td>Based on unscaled summarised animal data; no reference provided</td>
</tr>
<tr>
<td>1,800</td>
<td></td>
<td>12,411</td>
<td>11</td>
<td>Alleged fatal exposure from charge W = 136 kg at unspecified range, based on unscaled animal data and possibly clinical experience</td>
</tr>
<tr>
<td>Alleged fatal exposure from charge W = 4.5 kg at unspecified range, based on unscaled animal data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Committee on Amphibious Operations, (USN 1952)</td>
<td>300</td>
<td>2,068</td>
<td>60</td>
<td>No data provided; adds caveat that most of the data to date is invalid because of lack of experimental pressure measurements and experimentation conducted in shallow water</td>
</tr>
<tr>
<td>(Draeger, Barr et al. 1946)</td>
<td>500</td>
<td>3,447</td>
<td>41</td>
<td>Apparent quotation from Greaves(^{36}) (reference reads only “Draeger and others”)</td>
</tr>
<tr>
<td>Source</td>
<td>Year 1</td>
<td>Year 2</td>
<td>Year 3</td>
<td>Notes</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>(USN 2011), Navy Dive Manual Rev. 6</td>
<td>2,000</td>
<td>13,790</td>
<td>9</td>
<td>No reference provided</td>
</tr>
<tr>
<td>(Rawlins 1953)</td>
<td>500</td>
<td>3,447</td>
<td>41</td>
<td>Purported LD50 for a rat; no scaling for humans; no data provided</td>
</tr>
<tr>
<td></td>
<td>1,200</td>
<td>8,274</td>
<td>20</td>
<td>Purported LD90 for a rat; no scaling for humans; no data provided</td>
</tr>
<tr>
<td>(Williams 1944)</td>
<td>1,300</td>
<td>8,963</td>
<td>18</td>
<td>Unscaled, summarised animal data (no source reference)</td>
</tr>
</tbody>
</table>

Figure 10: Peak pressure guidelines shown vs. the year they were published. No visual trends can be seen with year of publication. The injury severity levels overlap and show little separation, even when published within the same decade.
Most of these references were based on unscaled, summarized animal data, e.g. (Williams 1944, Bebb and Wright 1951, Christian and Gaspin 1974), or referenced no data at all (USN 1952, Rawlins 1953). The current U.S. Navy “injury” standard of 500 psi appears to be derived from a paper by several prominent Naval Medical Corps researchers, Greaves, Draeger, Brines, Shaver, and Corey (USN 2011). They allege in their 1943 paper that when a compression wave of 500 psi or greater reaches the surface of the water “it breaks through into the air with a shredding effect and literally ‘blows off’ the surface.” This logic was then extended to the human body, claiming that when a compression wave greater than 500 psi is transmitted through the torso and reaches the airspace within the lungs, it tends to “‘blow off’ the surface of the tissues exactly as it blows off the surface of the water,” damaging the alveolar walls (Greaves, Draeger et al. 1943). This physically and physiologically unlikely assertion has never been tested, neither at the time of publication nor subsequently, yet it has propagated through the decades as the definitive guideline for underwater blast injury. Even as early as 1944 some experimenters tried to cast doubt on the guideline using clinical experience, e.g., (Ellis 1944), but without a scientifically substantiated replacement the 500 psi guideline continues to be published (Draeger, Barr et al. 1946, Cudahy and Parvin 2001, USN 2011). The U.S. Navy “safety” standard of 50 psi seems to be a simple reduction of this
500 psi value by an order of magnitude; no justification, testing, or validation of the 50 psi value could be found.

### 3.2.3 Guidelines Based on Charge Weight and Range

One medically and operationally useful type of guideline is a severity assessment by standoff range (distance from person to charge) based on charge weight. This type of guideline would be useful because it could be implemented without complex calculations and straightforwardly used in initial clinical severity assessments with estimated ranges. Many researchers have attempted to create such a guideline, usually based on the application of blast scaling laws such as Eq (2) (pg 123) to peak pressure guidelines (Arons 1954). Table 3 outlines the blast injury guidelines that prescribe a standoff range based on charge weight. These guidelines are also plotted in Figure 11.

**Table 3: Blast injury guidelines based on charge weight and range. All equations converted to metric units (kg TNT, m). *Calculated ranges based on 136-kg TNT charge weight. +Reference describes experimental data.**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Weight (kg TNT)</th>
<th>Given Range (m)</th>
<th>Range* (m)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Committee on Amphibious Operations, (USN 1952)</td>
<td>$R = 25.4*W^{1/3}$</td>
<td>131</td>
<td>Application of scaling law to $P_{\text{max}} = 200$ psi (1,379 kPa); basis for 200 psi guideline not given</td>
<td></td>
</tr>
<tr>
<td>(Ellis 1944)</td>
<td>2.3</td>
<td>10.1</td>
<td>--</td>
<td>Cites experiments by Williams, but no published data was found</td>
</tr>
<tr>
<td>(Greaves, Draeger)</td>
<td>136</td>
<td>50</td>
<td>50</td>
<td>Based on unscaled animal data, pressure approximated</td>
</tr>
<tr>
<td></td>
<td>272</td>
<td>67</td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>

58
<table>
<thead>
<tr>
<th></th>
<th>Formula</th>
<th>Weight</th>
<th>Range</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DANGER/INJURY</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Wright, Davidson et al. 1950)</td>
<td>$R = 18.1^*W^{0.5}$</td>
<td>211</td>
<td></td>
<td>As cited by (Cudahy and Parvin 2001)</td>
</tr>
<tr>
<td>(Cameron 1947)</td>
<td></td>
<td>136</td>
<td>5–640</td>
<td>As cited by (Cudahy and Parvin 2001)</td>
</tr>
<tr>
<td>Committee on Amphibious Operations, (USN 1952)</td>
<td>$R = 0.45*W^{1/3}$</td>
<td>56</td>
<td>20–91</td>
<td>Based on anecdotal information; no data source or reference provided</td>
</tr>
<tr>
<td>(Cudahy and Parvin 2001)</td>
<td>$R = 10.8^*W^{1/3}$</td>
<td>56</td>
<td>136–229</td>
<td>Application of scaling laws to Navy Dive Manual guideline of 500 psi (3,447 kPa)</td>
</tr>
<tr>
<td>(Ellis 1944)</td>
<td></td>
<td>136</td>
<td>229</td>
<td>Cites experiments by Williams, but no published data was found</td>
</tr>
<tr>
<td>(Nedwell 1988)</td>
<td>$R = 22.5^*W^{0.2}*d^{1/3}*h^{1/3}$</td>
<td>686</td>
<td>100–700</td>
<td>(d = diver depth, h = charge depth) As cited by Cudahy(^8)</td>
</tr>
<tr>
<td>(Rawlins 1953)</td>
<td></td>
<td>100</td>
<td>700</td>
<td>Given weight and range values intended to match (P_{max} = 25) psi (172 kPa); air blast injury criteria are adapted from White, 1961(^{REF}) and grouped with water blast injuries</td>
</tr>
<tr>
<td><strong>LETHAL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Auster and Willard 1943)</td>
<td></td>
<td>136</td>
<td>&lt; 91</td>
<td>Charge weight assumed to be standard US depth charge, given range refers to authors’ experience with survival rates of depth-charged sailors</td>
</tr>
<tr>
<td>(Bebb and Wright 1951); (Zuckerman 1969)</td>
<td>$R = 3.17^*W^{1/2}$</td>
<td>37</td>
<td>136</td>
<td>Equation first appears in Bebb, then is cited in English units in Zuckerman; square root scaling of 500 psi guideline for 300 lb depth charge</td>
</tr>
</tbody>
</table>
Committee on Amphibious Operations, (USN 1952) | R = 17.5*W^{1/2} | 204 | Application of scaling law to $P_{\text{max}} = 300$ psi (2,068 kPa)

(Ellis 1944) | 136 | 30 | Based on clinical experience

### Guidelines Based on Charge Weight and Range

![Graph showing ranges and charges](image)

**Figure 11:** Guidelines based on charge weight and range. Guidelines that were given in the form of ranges or equations are labeled with the year of publication so that they may be related to Table 3. Again, guidelines show no visual trend, as several “safe” exposures lie within the ranges predicted by some “lethal” guidelines.

Many of these guidelines provide equations for range based on charge weight, but several researchers also gave exact ranges from specific charge weights without
extrapolating to a generalized equation. These specific guidelines are typically based on the clinical experiences of the authors, who published statements summarizing their experiences treating blast victims from WWII (Greaves, Draeger et al. 1943, Ellis 1944, Cameron 1947, USN 1952, Rawlins 1953, White 1961). While these guidelines are based on human data, the cases involve sailors at the surface of the water; proximity to the surface alters the pressure waveform sufficiently that these data points cannot be used to create standards for any degree of immersion. The surface of the water reflects a negative pressure (rarefaction) wave that mitigates the positive pressure of the blast wave, so a sailor near the surface will receive a significantly lower exposure level than a fully-immersed diver, even at the same distance from the charge (Cole 1948). Therefore, to create standards for immersion, the exposures for sailors at the surface would need to be carefully computed or measured, taking into account the effects of the surface.

With the exception of the guidelines from Nedwell (1988), all of the range equations are derived from the application of different scaling laws to peak pressure guidelines (Nedwell 1988). The US Navy 500 psi guideline is by far the most frequent source for the development of these range equations (Cameron 1947, Bebb 1951, Bebb and Wright 1951, Cudahy and Parvin 2001). Scaling laws can similarly be applied to determine standoff ranges in air blast, but are less complicated by effects specific to the in-water environment (Zuckerman 1969).
3.2.4 Guidelines Based on Impulse

The blast impulse is a measure of intensity based on the maximum of the cumulative area under the pressure-time curve. It is related to the amount of blast momentum delivered to the person. Underwater, there are many factors that can influence the impulse, leading to high variability in impulse depending on circumstance. Additionally, some historical research groups prior to the advent of modern computers used differing methods for the calculation of impulse, potentially adding to the variability even further. Ideal explosives like TNT and C-4 show a tight coupling between peak pressure and impulse, but for non-ideal explosives such as thermobaric, aluminized explosives and for blasts near reflecting surfaces the peak pressure and impulse values may be essentially independent (Arons 1954). Some coupling of peak pressure and impulse variables is present both in air and in water for ideal explosives (Zuckerman 1969). Both sets of data were fit with second-order exponential decay functions.

It has long been postulated that the true destructive force of an underwater blast is linked more closely to the impulse than to the peak pressure (Cole 1948). This assertion has yet to be proved physiologically, but has been reiterated consistently through medical case reports and underwater blast analyses since World War II (Wright, Davidson et al. 1950, Rawlins 1953, Bebb 1954, Clemedson and Criborn 1955, Andersen
and Løken 1968, Richmond, Yelverton et al. 1973, Christian and Gaspin 1974, Richmond 1977, Alonso, Ferradas et al. 2006). Impulse has become the standard for predicting destruction of buildings and other structures, but little experimental data was found in the literature to either support or refute, conclusively, the same assertion for physiological damage (Yelverton and Richmond 2005). It seems unlikely that the contributions of peak pressure and impulse can be statistically separated for ideal explosives in underwater blasts, as the two variables are very well correlated.

The complexity of underwater blast waveforms means that impulse-based guidelines were of limited utility before validated computational models were developed to predict underwater blast. Even if the guidelines were solidly based in experimentation, they could only be used in environments that were similar to previously obtained test data.

Table 4 outlines the blast injury guidelines based on impulse, along with their calculated ranges for the test case. The guidelines are shown plotted in Figure 12. The purpose of this figure is to show that there is no discernible trend in the guidelines over time (e.g., becoming more or less conservative), and also to maintain consistency with the other guideline types.
Table 4: Blast injury guidelines based on impulse. *Calculated ranges based on 136-kg TNT test case. †Reference describes experimental data.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Impulse (kPa*msec)</th>
<th>Range‡ (m)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SAFE/DETERRENT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Christian and Gaspin 1974); British Standard 5607 (BSI 1998)</td>
<td>14</td>
<td>316</td>
<td>No reference provided for limits; guidelines seem to be based on (Richmond 1977) this guideline is sometimes referred to as the Gaspin Criteria and presented in English units as 2 psi*ms</td>
</tr>
<tr>
<td>(Richardson, Greene et al. 1991)†</td>
<td>0.212</td>
<td>319</td>
<td>Equation in reference: ( \ln(\text{Impulse}) = 3.68 + 0.3857 \ln(\text{weight}) ) solved using 77 kg; designed to predict injury risk for aquatic mammals</td>
</tr>
<tr>
<td>(Richmond, Yelverton et al. 1973)†</td>
<td>14–21</td>
<td>314–316</td>
<td>Injury threshold of 10 psi<em>msec (69 kPa</em>msec) determined using unscaled animal experiments; this threshold was then lowered to 2-3 psi<em>msec (14-21 kPa</em>msec) to provide a factor of safety</td>
</tr>
<tr>
<td>(Richmond 1977)†</td>
<td>6.9</td>
<td>318</td>
<td>Experiments based on preliminary guidelines set by (Richmond 1977)</td>
</tr>
<tr>
<td>(Wright, Davidson et al. 1950)†</td>
<td>138–276</td>
<td>263–289</td>
<td>Based on experiments listed in reference</td>
</tr>
<tr>
<td>(Yelverton and Richmond 1981)†</td>
<td>1.4e–5</td>
<td>319</td>
<td>Animal data with maximum animal mass 45 kg; mostly fish (have a different injury mechanism)</td>
</tr>
<tr>
<td><strong>DANGER/INJURY</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Zuckerman 1969)</td>
<td>690</td>
<td>200</td>
<td>Stated with an accompanying ( P_{\max} = 1800 \text{ psi} ) (12411 kPa); however, states higher impulses prove fatal even at lower ( P_{\max} ).</td>
</tr>
<tr>
<td>LETHAL</td>
<td>(Richardson, Greene et al. 1991)†</td>
<td>0.801</td>
<td>319</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>(Stuhmiller, Phillips et al. 1991)</td>
<td>600</td>
<td>212</td>
<td>LD50 value stated but un referenced; all other underwater blast information referenced to Richmond papers; no data referenced</td>
</tr>
<tr>
<td>(Zuckerman 1969)</td>
<td>827</td>
<td>183</td>
<td>Impulse value ascribed to guidelines from (Bebb and Wright 1951)</td>
</tr>
</tbody>
</table>
Figure 12: Impulse guidelines shown vs. the year they were published. The guidelines span several orders of magnitude. The only discernible relationship is the prescription of extremely low impulse values as “safe” following the 1970s.

3.3 Results

The distances prescribed by the different injury and lethality guidelines are plotted in Figure 13. The guidelines themselves are listed in detail in Tables 2-4, and discussed in detail in the previous sections. A total of 42 different guidelines were evaluated. When possible, these guidelines were traced back to their original sources. Of these 42 guidelines, only six were found to have associated experimental data;
however, even these six still showed gross inconsistencies. The publications with these six guidelines are described in more detail in the section 3.4.

As is evident from the figure, different range guidelines for the same degree of injury vary by orders of magnitude. When the injury types were assigned numerical values of 3 for Safe/Deterrent, 2 for Danger/Injury, or 1 for Lethal and plotted as a function of range, the resulting $R^2$ value was 0.21 for a linear regression fit curve. In other words, given the range value for a randomly selected guideline, there is no reliable way to determine whether that range value prescribes a “safe” guideline or a “lethal” guideline.
Figure 13: Published underwater blast guidelines from 42 separate references, 1943-present. Each guideline has been converted to a range from the center of an example explosion. Safe, Injury, and Lethal ranges between various sources vary by an order of magnitude.

This wide variability could not be explained as guidelines evolving over time. When the guidelines were divided into categories by injury severity, no statistically significant trends in range could be found over time for any category (p>0.69 for Safe/deterrent, p>0.48 for Danger/Injury, p>0.48 for Lethal).
3.4 Discussion

A total of forty-two guidelines for underwater blast exposure were found, and only six of those guidelines were linked to documented experimental data. However, even these six guidelines are based on non-ideal experimental designs. Corey et al. used strips of beef intestine inside a model of a human torso to try to determine the exposure levels required to create abdominal perforations (Corey 1946). The experimenters ignored the hundreds of available medical reports that document the overwhelming location of abdominal perforations near the ileocecal junction (Cameron 1947). It is probable that the structure of the junction and attachment to the abdominal wall contribute stresses that lead to perforations at much lower blast exposure levels, as they do in blunt force trauma (Stuhmiller, Phillips et al. 1991).

Wright et al. conducted extensive human experiments to find a deterrent blast level, but operated under the assumption that peak pressure was the crucial factor in determining exposure levels and therefore only occasionally reported impulse values (Wright, Davidson et al. 1950). This omission was despite the researchers’ own admission in the paper that impulse was a critical predictive factor. It was also later found that many of the pressure gauges used by this research group during this time period were possibly inaccurate by 25% or more, meaning that while the
“safe/deterrent” levels established are probably approximately accurate, higher-exposure values may not be correct (Williams and Sargent 1963).

Richmond et al. conducted meticulous animal and human experiments that are, to date, the most complete references for exposure found (Clemedson and Criborn 1955, Swift and Slifko 1968, Richmond 1977). However, even these meticulous analyses were performed mainly using animal data that was not scaled to approximate humans, and within the seminal 1973 paper itself Richmond calls for caution and further testing before applying these standards for human safety (Richmond, Yelverton et al. 1973). In spite of this warning, these experiments, with a factor of safety applied, are used to determine the current British standards for underwater blast exposure as found in British Standard 5607 (Bulson 2002). These standards, in their English-unit form of 2 psi*ms, are also published and used by the U.S. Navy as the Gaspin Criteria (Christian and Gaspin 1974). While no universal standard for underwater blast safety currently exists, the guideline developed by Richmond et al. seems to be the most commonly applied safety standard today.

Yelverton et al. and Richardson et al. also created standards for blast safety, but largely using animal data (Richmond, Yelverton et al. 1973, Richardson, Greene et al. 1991). These two authors attempted inter-species scaling, but had very limited data points for animals with body masses in the same range as humans. Yelverton et al. had
no data for animals above 45 kg, and most data were from fish. Fish are injured through a different physiological process than mammals, rupture of the swim bladder, and are far less sensitive to blast than humans. They are therefore not a valid test model for humans (Richmond 1976). Richardson et al. studied the effects of blast on large aquatic mammals and made no attempt to extend their model to humans. It is uncertain whether lung and gut blast pathophysiology of marine mammals and terrestrial mammals is similar.

Figure 14 illustrates the ranges predicted for the six guidelines based on experimental data. Even though they are all based on test data, they are still grossly inconsistent because of the listed limitations of those experiments. The Corey et al. guideline for injury risk is an order of magnitude less than the Richardson lethal guideline, and the available safe/deterrent guidelines lie in between the two. There is an obvious need for additional data and modeling to create a consistent, reliable set of guidelines similar to those available for air blasts. The impulse-based guidelines have a maximum range of 319.2 m because of the nature of the regression-fit curves; however, this model is still sufficient to show the gross inconsistencies between the guidelines. Properly constructed guidelines should, at the very least, predict fatal ranges as closer than dangerous ranges, and farthest from the blast should be the safety guidelines.
Currently available guidelines appear in random order from the blast, highlighting the lack of physiological foundation.

Figure 14: Ranges prescribed by guidelines that have a documented experimental basis. Only six guidelines were found that had documented experimental bases, and these guidelines were still grossly inconsistent with each other.
4. Human Injury Criteria for Underwater Blast Injuries

This chapter is adapted from (Lance, Capehart et al. 2015), with permission.

4.1 Introduction

There is extensive literature on pulmonary injury and fatality risk assessments for air blast, some of the work driven by potential nuclear weapons exposure (Bowen, Fletcher et al. 1968) and short and long peak overpressure duration military exposure (e.g. (Bass, Rafaels et al. 2008, Rafaels, Bass et al. 2010, Panzer, Bass et al. 2012)). More recently, neurotrauma injury and fatality assessments have been derived for blasts in air (Rafaels, Bass et al. 2011, Rafaels, Bass et al. 2012). Much of this work was based on scaling animal risk assessments to human exposure conditions. Owing to differences in coupling between air/torso and water/torso, it is unclear how these air blast studies may apply to underwater blast injury risk.

Though underwater blasts propagate further and injure more readily than air blasts (Rusca 1915), the current U.S. Navy underwater risk guidelines are not based on actual blast exposure data. Instead, they are based entirely on the untested assumption published in 1943 that since the surface of the water “shreds” (creates a plume) at approximately 3,440 kPa (500 psi), the same pressure guideline must apply for tearing the inside of the human lungs (Greaves, Draeger et al. 1943). This speculation has propagated through Navy literature since its original publication in 1943, and has never
been updated through experimentation, theoretical calculations or any other means (USN 2011). In fact, very few underwater blast injury guidelines have been based on data of any kind, and those guidelines that were based on data are still remarkably inconsistent with each other (Lance and Bass 2015). This inconsistency is likely caused by the non-ideal experimental setups and lack of appropriate inter-species scaling found in the majority of these experiments (Corey 1946, Richmond, Yelverton et al. 1973, Richmond 1977, Yelverton and Richmond 1981, Richardson, Greene et al. 1991). Despite the lack of accurate guidelines, military missions frequently expose personnel to underwater blast with an unquantified risk of injury or death. The purpose of the study described in this chapter was to use actual exposure data to create a meaningful underwater blast injury guideline.

4.2 Methods

4.2.1 Injury Ratings

In contrast with air blast, there is a very limited amount of well-characterized experimental animal or human exposure data for underwater blast (Cameron, Short et al. 1942, Richmond, Yelverton et al. 1973, Richmond 1977, Bebb, Temperley et al. 1981, Han, Wang et al. 2013).

However, during WWII at least as many military casualties were incurred from underwater blast as from air blast (Williams 1942). Hundreds of case reports of
underwater blast exposure were published by military physicians, and many of these case reports contain extensive information about the scenario creating the blast exposure (Mathew 1917, Breden, d’Abreu et al. 1942, Gordon-Taylor 1942, Auster and Willard 1943, Cameron 1943, Ecklund 1943, Gill and Hay 1943, Goligher, King et al. 1943, Hamlin 1943, Martin 1943, Palma and Uldall 1943, Pinnock and Wood 1943, Pugh and Jensen 1943, Webster, Ross et al. 1943, Ellis 1944, Moore 1944, Williams 1944, Gage 1945, Yaguda 1945, Corey 1946, Wright, Davidson et al. 1950, Bebb 1954).

Much of this literature is based on experiences in WWII when sailors in the water were exposed to blasts from depth charges, either from enemy vessels or from primed charges that detonated as their own ships sank. In addition, a handful of more recent human experiments and isolated blast incidents have been published with details of the exposures (Hirsch and Bazini 1969, Huller and Bazini 1970, Weiler-Ravell, Adatto et al. 1975, Richmond 1977, Theobald 1977, Adler 1981, Petri, Dujella et al. 2001, Fothergill, Schwallier et al. 2002). These cases were compiled into a historical database of blast exposures. The resulting database included 475 human exposures at various ranges from the blasts, making it the largest underwater blast injury database compiled to date.

The injuries described by the reporting physicians ranged from mild abdominal discomfort and coughing to near-instantaneous fatalities. Many case studies contain comprehensive anatomical information, but frequently a detailed description of
symptoms was the only medical information provided. Since modern injury rating systems do not rely upon symptoms alone, rating systems for both pulmonary and abdominal injuries were developed that included seven ordinal levels of severity. These numerical severity ratings were based on the reported symptoms, surgical findings, and autopsy reports. Severity estimates were derived from a collaboration of physicians and biomedical engineers including a colon and rectal surgeon with decades of experience treating intestinal abnormalities. For comparison, the injury ratings were associated with the Abbreviated Injury Scale (AIS) trauma injury scales for both pulmonary injuries (Civil and Schwab 1988) and abdominal injuries (Moore, Cogbill et al. 1990). The ratings were designed to minimize the effect of differences in medical care across the cases, relying upon initial presentation of the patient rather than long-term prognosis. The rating scales are shown in Table 5 and Table 6.
Table 5. Injury rating scale for abdominal injuries from underwater blast exposures.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Severity</th>
<th>Symptomatic Scale</th>
<th>AIS Scales for Small Bowel/Colon/Rectum [67]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Minor</td>
<td>X-ray evidence; OR mild hemorrhaging; OR discomfort/pain; OR localized rigidity; NO general rigidity</td>
<td>Contusion or hematoma without devascularization; OR partial-thickness laceration without perforation</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
<td>Moderate hemorrhaging; OR discomfort/pain/general rigidity indicative of perforations deemed not to require surgery based on standards of treatment at time of injury⁺</td>
<td>Laceration &lt;50% of circumference</td>
</tr>
<tr>
<td>3</td>
<td>Serious</td>
<td>Severe hemorrhaging; OR perforations severe enough to warrant surgery based on standards of treatment at time of injury⁺</td>
<td>Laceration ≥50% of circumference without transection</td>
</tr>
<tr>
<td>4</td>
<td>Severe</td>
<td>Multiple or unusually large perforations, possibly severe enough to cause death in 1943 but likely treatable by modern medical practices</td>
<td>Transection of small bowel/colon; Full-thickness laceration of rectum with extension into peritoneum</td>
</tr>
<tr>
<td>5</td>
<td>Critical</td>
<td>Untreatable in 1940s, would still likely be untreatable now; primarily palliative measures</td>
<td>Transection with segmental tissue loss in the small bowel/colon; OR devascularized segment in the small bowel/colon/rectum</td>
</tr>
<tr>
<td>6</td>
<td>Maximum</td>
<td>Fatality within 30 minutes of exposure</td>
<td>Maximal (currently untreatable)</td>
</tr>
</tbody>
</table>
The AIS Scale is provided only as a reference to compare severity of rankings, and is not intended to suggest common methods of treatment between the two independent scales.

*Modern medical standards mandate surgery for any size intestinal perforation. In contrast, surgery in the 1940s carried a large risk of infection, and antibiotics were far less available/effective. The decision to operate was used to assess, retrospectively, the severity of the patient’s symptoms upon presentation, not to denote an acceptable modern medical standard of care.
Table 6. Injury rating scale for pulmonary injuries from underwater blast exposures.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Severity</th>
<th>Symptomatic Scale</th>
<th>AIS Pulmonary Scale [66]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Minor</td>
<td>Some x-ray evidence but asymptomatic</td>
<td>Contusion (unilateral &lt;1 lobe)</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
<td>Coughing; OR shallow breathing</td>
<td>Contusion (unilateral whole lob); OR laceration (simple pneumothorax)</td>
</tr>
<tr>
<td>3</td>
<td>Serious</td>
<td>Mild hemoptysis; OR difficulty breathing</td>
<td>Contusion (unilateral &gt;1 lobe); OR laceration (persistent &gt;72hrs, airleak from distal airway); OR hematoma (nonexpanding intraparenchymal)</td>
</tr>
<tr>
<td>4</td>
<td>Severe</td>
<td>Severe symptoms, treatable by modern medical practice, possible recovery or fatality</td>
<td>Laceration (major airway leak); OR hematoma (expanding hematoma); OR vascular (primary branch intrapulmonary vessel disruption)</td>
</tr>
<tr>
<td>5</td>
<td>Critical</td>
<td>Severe cyanosis; OR severe hemoptysis; likely untreatable by modern medical practice; typically fatal</td>
<td>Vascular (hilar vessel disruption); OR multilobar lung laceration with tension pneumothorax</td>
</tr>
<tr>
<td>6</td>
<td>Maximum</td>
<td>Fatality within 30 minutes of exposure</td>
<td>Maximal (currently untreatable)</td>
</tr>
</tbody>
</table>

The AIS Scale is provided only as a reference to compare severity of the rankings, and is not intended to suggest common methods of treatment between the two independent scales.
After the rating scales were developed, the injuries in the database were independently assigned a numerical severity by three different reviewers: a former-Army physician with prior blast trauma experience (BC), a biomedical engineering professor with extensive experience in blast research (CB), and an engineering PhD student blast researcher (RL). Each reviewer blindly and independently rated each injury according to the scales and the Cohen’s kappa coefficient was calculated to determine inter-rater reliability between the physician and the experienced PhD reviewers (0.42 for the abdominal scale, 0.54 for the pulmonary scale). The PhD student’s ratings were used only as a tiebreaker to determine a final injury value for cases with conflicting reviewer values. The Cohen’s kappa coefficients between the physician reviewer’s values and the final values were 0.65 and 0.70 for abdominal and pulmonary injuries respectively, and the coefficients for the experienced PhD reviewer were 0.71 and 0.77 respectively. These high kappa values indicate that the scale developed is sufficiently detailed to consistently describe the level of injury for the cases in the database.

4.2.2 Blast Assessment

Many of the case reports contained sufficient detail to completely reconstruct the exposure scenarios, including charge type and estimated distance from the explosion center. Some of the publications issued during WWII did not contain detailed
information on charge types because the information was still considered sensitive at the time of publication, but the charge types could be determined retroactively based on incident dates, vessels involved, locations, and personnel nationalities. Most of the exposures were depth charges, which had either a preset detonation depth or a very limited number of user-selectable detonation depths. Based on the depth charge model and the type of warfare being conducted when the vessel was sunk, the detonation depth could usually be determined fairly conclusively. If a case did not contain sufficient information to determine all of the scenario parameters, that case was eliminated from the final dataset.

Though there are no simple theoretical models for underwater explosions, they can be accurately modeled using finite-element and finite-volume methods. These computational programs can account for the many factors that complicate underwater blasts (Shin 2004, Miller, Jasak et al. 2012). One of the most prominent pieces of modeling software is the US Navy’s DYSMAS (Dynamic System Mechanics Advanced Simulation) hydrocode, which uses the Gemini Eulerian solver to model the pressures resulting from underwater blasts. This software has been extensively validated and shown to accurately mathematically reproduce the effects of underwater blasts, even in complex environments (Wardlaw, McKeown et al. 1998, Mair 1999, Wardlaw, Luton et al. 2003, McKeown, Dengel et al. 2004, Ferencz, DeGroot et al. 2008, O’Daniel, Harris et...
al. 2011). DYSMAS provided general pressure time histories based on ranges and explosives from the case literature to correlate with the observed injuries from underwater blast. Using this software, the exposures could be accurately modeled to include all known confounding variables such as bottom depth, proximity to the surface, and varying degrees of bottom reflectivity.

Once the exposures were reconstructed, the US Navy’s Gemini Eulerian solver was used to compute the peak pressures and impulses at the reported location of each blast injury victim. For blast victims immersed from the neck down at the surface of the water, the lungs were approximated as 10 cm beneath the surface and the lower abdomen was approximated as 30 cm beneath the surface. Though these differences are generally a much shorter length scale than the horizontal separations from the charge, the resulting pressure time histories were sensitive to the distance of each organ system under the water. For example, this 20-cm distance typically yielded peak pressure and impulse values that differed by a factor of 2-3 owing to the rarefaction wave reflecting off the surface of the water. The abdominal exposures were therefore significantly different from the pulmonary exposures for the same person (p<0.001 for both peak pressure and impulse values). Orientation in the water was reported in some case studies, but was generally not reported with enough frequency or descriptive detail to use it to determine vertical position on a finer scale.
The sensitivity of the results to variations in the reported surface distances was evaluated by varying a subset of sample cases by ±20% and evaluating the magnitude of the change in the exposure levels seen by the blast victims. Before the age of radar ranging, accuracy of distance estimation by eye for trained observers measured as approximately 5-10% at ranges similar to those used in this study (Turner and Fulmer 1917). More recent reports include range estimation errors of approximately 10% for untrained ground soldiers (Gibson 1950) and less than 20% estimation error in assessing distance to boats (Galanter and Galanter 1973). More recent studies with military personnel include Wright (1995) (9-13% estimation error) (Wright 1995), Lampton et al. (1995) (<5% error at 10 m range) (Lampton, McDonald et al. 1995), and Sun (2004) (<10% error for several tasks) (Sun, Campos et al. 2004).

These conservative distance error estimates were incorporated into a sensitivity analysis on the distances from the charges and resulting impulse values. Based on a potential 20% distance variation, a set of 100 risk analyses was performed for each risk assessment developed in this study with each impulse value perturbed by a Gaussian random number with zero mean and a standard deviation representing the calculated impulse at ±20% distance variation. Because the variation of impulse is not symmetric with distance, closer distances have larger impulse increases than proportionally larger distances have impulse decreases.
4.2.3 Protection

Throughout the historical literature, authors repeatedly state their beliefs that life preservers should help mitigate the injurious effects of underwater blast in the lungs (Greaves, Draeger et al. 1943, Zuckerman 1969). These beliefs were stated without any evidence and were contended even as early as their initial publication in 1943 (Pugh and Jensen 1943). Recent investigation shows that modern personal protection in air blast offers substantial protection to the lungs (Wood, Panzer et al. 2013), potentially increasing the relative occurrence of abdominal injuries (Cripps and Cooper 1996); however, the protection studied covers more of the chest and is much closer-fitting than the “Mae West” or belt-style life preservers of the time period.

While some testing has been performed to determine the protective effect of life preservers, the tests have either been inconclusive or determined that the area of protection needs to cover the entire torso to be effective (Friedell and Ecklund 1943, Greaves, Draeger et al. 1943). In the absence of experimental data, statistical analysis of the exposure dataset was performed to determine if wearing a life preserver provided a protective effect. Since the “life preserver” dataset was relatively small, the protective effect of life preservers was investigated by comparing relative injury levels between abdomen and pulmonary systems of protected and unprotected wearers. If life preservers provided protection to the lungs, then for a comparable level of pulmonary
injury the abdominal injuries for personnel wearing life preservers should have been worse than for personnel who were not wearing life preservers.

Abdominal injury severity was plotted as a function of pulmonary injury severity for the 187 injury data points reporting life preserver use. Cases with no reported injuries were eliminated from this phase of the analysis. The personnel not wearing life preservers and the personnel wearing life preservers were treated as two completely separate groups, and a linear model was fit to each set of data. The slopes of these lines were compared, and statistical significance was evaluated to determine the effect of life preservers. An ANCOVA analysis was also performed on the data, as well as Mann-Whitney U tests at each level of lung injury severity. No significant effect could be detected by any of the tests, so life preserver use was eliminated as a statistical variable. The results of these analyses are presented below.

4.2.4 Survival Analysis

The injury levels for each organ system were separated into one of three groups: non-injury, injury, and fatality. Injury severity levels 0 and 1 were grouped as “non-injury” because level 1 injuries are, by definition, asymptomatic. Injury levels 2-4 were grouped as “injury” since the medical treatments for these levels would be similar and the patients would have a good chance of survival. Injury levels 5 and 6 were grouped as fatal because, even by modern standards, these patients would likely result in
fatalities. While several level 4 cases resulted in fatalities, they were grouped as injuries because many of these cases died from infection and would likely be treatable with modern antibiotics, imaging, and surgical techniques.

Parametric survival analyses were performed for each organ system using Minitab (Version 17, Copyright ©2014, State College, PA, USA) resulting in four total impulse-based risk functions for blast exposure. The risk functions were in the form of a Weibull distribution, shown as Equation 12.

\[
 f(I) = \frac{\beta}{\eta} \left( \frac{I}{\eta} \right)^{\beta-1} e^{-\left(\frac{I}{\eta}\right)^\beta}
\]

When calculating the injury risk functions, severity levels 0-1 were considered as right-censored uninjured and levels 2-6 were considered interval-censored injuries, with possible injurious values between 0 and the calculated blast impulse. The same procedure was followed to determine the fatal risk functions, with injuries ≤4 considered nonfatal and injuries level 5-6 considered fatal. Cases that gave a range of possible distances were considered right-censored from the minimum possible exposure if an injury or fatality did not occur and interval-censored between 0 and the maximum possible exposure if an injury or fatality did occur.
The probability of injury or fatality can be calculated using the cumulative distribution function for the Weibull distribution. This function is shown as Equation 13, where $F$ signifies the risk of injury or fatality.

\[ F(I) = 1 - e^{-\left(\frac{I}{\eta}\right)^\beta} \]

### 4.2.5 Range Predictions

To provide safe distance estimates for underwater blast, the 20% and 50% risk values from the pulmonary and abdominal injury and fatality curves were translated into a function of range ($R$) vs. charge weight ($W$) using the experimentally-validated scaling law for impulse ($I$) shown in Equation (3) (page 123). The impulse values for injury were lower for either the abdominal or pulmonary risk functions, depending on the percent risk, but the impulse values for fatality were always lower for the pulmonary risk functions. Overall injury or fatality risk by range is calculated by the organ system that gives the highest risk at the lowest impulse values.

Values for $k$ and $\alpha$ corresponding to TNT were used in this analysis ($k = 6,698; \alpha = 0.94$) (Arons 1954). While TNT itself is rarely used for modern military purposes, it remains the standard for comparison of charge strengths. Owing to the rarefaction wave reflected off the surface, Equation (3) describes only fully immersed cases that are deep enough to avoid the protective effect of the surface. Swimmers on the surface
would be safe at greater distances than submerged swimmers because of the reduction in pressure from the reflected tension.

4.3 Results

4.3.1 Sensitivity Analysis

The means for all of the ensemble perturbed risk calculations are within the 95% confidence interval for the calculated risk functions for lung and abdominal injury and fatality at the 50% risk levels. The mean 100 random ensemble value for impulse at 50% risk for lung injury was 269±11 kPa-ms, for lung fatality was 422±138 kPa-ms, for abdominal injury was 221±20 kPa, and for abdominal fatality was 839±77 kPa. It was therefore concluded that the estimated distances served as valid approximations for calculation of survival curves.

4.3.2 Protection

The injury data and regression fit lines for the life preserver analysis are shown in Figure 2. Both regression lines are acceptable fits to the data (slope= 0.58, intercept= 1.44, R²= 0.63 with life preserver; slope= 0.60, intercept= 1.09, R²= 0.55 without life preserver). The sizes of the markers in Figure 15 are proportional to the number of data points at those locations.
Figure 15: Abdominal injury severity as a function of pulmonary injury severity. For two groups wearing and not wearing life preservers at the time of blast exposure. Marker size is proportional to the number of data points.

While the $R^2$ values are moderate, the p-values (<0.0001) for the slopes of both lines confirm that there is a statistically significant increase in abdominal injury severity with increasing pulmonary injury severity. This result is not surprising, since more severe injuries to both systems would logically result from an overall higher blast exposure. However, there is no significant difference between the slopes of the lines (p>0.46). Similarly, ANCOVA analysis confirmed the dependence of abdominal injury
on lung injury but showed no relationship with life preserver use ($p_{\text{lung injury}} < 0.0001$; $p_{\text{interaction}} > 0.31$). In addition, Mann-Whitney U tests were performed on the distribution of abdominal injuries within each ranking category of lung injury. None of the seven separate Mann-Whitney U tests showed a statistically significant difference between the two groups. Life preserver use was therefore eliminated as a variable in injury risk.

### 4.3.3 Survival Analysis

Figure 16 shows the injury data for both organ systems plotted against peak pressure and impulse of exposure. For simplicity, cases with a range of possible distances are shown plotted at the exposure values corresponding to the mean distance. These results are compared with the current US Navy guidelines for safe exposure levels and probable injury threshold.
Figure 16a: Abdominal injuries.

Figure 16b: Pulmonary injuries. Injuries plotted against peak pressure and impulse of exposure. Dotted and dashed lines represent current US Navy guidelines for “safe exposure” (50 psi, or 345 kPa) and “probable injury” threshold (500 psi, or 3,447 kPa).
Figure 17 shows the pulmonary and abdominal injury and fatality risk functions as computed by Minitab. The coefficients of the equations are shown in tabular form in Table 7, and the equation to calculate risk is described in section 4.2.4.

Figure 17a: Abdominal injury risk function.

Figure 17b: Abdominal fatality risk function.
Figure 17b: Abdominal fatality risk function.

Figure 17c: Pulmonary injury risk function.

Figure 17d: Pulmonary fatality risk function.
Table 7: Risk function constants and 50% risk values.

<table>
<thead>
<tr>
<th></th>
<th>Injury Risk Function</th>
<th>Fatality Risk Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdominal</td>
<td>$\beta= 0.885 ; \eta= 386.6$</td>
<td>$\beta= 8.048 ; \eta= 802.5$</td>
</tr>
<tr>
<td>Pulmonary</td>
<td>$\beta= 2.197 ; \eta= 277.5$</td>
<td>$\beta= 8.068 ; \eta= 316.5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Injury Risk (kPa*ms)</th>
<th>Fatality Risk (kPa*ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdominal</td>
<td>30 ±56/-19</td>
<td>256 ±110/-77</td>
</tr>
<tr>
<td>Pulmonary</td>
<td>100 ± 36</td>
<td>235 ± 35</td>
</tr>
</tbody>
</table>

4.3.4 Range Predictions

The calculated range guidelines for immersion for injuries and fatalities are shown in Figure 18.
Ranges were calculated via Eq (3), rearranged to solve for R. The corresponding constants remain unchanged ($k=6,698; \alpha=0.94$)(Arons 1954). The two scaling constants for TNT, $k$ and $\alpha$, were converted to Metric values from those found in Ref (Arons 1954). These curves predict ranges based on impulse for ideal explosives that have been converted to a TNT standard. For a non-ideal explosive with a higher relative impulse value (e.g., aluminized charges), these range predictions will likely underestimate safe range. However, these scaling laws may overestimate required range for shock waves with less than roughly 133 kPa peak pressure (74). In addition, these scaling laws apply
only to ideal, fully-immersed cases without significant bottom reflection. Calculation of ranges in non-ideal conditions requires the use of more complex modeling techniques.

4.4 Discussion

The current US Navy 500 psi guideline for ‘probable injury’ (dashed lines, Figures 3a and 3b) is qualitatively different than the results of the injury assessments from this study. The largest grouping of human fatalities from underwater blast exposure has exposure levels that are lower than the US Navy ‘probable injury’ guidelines. The safety guidelines developed by Richmond et al. (Richmond 1976, Richmond 1977) are the most meticulously-developed standards to date, but even these were not based on human injury data. Instead, they were developed to assert safe levels only, and were based on extrapolations from animal data that were then given a factor of safety. In addition, the gauges in Richmond’s experiments were located 30 cm below the surface with vertical subjects immersed to the neck, so the gauges did not measure the exposure levels seen by organs closer to the surface of the water. The exposure levels closer to the surface of the water can be significantly different from those as deep as 30 cm (p<0.001 for a depth of 10 cm), as discussed in detail in the section Methods: Blast assessment. Richmond et al. attempted to remedy this experimental flaw by retroactively calculating exposure values at shallower depths; however retroactive calculations in a region sensitive to small changes can never be considered as reliable as experimental measurements.
The results of this study are compared directly with air blast fatality risk curves of Bass et al. (Bass, Rafaels et al. 2008) as a function of peak pressure and impulse using a Friedlander approximation (Figure 19).

Figure 19: Blast Injury Guidelines. Plotted with the pulmonary data from Figure 16b.

For a blast peak pressure of 1,800 kPa, the corresponding ideal blast in air with a duration of 2 ms would have an impulse of 1,325 kPa*ms and an approximately 50% risk of fatality. At this impulse level, this study predicts an over 99% chance of fatality for pulmonary and abdominal injuries. An example Friedlander blast at the threshold for injury in air ($P_{max} = 703$ kPa, duration = 2 ms, impulse = 517 kPa*ms) would have an approximately 72% chance of injury in water. This is consistent with the biomechanics
of transmission of blast to the chest in air compared with in water. It is expected that water transmission will result in better coupling to the chest because of the relative impedance values of air and water, leading to lower impulse values for injury risk.

Comparing Richmond’s experiments with the current study, Richmond predicts a safe level of 14 kPa*ms impulse for swimmers, while this study finds a 1% injury risk level at 34 kPa*ms (95% confidence interval 20-59 kPa*ms) for the chest and 2 kPa*ms (95% confidence interval 0.3-15 kPa*ms) for the abdomen. Since minor chest and abdominal injuries are unlikely to be diagnosed relative to major injuries, the results of this study and Richmond’s guideline are similar in magnitude and are consistent.

Previous investigators have suggested that impulse is a better correlate with human injury than peak pressure, but Figure 16 shows that peak pressure and impulse are very highly correlated with each other for this dataset. Statistical testing also concluded that either could be used to accurately predict injuries for this dataset, in contrast with the assertions of previous investigators. Logically, both peak pressure and impulse may be necessary to accurately predict injury risk, similar to the use of both peak pressure and overpressure duration to predict injury risk in air blast. The dataset used in this study, however, almost exclusively contains exposures from ideal high explosives at the surface of an open body of water. Ideal explosives show a close correlation between peak overpressure and impulse values, so while both variables were
determined to be predictive of injury risk when used independently, this dataset was not sufficient to separate their relative contributions in a statistically meaningful fashion. In an enclosed space, or with non-ideal explosives, peak pressure and impulse are not always as simply correlated. Experience with damage to underwater structures and pathobiology of air blast at long durations indicate that impulse should be a sensitive predictor of injury severity cf. (Wightman and Gladish 2001, Bulson 2002), but it is difficult to demonstrate this without additional data from a wider variety of exposure types.

From a clinical point of view, the results emphasize that blast pulmonary and gut injuries may occur at great distances in water from the source of an explosion. For instance, using conservative scaling laws for a fully-immersed case, there is a 20% risk of pulmonary/gut injury at 1 km from a 20 kg source (crossref Fig 5). This result suggests that injury may occur in the water at quite long ranges compared with air blast (e.g. (Bass, Rafaels et al. 2008, Rafaels, Bass et al. 2010, Panzer, Bass et al. 2012)). This increase in range is relevant in both civilian and military settings. The presence of potential blast pulmonary and gut trauma may be particularly underappreciated in civilian settings (existing civilian reports include (Abu-Zidan and Aman 2001, Petri, Dujella et al. 2001) and others). It is especially important to appreciate the distance from the source at which such injuries may occur, and that there may be long term sequelae from such
events at much larger ranges than implied by air blast experience cf. (Ross, Macdarmid et al. 2007).

This study provides the first underwater blast injury risk functions based on human data. The substantial difference between current US Navy guidelines and the available human data emphasizes the need for more realistic underwater blast guidelines. The current US Navy guideline for “probable risk of injury” is at a peak pressure value higher than most of the fatalities evaluated in this study. The guidelines adopted from Richmond’s experiments provide an impulse value for safe underwater exposure, but do not provide a conversion from impulse to range. The Richmond guidelines also do not provide information about risk of injury or fatality if personnel are within the recommended range. Using the guidelines published in this study, for the first time military operators can reasonably estimate the risks of injury or death from underwater blast exposure.

Previous clinical literature suggested that the intestinal tract was more vulnerable to injury than the lungs in underwater blast. The majority of this literature consists of medical case reports that are limited to qualitative analyses of the injuries (Breden, d’Abreu et al. 1942, Yaguda 1945, Draeger, Barr et al. 1946, Theobald 1977), but this assertion also appears in research documents used to determine current US and UK military safety policies (Christian and Gaspin 1974). However, this study demonstrated
that the abdominal cavity is not more vulnerable; instead, it is exposed to substantially higher levels of blast when the victim is at the surface. Since the majority of historical exposures have occurred at or near the surface, the frequency of severe abdominal injuries has remained subject to this misinterpretation. Our study emphasizes the large distances at which pulmonary and gut injuries may occur. These large distances, while often not appreciated in military and occupational practice, are important for diagnosing potential blast injuries following exposure.

This model has several limitations, primarily based on its use of reconstructions based on historical data. While the DYSMAS hydrocode has been extensively validated, computational reconstruction will always introduce uncertainty compared with real-time measurement of values. In addition, the ranges provided were largely self-reported. Distressed sailors abandoning a sinking ship while swimming rapidly may provide only a gross estimation. At the beginning of the model development, this shortcoming was a concern and was extensively tested. Based upon the sensitivity analysis presented in the Methods and Results sections, it was concluded that reasonable variations in the distance estimates did not lead to any significant alterations in the calculated results. Proximity to the surface could provide an additional complicating factor, especially for the pulmonary risk curves. The lungs were estimated to be 10 cm below the surface of the water; however, the organs span a vertical range broad enough
for different exposure values at the proximal and distal boundaries when at this shallow depth of immersion. While 10 cm is a realistic mean value, the high variability near the surface could introduce an additional element of uncertainty into the results and reinforces the need for prospective validation.

This study is limited to ideal pressure profiles in open water. Future work may include long-duration, high-impulse explosive types and closed-environment data if available. This type of data would serve to better separate the influences of impulse and peak pressure for a wider range of applicability.
5. Suffocation Risks for the Crew of the *HL Hunley*

This chapter is adapted from (Lance, Moon et al. 2016), with permission.

5.1 *Introduction*

Confederate military commanders hoped that the *Hunley* could sink some of the Union ships blockading Charleston harbor, and thereby end the Union blockade (Kloeppe 1987, Alexander Sunday June 29, 1902). Several military submarines had previously been constructed, such as Alfred Bushnell’s *Turtle* during the Revolutionary War, and the Confederate vessels *Pioneer* and *American Diver*, but before the *Hunley* none had been successful in combat (Murphy, Lenihan et al. 1998).

The *Housatonic* was quickly sunk by the *Hunley’s* torpedo, and five members of her crew were killed. However, the *Hunley* disappeared immediately after its attack, and even though it was raised from the ocean floor in 2000, the cause of its sinking remains a mystery (Hunley 2014). It is possible that the vessel was sunk because the crew, in their sealed volume, consumed their limited oxygen supply and succumbed to the effects of hypoxia and/or hypercapnia. This study analyzes limits on the air supply for the crew of the *H.L. Hunley*. The analysis was conducted under the assumption that the historical accounts are accurate, and that the bellows did not function to ventilate the atmosphere of the submarine. This is a conservative assumption since increased ventilation would delay the effects of either hypoxia or hypercapnia.
5.2 Methods

5.2.1 Volume Estimation

Estimates of oxygen supply within the submarine began with a calculation of the net volume of gas within the submarine. The internal volume was calculated by creating a model of the vessel’s hull, then subtracting the volumes of all moderate- to large-sized internal objects. Complex structures (vessel hull, snorkel box and pipes, conning towers, cutwaters, structural ribbing, ballast bulkhead walls, and dive planes) were modeled using the engineering modeling software SolidEdge ST7 (version 107.00.00.104x64, Siemens, 2014) to calculate volumes and masses. Volumes and masses of simpler items were calculated manually. Dimensions were obtained both from values published in released documents (e.g., (Murphy, Lenihan et al. 1998, Hunley 2005, Hunley 2013)) and by measuring items from published photographs that included measurement stadia. A summary of item measurements and volumes are shown in Table 1. While dimensions were measured from photographs rather than the vessel itself, the resulting model closely matches published scans and drawings of the recovered submarine (Figure 20).
Figure 20. The rendered model, shown as a black outline, compared to grey-filled tracings of the recovered vessel (top view drawn from laser scan (DeVine 2002), side view drawn from published diagram (Jacobsen, Blouin et al. 2012)). Some details, such as dive planes and keel ballast weights, are eliminated from the outlines to provide clearer views of the hull. The tracing and diagram show some damage as a result of underwater exposure.

The volumes of the crewmembers were also estimated and subtracted from the internal volume of the vessel. The heights and descriptions of each crewmember were published by the Friends of the Hunley after analysis of the remains by specialists from the Smithsonian Institution (Hunley 2004, Hunley 2004, Hunley 2004, Hunley 2004, Hunley 2004, Hunley 2004, Hunley 2004, Hunley 2004, Hunley 2004, Hunley 2004, Hunley 2004, Jacobsen 2005). The average body mass index of adult male military personnel entering West Point between 1874-1894 was 20.22 (±1.99 SD); this value was used to compute masses of the crewmembers (Cuff 1993). The displacement volume of the crew was calculated using a density of 1.05 g/mL, a reported mean value for military males (range 1.06-1.04 for ages 20-44) (Kryzywicki and Chinn 1966).
The volume of the ballast water was also calculated and subtracted from the internal volume. In 1902, former crewmember William Alexander published his account of the Hunley operations, including a diagram of the vessel’s position in the water column when operating “light,” or with the conning towers fully above the waterline. The submerged volume of the vessel was calculated using the SolidEdge inspection tool. This volume was used as the displacement volume of the submarine when operating “light.” Figure 21 shows the sliced SolidEdge model juxtaposed with the original drawing from the publication by William Alexander. Visual approximation was considered sufficiently accurate to position the cut, as the original drawing was an estimate.

Figure 21. The Hunley’s position in the water column when ballasted “light,” modified from a sketch in William Alexander’s descriptive article (Alexander Sunday June 29, 1902).
The positive buoyant force on the vessel was then calculated using this submerged volume. Comparison of the buoyant force to the mass of the vessel and internal objects provided the estimated volume of ballast water needed. This water volume was also subtracted from the internal volume of the vessel. Since the calculation of ballast water was considered to be the most sensitive aspect of the methods, all calculations were additionally performed assuming both zero ballast water and full ballast tanks. These additional calculations served to bound the upper and lower limits of the available oxygen supplies, and assess whether the qualitative results of the analysis varied at these extremes.

5.2.2 Gas Consumption

To calculate how long the oxygen supply onboard the Hunley could last, it is important to use realistic estimates of crew consumption. Seven of the crewmembers powered the Hunley by turning a hand crank attached to the propeller via a gearing mechanism. Research with arm ergometers has shown that the mean maximum rate of oxygen consumption (VO$_2$) for a male performing a sustainable but high level of arm cranking exercise is 3.2 L/min, and a mean value for moderate but submaximal exercise is 1.5 L/min. Additionally, moderate changes in the rate of pedaling do not significantly impact the rates of oxygen consumption for a given level of physical exertion (Smith, Price et al. 2001). These values are consistent with the expected values for moderate
exercise. A range of 1.5-3.2 L/min was therefore used to estimate oxygen consumption by the seven cranking crewmembers.

Lieutenant George Dixon manned the forward position in the submarine, and was in charge of navigation and the torpedo rather than cranking the propeller (Hunley 2004, Hunley 2004). His oxygen consumption was therefore estimated as 1.5 L/min, consistent with someone performing a mild to moderate activity level (Åstrand and Rodahl 1977). The total time of useful consciousness was calculated using Equation 14.

\[
\text{Eq (14)}
\]

\[
t_{O_2} = \frac{V_{\text{net}}(F_{O_2 \text{ initial}} - F_{O_2 \text{ LOC}})}{V_{O_2}}
\]

This equation predicts the time \(t_{O_2}\), in minutes, before risk of loss of consciousness from hypoxia. Its variables are net internal volume of the gas space \(V_{\text{net}}\), rate of oxygen consumption \(V_{O_2}\), and fractional percentage of oxygen both at the start \(F_{O_2 \text{ initial}}\) and where risk of loss of consciousness occurs \(F_{O_2 \text{ LOC}}\). For the purposes of these calculations, fractional percentage is equivalent to partial pressure \(F_{\text{gas}} = p_{\text{gas}}\) for all gases, as all aspects of this analysis take place at one atmosphere of pressure.

At the moment the hatches were closed, starting initial fraction of oxygen was estimated as 0.21; therefore \(p_{O_2} = 0.21\) atm was the initial oxygen partial pressure. No studies were found that estimated time of useful consciousness under measured, progressively decreasing oxygen levels. During acute hypoxia, the time of useful
consciousness is reduced to minutes for pO$_2$ levels in the range of 0.063-0.10 atm (Mackenzie, Riesen et al. 1945, Hall 1949, Webster and Reynolds 1950, Hall and Hall 1951). The 0.063 atm value was used as the minimum cutoff to estimate risk of loss of consciousness, though with progressively decreasing levels it is likely the crew would experience hypoxia before this level. This partial pressure value therefore represents an extreme lower bound. The calculations were also performed assuming risk of loss of consciousness at pO$_2$ = 0.10 atm to provide a more conservative upper bound.

A respiratory exchange ratio (RER) of 0.95 was used to calculate CO$_2$ production by the crew. RER is the ratio of volume of CO$_2$ produced per volume of O$_2$ consumed in a breath. The total time until risk of symptomatic hypercapnia (t$_{CO2}$) was calculated in minutes using Equation 15.

Eq (15)

$$t_{CO2} = \frac{V_{int} \cdot P_{CO2}}{(VO_2) \cdot RER}$$

$P_{CO2}$ represents the partial pressure of CO$_2$ at which the crew experiences sufficient symptoms to recognize the need for ventilation and opens the hatches.

Tests of CO$_2$ inhalation indicate that most subjects experience a physiologically noticeable, statistically significant appearance of symptoms at approximately pCO$_2$ = 0.05 atm, with definite symptoms expected in subjects above pCO$_2$ = 0.07 atm at atmospheric pressures (Woods, Charney et al. 1988, Stegen, Neujens et al. 1998, Bailey, Argyropoulos
et al. 2005, Poma, Milleri et al. 2005). Under resting conditions 7% CO₂ has been reported as tolerable for long periods, but with difficulty. Haldane (1892) reported that when CO₂ concentration progressively rose above 5%, “…the breathing was painfully labored, and required so much exertion as to produce great exhaustion” (Haldane and Smith 1892). Since the Hunley crew were mostly exercising, pCO₂= 0.05 atm was therefore used as a cutoff limit. Additional calculations were performed with pCO₂= 0.07 atm for conservatism.

Note that while VO₂ and VCO₂ are conventionally reported as L/min STPD (standard temperature and pressure, dry: 0°C, barometric pressure 760 mmHg), these rates have been converted to ATPD (atmospheric temperature, estimated at 30°C for the interior of the Hunley), approximately 10% higher. Owing to the cranking movement of the men inside a small volume we assumed complete mixing of gas within the hull.

Since former crewman William Alexander reported candle tests to determine the crew’s oxygen supply (Alexander Sunday June 29, 1902), the estimated duration of the candle flame was also included in the calculations. Most sources report wick-fed flames extinguish in atmospheres of approximately 17%, with only one source indicating flames surviving as low as 15.7% oxygen (Clowes 1894, Blount 1906, Dollwig, Kolls et al. 1917). It has also been observed that matches burn with difficulty in air when the CO₂ level...
exceeds 5% (Haldane and Smith 1892). The value of $pO_2 = 0.17$ was therefore used in Eq 1 to estimate the duration of the flame.

5.3 Results

5.3.1 Volume Estimation

Table 8 shows a summary of calculated volumes and masses for all non-trivial objects aboard the *Hunley*.

Table 8. Summary of masses and volumes of all non-trivial objects aboard the *Hunley*. A full listing of items and estimated dimensions is freely available for non-commercial use by request to the authors.

<table>
<thead>
<tr>
<th>Object</th>
<th>Volume (cm$^3$)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast blocks (internal)</td>
<td>277273</td>
<td>2024</td>
</tr>
<tr>
<td>Ballast blocks (keel)</td>
<td>---</td>
<td>1369</td>
</tr>
<tr>
<td>Bench, main crew</td>
<td>68447</td>
<td>34</td>
</tr>
<tr>
<td>Crank</td>
<td>10963</td>
<td>168</td>
</tr>
<tr>
<td>Crew</td>
<td>477810</td>
<td>502</td>
</tr>
<tr>
<td>Internal medium-sized objects*</td>
<td>152208</td>
<td>---</td>
</tr>
<tr>
<td>All medium-sized objects*</td>
<td>---</td>
<td>643</td>
</tr>
<tr>
<td>Hull assembly (from SolidEdge)$^\dagger$</td>
<td>8993312 (internal)</td>
<td>4408</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>8006612</strong></td>
<td><strong>8505</strong></td>
</tr>
<tr>
<td>Calculated ballast water</td>
<td>394026</td>
<td>404</td>
</tr>
</tbody>
</table>

* Includes: bellows, bellows pipe, bench (Dixon’s), canteens (8), cask/barrel, compass box, copper plate, crank wall mounts, flywheel, gears, piping, pumps (aft and fore), ribbing, rudder control rods, shelf, and various tools
+ Includes: bellows pipe, bench (Dixon’s), canteens (8), cask/barrel, chain (primary), chain (spare), compass box, copper plate, crank wall mounts, flywheel, gears, piping, propeller, pumps (fore and aft), rudder, rudder control rods, shelf, and various tools
‡ Includes: central hull, bow and stern tapered hulls, bow and stern cast pieces, snorkel box and pipes, conning towers, cutwater, ribbing through hull/bow/stern (mass only), dive planes

The displaced water volume was calculated as 9.31 m$^3$, resulting in a required ballast water volume of 0.39 m$^3$. This ballast volume results in a net internal gas volume of 7.61 m$^3$. Figure 22 shows the calculated volume of ballast water.

![Figure 22: Cutaway side view of the HL Hunley model with calculated ballast levels. Crosshatching indicates water volume.](image)

A net internal volume of 7.61 m$^3$ (7613 L) with 21% oxygen provides 1599 L of oxygen at the moment the conning tower hatches are closed. All calculations were additionally performed assuming zero ballast water and full ballast tanks, which provided 1682 L and 1351 L of initial oxygen, respectively.

### 5.3.2 Gas Consumption

Equations 13 and 14 were used to calculate the estimated times until risk of hypoxia/hypercapnia for the upper and lower consumption levels as well as for the three initial oxygen volumes. Levels of oxygen and carbon dioxide were also calculated as functions of time. The results of these calculations are shown numerically in Table 9 and graphically in Figure 23.
Table 9. Calculated times (minutes) until risk of hypoxia and hypercapnia. Minimum, calculated, and maximum volumes represent 1351, 1599, and 1682 L of oxygen upon closing the hatches, respectively. Oxygen consumption rates indicate rates for the 7 working crewmembers, with Dixon consuming 1.5 L/min.

<table>
<thead>
<tr>
<th>VOL (L)</th>
<th>O₂ CONS. RATE (L/min)</th>
<th>Hypercapnia</th>
<th>Hypoxia</th>
<th>Candle Extinguish</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CO₂ 0.05 atm</td>
<td>CO₂ 0.07 atm</td>
<td>O₂ 0.063 atm</td>
</tr>
<tr>
<td>MIN</td>
<td>1.5</td>
<td>28 (minutes)</td>
<td>40 (min)</td>
<td>79 (min)</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>14</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>CALC</td>
<td>1.5</td>
<td>33</td>
<td>47</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>17</td>
<td>24</td>
<td>47</td>
</tr>
<tr>
<td>MAX</td>
<td>1.5</td>
<td>35</td>
<td>49</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>18</td>
<td>25</td>
<td>49</td>
</tr>
</tbody>
</table>
Figure 23: Levels of oxygen and carbon dioxide as functions of time, for two different rates of oxygen consumption for the working crew (A: 1.5 L/min, B: 3.2 L/min). Dixon’s oxygen consumption was held constant at 1.5 L/min. Calculations performed at the calculated, maximum, and minimum internal gas volumes of the vessel.
The predicted gas levels in Figure 23 are truncated where either hypoxia or hypercapnia would independently cause debilitating physiological symptoms that would force a reduction in activity level (pO$_2$<0.063 atm or pCO$_2$>0.07 atm).

William Alexander reported a time of 25 minutes before the candle flame spontaneously extinguished, with the crew submerged and cranking for a total of 2 hours 35 minutes before surfacing. The snorkel system was not in use since the test took place on the ocean floor (Alexander Sunday June 29, 1902). The above calculations show a range of possible times for the candle flame to be extinguished by hypoxia; they range from 11 to 27 minutes. At the calculated initial gas volume, the atmosphere would reach 17% and the candle would extinguish after 25 minutes if all crewmembers were consuming 1.5 L/min. After 25 minutes at this work rate the submarine atmosphere would be 3.7% CO$_2$. After the first 25 minutes, the crew would have had to reduce their oxygen consumption to 0.51-0.78 L/min to maintain oxygen supply for an additional 130 minutes (0.1-0.063 atm hypoxia cutoff values, respectively). These values are consistent with rest to mild activity; however, by the end of this time period the atmosphere would be 11.6-15.2% CO$_2$. Alternatively, matching the reported abort time of 2 hours 35 minutes would require a work rate of 0.196-0.275 L/min per crewmember (0.05-0.07 atm CO$_2$ cutoff values, respectively). If instead the crew maintained a constant work rate of 1.5 L/min, they would have definite symptoms of hypercapnia (pCO$_2$=0.07 atm) by 47
minutes after the start of the test, or 22 minutes after the candle would have extinguished.

5.4 Discussion

The crew of the Hunley was reportedly commanded to maintain the vessel at the surface and to refrain from submersion (Kloeppel 1987, Quinn-Smith 2009). This order was documented 14 years after the attack, and so, must be treated with some skepticism. However, assuming the order was given and followed, the conning tower hatches were above the water line during the attack and could have been opened at any time. If the crew did submerge, even with full ballast tanks there is a calculated minimum of 10 minutes between the onset of hypercapnia symptoms and the earliest possible onset of hypoxia sufficient to cause unconsciousness (Table 9). These calculations are more conservative if limited mixing occurred with the hatch open since CO$_2$ is slightly denser than air. The crucial result of this analysis is that hypoxia was not a likely risk for the crew of the Hunley before noticeable symptoms of hypercapnia would have occurred.

While hypoxia may go unnoticed, hypercapnia is impossible to ignore. Figure 23 clearly shows that CO$_2$ production becomes problematic long before hypoxia becomes a realistic concern, for all combinations of gas volume and oxygen consumption. Even with conservative calculations, the entire crew would have been experiencing noticeable hyperventilation, gasping for breath, choking, symptoms of panic, and possibly physical
pain a minimum of 10 minutes before any risk of loss of consciousness. It is not plausible that the crew would have ignored these strong symptoms and not attempted to open the hatches. Hypercapnia is not consistent with the evidence that the crew remained at their stations when the Hunley came to rest on the bottom.

This study and Haldane’s test are also both consistent with the scientific analysis of the atmosphere of the sunken submarine HMS Thetis (Alexander, Duff et al. 1939). Following the sinking of the Thetis, four crewmembers escaped and reported the measured atmospheric composition onboard the sub at the time of the escape. The remaining crewmembers did not survive. In an attempt to recreate the final moments of the submariners remaining on board, and to determine if they were killed by hypoxia or hypercapnia, British scientists enclosed themselves in a sealed chamber, wherein they had to rebreathe their own gas supply while remaining sedentary. Inside the chamber was a volume of 967 L/person (note that the internal hull volume of the Hunley was a calculated 952 L/person, a difference of less than 2% from the experiment). The scientists started with 6.1% carbon dioxide in the chamber, but only managed to rebreathe this gas mixture for 30 minutes before being forced to purge the chamber with air to lower the CO₂ levels. After another 30 minutes, all scientists were described as “panting severely,” despite the fact that oxygen levels had been maintained at a
physiologically comfortable level of no lower than approximately 18 percent (Alexander, Duff et al. 1939).

The description of the candle tests to determine air supply was written in a newspaper article in 1902, 38 years after the sinking of the vessel. Alexander reported that the candle extinguished 25 minutes after submergence, and that the crew remained submerged, cranking, and able to bring the submarine back to the surface after 2 hours and 35 minutes (Alexander Sunday June 29, 1902). Three scenarios were explored: 1) A constant work rate to match the reported abort time, 2) One work rate to match the candle time then a second rate to match the abort time, and 3) A constant work rate to match only the candle time. The oxygen consumption values required by these three scenarios are discussed above. However, assuming the first scenario, oxygen consumption rates of 0.196-0.275 L/min are unrealistically low for adult males as the oxygen required to maintain basal metabolic rate would be 0.22 L/min for the eight crewmembers (3.5 mL/min/kg, 502 kg total for all crewmembers) (Kwan, Woo et al. 2004). The second scenario is also not likely, as CO₂ percentages of 11.6-15.2% are well above tolerable levels and would have been intolerably painful if not incapacitating. The third scenario predicts an abort after 47 minutes, far shorter than the reported time.

No combination of gas consumption rates could be found that matched both the candle time and the abort time. Similarly, when the calculations were re-performed
using hypoxia as a driving factor in the decision to abort, no combination of gas consumption rates could explain both times. It seems most likely that, while the time until the loss of the candle flame may have been accurate, the report of 2 hours 35 minutes was either a deliberate exaggeration or an inaccurate estimate made many years after the actual experience. Indeed, Alexander’s account relates a test wherein all crewmembers, despite immersion in total darkness and a complete lack of communication, simultaneously and in unison declared the word “UP” to signal the end of the test (Alexander Sunday June 29, 1902). This unlikely degree of synchrony implies an idealized remembrance of the test.

The crew of the Hunley would have suffered symptomatic hypercapnia before any risk of hypoxia, and most likely would not have remained seated peacefully at their stations. High carbon dioxide levels have been shown to cause severe psychological discomfort and panic, in addition to the physical symptoms. They are impossible to willingly ignore, and they are impossible to sleep through. The theory that a crew of eight men voluntarily submitted to painful asphyxiation by hypercapnia in a cold, dark environment, without any attempt at escape, defies human nature. Upon raising the downed submarine S-51, submariner Swede Momsen remembered for decades “the horribly contorted faces and the flesh-shredded fingers of those in the S-51 who had not drowned immediately, who instead spent the final minutes of their lives trying to claw
their way out of a steel coffin.” (Maas 1999) This analysis suggests strongly that asphyxiation was not the probable cause of the sinking of the *H.L. Hunley*, and that the crew’s final moments were most likely, in the words of Warren Lasch, “quick and decisive.” (Hunley 2001)
6. Evaluation of the “Lucky Shot” Theory for the Sinking of the HL Hunley

This chapter is adapted from (Lance, Warder et al. 2016), with permission.

6.1 Introduction

Among the many discoveries made during excavation and conservation of the Hunley, archaeologists have discovered a large area of damage to the fore conning tower that, according to sediment analysis, likely occurred during or soon after the attack itself (Jacobsen, Blouin et al. 2012). The excavation also revealed a small piece of cast iron, shaped consistently with the edge of the undamaged porthole, buried near the bottom of the sediment below the fore conning tower (Jacobsen, Blouin et al. 2012). This location indicates that the porthole was damaged before or soon after the vessel sank, before settling to its final position on its starboard side. They also discovered that the eight men inside, responsible for navigating the vehicle and propelling it by hand crank, died while seated at their respective battle stations without switching the pumps to bilge out water, and without any signs of skeletal damage or apparent attempts to escape (FOTH 2008, FOTH April 16, 2001).
6.2 Methods

6.2.1 Ballistic Testing

To assess the plausibility of the principal hypothesis that the *Hunley* sank rapidly owing to a “lucky shot” that led to a large hole in the conning tower, a reproduction Civil War firearm was used to shoot Minié rounds at cast iron samples of different thicknesses. While vintage Civil War firearms can still be found, it is difficult to confirm their structural integrity and that they are safe to fire repeatedly. The replica was therefore used for safety reasons. Two thicknesses of cast iron samples were used as targets: 3.2 mm (1/8”) and 12.7 mm (1/2”). The firearm was a replica of an 1853 Enfield, firing 475-grain (30.8 g) Minié bullets using 60 grains (3.9 g) of FF grade black powder from a distance of 25 meters (27.3 yards). This distance was determined to be 25% closer than the minimum plausible distance between the guns and the *Hunley*, based on the structure of the *Housatonic* (USN 1874, Martin and Case 2011). While the Enfield was traditionally the firearm of the Confederacy, it was extremely similar in construction to the Springfield rifles used by the Union and also fired the same rounds with the same muzzle velocity (274-304 m/s); the difference from a terminal ballistics perspective is therefore not experimentally important (Dougherty and Eidt 2009, Burns 2012). The site of impact was filmed using high-speed photography, and videos have been posted as supplementary information.
6.2.2 Calculating the Sinking Rate

To calculate the possible rates of sinking of the Hunley after hull breaches of various sizes, a system of equations was established to describe the various forces acting on the vessel. This system of equations is shown in Table 10.

Table 10. Equations used to calculate the sinking motion of the Hunley. All units in m, kg, s. Simplifying assumptions are described in the text.

<table>
<thead>
<tr>
<th>Description</th>
<th>Equation</th>
<th>Eq. #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bernoulli’s equation</td>
<td>( v_{H2O}(t) = \sqrt{\frac{2}{\rho_{H2O}} \cdot [P_{H2O}(t) - P_{GAS}(t)]} )</td>
<td>(1)</td>
</tr>
<tr>
<td>Total volume of water entering the hull</td>
<td>( V_{H2O}(t) = \int_{0}^{t} A \cdot v_{H2O}(t) , dt )</td>
<td>(2)</td>
</tr>
<tr>
<td>Drag force on a cylinder</td>
<td>( F_d(t) = \frac{1}{2} \cdot C_d \cdot \rho_{H2O} \cdot v_{HUNLEY}^2(t) \cdot W )</td>
<td>(3)</td>
</tr>
<tr>
<td>Newton’s First Law</td>
<td>( a(t) = \frac{1}{m_{HUNLEY} + \rho_{H2O} \cdot V_{H2O}(t)} \left( -m_{HUNLEY} \cdot g + \rho_{H2O} \cdot g \cdot [V_{HUNLEY} - V_{H2O}(t)] + F_d(t) \right) )</td>
<td>(4)</td>
</tr>
<tr>
<td>Vertical distance traveled</td>
<td>( d(t) = \int_{0}^{t} v_{HUNLEY}(t) , dt )</td>
<td>(5)</td>
</tr>
<tr>
<td>Water pressure at the hull breach</td>
<td>( P_{H2O}(t) = P_{ATM} - 10069 \cdot d(t) )</td>
<td>(6)</td>
</tr>
<tr>
<td>Ideal gas law</td>
<td>( P_{GAS} = \frac{P_{ATM} \cdot V_{INT}}{V_{INT} - V_{H2O}} )</td>
<td>(7)</td>
</tr>
</tbody>
</table>
$A$ Surface area of the hull breach (1.96x10^{-3} or 2.14x10^{-2}$ m$^2$)

$a(t)$ Vertical acceleration of the vessel as it sinks

$C_d$ Drag coefficient on the cylinder (discussed below)

$d(t)$ Depth of the vertical center point on the conning tower

$F_d(t)$ Drag force on the sinking vessel

$m_{HUNLEY}$ Mass of the vessel (8,505 kg)

$P_{ATM}$ Atmospheric pressure (101,325 Pa)

$P_{GAS}(t)$ Pressure of the gas remaining inside the vessel

$P_{H2O}(t)$ Water pressure at the level of the hull breach

$\rho_{H2O}$ Density of sea water (1026.98 kg/m$^3$)

$V_{H2O}(t)$ Volume of water inside the vessel ($V_{H2O}(0)=0.39$ m$^3$ of ballast water)

$V_{HUNLEY}$ Total volume of the vessel (9.46 m$^3$)

$V_{INT}$ Starting internal gas volume of the vessel (7.61 m$^3$)

$v_{H2O}(t)$ Velocity of water entering the hull breach of the vessel

$v_{HUNLEY}(t)$ Vertical velocity of the vessel as it sinks

$W$ Width of the Hunley (1.22 m)

These equations were programmed into the computing software Matlab (Version R2015b, ©The Mathworks, Inc.) and integrated iteratively using Euler’s method with a time step of 0.01 seconds. To compute drag force, the vessel shape was approximated as a cylinder. Drag coefficient was also assumed to be constant at either the maximum or minimum possible value (1.0 and 0.5 respectively) for the relevant range of Reynold’s numbers.

Sinking times for two scenarios were assessed: the fastest plausible case and the slowest plausible case. The fastest case used the minimum drag coefficient (0.5) and assumed that the hull breach was instantly flooded over its full surface area. The surface area of the damage to the conning tower was measured to be $1.94 \times 10^{-2}$ m$^2$ plus the area
of the 2” diameter window (Figure 9). The slowest possible case used the maximum
drag coefficient (1.0) and a surface area of $1.96 \times 10^{-3} \text{ m}^2$ (surface area of just a broken 2”
diameter conning tower window, with no additional damage). The code specified that
should the internal gas pressure exceed the external water pressure, inward water flow
would stop. The slowest case was additionally varied so that the window gradually
filled with water starting at its lower edge rather than being instantly swamped
instantaneously over its full surface area.

To begin sinking via water intrusion, the *Hunley* would first have to sink
sufficiently that the theorized hull breach was at the water line. Using the 3D model
described in full detail in Ref. (Lance, Moon et al. 2016), the amount of water required to
sink the vessel to this level was calculated to be $0.78 \text{ m}^3$, equivalent to about double the
volume of ballast water in the vessel during the time of the attack. The conservation
efforts revealed that the rest of the hull was likely intact at the time of sinking and the
vessel first settled on the ocean floor in an upright position (Jacobsen, Blouin et al. 2012).

### 6.2.3 Tidal Analysis

To estimate the tidal currents in 1864, first modern tidal levels were found that
matched the tides at the time of the attack. Next, measured data of current speeds for the
modern tides were used to estimate the currents seen by the *Hunley* in 1864.
Charleston Harbor is a harmonic tidal station; therefore it is possible to accurately calculate the tidal levels surrounding the time of the attack on the *Housatonic* even though no measured data exist (Oceaneering International 2000, Chon and Mendelson 2014). The tidal levels for Charleston Harbor on February 17, 1864 were calculated using the National Oceanic and Atmospheric Administration's Center for Operational Oceanographic Products and Services (NOAA CO-OPS) website (station ID 8665530; location 32.7817, -79.925) (NOAA). Next, a modern date (February 21, 2013) was found with almost identical ($R^2=0.999$, see Figure 4 below) tidal levels and at a similar point in the lunar cycle; the tidal patterns were offset within the day by 33 minutes compared to the tides of February 17, 1864. The tidal current velocities had been measured and recorded on the 2013 date using tidal current stations downstream from the mouth of Charleston Harbor; these current velocities were obtained from the NOAA CO-OPS website for the station closest to the wreck site of the *Housatonic*: Charleston Harbor Fort Sumter Range, Buoy 8 (NOAA). This station is 1.57 km from the wreck site of the *Housatonic* along a compass heading 253.09° (Figure 7).

Since Buoy 8 is located more centrally relative to the mouth of Charleston Harbor, it receives more direct current flow from between the jetties at the harbor entrance. Based on the changes that have been made to Charleston Harbor and its entrance that would likely serve to alter the direction and substantially increase the
speed of the ebb tidal current, we assert that the currents measured in 2013 provide an extreme upper bound on the current speeds that could have moved the *Hunley* in 1864 following the attack. The recorded current patterns from the tides in 2013 were offset by 33 minutes to align them with the timing of the tides in 1864 during the *Hunley* attack.

The reconstructed current velocities were integrated starting at the time of the attack to provide estimates for the total distances the *Hunley* could have traveled. The travel distance was calculated for each of the calculated rates of sinking, and also until the time of the next slack tidal current. This calculation was also used to estimate the minimum length of time it would have taken for the vessel to travel the 310 m distance between the *Hunley* and *Housatonic* wreck sites without additional motive power (Conlin, Bell et al. 2005). It was assumed that the distance moved by the *Housatonic* following the attack was negligible compared to its final wreck site since it sank in less than three minutes (USN 1874).

6.3 **Results**

6.3.1 **Ballistic Testing**

The thinner 3.2 mm (1/8”) cast iron samples shattered into multiple pieces on impact. However, the rounds fully penetrated the 12.7 mm (1/2”) thick sample representative of the *Hunley* conning towers. The sites of penetration were only slightly
larger than the Minié rounds themselves, with indications of minor plastic deformation around the edges (Figure 24).

Figure 24: Cast iron samples after ballistic testing. The hemispherical thinner samples (a) fractured cleanly in a radial pattern, while the plate the same thickness of the Hunley’s conning towers (b) showed clean penetration by the Minié rounds and only minimal signs of fracture after repeated shots. The black dot illustrates the cross-sectional area of the rounds.
6.3.2 Sinking Rate of the Vessel

As discussed in the Methods, two cases were modeled: a fast case and a slow case, with some variations implemented in the slow case to assess the sensitivity of the model. The fast case, which modeled the full extent of the damage seen to the conning tower, indicated that the keel of the boat sank to a depth of 9 m (depth of the ocean floor at the wreck site) in 1 minute 42 seconds, while the slowest case computed a sinking time of 5 minutes 27 seconds. However, when the parameters of the slowest case were varied so that the broken window area filled gradually rather than being instantaneously swamped with water, the total sinking time increased to nearly 58 minutes.

6.3.3 Tidal Analysis

The tidal patterns for February 21, 2013 and February 17, 1864 are shown graphically as Figure 25 and the resultant tidal current speeds are shown as Figure 26.
Figure 25: Tidal patterns. The heights of the tides surrounding the Hunley’s attack on the *Housatonic* in 1864, as well as the tides on February 21, 2013. The tidal levels are almost identical in both magnitude and timing, with $R^2=0.999$.

Figure 26: Maximum possible speeds of the tidal currents occurring outside Charleston Harbor, overlaid with maximum possible distance traveled. Maximum distances are the current levels integrated with respect to time starting at the time of the attack. The extreme furthest distance that could have been traveled after the attack as a result of the tidal currents was calculated to be 1.57 km. Current speeds are negative to indicate outgoing tide.
Integrating starting at the 8:45 pm time of the attack allowed for an estimate of how far the vessel would travel as a result of the tidal currents. The vessel could have traveled 1.57 km before the time of the next slack tide, and it would have taken at least 14 minutes 30 seconds to travel the 310 m between the Hunley and Housatonic wreck sites. The “lucky shot” theory states that the Hunley started sinking immediately after it was hit by rifle fire during the attack. If the vessel began sinking immediately and sank over a period of 14 minutes 30 seconds, it would have been filling through a hole no more than 1.8 cm (0.7”) in diameter. However, for the fastest case, in the 1 minutes 42 seconds estimated time to sink, the vessel could have traveled at most 38 m based on modern current levels. For the slowest case, in the 5 minutes 27 seconds estimated time to sink the vessel could have traveled at most 119 m. A distance value was not computed for the slow case with gradual filling of the window area because, at nearly 58 minutes to sink, this case required more time than the relevant tidal cycle. The estimated maximum possible distance traveled is shown overlaid with current speeds as a function of time in Figure 26. Figure 27 shows the horizontal distances traveled for each case, with the actual distance between the wreck sites.
Figure 27. The calculated trajectories of the sinking submarine for the various cases. Calculated distances are maximums because of elevated current speeds in 2013 relative to 1864.

6.4 Discussion

The historical documentation of ballistic testing of cast iron shows similar results to the tests presented herein, with rounds either plastically denting or passing cleanly through the sample. Figure 28 shows an example of the results from two such ballistic tests. The test in part (a) used a cast iron plate of thickness 11.4 cm (4.5’’), which is thicker than the Hunley’s 12.7 mm (½’’) conning towers by a factor of L=9. The projectile mass of 32.2 kg (71 lbs), when divided accordingly by 9, results in a scaled mass of 44.3 grams. Standard Minié rounds weigh at most 34.0 grams (525 grain). Therefore, this plate was hit with projectiles 30% larger than the scaled projectiles used to target the Hunley, and fired by Whitworth cannons that use much higher muzzle velocities than rifles. However, this historical data suggest that even this increase in firepower was
insufficient to cause widespread damage of the type seen in the conserved conning tower. This historical test, which also produced small, clean penetrations through the target, therefore indicates that the 12.7 mm (½”) sample used to model the conning tower would likely need to be hit with a much larger projectile before it experienced extensive damage similar to the conning tower of the *Hunley*. It is therefore unlikely that the damage to the conning tower observed upon its raising was caused by arms fire from the crew of the *Housatonic*. 
Figure 28. Results from 1863 ballistic testing using cast iron targets (CSA, 1864). (a) The image states that this 4 ½” thick cast iron plate was shot multiple times with cast steel shot weight 71 lbs. Each circular site represents a separate test shot, with all sites showing plastic deformation or clean penetration by the projectile. (b) Historical photos from Confederate testing of cast iron plates, showing clean penetration or plastic deformation at the site of impact rather than large-scale shattering. The historical tests indicate that cast iron with the thickness of the conning tower would either be dented or penetrated cleanly by rifle fire, but likely would not have been shattered.

The 1864 tidal patterns are consistent with historical testimonies that the crew of the Hunley would have timed their departure with the outgoing tide to maximize their speed and minimize the required effort (Kloeppel 1987, Alexander Sunday June 29,
1902). They are also consistent with the testimony of the crew of the Housatonic, whose
reports stated that the tide was either “half ebb” (pgs. 587, 591) or “low water” (pg. 540),
with the tidal currents setting to the northeast (USN 1874).

The computed sinking rates of the vessel also show stark contrast with the main
assertion of the “lucky shot” theory that the Hunley began sinking during or
immediately after its attack. Assuming the Hunley began sinking immediately, none of
the calculated sinking times provide sufficient travel time for the Hunley to reach its final
resting location, even though the 2013 tidal current speeds are almost certainly higher
than those that occurred in 1864. If the conning tower was indeed broken by rifle fire, or
even if only a window was broken, and the vessel began to swamp immediately, it
would not have spent enough time subject to the tidal currents to reach the location at
which it was discovered in 1995. The hole size required for the vessel to start sinking
immediately and sink at a rate that would allow it to travel 310 m is a maximum 1.8 cm
(0.7”) diameter. However, this maximum hole size is still smaller than the holes in the
thick cast iron sample during the ballistic testing, which were 2.2 cm (0.9”) diameter and
larger.

Based on the results of this study, it seems unlikely that the crew survived the
attack on the Housatonic. The tidal currents and the rate of sinking indicate that the
submarine stayed afloat for some period of time following the attack, or alternatively
sank very gradually. When this study is combined with the archaeological evidence showing that the bilge pumps were not set to bilge water and the crew did not attempt to escape the vessel, it seems unlikely that they merely continued to crank as the interior of the vessel slowly filled with water (FOTH 2008).

The primary limitation to this study is the number of changes that have taken place at the Charleston Harbor entrance since 1864. These changes have most likely served to massively alter the flow of water out of the harbor during an outgoing tide. However, by using modern current levels, we can set the upper bound on the plausible distance the Hunley could have traveled as a result of tidal current.

It is impossible to verify identical composition of modern cast iron against the Hunley’s conning tower without taking a material sample, which would violate the legal regulations protecting this historic artifact. It is therefore possible that our modern tests vary in their response to the ballistic projectiles. However, the consistency of our results with the Confederate tests of armor plate indicate that the observed conning tower damage was most likely not the result of ballistic trauma, and even if ballistic trauma did occur the resultant rate of sinking is not consistent with the final location of the vessel.

The first known reference to the “lucky shot” theory was the testimony of the crew of the Housatonic in the Naval Court of Inquiry following its sinking. The theory
was revived in modern times by James Kloeppe in his seminal book on the \textit{Hunley}, written in 1987 (Kloeppel 1987). When these two documents were written, there was sufficient mystery shrouding the condition and location of the still-lost \textit{Hunley} that the theory was plausible and needed to be considered. However, given the modern discoveries unearthed during its excavation and conservation efforts, it seemed that the plausibility of the “lucky shot” theory should be re-evaluated. The calculations and experiments presented herein indicate that the vessel instead drifted with gradual intrusion of water until settling where it was discovered, and indicate that the “lucky shot” theory is improbable.
7. Blast Injuries Killed the Crew of the HL Hunley

7.1 Introduction

Since the two primary previous theories have been determined to be unlikely, are there other explanations for the mysterious sinking of the Hunley? One natural suspicion is that the 61.4 kg charge itself somehow caused the deaths of the crew, especially considering the modern blast fatalities in air and in water that leave the bodies externally intact, but destroy the lungs and brain (Bass, 2008, Bass, 2012, Lance, 2015, Lance, 2016). Common cinematic portrayals of blast (e.g. Swordfish, 2005) often misrepresent the relatively low levels of physical disruption necessary to kill from blast (Bass, Rafaels et al. 2008). This common misconception may have caused blast-related injuries to be overlooked as a possible causative mechanism for the deaths of the crew and the sinking of the HL Hunley. So, the hypothesis of this dissertation is that blast shock from the Hunley charge propagated through the water, through the hull, developing air shock waves on the interior of the hull. These air shock waves propagated into the interior of the submarine, killing or severely injuring the occupants from the internal airblast.

The hull of the submarine was found to be intact when it was raised. An intact hull would certainly protect the crew inside from a large portion of the torpedo’s effects. However, even if they do not rupture or permanently deform, structural walls flex and
bend at high frequencies when they are hit with a blast wave (HooFatt 1997). When the walls of a structure are rapidly flexed inward by the impact of an external blast, their motion can create a second shock wave propagating off the internal face (Anderson 2004, Peng, Zhang et al. 2011). This secondary or “backface” shock wave, if present, could potentially have immediately killed the crew of the Hunley or at least injured them sufficiently that they would have been unable to pilot their boat to safety.

A combination of methods was used to test this theory, since it was impractical to build a full-sized submarine and charges for experimentation. A scale model was blasted using both live charges and shock tubes underwater, the underwater behavior of black powder was investigated, and tests of shock wave propagation off the reverse of a metal plate were conducted in air. Cumulatively, the results from these tests allow us to evaluate the likelihood that the crew of the Hunley died from blast injuries to the lungs and brain despite being partially protected by the vessel’s hull.

7.2 Methods

7.2.1 Construction of the Scale Submarine Model

A 1/6 length-scaled model of the HL Hunley was constructed out of 16-gauge mild steel sheet metal, which is materially similar to the wrought iron of the submarine’s hull in many properties including those that dictate structural response to blast exposure (Table 1) (NCRE 1948, Hoo Fatt 1997, Jacobsen, Blouin et al. 2012).
Table 11. Material properties of wrought iron and mild steel. Mild steel is similar to wrought iron in the material properties most critical to accurate replication of the effects of blast transmission.

<table>
<thead>
<tr>
<th>Property</th>
<th>Wrought Iron</th>
<th>Mild Steel</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ($\rho$) (kg/m$^3$)</td>
<td>7,677 (Barker 1892)</td>
<td>7,833 (Mamalis 2001)</td>
<td>+2.0 %</td>
</tr>
<tr>
<td>Speed of sound (c) (m/s)</td>
<td>5,056 (Avadhanulu and Kshirsagar 1992)</td>
<td>5,050 (Avadhanulu and Kshirsagar 1992)</td>
<td>-0.1 %</td>
</tr>
<tr>
<td>Impedance ($z$) (kg/(m$^2$*s))</td>
<td>3.88 x 10$^7$</td>
<td>3.96 x 10$^7$</td>
<td>+2.1 %</td>
</tr>
<tr>
<td>Modulus of elasticity (E) (GPa)</td>
<td>196 (Barker 1892)</td>
<td>210 (Sarkar 2003)</td>
<td>+7.1 %</td>
</tr>
<tr>
<td>Bulk modulus ($\kappa$) (GPa)</td>
<td>160 (Parasnis 1986)</td>
<td>159 (Fragomeni and Venkatesan 2010)</td>
<td>-0.6 %</td>
</tr>
</tbody>
</table>

The key physical design properties of the original *Hunley* were incorporated in the scale model construction, including ballast tanks that could be filled with water and ballast weighting by lining the keel with lead. More information about the methods used to obtain the measurements of the *Hunley* that formed the basis of the scale model are presented Chapter 5.2.1, page 104. The finished model is shown in Figure 29.

Figure 29. Photograph of the scale *Hunley* model, nicknamed the *CSS Tiny*. [a] threaded attachment for spar [b] access port (2 total, one each at bow and stern) to fill and empty the ballast tanks, can be sealed with threaded insert [c] Rings (3 on model) for carrying the vessel and attaching lines [d] Gasket-sealed panel for interior access [e] Data ports (2 on model) for gauges [f] Bulkhead fittings (4 on model) for gauge wires
Steel spars were constructed to thread into the attachment point of the model (Figure 29, [a]). The spars were designed to place the charge at the same angle and scaled position relative to the vessel as the suspected position of the original Hunley torpedo. The Hunley model, nicknamed the CSS Tiny, was exposed to underwater blasts via three primary experimental methods: shock tube exposures, black powder charges attached to the bow with a size-scaled, angled spar, and black powder charges directed at the side of the hull.

7.2.2 Gauges and Data Processing

7.2.2.1 Acquisition and Filtration

For each blast test with the scale model, an omnidirectional incident pressure gauge was suspended in the center of the interior of the hull. An identical pressure gauge was also suspended in the water external to the boat, at the centerline along the length of the boat and at a 6 cm horizontal standoff from the side of the hull. The gauges used were oil-filled tourmaline gauges validated for measurement of underwater and air blasts (Naval Surface Warfare Center Carderock Division, Bethesda, MD), amplified with a PCB Piezotronics 402A amplifier and powered with PCB Piezotronics model 482A10 and model 482 power supplies (PCB Piezotronics, Inc., Depew, NY). The gauge cables were foam-covered and insulated along the length of the cable between the boat and the pier to protect against potential losses from water immersion. Data acquisition
was performed at a 1 MHz sample rate with 500 kHz antialiasing filters using a Hi-
Techniques MeDAQ Win600e (Hi-Techniques Inc., Madison, WI).

**7.2.2.2 Assessment of Pi Group Scaling**

The rate of pressure transmission into the scaled model hull was scaled to be
similar to the rate of pressure transmission into the full-sized *Hunley*. The dimensionless
analyses governing blast transmission are discussed further in the Background section
2.2.2, but the key pi groups dictating shock wave transmission into a structural wall are
repeated here for ease of reference.

\[
\varepsilon = \frac{\rho c}{mn \sin \varphi}
\]

Taylor, 1963

\[
\beta_s = \frac{\rho_s U_s t_i}{\rho_p h_p}
\]

(Kambouchev, Noels et al. 2006)

\( Q_s = \) mass density of the material in front of the structure
\( U_s = \) propagation speed of the incident blast wave
\( t_i = \) time constant of the incident blast wave (seconds)
\( Q_p = \) mass density of the structure
\( h_p = \) structural thickness
Wave propagation speed, mass densities, and geometry of the structure itself remained approximately constant between the scale model and the full-sized explosion; therefore, the remaining parameters were structural thickness and time constant of the incident blast wave. Some changes, such as the change in density from salt to fresh water, were experimentally unavoidable, but the effects are expected to be small (differences in density and bulk modulus increase the speed of sound in salt water 2-4% over that in freshwater). Since the blast impinges on the Hunley hull at an angle, the pi groups were multiplied by the sine of the angle between the direction of blast propagation and horizontal at the centerline of the keel (calculated to be 11°). The structural thickness was scaled by 1/6 during construction since Hopkinson scaling, often used for blast, suggests that the time constant of the incident blast wave should already scale by 1/6 with the scaling of the charge weight (Cole 1948, Kedrinskii 1972). This scaling is appropriate for a wide variety of low and high explosive types including black powder. (Cole 1948, Arons 1954, McGrath 1966, Bjørnø 1970). TNT has been validated to obey this principle for charge sizes ranging from 0.2 g to several hundred kilograms, demonstrating that the principle applies across a wide range of size scales (Arons 1954, Bjørnø and Levin 1976).

However, one of the most prominent lessons of the literature review prior to testing was that black powder can behave erratically in an experimental setting and can
sometimes perform inconsistently with expectations that were set by the behaviors of other explosive types (duPont 1969). Therefore, several underwater tests were conducted with variations in charge size, casing construction, and range to the point of measurement to assess black powder’s performance with respect to the scaling of time constant for the non-dimensional groups. Charge size was varied, with sizes of 283 g, 455 g, and 1 kg, and range between the charge and the point of measurement was varied between 80 cm and 1.8 m. The range values were selected to validate the scaling principles in the regions most relevant to have the scaled tests represent the *Hunley*. Charge size was limited to the 1 kg maximum size by the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) personnel assisting with this effort. Initial testing showed that orientation and position of the charge relative to the gauges had a measurable effect on the pressure waveforms. Therefore, test data were only used for this portion of the analysis if they had the same charge orientation and depth as the tests with the scale boat model, and gauge locations that would fall along the length of the submarine hull. In other words, because orientation and position of the charge relative to the gauge proved to have an effect in addition to the effect of range alone, data were eliminated from the scaling dataset if they were taken in a manner inconsistent with the exposures that would occur along the length of the *Hunley's* keel because it is possible that the effects of orientation could impact the time constants measured. The data that
were excluded were primarily from the tests of confinement strength because the charges and the gauges were positioned at the same depth for these tests, rather than at offset depths like the spar-mounted torpedo of the *Hunley*.

For conventional high explosives, underwater blasts decay exponentially for one time constant following the initial peak (Kedrinskii 1972). While black powder is not a conventional high explosive, the measured pressure waveforms still had initial decay rates that were exponential. The initial time constant of decay (θ) was measured for all blasts. Theta was scaled using Hopkinson scaling by division by the cube root of charge weight ($W^{1/3}$) (Eq (4), page 123). This value was then plotted as a function of the scaled distance ($W^{1/3}$/Range) at which the waveform was measured. A power law equation was fitted to the data using least-squares regression. This method is the standard procedure for describing the time-scaling behavior of explosives and is referred to as the principle of shock wave similitude (Cole 1948, Arons 1954).

### 7.2.3 Overview of Experiments to Test Blast Transmission

Transmission levels were measured with the scale boat model via two experimental methods: shock tube tests and live explosives tests in water. The shock tube tests were used to perform an initial characterization of the expected transmission levels, and to refine the experimental setup. These tests also provided additional data for transmission levels from blasts with longer time constants. The live explosives tests
evaluated the boat’s response to and transmission of exposures from black powder charges. Additional tests were performed with a thick steel plate in air to assess the plausibility of a sharp-rising shock wave propagating through a structure with at least the thickness of the full-sized Hunley. These tests were then evaluated in combination to assess the plausibility of the theory that the crew was injured or killed by airblast injuries.

7.2.4 Blasts Performed with Shock Tubes

A live charge creates spherically expanding shock waves, so because the Hunley’s spar held the torpedo at a downward angle the Hunley would have been directly exposed from along the entire length of its hull and keel. Since shock tubes create highly directional shock waves rather than spherical shock waves, the shock tube was used to characterize which sections of the hull were responsible for transmitting the effects of blast. Since preliminary tests showed that the bow of the vessel transmitted negligible blast effects into the main cabin, the transmission tests were performed by directing the shock tube at the bottom and side of the hull. The dimensions of the test site necessitated that for the driver section to be at a correct torpedo angle, it would need to be some distance from the boat model at the surface. The preliminary angled test therefore failed to achieve external pressure levels that were considered sufficiently high, and the tests
were conducted with the shock tube oriented perpendicularly towards the side of the vessel.

The shock tube exposures were performed in the Duke University Reclamation Pond. The shock tube was composed of a driver section only, made of standard size 3 high-pressure stainless steel pipe flanges, fitted with a variable number of Mylar membranes. When the driver section is pressurized via a fill port on the back, the Mylar membranes rupture, creating a shock wave in the direction that the driver is oriented.

The shock tube driver is shown in Figure 30.

Figure 30. Shock tube driver. Pressurization of the driver section leads to rupture of the Mylar membranes and creation of a shock wave in the direction of the blue arrow. This picture was taken after a test, and the ruptured membranes can be seen in the center of the opening. The fill port is on the reverse side. The ropes were used to raise and lower the driver into the water.
The shock tube driver was braced from behind with water-saturated wooden rails and was pressurized with helium to a pressure at which the Mylar membranes ruptured, creating a shock wave. The on-site experimental setup is shown in Figure 31, in the preliminary configuration used to test transmission through the bow of the boat.

![Figure 31. The experimental test setup in the Duke reclaimed water pond.](image)

[a] Scale boat model [b] Insulated gauge cables [c] Wooden brace rails [d] Approximate location of shock tube driver for this test. The wooden rails form the brace behind the driver section of the shock tube, which is fully submerged. The test configuration shown examined levels of propagation through only the bow of the scale model, with the shock tube driver aimed horizontally at the bow. For other configurations, the angle of the rails relative to vertical was altered, and the position of the model boat was altered.

The external pressures were estimated to be the perpendicular component of a blast with the correct direction of propagation, and so were divided by \( \sin(11^\circ) \) to calculate the overall peak pressure values of the estimated blast (Reid 1996).
7.2.5 Blasts Performed with Live Explosives

The test site for the live charges had a bottom depth slightly greater than the scaled value (9 m/6 = 1.3 m) of the bottom depth at the location of the Hunley attack on the Housatonic (USN 1864). This depth would ensure that reflections of the blast waveform off the bottom would be equal to or less than those experienced by the Hunley, and so would either approximate the amount of bottom reflection or err on the low side since bottom reflections can augment the strength of an underwater blast exposure (Cole 1948). A bathymetric map of the test site is shown in Figure 32, and a photograph of the test site is shown in Figure 33.

![Map of the test site for the live explosives. The black star indicates the location of the model Hunley during testing, and also the location of the isolated charges during preliminary testing. The line and square indicate the pier, shown in the photograph below. Map drawn to scale.](image-url)
Figure 33. Wide-angle photograph of the test site for live explosives testing.

All necessary permits and legal permissions were obtained prior to each round of testing. Charges were filled with 4Fg black powder (Goex Powder, Inc., Minden, LA) with casings constructed out of schedule 80 PVC pipe with threaded end caps. The historical drawing of the Hunley torpedo indicates that it was filled with grade FF cannon powder (see Figure 6, page 34). However, samples of powder from recently uncovered Union cannonballs from the Civil War indicate that the historic FF grain size may more accurately match the modern 4F grain-size standard for musket powder (Kosanke, Kosanke et al. 1995). Per Hopkinson scaling, the burn rate of the black powder should be increased by the length scale L (factor of 6) during the scale model experiments. An increase in burn rate up to a factor of 2 is achieved with smaller grain sizes, so the 4F powder was used to scale the burn rate as much as reasonably possible (Kosanke and Kosanke 2003, von Maltitz 2003). The inability to scale burn by the full factor of 6 would be a conservative change from the full-sized explosion, because it
would create lower peak pressures from the charge. The charges were triggered using NPb squibs (40 mg charge, Martinez Specialties, Groton, NY). Black powder charges of four sizes were constructed for use with the scale model: 283 g and 455 g charges, corresponding to 1/6 and 1/5 size scale of the 61.4 kg (135 lb) Hunley torpedo, 490 g charges, and 1 kg charges, which were the maximum size as requested by the ATF.

A preliminary round of testing was performed using 100 g black powder charges only, with no boat, to evaluate the performance of the charges and gather data without interference from nearby reflecting surfaces. Isolated squibs were also set off to evaluate their detonation signatures at the distances of interest, but were determined not to have a noticeable impact on the pressure waveforms. All charges for this preliminary series were oriented so that the cylindrical axis was horizontal and were set at a depth of 52 cm, equivalent to the calculated depth of the Hunley’s torpedo scaled by 1/6. This depth was calculated using the known spar length of 5.2 m (17’), downward spar angle of 68°, and estimated waterline depth of the vessel at its time of attack (Hicks and Kropf 2007, Lance, Moon et al. 2016). The gauges were positioned a horizontal distance between 80 cm and 1.8 m from the charges. These distances correspond to the distance between the torpedo and forward edge of the boat hull, and the distance between the torpedo and center of the keel respectively.
The scaled submarine model was blasted with black powder charges of three different sizes: 283 g, 455 g, and 1 kg. While 283 g is the mass-scaled value for black powder, the larger charge sizes were constructed to evaluate the efficacy of propagation of larger blast sizes through the hull wall. Experimental limitations on scaling burn rate and construction of strongly confined casings make the 283 g charges underestimate the strength of the exposure from the original torpedo; larger charges were therefore also tested to evaluate how the transmission properties changed with appropriately scaled external pressure applied to the hull without having to scale the charge-related propagation to from the blast to the hull.

All charges except one were attached via a size-scaled spar to position them in the same manner as the Hunley’s charge. The final charge was positioned beside the boat to simulate a higher-strength charge, like the methods explained in section 7.2.3 with the perpendicular shock tube tests. This charge had a direction of propagation perpendicular to the hull of the boat; therefore, the measured pressure in the water is comparable to the perpendicular component of a shock wave traveling outward from the location of the spar-mounted charge. Since the parallel component of such a shock wave is not expected to contribute to the transmission, division by the sine of the angle (11°) calculates the total external peak pressure from a spar-mounted charge that would have the same amount of propagation through the hull. This angular correction for
direction of transmission is often used in structural shock testing for charges in different geometric orientations from their targets (Reid 1996).

7.2.6 Analyzing the Data from the Shock Tube and Live Explosives Tests

The goal of these tests was to measure the amount of blast transmission through the hull of the scale model and therefore through the hull of the Hunley. As discussed in the Background, degree of impulse transmission into an air-backed metal barrier has been well studied experimentally and computationally and is a function of known pi groups (Eq (7) & Eq (1)) (Kambouchev, Noels et al. 2006, Kambouchev, Noels et al. 2007, Peng, Zhang et al. 2011, Grujicic, Snipes et al. 2013). However, none of these previous analyses have attempted to extend beyond the structure wall and assess the pressures on the inside of the vessel.

The time constant of decay was determined using the measured in-water waveforms and was used to calculate the value of the Kambouchev et al pi group ($\beta$) for each test (Kambouchev, Noels et al. 2006). Incident peak pressure was similarly measured off each in-water waveform. The peak pressures of the tests with spar-mounted charges were multiplied by $\sin(11^\circ)$ to calculate the pressure level that was directed perpendicular to the hull of the model from the charge (Reid 1996). The peak pressures of shock tubes tests and the perpendicular live charge test were not adjusted because these tests already measured the perpendicular component of the blast
transmission. The peak pressures were also measured from the waveforms internal to the boat. Tests of blast injury within an enclosed environment have shown that the magnitude of peak pressure of a complex, non-ideal waveform with a locally rapid rise time is associated with injury risk, regardless of when during the waveform that peak occurs (Richmond, Damon et al. 1968, Bass, Rafael et al. 2008). Therefore, the internal boat peak pressure was determined to be the peak pressure of the waveform that was achieved via a rapid (<1 ms) rise time.

Previous groups examining blast transmission into a structure have analyzed the ratio of impulse transmitted to the structure relative to the incident external impulse and developed empirical curves to describe the observed pattern of behavior (Figure 34).

![Figure 34. Ratio of transmitted to incident impulse for structures impacted by a shock wave, calculated from Ref (Kambouchev, Noels et al. 2007). The curves shift towards more positive values with increase ratio of incident shock wave pressure to ambient pressure (Ps/P0).](image-url)
It is important to note that the percentage transmitted shifts towards more positive values with an increase in the ratio of incident shock pressure to ambient pressure ($P_s/P_0$). In other words, an increase in external pressure also results in an increase in the percentage of that pressure that is transmitted. The results from the transmission tests were grouped per the value of their exposure ratio ($P_s/P_0$): one group with values ranging 1-2 (mean 1.2) and a second group with values ranging 3-5 (mean 3.4). There was insufficient data to conclusively characterize how much the transmission curve for peak pressure shifted upward with increasing values of $P_s/P_0$. Curves of the empirical shape described by Kambouchev et al. (Equations (16) & (17)) were fit to the two separate groups in Matlab using sum of squared error (MATLAB v. R2016b, MathWorks, Natick, MA) (Kambouchev, Noels et al. 2007).

\begin{align*}
\text{Eq (16)} \quad \frac{\text{Transmitted}}{\text{Incident}} &= a(\beta/\pi)^{\beta/(1-\beta)} \\
&= a(\beta) \, b^{\beta/(1-\beta)} \\
\beta &= \pi \text{ group value} \\
a &= \text{constant calculated using Eq (16)} \\
b &= \text{constant found using curvefit}
\end{align*}

\begin{align*}
\text{Eq (17)} \quad a &= 8 - 42 \frac{P_0}{P_s} \ln \left( 1 + \frac{P_s}{7P_0} \right) \\
&= 8 - 42 \frac{P_0}{P_s} \ln \left( 1 + \frac{P_s}{7P_0} \right) \\
P_s &= \text{Incident shock peak pressure} \\
P_0 &= \text{Ambient pressure}
\end{align*}

The original equations published by Kambouchev et al. provide analytical equations to calculate $b$; however, these analytical equations are based on the
assumptions that the shock wave impacts a flat plate in air and therefore cannot be
directly applied to the *Hunley* experiments. Instead, the constants were fit to the
experimental data to more accurately reflect the complex geometry of the *Hunley* hull.

The tests discussed herein exposed the scale model to charge amplitudes, and
therefore $P_s/P_0$ ratios, smaller than those estimated to have occurred from the full-sized
*Hunley*. Therefore, the lower bound of possible percent transmission was estimated to be
the smallest value observed during experimental testing, and the actual percent
transmitted was obtained from the curve fit to the group with $P_s/P_0$ values ranging from
3-5. The upper confidence interval from this group was used as an upper bound on the
calculations. Shock Tube Blasts of a Thick Metal Plate in Air

While it is known that that blast-induced pressures impinging on structures can
propagate through structures (Grujicic, Snipes et al. 2013), there is no extant data for
transmission at peak pressures, initial rise time and durations similar to those
experienced by the Hunley through material that is similar to the Hunley construction.
Especially important is determination of whether sharp-rising pressure shock waves can
propagate from the interior surface following sharp rising input on the exterior surface.
Such shock waves have the potential for causing injury or fatalities without overt
external disruption of the body (cf. (Bass, Rafaels et al. 2008, Lance, Capehart et al.
2015)). So, shock pressure propagation through the Hunley structure was investigated
using a mild steel plate with greater thickness (1.6 cm, 5/8”) than the original *Hunley* hull (1.0 cm, 3/8”). The steel plate was a square 61 cm (24”) on each side and was exposed to airblast using a helium-driven shock tube. The shock tube was 30.5 cm (12”) in diameter and was aimed at the center of the plate. A standoff distance of 4 cm was set between the plate and the end of the tube to allow lateral venting of the shock and provide reduced impulse on the plate relative to peak incident pressure. Incident pressure was measured at the end of the shock tube using 200 psia Endevco pressure gauges (Model 8530B-200, Meggitt Sensing Systems, Irvine, CA) that were flush with the internal wall of the tube body. Two additional Endevco pressure gauges were rigidly fixed behind the center of the steel plate, with 10 cm between the back of the plate and the center of the gauge faces. Both gauges were oriented to measure incident pressure. The wall was 20 cm behind the gauges (30 cm total behind plate) and padded with anechoic foam. The experimental test setup is shown in Figure 35.
Figure 35. Experimental test setup for the plate blasts in air. Only the end of the shock tube is visible. Gauges were threaded in to the end of the shock tube (not pictured), and also positioned behind the plate. The wall behind the plate is padded with anechoic foam.

The magnitude of the peak overpressure produced by a shock tube can be adjusted by varying the thickness and number of the mylar rupture membranes at the front of the driver section (see Figure 30, page 147). This shock tube test was performed at two different membrane thicknesses (70 mm and 140 mm) to expose the plate to two different pressure levels. Two repetitions were considered sufficient because the goal of this test was to demonstrate that a shock wave with a sharp rise time could propagate behind a thick metal structure; the data from the two repetitions showed a sharp rise
time, so further characterization of the propagation was not considered necessary for the purposes of this project.

### 7.2.7 Assessment of Risk of Injury or Fatality for the Crew

The internal pressure waveforms were expected to be complex because of the transmission through the hull wall and the multiple reflections that were expected to occur within the enclosed volume. Complex waveforms show multiple peaks over their duration, rather than the single peak and smooth decay of a Friedlander waveform. The elevated pressure levels from black powder explosions are generally expected to have a duration that is long compared to air blasts from high explosives such as TNT (Panzer, Wood et al. 2014). Using Hopkinson scaling, the durations in the scale model must multiplied by a factor of 6 following the initial peak to represent the durations of the full-scale Hunley. Therefore, the injury assessments used in this dissertation will be derived from airblast risk assessment with long durations (e.g. Panzer, 2012).

The blast exposure inside the vessel hull was primarily the product of flexion of the walls, per the theoretical analyses (HooFatt 1997, Peng, Zhang et al. 2011). It was therefore estimated that the direction of airblast propagation was perpendicular and inward from the surface of the vessel hull. The positions of the crew and estimated direction of blast propagation are shown in Figure 36.
Figure 36. Position of the *Hunley* crew inside the vessel, with arrows indicating estimated direction of blast propagation. The hull was approximately cylindrical in shape, with a diameter of only 1.2 m. The mean height of the crew was 1.76 m (5’9.4”), forcing them to hunch over within the close quarters to turn the crank that powered the propeller.

The injury risk assessment from Panzer et al, 2012 for pulmonary fatality and injury is the most appropriate because it has the largest body of experimental backing and specifically evaluates long-duration airblasts (Panzer, Bass et al. 2012). The crewmen of the *Hunley* were pressed against the curved inside wall of the vessel; however, previous analyses have shown that the presence of a reflecting surface does not significantly increase injury risk, contrary to the results of some preliminary studies (Rafaels, Bass et al. 2010). The analysis by Panzer et al. defined long-duration blasts as
those with durations lasting longer than 10-30 ms. They and others concluded that for this blast exposure type, injury risk is primarily determined by peak overpressure and has little duration dependence (Bowen, Fletcher et al. 1966, Bowen, Fletcher et al. 1968, Panzer, Bass et al. 2012). The durations for the complex waveform types seen inside the vessel hull are difficult to conclusively measure, but previous work examining blast in enclosed spaces has determined that these complex waveforms are equivalent to a “quasi-static pressure increase” that injures comparably to a long-duration blast with the same peak overpressure value (Johnson, Yelverton et al. 1993). Therefore, the duration for Hunley exposures was conservatively estimated to be 30 ms for the risk assessments developed by Panzer et al. The waveforms seen experimentally showed durations of at least 10 ms for all tests; with scaling, this is equivalent to a duration of at least 60 ms for the Hunley crew. Longer durations would have a higher associated risk. While this is a conservative assumption, the relative insensitivity of risk level to exact duration value for long-duration blasts also means that the results change little if a longer-duration assumption was made.

7.2.8 **Analysis Using TNT Equivalency**

Risk curves for airblast typically assume an ideal Friedlander waveform, and while they can be applied to complex exposure types like those measured inside the scale model (Johnson, Yelverton et al. 1993), they are more conventionally used for
exposures with simply characterized peak pressure and durations (Bowen, Fletcher et al. 1966, Bowen, Fletcher et al. 1968, Bass, Rafaels et al. 2008, Rafaels, Bass et al. 2010, Rafaels, Bass et al. 2011, Panzer, Bass et al. 2012, Rafaels, Bass et al. 2012). So, the risk of injury and fatality were estimated using two related but independent methods. A diagram of the methods is shown as Figure 37 for clarity, in addition to being described in the text.

**Figure 37.** Diagram of the Hunley and charge, illustrating the steps of the analyses using relative equivalency (not to scale). Analysis was performed both starting with known black powder equivalencies and calculating risk to the crew, and also by starting with the minimum internal pressure required to cause fatality and calculating necessary TNT equivalency.

Previous studies have shown that though black powder deflagrates rather than detonates, when it is used in confined casings, high explosive scaling laws (TNT scaling) accurately predict charge output (Dobashi, Kawamura et al. 2011). While the relative equivalency (RE) for black powder can vary based on exact experimental setup and level of charge confinement, values in the literature for confined black powder were found to be within the range of 0.24-0.46 (median value 0.43) (Napadensky and Swatosh 1972,
Cooper 1994, Crocker 1998). The range of equivalency values were applied to the known Hunley charge weight of 61.4 kg to calculate the range of estimated equivalent charge weights of TNT. Hopkinson scaling laws were then used to calculate the peak pressure resulting from such a blast at the central point of the vessel’s hull (range R= 10.8 m). The peak pressure was multiplied by the sine of the angle between the direction of blast transmission and horizontal (11°) to determine the component perpendicular to the surface of the keel (Reid 1996). The experimentally determined transmission percentages described in section 7.2.6 were used to calculate the peak pressure that would have been transmitted to the interior crew cabin. This peak pressure was then used, with a duration estimate of 30 ms, to calculate the risks of injury and fatality to the crew (Panzer, Bass et al. 2012).

The second method of analysis performed the same steps but in reverse to calculate the minimum required equivalency necessary for the crew to avoid injury or fatality. Risk was calculated as a function of peak overpressure for a 30 ms duration blast using the curves from Panzer et al. The experimentally determined percent transmission levels were then used to calculate the peak pressures required of the external blast exposure for sufficient transmission to cause those levels of risk. This external blast exposure was assumed to be the component perpendicular to the hull, and was therefore divided by an angular correction factor (sin(11°)) to calculate the total pressure. The required total
external peak pressure levels were used with Hopkinson scaling to calculate the weight of TNT that would create those pressures in water at the distance of the center of the Hunley’s keel (Eq (2), page 123). Dividing the required TNT charge weight by the known weight of the Hunley’s black powder charge resulted in the minimum TNT relative equivalency that would be necessary for the black powder to produce at least that level of airblast exposure inside the Hunley (Eq 1, page 155). Calculated relative equivalencies that were atypically low compared to the measured values for black powder could then be considered to support the theory that the Hunley torpedo created a blast wave at least strong enough to cause injury and fatality to the crew inside.

7.3 Results

7.3.1 Preliminary Tests of Charge Orientation and Construction

Preliminary tests showed that the charge output was dependent on charge orientation (Figure 38).
Figure 38. Output of two identically constructed 490 g charges, measured at different positions relative to the longitudinal axis of the charge. The line measured from the end represents output as measured from the correct location of the bow of the Hunley. Output from the side is measured from the side of the long axis of the charge.

Testing also indicated that charge output was highly dependent on degree of confinement and strength of the shell casing, as shown in Figure 39. However, the exact methods of confining the charges and strengthening the casings has been omitted from this dissertation at the request of the ATF.
Tests were performed at four charge sizes (283 g, 455 g, 490 g, 1 kg) and two different ranges (0.8 and 1.8 m). Representative curves of the initial shock waves from two different charge sizes are shown as Figure 40. The waveforms of the remaining data used for this section of the analysis are shown in Appendix A, Figure A1.
Figure 40. Representative curves of initial shock wave from black powder charges of two sizes. The red circle indicates the peak of the shock wave, and the green circle indicates one time constant of decay. The 1 kg charge was at a range of 1.8 m with a time constant of 265 µsec ($\theta/W^{1/3}=477, W^{1/3}/R=0.556$). The 490 g charge was at a range of 0.8 m with a time constant of 408 µsec ($\theta/W^{1/3}=414, W^{1/3}/R=0.99$).

The scaled time constants ($\theta/W^{1/3}$) are shown plotted against scaled distance ($W^{1/3}/R$) in Figure 41.
Figure 41. Scaled time constant as a function of scaled distance. The data for black powder show the power law trend consistent with other known explosive types.

The resulting curvefit equation is shown below as Equation (18). The equation showed an $R^2 = 0.78$ fit with the data.

$$\frac{\theta}{W^{1/3}} = 361.4 \left(\frac{W^{1/3}}{R}\right)^{-1.053}$$

\(\theta = \) time constant of initial decay (\(\mu\text{sec}\))
\(W = \) charge weight (kg)
\(R = \) distance from charge (m)

The values of the pi groups for both the scale model and the full-sized *Hunley* explosion are calculated below. Speed of the blast wave was not directly measured and has been estimated as the speed of sound in water. The scaled model shows a decrease from the full-size *Hunley* explosion of 6.5% in the Taylor pi group value (Eq (7)) and
2.8% in the Kambouchev et al pi group value (Eq (1)) (Taylor 1963, Kambouchev, Noels et al. 2006).

Table 12. Values for pi groups that determine blast transmission. Water temperatures were measured at 13° C for the scaled experiment, and estimated as 10° C for the Hunley explosion. 10° C is the mean temperature outside Charleston Harbor in February (NOAA 2016). Material values from Table 11.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Scaled Experiment</th>
<th>Full-Sized Hunley Explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho, \rho_s ) = density of medium in front of the structure (kg/m(^3))</td>
<td>1000</td>
<td>1026 (Karleskint, Turner et al. 2012)</td>
</tr>
<tr>
<td>( c ) = speed of sound in medium in front of the structure (m/s)</td>
<td>1498 (CRC 1968)</td>
<td>1531 (CRC 1968)</td>
</tr>
<tr>
<td>( m ) = areal density of the structure (kg/m(^2))</td>
<td>12.4 (scales with L)</td>
<td>73.1</td>
</tr>
<tr>
<td>( n ) = inverse time constant of decay of the blast wave (1/seconds)</td>
<td>1.85 e +3 (Calculated using Eq (1))</td>
<td>3.07 e +2 (Calculated using Eq (1))</td>
</tr>
<tr>
<td>( \phi ) = angle of the structure surface, if conical</td>
<td>90°</td>
<td>90°</td>
</tr>
<tr>
<td>( U_s ) = propagation speed of the incident blast wave</td>
<td>1498 (approximated as speed of sound)</td>
<td>1531 (approximated as speed of sound)</td>
</tr>
<tr>
<td>( t_i ) = time constant of the incident blast wave (seconds)</td>
<td>5.42 e -4 (Calculated using Eq (1))</td>
<td>3.25 e -3 (Calculated using Eq (1))</td>
</tr>
<tr>
<td>( \rho_p ) = mass density of the structure (kg/m(^3))</td>
<td>7677</td>
<td>7833</td>
</tr>
<tr>
<td>( h_p ) = structural thickness (m)</td>
<td>1.59 e -3 (1/16”)</td>
<td>9.53 e -3 (3/8”)</td>
</tr>
<tr>
<td>Taylor pi group value</td>
<td>82.6</td>
<td>88.4</td>
</tr>
<tr>
<td>Kambouchev pi group value</td>
<td>84.3</td>
<td>86.7</td>
</tr>
</tbody>
</table>
7.3.3 Shock Tube Tests in Water

The data from the test assessing transmission through the bow of the boat (test setup depicted in Figure 31) are shown in Figure 42. Little to no discernible transmission was observed for tests in this orientation with this level of shock impingement.

![Graph showing pressure over time](image)

**Figure 42.** Data from shock tube test evaluating transmission through the bow of the boat. Little to no internal shock wave is observed.

A representative waveform showing transmission through the side of the boat are shown as Figure 43. Additional waveforms for the remaining shock tube tests are shown in Appendix A, Figure A2.
Figure 43. Representative waveform showing transmission into the scale model. This test had a shock tube orientation perpendicular to the side of the scale model. [a] Waveform in water [b] Waveform inside the boat hull

Peak pressures and time constants were evaluated for these tests. However, the shock tube does not have the same time constant of decay or waveform shape as the black powder charges. These waveforms are therefore not comparable to the full-sized Hunley explosion, but still provide an additional range of data for the overall analysis of transmission.
7.3.4 Live Explosives Tests with the Scale Model

A waveform for a test of blast transmission into the hull of the scaled boat from a 1 kg charge at the spar position is shown as Figure 44.

![Graphs of blast transmission and peak pressure](image)

**Figure 44.** Blast transmission into the model hull of 1 kg charge on a spar. The red circle indicates the selected point of peak pressure with less than 1 ms local rise time.

The peak pressure of the external waveform was 117 kPa (17.0 psi), which was calculated to have a perpendicular component of 22.3 kPa after multiplication by...
\(\sin(11^\circ)\). The peak pressure of the internal waveform was determined to be 3.41 kPa (0.49 psi), resulting in a calculated 15.3% transmission. The waveform from the test with the 283 g charge oriented at the side of the hull is shown as Figure 45.

![Pressure in water and inside scale model](image)

**Figure 45.** Blast waveforms from 283 g charge oriented at the side of the hull. The red circle indicates the point determined to be the peak pressure. The in-water waveform shows a secondary peak \((t = 0.75 \text{ ms})\) from the reflection back off the hull of the scale model.
The external pressure from this test was measured as 336 kPa (49 psi). The internal pressure was measured as 16.03 kPa (2.32 psi), resulting in a 4.8% transmission. The secondary peak in the data (t= 1 ms, amplitude 831 kPa) coincides with the calculated delay time for the shock wave to bounce off the model hull and return to the in-water gauge. Additional waveforms showing transmission from the remaining live charge tests are shown as Figure A3.

7.3.5 Metal Plate in Air

The blasts of the metal plate showed clear transmission of a shock wave with a sharp rise time at both pressure levels of exposure. The waveforms are shown in Figure 46.
Figure 46. Waveforms transmitted through the 1.6 cm (5/8”) thick mild steel plate. Shock tube waveforms have been overlaid with the ‘external’ incident pressure Friedlander curves produced by these shock tubes in this configuration without the reflection from the steel plate. Gauge 1 in the 140 mil tests was dislodged during the test and shows some spike-shaped anomalies.

The incident pressure gauges positioned in the shock tube also measured a clear secondary peak that is a reflection off the steel plate back into the tube. These shock tubes have previously been extensively characterized and produce repeatable, uniform Friedlander curves across the mouth of the tube [CITE BASS 2008]. The durations of the Friedlander curves from the characterization data for this tube configuration have therefore been overlaid on the measured curve to provide information about the wave actually produced by the tube itself without the reflection back into the gauges.
The 70 mil test yielded a peak pressure at the end of the shock tube of 380 kPa (55.1 psi) and a peak behind the plate of 22.5 kPa (3.3 psi). The 140 mil test yielded a peak pressure at the end of the tube of 681 kPa (98.8 psi) and a peak behind the plate of 30.5 kPa (4.4 psi). It is important to note when calculating percent transmission that some decay also occurs in the distance between the tube and the plate, and also between the plate and the gauges; the decay between the tube and the plate has been characterized by previous tests but the decay between the plate and the gauges is unquantified (Rafaels, Bass et al. 2012). However, it is less accurate to measure the pressures directly on the surface of the plate because the fluid-structure interaction that causes the flexion of the plate largely reduces the peak pressures seen directly at the surface (HooFatt 1997, Peng, Zhang et al. 2011, Grujicic, Snipes et al. 2013). With that limitation in mind, the percent transmitted from the 70 mil test was 5.9%, and 4.5% from the 140 mil test. Most importantly, both tests showed a clear and definite pressure increase with a sharp rise time.

7.3.6 Analyzing the Data from the Shock Tube and Live Explosives Tests

The group with pressure ratio $P_s/P_0= 1.2$ had curve fit values of $a= 2.46$, $b= 0.79$; group $P_sP_0= 3.4$ had values of $a= 3.11$, $b=4.28$. The curves are shown in Figure 47.
Figure 47. Ratio of peak pressure propagating through the wall. Curves drawn using the methods established by Kambouchev et al. to describe ratio of impulse transmitted (Kambouchev, Noels et al. 2006, Kambouchev, Noels et al. 2007). Dashed lines show 95% confidence intervals. The red line indicates the $\beta$ value calculated for the Hunley explosion.

The $P_s/P_0=3.4$ group yielded a 14.3% transmission level; this value was used as the calculated transmission rate that occurred during the Hunley explosion. However, the value is still lower than anticipated during the 1864 blast because the $P_s/P_0$ ratio would have been higher than 3.4, therefore both the level of exposure and the rate of transmission would be higher. The upper confidence interval for the $P_s/P_0=3.4$ fit curve was used as the upper range for the transmission estimate for the Hunley (18.0%), and
the lower confidence interval was used as the lower range for transmission (10.7%). The values of $a$ were calculated using an analytical equation that was developed based on assumptions about a flat-plate geometry; however, variation of the $a$ values within a factor of 20 showed a change in the calculated percent transmissions by less than 0.4%.

7.3.7 Analysis of TNT Equivalency and Risk of Injury and Fatality

The results of the calculations relating TNT equivalency to fatality are shown graphically in Figure 48.
Figure 48. Risk fatality for a range of TNT relative equivalencies and transmission levels. The Hunley exposure was estimated using a 14.3% transmission level and RE=0.46, the median value found in the literature. This exposure is a low estimate because 14.3% was the transmission occurring at the low experimental overpressure ratio of 3.4, and rate of transmission would continue to increase up to the Ps/P0=66 expected of the full-sized explosion.

The lower bound of experimentally measured black powder equivalencies (0.24) results in a calculated 9.8 MPa exposure outside the hull, 267 kPa inside the hull, and 98% risk of fatality from airblast at the calculated 14.3% transmission level. There is a calculated 90% or higher risk of fatality for the full range of RE values and
experimentally determined transmission percentages. Performing the analysis from the reverse direction concludes that with the calculated 14.3% transmission level, an RE of 0.05 or lower is required for less than a 50% chance of fatality to the crew; this value is an order of magnitude lower than realistic values for even “weak” modern explosives (Cooper 1996).

7.4 Discussion

7.4.1 Preliminary Tests

The results of the scaling tests indicate that the time constant of decay scales per Hopkinson scaling laws. Therefore, the scaled charges used in the live explosives experiments should produce waveforms that are comparable to the pressures produced by full-sized, similarly constructed charges at correctly scaled distances. The charges also produce waveforms with rates of decay that are scaled in time by the length scale L.

The black powder charges used were calculated to be underpowered compared to the estimated output of the Hunley’s torpedo. Preliminary tests with various casing types confirmed that the strength of the blast wave produced by black powder is sensitive to the strength of the external casing within which the powder is confined. This result is consistent with the known performance characteristics of deflagrating low explosives where gaseous product is produced within the casing more slowly than in
the detonations of high explosives subsequently increasing the internal pressure until
the shell reaches a failure point (Brown and Collins 1967). Unconfined or poorly
confined black powder deflagrates slowly enough that it generally does not produce a
shock wave on shell failure. The presence of shock waves in the underwater
experimental data indicates that the peak pressures achieved were the result of the
sudden failure of the casings and the subsequent detonation-like release of the gaseous
products (Kosanke and Kosanke 2003). Therefore, it is unlikely that the burn rate of the
black powder played a critical role in determining the pressure output, and that the
pressure output was instead dependent upon the strength of the charge casing. Analysis
of the pi groups governing casing deformation indicated that, to reproduce the peak
pressures of the original torpedo, the charge shell for the small-scale charges should be
constructed of copper with the same thickness as the Hunley’s original torpedo
(Hoffman and Hong 2006). However, copper charges of this thickness pose shrapnel
corns for our test location, and were therefore not pursued experimentally.

Historical data of black powder manufactured during the late 1800s showed that
a 61.4 kg black powder charge, when confined, reached a peak internal pressure of
167,000 kPa (24,200 psi) (duPont). The transmission of only 336 kPa into the water near
the charge indicates it is highly unlikely that the modern experimental charges reached
this better-confined value of 167,000 kPa. Conservation of the Hunley’s spar clearly
revealed that the copper torpedo shell was forced backwards in ribbons over the end of the spar, indicating that the copper casing had fully confined the black powder charge to cause a uniform explosion (Figure 8, page 40).

Therefore, it is likely that the charges used output peak pressure values lower than the pressures produced by the *Hunley’s* charge, potentially by up to a factor of 64 based on the 2.6 MPa rated failure pressure of the construction materials (Workman 2011). US Navy testing of a full-sized black powder charge designed to measure the output of the *Hunley’s* torpedo showed peak pressure values of approximately 7,600 kPa (1,100 psi) at a measurement location comparable to the keel of the *Hunley*. This pressure is an increase of a factor of 43 over the maximum 176 kPa peak pressure measured along the vessel hull of the scale model from spar-mounted charges, confirming that the charges used for the blast tests with the scaled model were less strongly confined in comparison to the copper charge of the full-sized *Hunley*.

### 7.4.2 Experimental Results and Risk Assessments

The results from the shock tube and live charge tests show that the transmission behavior of peak pressure is consistent with the behavior of the transmission of impulse. The ratios of transmitted peak pressures show that the charge of the *Hunley* could transmit sufficient blast levels inside the vessel to cause a high risk of injury and fatality to the crew. It is important to note that the gauges used measured incident pressure, but
were omnidirectional and therefore do not provide information on direction of propagation; the perpendicularly is therefore simply a best estimate based on the theoretical evaluation of the methods of blast transmission. However, since risk levels are not sensitive to whether the exposure occurs from the side or the front of the torso, this assumption does not affect the results of the analysis. In other words, if the airblast propagated inward at an angle relative to the length of the submarine’s cylindrical axis rather than perpendicular to it, the risks of fatality would be the same for the crew.

7.4.3 Effects on the Crew, and the Night of the Sinking

A common misconception is that people exposed to blast are always physically thrown by the blast (e.g. in movies or television). However, blasts too weak to move or translate a human body noticeable distances are still often intense enough to cause lethal pulmonary trauma (Bass, Rafaels et al. 2008). For the *Hunley*, since the hull was exposed from all radial directions simultaneously and accompanied by motion of the ship itself, there may be no clear direction of motion even if the pressure wave did translate the crewmen. Lethal pulmonary blast injuries are therefore consistent with the lack of skeletal trauma and the positions of the crew at their battle stations.

Respiratory distress is one of the hallmarks of pulmonary blast injury; even if any crewmen had survived the initial blast they would have likely still been above the injury threshold and would have experienced symptoms such as shortness of breath,
hemoptysis, tachypnea, and hypoxia (Hirshberg, Oppenheim-Eden et al. 1999, Bass, Rafaels et al. 2008, Lance, Warder et al. 2016). Additionally, the majority of patients with pulmonary blast trauma show a reduced arterial to inspired oxygen ratio (PaO$_2$/FiO$_2$), with a mean of 158 and some patients as low as 51 (Hirshberg, Oppenheim-Eden et al. 1999). This low ratio indicates that even when blast lung patients are physically able to inhale normally, less of the inspired oxygen is conducted to the bloodstream. The clinical guidelines for acute respiratory distress include a ratio of 300 or less, and attempts at physical work would have further exacerbated symptoms from this vascular hypoxia. Therefore, even if some crewmen had survived the initial blast they would have likely been crippled in terms of respiration and physically unable to power the handcrank to move the submarine. If anyone had survived, they may have tried to release the keel ballast weights, set the bilge pumps to bilge water, or tried to get out the hatches, but none of these actions were taken. Based on the analysis above, the whole crew was instantly killed by pulmonary blast trauma.

Eyewitness reports stated that they saw a blue light on the water after the attack, the *Hunley*'s pre-arranged symbol for victory (Kloeppel 1987, FOTH 2012). However, eyewitness reports are notoriously unreliable especially in the heat of battle, as evidenced by the *Housatonic* crew’s inability to agree on either the level of the tide or direction of the current at the time of the attack (USN 1874). The *Housatonic* crew did,
however, agree that the attack took place between 8:45-9:00 pm in the Union method of
timekeeping, including the testimony of the watchman responsible for monitoring and
recording the time of key events onboard the ship (USN 1874). The pocket watch of
*Hunley* commander Lieutenant George Dixon, when recovered from the inside of the
*Hunley*, showed a time of 8:23 pm, equivalent to 8:49 on the Union clock, within the
window of the attack (FOTH August 8, 2003). The watch was also determined to have
been broken, rather than wound down gradually (FOTH December 14, 2007).
8. Conclusion

This work has several limitations. The largest limitation is weak charge confinement owing to the construction of the scaled charges. However, the pressure values transmitted inside the boat demonstrated that even at these low blast levels sufficient transmission would have occurred to cause fatal pulmonary trauma to the crew.

The Pyrrhic attack of H.L. Hunley was responsible for the deaths of 21 Confederate crewmen and 5 Union sailors. An earlier Confederate vessel that successfully used a spar torpedo, the David, was made of wood and floated much higher in the water. Additionally, earlier designs of the Hunley had the submarine towing the torpedo on the surface of the water far behind its stern, and were successfully used in trial runs in the harbor (Kloeppel 1987). It was the combination of all the simultaneous design changes: conversion from wood to wrought iron, sinking the vessel deeper in the water, lowering the torpedo, and attaching the charge much closer at the end of a spar that ultimately led to the demise of the crew.

Researchers determined that Hunley pilot Lt. Dixon’s pocket watch was stopped by a sudden damaging force, such as water intrusion or a strong impact because the small fiber used to wind the watch was broken. I maintain that the watch was stopped by the same shock wave that killed the crew, forever memorializing the exact moment of
their successful attack, and followed by the *Hunley* herself then drifting to rest. The results from my tests show that shock waves in the water can transmit into the cabin of the submarine, that shock waves with sharp rise times can propagate even through the full-thickness hull, and that enough propagation can occur to cause injury and lethality to the crew inside.
Appendix: Data
Figure A1. Shock waves from black powder charges used to assess the scaling of the black powder time constant. *Data from this 455 g charge was truncated because the gauge showed noise and artifacts following the initial peak.
Figure A2. Transmission through the hull of the scale model during underwater shock tube testing. These tests were performed with the shock tube oriented perpendicular to the hull. [a] Pressure in water [b] Pressure inside scale model hull. In-water measurements correspond to the in-boat measurement immediately below.
Pressure inside scale model

Pressure in water

455 g charge #2
186 g charge

Pressure inside scale model

Pressure in water
Figure A3. Additional waveforms showing transmission into the scale model hull live black powder charges. Red circles mark which points were determined to be the points of peak pressure. Point of peak pressure was defined as the maximum pressure achieved with a preceding sharp (<1 ms) rise time. A different in-water gauge was used for the 183 g charge. This waveform is truncated because it is not considered reliable after the initial peak.
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Biography

Rachel Lance is originally a native of the great state of Michigan. She graduated with her bachelor’s and master’s degrees in Biomedical Engineering from the University of Michigan in 2005 and 2007 respectively, then in 2008 began work with the US Navy in Panama City, FL. At the encouragement of her Naval base, she returned to study Biomedical Engineering in the pursuit of a PhD in August 2011. Rachel is the recipient of the SMART Scholarship, which funded her PhD education, and her academic publications are listed below:


