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Determining and mitigating the effects of firing a linear shaped charge under water

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DETERMINING AND MITIGATING THE EFFECTS OF FIRING A LINEAR SHAPED CHARGE UNDER WATER

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ABSTRACT

When fired under water, a Linear Shaped Charge (LSC) does not penetrate a steel target as well as in air. This lack of performance has been a problem for shaped charge manufacturers and their clients. It was obvious that this degradation of performance is due to water having a higher density than air and water being incompressible compared to air. This study aimed to better determine how the water was affecting the LSC and to provide a method of mitigation.

LSCs of different sizes were submerged under water and fired through the water with and without a target. It was observed that the liner of the LSC did not close completely to form a “blade”. This blade is the key component of an LSC’s cutting ability. Under water the blade was forming a less effective cutting tool. The targets showed blunt impact, which confirms the blade being ineffective. The blunt impact also indicates the water was transferring the force rather than a blade impacting the target. This confirms that both the mass and incompressibility of water are at work. The difference in sizes between LSCs did not have a noticeable impact.

In order to mitigate these negative effects, foam was used to fill the entire volume of the standoff between the LSC and the target. Various foams were tested, again on different sizes of LSCs. The foam displaced the water, so the path of the blade formation had a much lower density and a compressible medium. The results showed the foam was effective. LSCs fired through foam under water had similar penetration profiles compared to the benchmark tests in air.

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NOMENCLATURE

Symbol	**Description**
F_D	Drag Force
C_D	Drag Coefficient
A	Cross-sectional Area (Drag Equation)
ρ	Density
v	Velocity
M	Mass of Flyer Plate
N	Mass of Tamping Material
C	Mass of Explosive Charge
E	Material Constant (Gurney Model)
C_0	Bulk Sound Speed
P	Pressure
s	Material Constant (Hugoniot)
U	Shock Velocity
u	Particle Velocity
Z	Shock Impedance

1. INTRODUCTION

A shaped charge is an explosive device that utilizes a specific geometry, or "shape," to focus its energy in a specific direction. This focus is achieved by creating a cavity within an explosive charge. As the explosive detonates, it projects the energy away from its surface, and the energy is focused inside the cavity. As this focused energy comes together it directs a larger portion of the energy away from the cavity similar to an addition of vectors, making it more efficient when used for either cutting or drilling purposes. This process is a combination of both the Munroe and Misznay-Schardin Effects.

The two common types of shaped charges are the Conical Shaped Charge (CSC), as illustrated in Figure 1.1, and the Linear Shaped Charge (LSC), as illustrated in Figure 1.2. The CSC focuses the explosive blast to a point that projects out along a single axis. Usually CSCs have a copper liner that forms into a "jet". LSCs usually have a copper liner that forms into a "blade" (Lim 2003). Their difference in mechanics is due to a function of both a different symmetry and a different direction of initiation.

CSCs are often used in the petroleum industry for perforating well liners. They are also used by the military to quickly create holes for cratering charges. LSCs are used primarily in the demolition industry to cut steel, but have niche uses in many other industries as separation systems. The use of shaped charges for underwater operations is an even more specialized application.

The general benefit of shaped charges is the same; more of the explosive acts in the desired direction, increasing effectiveness, reducing materials, and decreasing protection requirements.

Figure 1.1: Conical Shaped Charge. The underside (left) shows the conical depression. (Ribbands Explosives)

Figure 1.2: Linear Shaped Charge. (Accurate Energetic Systems)

Surrounded by water, an explosive's effect can either be enhanced by the hydraulic effect of water's incompressibility or degraded by both the incompressibility and the greater density, depending on the desired effect. The former is an advantage utilized by the US Navy in their torpedoes and underwater mines (Jolie 1978). The latter is a disadvantage when using shaped charges as they are currently utilized for demolition.

The motivation for this thesis work was to research a solution to this specialized need and to pioneer research in an academic area where specific research is lacking. Some research has been done to investigate the performance of linear shaped charges in traditional uses in air. However, little to no research has been conducted on LSCs in an underwater environment. Work has been done using CSCs under water, but general underwater explosive research has focused on the realm of naval warfare.

The work in this thesis focused on the operation of LSCs underwater. The study itself had a two-fold purpose. First, it was conducted to better understand LSC behavior underwater. The primary concern was that the blade, which is what cuts through the target, would form much differently when submerged under water. Comparison tests between air and water were conducted. Analysis of these tests' results provided insight into these effects.

The second purpose was to test the hypothesis that filling the standoff volume between the LSC and the target with waterproof foam would negate the detrimental effects of an underwater environment. This was of course assuming the initial tests showed an underwater environment degrades the performance of the LSC. It is a simple answer, which may prove a practical application. Regardless of practicality, it provided a second method of producing tangible data for additional analysis of LSC performance. Both purposes required a brief look at how fluid mechanics affect the scenario.

1.1 PROBLEM STATEMENT

Both the application and performance of LSCs in an underwater environment has thus far been largely overlooked in the research and development of LSCs. This oversight is likely due to the fact that underwater usage comprises a very small amount of total explosive industry usage, even in the application of shaped charges. However, the practical application does exist and therefore warrants study. Past uses of LSCs under water have proved difficult and forced users to employ larger sized LSCs than necessary in order to make a brute force cut through the water and target. Manufacturers would benefit from a design for underwater use by being able to manufacture a specific attachable component to work with their specific type and size of LSC.

Consider how an underwater environment affects the performance of a common LSC as manufactured for standard industry use. To explore this, one needs to consider the events following detonation. First, the explosive detonates, creating both a shockwave and rapidly expanding gases. These forces push in a direction normal to the surface of the explosive and against the copper lining. (This is known as the Misznay-Schardin Effect and is addressed later in this thesis.) The copper lining begins moving in reaction to these forces. The liners on the two sides of the V-shape cavity are forced together, producing a blade, as illustrated in Figure 1.3.

Figure 1.3: Blade Formation Process. The explosive forces normal to the surface force the liner on the two sides of the cavity together into a blade. The resultant force projects the blade away from the apex of the cavity.

Submerged, the moment the copper lining begins moving away from the explosive it begins pushing against the water and inhibits the inner “V” from coming together to form a blade. At standard temperature and pressure, air has a density of 1.205 kg/m^3 (0.0752 lb/ft^3); water has a density of 1000 kg/m^3 (62.4 lb/ft^3) (Lindeburg 2012). Explosive force is consumed pushing a larger mass out of the way to allow the blade to form and reach the target. So water’s greater density is the first major factor that inhibits blade formation and degrades cutting performance.

Density has an additional effect of increasing drag force on the blade. As the blade is forming and begins to separate from the rest of the LSC it is no longer pushing against the water, but rather pushing through it and is then subject to drag force, as defined in Equation 1.1 (Lindeburg 2012).

$$F_D = \frac{C_D A \rho v^2}{2} \tag{1.1}$$

where F_D is drag force against the blade, C_D is the drag coefficient based on the blade's shape, A is cross-sectional area of the blade, ρ is the blade density, and v is the blade velocity. Assuming all other factors to be equal, the greater density of water will increase the drag force on the traveling blade, further degrading LSC performance.

Another property which must be accounted for is compressibility. Water has a miniscule compressibility when compared with air. At standard temperature and pressure, air has a compressibility of 0.049 1/psi, and water has a compressibility of 0.0000033 1/psi (Lindeburg 2012). Compressibility will change as pressure and temperature increase, but this rate of change is insignificant. For the purpose of understanding the problem addressed in this study these values suffice. Because of this, water is considered incompressible for experimental purposes (Cole 1948).

Because water is incompressible, forces upon it have a hydraulic effect. Force on any part of the water is translated through the entire fluid. This means that as the explosive force works against the mass of the water inside the standoff, the water inside the standoff must then work against the surrounding volume of water, thus adding to the amount of mass the explosive force must move. It also means that if water is trapped inside the collapsing blade the blade will not be able to fully close. Compounding the problem with water's greater density, incompressibility will also inhibit blade formation and degrade cutting performance.

Consider the remaining system in action. Water surrounding both the sides and top of the LSC affects the charge's performance. A higher density material (i.e. water) acts as a tamping material against an explosive (Bartholomew 1992). (Tamping is often known as stemming when used in mining applications.) Tamping an explosive will increase its effectiveness in directions opposite the surfaces tamped, as illustrated in Figure 1.4 (Zukas 1998).

Figure 1.4: Tamping. Tamping an explosive charge with sandbags directs more energy into the target to create a more effective blast (Zukas 1998).

The Gurney Model for an asymmetrical sandwich is a mathematical explanation of tamping, as illustrated in Figure 1.5 and Equations 1.2 – 1.3 (Cooper 1996).

Figure 1.5: The Gurney Model for an Asymmetrical Sandwich. M is a flyer plate, C is the charge, and N is a heavier flyer plate. The inertia of the heavier plate pushes more explosive force into plate M, which will now have a higher velocity (Cooper 1996).

$$A = \frac{1+2(\frac{M}{C})}{1+2(\frac{N}{C})} \tag{1.2}$$

$$\frac{v}{\sqrt{2E}} = [\frac{1+A^3}{3(1+A)} + \frac{N}{C}A^2 + \frac{M}{C}]^{-\frac{1}{2}} \tag{1.3}$$

Where A is simply used to clarify the velocity equation, M is the mass of the flyer plate, N is the mass of the tamping material,, C is the mass of the explosive charge, $\sqrt{2E}$ is a constant, the Gurney Coefficient, which is based on the explosive type, and V is the velocity of the flyer plate.

The larger mass N has a greater reactionary force against the force of expanding gases. As the mass of N increases the value of A decreases, which increases velocity. Thus, the surrounding water having a larger mass than air will cause a tamping effect and counteract some loss of performance. However, this tamping effect will be insignificant until foam is introduced.

From this understanding of explosive and hydraulic principles it is inferred that using currently available manufactured LSCs underwater will have a detrimental effect on their performance. Both the increased mass and decreased compressibility will impede the blade closing and retard any effective cutting at any standoff. The blade may form and partially cut if fired from a different standoff, but this is uncertain given the expected loss of energy against the water. The LSC may produce some penetration by sheer blunt force if placed directly against the target.

Two hydraulic factors that could affect performance but could not be feasibly tested include hydrostatic pressure at greater depths and the hydraulics of a large body of water, as illustrated in Figure 1.6. While increased hydrostatic pressure will further reduce water's compressibility, this is an insignificant concern. Hydrostatic pressure is more of a concern regarding the use of foam. If the foam is not strong enough it will be crushed under the pressure, and therefore not be usable. A larger body of water could possibly increase the incompressible effects. The testing environment simply could not accommodate a body of water large enough to examine these two factors.

Figure 1.6: Hydrostatic Pressure. Diagram of hydrostatic pressure on an object, also known as buoyancy. A charge is subject to higher pressures at greater depths. (Georgia State University, left) (University of Colorado at Boulder, right)

1.2 GOAL

The first goal of this research was to analyze the operation and performance of LSCs when submerged in water. The second goal was to test an apparatus to supplement the currently manufactured LSC for use underwater. The ultimate method of analysis involved measuring both the cut penetration and the run-up. Additional analysis was gained from a thorough visual inspection of the penetration profile, the recovered blade, and the recovered copper jacket shrapnel.

The system can regain performance through a minor alteration to the LSC apparatus. If the greater mass (water) inside the V-shaped cavity is the driving factor reducing performance, then displacing this mass will minimize, if not negate entirely, the performance reduction. Closed-cell (waterproof) foams such as Styrofoam have a much lower density than water, and can easily be cut to fit the standoff volume in order to fully displace water. Thus filling the entire standoff volume with low-density, waterproof foam will displace the water and allow the blade to close and cut under water with minimal losses in performance (when compared to similar scenarios in air).

2. PREVIOUS WORK AND LITERARY RESEARCH

The shaped charge, as used today, is the result of many years of trials and tests. Like most explosives, it has evolved numerous times to meet both industry and military needs. Although these uses differ, the principles which govern the performance of the shaped charge remain the same. (Author's note: throughout this section are multiple references to Dr. Kennedy's work, wherein he provides many more sources for his work. Unfortunately the author was unable to obtain some of these sources for direct reference, but the citations can be found in Dr. Kennedy's work.)

The first documented discovery that led to the shaped charge effect was in 1792 by a German mining engineer named Franz Xaver von Baader. Von Baader found that depressing inward the end of a blasting charge, into a conical-shaped space, made the blast more effective. (The author was unable to obtain primary sources regarding Von Baader; however numerous secondary sources mention his name and work dating to the 1790s.) This shape and its results became known as the cavity effect. However, a large footnote accompanies von Baader's discovery. Miners at the time used black powder, which does not detonate and does not produce a shock wave (Kennedy 1990). Therefore, while many recognize von Baader for discovering this cavity effect, the first shaped charge, as defined today, was not used until 1883 when detonable high explosives were available.

Max Von Foerster, a German Army officer, is credited with the first true documentation of the shaped charge effect in 1883 in Germany. Von Foerster used an unlined cavity to produce his work (Kennedy 1990). He extended Von Baader's work to demonstrate that the cavity effect was also applicable to high explosives.

In 1886 a German man, Gustav Bloem, took this design to patent by adding a liner around the cavity for use in blasting caps, and this design is the first documented design of a lined shaped charge (US Patent 342243). Bloem wrote regarding the cavity effect, "the concentration of the effect of the explosion in the axial direction…is increased", (Kennedy 1990).

The shaped charge effect became known as the "Munroe Effect" as a result of the work conducted by Charles Munroe from 1888 to 1900. Munroe, a civilian chemist for the United States Navy, both researched and demonstrated the application of the shaped charge effect to defeat large targets. His crude design of "sticks of dynamite around a tin can" was able to blast open a safe 4.75 inches thick using 9.5 pounds of dynamite; a solid, unshaped dynamite charge of the same weight could not do so (Kennedy 1990).

After those early days of discovery in Germany and the US many countries conducted their own independent research. Russia, Italy, and the UK each presented similar results using lined cavities. However, no one seemed to recognize the effect of the liner as anything more than either a protective covering or a case to hold the explosive. Additionally, the lined shaped charge was deemed impractical for military use throughout this time despite minor research identifying what is now known as the explosively formed projectile (EFP), an item presently used extensively in the military (Kennedy 1990).

In the late 1930s and 1940s, the warring countries in WWII continued independent research on shaped charges, almost simultaneously discovering the advantage of the metal liner during this period. Upon seeing each other's work, Swiss researcher Henry Mohaupt joined British professor D. E. Matthias and Frenchman Erick Kauders to apply for a patent for a lined cavity charge. Their work at Zurich, Switzerland was proof of the liner having improved results (Kennedy 1990). With their patent on 9 November 1939 the liner on a shaped charge was finally treated as a new technology in the explosives field (Australian Patent 113685 dated 27 November 1940 lists a French Patent date of 9 November 1939) (AUS Patent 113865).

Meanwhile in Germany, Franz Thomanek began to see improvement by altering the liner's material, size, and shape. He noted that mild steel and copper were superior materials. The thickness and the shape of the cavity and liner also greatly impacted the shaped charge's performance. His patent was awarded on 9 December 1939, a mere month after Matthias, Mohaupt and Kauders. Thomanek claims to have made his discovery in 1938 (the author was unable to verify these dates through primary sources) (Walters 1990). Thomanek went on to start a company producing shaped charge munitions that would be used by the Reich in WWII (Kennedy 1990).

Most of these discoveries were accidental, and progress was restrained somewhat by a less-than-effective deployment of shaped charges. At the time, explosive charges were initiated with multiple caps. These caps were placed off-axis around the base, or the middle, of the charge. Caps were not placed at the top-center as is done today. Many designs also included either multiple liners in the explosive or a tube running through the central axis of the charge. Each was meant to force the explosive to form projectiles or jets. Unfortunately, each had the opposite effect (Kennedy 1990). Thus, while the world made great strides in both the research and the application of shaped charges, it seems not all fully understood how the liner functioned.

Following the war, extensive research continued to further the shaped charge's military usage and performance. This research focused on the effects of different liner materials, operation in various environments (including underwater), and the performance of specific tasks. These specific tasks now range from anti-armor devices and precision obstacle breaching to building demolition and use by NASA in spacecraft to release cables and ties (NASA 2005).

Linear shaped charges were first developed at Frankford Arsenal and Sandia National Labs with support from Ensign-Bickford in 1956 for strategic missile and launch vehicle programs (Ensign-Bickford 2014). Early designs used a lead jacket/liner with a PETN explosive core extruded into a "D"-shaped cross-section. This "D" shape was quickly replaced with a flat "U" shape in an attempt to utilize the Munroe Effect (Novotney 2007). Researchers continued to explore various geometries, sizes, liner materials, and explosive types in an attempt to optimize penetration while maintaining the extrusion method of manufacturing (Mallery 2005).

Linear shaped charges were originally thought to function like conical shaped charges. Because of this original theory, little research was done to understand the process of how LSCs function. Initial research specific to LSCs attempted to investigate what was believed to be a jet/slug mix similar to that found in CSCs (Brown 1969).

Expounding on the many wartime shaped charge discoveries, linear shaped charges were designed to fit military applications such as warheads, as illustrated in Figure 2.1.

Figure 2.1: “Representative Warhead Configuration Using LSC Principle” (Brown 1969). An early attempt at military application of LSCs.

A 1992 report by Sandia National Labs introduced a design for a precision LSC (PLSC) with separate jacket and liner components, as illustrated in Figure 2.2. This process was intended to allow better quality control of the LSC liner. Instead of using the same material and manufacturing for the containment jacket, this separated design allowed for cheap manufacturing a crude tamping material that could be altered independently of the liner (Vigil 1992).

Figure 2.2: Precision LSC Design with Separate Liner and Tamping Parts (Vigil 1992).

In addition to using water for tamping effect, water can be used as the liner material of a LSC. Researchers at the US Army's Armament Research, Development and Engineering Center (ARDEC) successfully designed a hydrodynamic LSC (HLSC) with deta-sheet and surrounding plastic cases in place of the jacket and liner to be filled with water (Baker 2013). This design is reported to be lighter than other LSCs if the water is added on-site. However, this design requires more time and preparation to emplace, and under the current design the orientation must be predetermined prior to manufacturing so the fillable opening is at the top. It should be noted that this design, when taken into consideration regarding this thesis, would still be subject to the detrimental effects of the surrounding body of water.

2.1. UNDERSTANDING SHAPED CHARGES

Shaped charges are a product of the combination of two effects: The Munroe Effect and the Misznay-Schardin Effect. However, linear shaped charges specifically only work using principles of the latter. LSCs are also subject to effects called “run-up” and “run-down”.

2.1.1. Munroe Effect. By forming a deep cavity in the face of an explosive charge opposite the point of initiation the resulting explosion will invert the cavity. The inversion of the cavity forms into a “jet” or “slug” (depending on cavity geometry) of fluidized liner material, which has excellent penetrating properties. An explosively formed projectile (EFP) is an example of this, as illustrated in Figure 2.3. This effect is known as the Munroe Effect. Munroe first observed this phenomenon by stamping letters into the face of blocks of gun-cotton (nitrocellulose). When the blocks were placed letter-side down the detonation would leave letter shaped depressions in the target (Munroe 1887). Munroe’s discovery led to the conical shaped charge (CSC).

Figure 2.3: Slug Formation Process in an Explosively Formed Projectile (EFP) Version of a Shaped Charge. The shaped cavity liner inverts as it forms the jet/slug. The interior of the cavity travels faster than the exterior to become the nose of the jet/slug.

2.1.2. Misznay-Schardin Effect. Upon detonation of a high explosive, forces from both the shock wave and the expanding gases act normal to the planar surface of the explosive charge. This effect is known as the Misznay-Schardin Effect as a result of the two men's effort to create a better anti-tank mine (Schardin 1954). It is best observed when using broad, flat sheet explosives. Placing a heavy backing material against one side will direct more of the explosive energy orthogonally outward through the side opposite the backing material. An excellent practical application of this is seen in explosively formed projectiles (EFP). An EFP is similar to a shaped charge. Unlike a shaped charge, however, the cavity is rounded and very shallow. Instead of producing a cutting jet/slug mix with the metal liner, it produces only a slug.

This effect is also apparent in the shape of the US Army's M18A1 claymore mine. The claymore is a curved block of explosive in which the concave face has a backing material, and the convex face is covered in ball bearings. The convex shape spreads out the ball bearings as shrapnel in a wide angle from the single point where it was placed, as illustrated in Figure 2.4.

Linear shaped charges (LSC), as described in the introduction and shown in Figure 1.2, were originally thought to use the Munroe Effect (Lim 2003). The geometry of the LSC is a cross-section of the CSC model extruded into a long V-shaped bar. However, rather than creating a jet that penetrates at a point, LSCs create a solid blade. The LSC's blade does not work in accordance with the Munroe effect, but it is better described by the Misznay-Schardin Effect (Lim 2006). The LSC blade forms by closing the two sides of the cavity together like a book. The exterior edges become the nose of the blade, as illustrated in Figure 2.5.

Figure 2.4: Claymore Mine. The claymore mine is an example of the Misznay-Schardin Effect in a shaped explosive device.

Figure 2.5: Photograph of LSC Blade Forming (Lim 2012). The liner of the LSC closes together like a book to form the blade. The exterior edges become the nose of the blade.

2.1.3. Run-up. Upon initiation, the shock wave front in any explosive propagates radially way from the point of initiation. The wave front progresses as a circle of growing radius. Inside the LSC this wave front becomes an arc of lessening curvature. The optimal area of operation in an LSC occurs when the shock wave front is nearly planar in shape, as illustrated in Figure 2.6. The detonation propagation requires a short distance to achieve a planar front, known as "run-up" (Lim 2003). An example of run-up is shown in Figure 2.7. This portion generally has a linearly increasing penetration capability until it reaches maximum penetration.

2.1.4. Run-down. Run-down occurs at the end of the length of the LSC when the explosive reaction is no longer contained by enough material, as illustrated in Figure 2.6. Run-down has a shorter length than run-up over which penetration generally decreases linearly, as shown in Figure 2.7.

Figure 2.6: Causes of Run-up and Run-down. Run-up occurs until the shock wave flattens to a nearly planar front. Run-down occurs when the explosive material no longer provides containment.

Figure 2.7: Run-up and Run-down in a Penetration Profile. Run-up is evident from an increasing penetration profile near the point of initiation. Run-down is evident from a higher-sloped decrease in penetration at the end of the length of the LSC.

2.2. UNDERWATER EXPLOSIVES RESEARCH

Most underwater explosive research revolves around torpedoes and other naval military uses. A compendium gathered and published in 1951 provides a great wealth of knowledge on underwater explosions. A discussion of underwater explosions is best summarized in three parts: the primary underwater shockwave, hydrodynamic effects under an incompressible theory (pertaining to the resulting gas pressure bubble), and the effects of these two phenomena on structures (Naval Research 1951).

A shockwave propagates through water much like through any medium. It reacts to the explosive/water interface as expected through a similar high/low impedance discontinuity, as illustrated in Figure 2.8 and Equations 2.1-2.4. Shockwave velocity peaks at the source (the explosion) and travels as a compressive wave at a velocity dependent on the particle velocity and the sound velocity for the medium according to the U-u Hugoniot (Eq. 2.3). (Cooper 1996)

$$P = \rho_0 u U \tag{2.1}$$

$$Z = \rho_0 U \tag{2.2}$$

$$U = C_0 + su \tag{2.3}$$

$$P = \rho_0 C_0 u + \rho_0 s u^2 \tag{2.4}$$

Figure 2.8: Diagram of Shockwave Reaction at a High/Low Impedance Interface (Impedance A > B). (Top) The wave approaches the interface. (Bottom) The wave reflects back into the higher impedance material and transfers at lower pressure through the lower impedance medium. (Next Page) The wave after interacting with the high/low impedance interface.

Figure 2.8 (continued): Diagram of Shockwave Reaction at a High/Low Impedance Interface.

The magnitude of the reflected wave is ultimately dependent primarily upon the density of the second material. Shock velocity (U) changes with pressure, but the rate of change is usually insignificant, so U can be considered a constant in most cases. A higher density material will often have a higher impedance (Z), and vice versa. It follows that the higher the density of the material, the higher the pressure of the reflected shock wave. Equation 2.4 is known as the P-u Hugoniot equation (Cooper 1996). Given that water has a higher density than air; it will reflect a lower pressure shock wave back into the LSC, which will decrease the particle velocity in the blade.

A unique phenomenon observed in underwater explosions is the bubble formed by the detonation's high pressure gas products, as illustrated in Figure 2.9. These gases have a much greater pressure than the hydrostatic pressure of water, which causes the gas bubble to expand outward from the point of detonation. Because of the large magnitude of the pressure difference, the bubble expands rapidly and accelerates until the pressure inside the bubble reaches hydrostatic pressure. At this point the water at the gas/water interface begins to decelerate, but the water's momentum continues to expand the bubble past the pressure equilibrium until the interface finally decelerates to zero velocity. The hydrostatic pressure outside is now greater than the gas pressure inside, and the bubble contracts. The interface accelerates in contraction until the gases again reach equilibrium. This physical process of accelerating and decelerating creates a dampened oscillating reaction. (This reaction is visually similar to a rubber ball bouncing; each bounce, the ball travels back up a shorter distance until the energy dissipates and the ball comes to rest.) This process of expansion and shrinking continues to oscillate until the energy is lost. Some is lost to heat, some to parts of the bubble breaking apart and some to other irregularities in the underwater environment (Bartholomew 1992).

The majority of academic research in the use of underwater explosives has focused on the gas pressure bubble formed by the explosive gases. This focus, however, does not impact this particular LSC research, as these pressure bubbles are many times larger than the size of the explosive charge. The major concern of a LSC's activity is limited to a distance roughly two to three times the size of the charge diameter. Thus, it is assumed that the gas bubble effect does not interfere with LSC performance; the distance to the target is much shorter than the radius of the pressure bubble.

Figure 2.9: Gas Bubble. An explosive charge detonated underwater creates a gas bubble. The bubble expands and contracts as water pressures push it towards the surface. (Bartholomew 1992)

Finally, the discussion of target damage is generally tailored to the use of spherical charges. Although Munroe discovered the shaped charge effect while working at the US Naval Torpedo Station, the shaped charge was not adopted in practical military use until its use in the bazooka, as shown in Figure 2.10 (Wikipedia).

Shaped charges were not adopted into torpedo technology during Munroe's time for a few reasons. First, as previously mentioned, at that time the conventional placement of explosive initiators was inefficient. Second, the integrity of the shape was deemed too difficult to maintain in an aerodynamic projectile. Third, and probably most important, torpedoes needed to cause effective damage without a direct hit. A shaped charge warhead would require not only a direct hit, but also a hit at the proper angle. Around 1910, torpedoes were designed to detonate as the result of a glancing blow from any direction through the use of "whiskers", as shown in Figure 2.11 (Jolie 1978).

Figure 2.10: Bazooka. The US Army's M1 Rocket Launcher "Bazooka" is considered the first practical combat use of the shaped charge (Wikipedia).

Figure 2.11: Torpedo Whiskers (International Ammunition Association). The four metal extensions "whiskers" at the nose of the torpedo detonated the main charge if the torpedo did not directly strike its target. In the event of this kind of detonation, a shaped charge would have been ineffective.

Military technology is often a closely guarded secret, so it is possible that other shaped charge designs exist, but the only documented modern torpedo with a shaped charge payload is the Mk 50, which carries a 100-pound shaped charge warhead. Most modern torpedoes use a larger bulk explosive payload. The primary torpedo in use today by the US Navy is the Mk 48, which carries 650 pounds of bulk explosives (Thomas 2008). This use of bulk explosives would serve to explain why only spherical explosive charge research is documented, for the purpose of target damage, in an underwater environment.

Shaped charges appear to be best utilized underwater for both salvage and structural demolition work. The US Navy created underwater demolition teams in 1943 to remove underwater enemy obstacles. These teams have since split into two groups: explosive ordinance disposal (EOD) and Sea, Air, and Land (SEAL) special warfare teams (Naval 1988).

2.3. UNDERWATER APPLICATIONS OF SHAPED CHARGES

Nitrex Explosive Engineering has designed and used conical shaped charges for rock blasting underwater. This charge appears to be a standard CSC placed inside a water-proof container and set in a concrete base to provide both proper standoff and ballast, as shown in Figure 2.12. (Unfortunately the company could not be reached for confirmation.) Because these charges are used for large scale rock blasting, the CSCs are secured into a pattern that allows all of them to be placed as a single unit. This design was successfully used to excavate 20m of basalt rock at a depth of 100m under water in Lake Mead, Nevada (Folchi 2012).

Military use for salvage and demolition is mentioned in the *U.S. Navy Salvage Engineer's Handbook*. This book contains an excellent discussion on not only how explosives work in general but also how they operate underwater. Detailed equations provide both the distance and the charge weights required to damage a ship's hull. For rock blasting, appropriate charge sizes calculated in air are adjusted for underwater rock blasting. The book helps explain how water has a tamping effect on smaller scale operations. Shaped charges should be placed securely against their target, and the standoff volume should be contained in a water-proof container, as is already in practice with CSCs (Folchi 2012).

Figure 2.12: CSC Underwater Apparatus. Nitrex Explosive Engineering makes and uses this apparatus in large scale underwater blasting. The CSCs are secured with concrete to stabilize the charge and waterproof the standoff (Folchi 2012).

Although using a concrete enclosure had already proved successful, foam was chosen for experimentation for a few reasons. Foam is cheaper, and is much easier to handle and shape for fit. Most importantly it fulfilled the requirements desired of a material to fill the standoff.

3. EXPERIMENTAL SETUP

A series of tests were conducted to investigate the effects of using LSCs under water and the viability of using a foam filled standoff. The tests were designed to change a single variable between each test. First, control tests were conducted in air. Second, the same tests were conducted under water. Third, different variables were tested while under water. These variables were standoff distance, type of foam, and shape of foam. These series of tests were all conducted for three different sizes of LSC: 600 gr/ft, 1200 gr/ft, and 2000 gr/ft. A complete list of tests is indexed in Appendix A

3.1. BASELINE LSC TESTS IN AIR

The first battery of tests was simply a series of tests comparing LSCs fired at mild steel targets through air. These tests provided a baseline result for comparing LSC performance and results in water and water/foam. The following subsections cover the materials and procedures used.

3.1.1. Materials. The following materials were used in all the tests:

- 4”-6” long LSC at 600, 1200, and 2000 gr/ft
- 1” and 2” thick mild steel plates of sufficient length and width
- Standoff material. Insulation foam board is commonly used in the industry.
- Popsicle sticks for securing the booster to the LSC, also common in the industry.
- Electrical tape
- Utility knife
- Calipers for measuring standoff

- Booster (8 gram pentolite stinger)
- Electric blasting cap
- Blasting cable
- Scorpion firing box or other power source

3.1.2. Procedure. The following was the standard procedure used for the tests in air, and is the starting point for the procedures of the later tests:

1. The foam was cut to the appropriate standoff height for the size of LSC. The length was as short as possible so as to not interfere with air being the primary medium.
2. Electrical tape and the two Popsicle(TM) sticks were used to secure the booster to the end of the LSC, as illustrated in Figure 3.1.

Figure 3.1: Booster. The booster is securely attached to the end of the LSC.

3. The LSC was placed onto the target and supported with the standoff material. The LSC was secured to the target with the tape, as illustrated in Figure 3.2.
4. The blasting cable was run from the LSC to the firing point.

5. The blasting cap was carefully inserted into the booster, trying not to disturb the position of the LSC. The blasting cap was a very tight fit in the booster, so the standoff was always checked once the entire charge was assembled, as illustrated in Figure 3.3.

Figure 3.2: LSC Secured to the Target. Pieces of foam maintain the standoff distance between the LSC and the target.

Figure 3.3: Blasting Cap. The blasting cap is inserted into the booster. The standoff is double-checked.

6. The blasting cap wires were connected to the blasting cable.

7. The power source was connected and the LSC was detonated.

3.2. UNDERWATER TESTS

LSCs were tested at various standoffs underwater. The goal of these tests, in addition to general curiosity, was to determine if perhaps the water wasn't negating blade formation, but rather slowing it down or speeding it up. LSCs were also tested under water without a target in order to catch blades that had no interaction after the formation process. These untouched blades would aid in understanding what effects the water alone was having on the blade formation process. The tests without a target had about 24" of clearance from the LSC to the bottom of the container to ensure no interference.

The underwater battery of tests was conducted almost exactly as those conducted in air. The only difference was the target and LSC were submerged underwater approximately 10-12". Testing was done at a shallow depth for the sake of convenience and ease of recovery of target.

One problem addressed during testing involved finding an efficient method for retaining water in which the LSC could be fully submerged. Simple and economical solutions were used which would not affect the quality of data obtained. Initial tests used a 55 gallon plastic drum for holding the water and apparatus. For smaller LSCs, these drums could be reused 2-3 times by hanging a trash bag inside the barrel. The larger LSCs rendered the barrels unusable after a single test, as shown in Figure 3.4.

Figure 3.4: Destroyed Barrel. The 55 gallon drums were destroyed by the first water tests and could not be reliably reused.

The next method used a thin wire fencing material in a cylindrical shape to hold the trash bag. The trash bag retained the same amount of water and allowed the blast pressure to escape between the wire fencing without destroying the apparatus. After several attempts, this method worked better than the 55-gallon drum. After each shot the wire was easily manipulated into a usable shape, and the trash bag was replaced with a new one, as shown in Figure 3.5.

The following subsections cover the materials and procedures used.

3.2.1. Materials. In addition to the materials for the baseline test this test used the following materials:

- Wire fencing at least 5’ long and 3’ high
- Trash bags (55 gallon size)
- Water source

3.2.2. Procedure. In addition to the procedure for the baseline test this test used the following procedure:

1. The wire fencing was formed into a barrel shape. The 3’ side was oriented as the height of the barrel.
2. The fencing was secured together with used blasting cap wire (Figure 3.6).

Figure 3.5: Water-containing Apparatus. The apparatus for containing the water was improved. The fencing does not absorb the force of the explosion and can be formed back into shape for reuse. The trash bag worked as a cheaply replaceable way to contain the water up to detonation.

3. A trash bag was placed inside the fencing.

4. The LSC and target were readied inside the trash bag and the water was added, as illustrated in Figure 3.6. There was a minimum of 8” of water above the charge for all tests. This test was run at varying standoffs, as listed in Table 3.1.

Figure 3.6: Adding Water. After the charge was placed inside the trash bag, the bag was filled with water.

Table 3.1: Different Standoffs Tested. Marked in bold is the standard standoff in air.

	600 gr/ft	1200 gr/ft	2000 gr/ft
	.8"	1.0"	1.0"
Standard Standoff	**.6"**	**.75"**	**.75"**
	.4"	.6"	.5"
	.2"	.4"	.25"
	0"	.2"	0"
		0"	

3.3. FOAM

Given that the purpose of this project was to displace water, only water proof foams were considered. Foams are classified as either closed-cell (waterproof) or open-cell (not waterproof). Since the purpose of displacing water was to lower the mass in the path of the LSC blade, lower density foam was chosen.

Five such foams were purchased and screened for this study, as shown in Figure 3.7. The foams were then separated according to density, as shown in Table 3.2.

- White craft foam
- Green craft foam
- Expanding spray foam
- Packaging Styrofoam
- Blue sheet insulation foam board. (This foam is currently often used to provide standoff for LSCs in air.)

The spray foam and blue insulation foam were not tested because their densities were close enough to the other foams that it was not expected to yield noteworthy results. This decision was also made to save time and resources during the testing phase.

These foams were also chosen because of their relative rigidity and stiffness. Thus, they were more likely to stand up to hydrostatic pressures than less dense foams that could deform. Their rigidity also made them easier to cut and shape so they would fit inside the V-shape of LSCs.

Figure 3.7: Foams Considered for Testing. Clockwise from top-left: white craft foam, green craft foam, blue insulation foam (Fretzel 2013), expanding spray foam (Wikipedia), polystyrene (Styrofoam) (Feirer 2014).

Table 3.2: Foams Ordered by Density. The two foams in red were not tested.

	Density	
Foam	**kg/m^3**	**lb/ft^3**
White	37.827944	2.3615985
Spray	32.946919	2.0568761
Green	28.676022	1.7902441
Blue	26.235509	1.6378829
Styrofoam	18.303844	1.142709

A small portion of the study investigated the difference in cross-sectional shapes of the foams. This was intended to determine if the porosity of the foam allowed water around the exterior of the foam to interfere with the LSC performance. These shapes are illustrated in Figure 3.8.

Although performance is paramount, it was noted whether certain foams were easier to handle and shape. Foam shapes could likely be manufactured. However, work in the field is not always as simple as setting a charge on the ground. Sometimes, a charge must be manipulated by hand to fit, or set, correctly. Durability is also a factor.

Figure 3.8: Cross Sections of the Foam Shapes Tested. The simplest shape (left) simply filled the standoff area with foam. Additional material (center) was added as a buffer to ensure water was kept away from the standoff area. A plastic bag (right) sealed out water leaving a pocket of air. No single shape proved superior.

3.4. UNDERWATER FOAM TESTS

The underwater foam tests were conducted in a manner very similar to the previous underwater tests. However, in these tests, different foams were shaped to fill the entire standoff volume between the LSC and the target, as shown in Figure 3.9. To ensure the best fit to the LSC, a hacksaw with a very fine tooth pattern was used. The utility knife was used to refine the shape as needed.

Figure 3.9: Foam-filled Standoff. Foam is used to completely the fill the volume of the standoff between the LSC and the target.

The test was run at varying standoffs for each type of foam and for each size LSC. A list of tests is outlined in Table 3.3. Once all of the tests were completed, the steel target plates were cut with a band saw to show the cross section of the penetration for analysis.

Table 3.3: Summary of Tests by Type.

Test	No.
Air	3
Water (w/o target)	3
Water (w/ target)	16
Water, White Foam	8
Water, Green Foam	5
Water, Styrofoam	5
Foam Shape	3

4. RESULTS

4.1. COMPARISON OF AIR VS. WATER

The tests performed under water revealed a drastic loss in cutting performance, as illustrated in Figure 4.1. So much performance was lost, that the only evidence of cutting was very minor in the spot where the pieces of foam were providing standoff. LSCs placed at a close standoff resulted in a smooth indentation in the target. The 600 gr/ft placed at 0.0" standoff produced a shallow and slightly wider penetration in the target than those from the benchmark tests. This penetration appeared to be a result of the liner being mashed into the target rather than cutting, which makes sense given the LSC's proximity to the target.

Recovered liners from these tests were mangled and showed no discernable signs of making cuts, as shown in Figure 4.2. This lack of signs does not indicate any new information, but rather reinforces the rest of the conclusions drawn from these tests. Some of the recovered blades had a "W" shape that appeared to have been caused by the blade trying to travel faster through the two pieces of foam. It should be noted that because of the open testing environment some of the copper pieces from a few of the tests were not recovered.

The results of the 600 gr/ft test fired under water with no target show the lack of energy needed for the liner to completely close and properly form the blade, as shown in Figure 4.3. The results of the same tests for the 1200 gr/ft and 2000 gr/ft LSCs are shown in Figures 4.4 – 4.9. These results were similar to the 600 gr/ft LSC.

Figure 4.1: Air vs. Water Results (600 gr/ft LSC). Results of the tests comparing a 600 gr/ft LSC that was placed under water (left) with that placed in air (right) show a degraded performance. The two indentations from the underwater test are where the pieces of foam were placed to create standoff.

Figure 4.2: Liner (600 gr/ft LSC) with Target. Recovered pieces of the copper liner collected from the 600 gr/ft underwater test.

Side

Side

Side

Side

Blade

c

Figure 4.3: Liner (600 gr/ft LSC) with No Target. Recovered copper liner from the 600 gr/ft LSC fired under water without a target. The pieces are the same in each photo, but have been flipped over to show both sides. The bottom piece is the blade. Notice that the blade did not fully close.

Water

Air

Figure 4.4: Air vs. Water Results (1200 gr/ft LSC). Results of the tests comparing a 1200 gr/ft LSC that was placed under water (left) with that placed in the air (right). Again, the two indentations from the underwater test are where the pieces of foam were placed to create standoff.

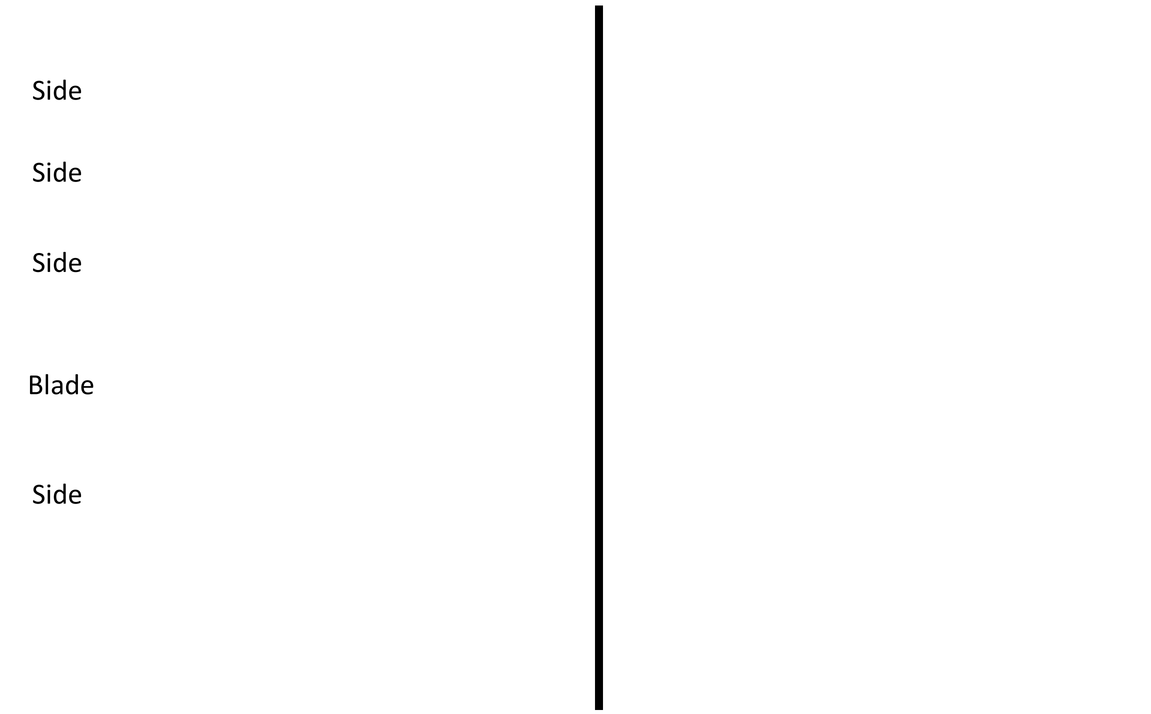

Figure 4.5: Liner (1200 gr/ft LSC) with Target. Recovered pieces of the copper liner collected from the 1200 gr/ft underwater test. The pieces are the same in each photo, but have been flipped over to show both sides.

Figure 4.6: Liner (1200 gr/ft LSC) with No Target. Copper liner of the 1200 gr/ft placed under water without a target. The two top pieces are the blade, which split along one side. The rest of the blade did not fully close [form]. A cross-section of the liner is shown on the right.

Water Air

Figure 4.7: Air vs. Water Results (2000 gr/ft LSC). Result of the tests comparing a 2000 gr/ft LSC placed under water (left) with that placed in air (right). Again, the two indentations on the underwater test are where the pieces of foam were placed to create standoff.

Blade

Side

Side

Side

Side

Figure 4.8: Liner (2000 gr/ft LSC) with Target. Recovered pieces of the copper liner collected from the 2000 gr/ft underwater test. The mangled pieces at the top would have formed the blade. The pieces are the same in each photo, but have been flipped over to show both sides.

Side

Side

Side

Blade

Figure 4.9: Liner (2000 gr/ft LSC) with No Target. Copper liner from the 2000 gr/ft placed under water with no target. The bottom piece is the blade. Although it appeared to close, the metal was not pressed together, suggesting it did not form into an effective blade.

In summation, the water had a tremendous impact on LSC performance. Because of water's greater mass, more force was used to push the liner against the water than was used to push against the air. Because water is incompressible (confirmed by the hydraulic effect causing the smooth indentations), any force on the water acts against the whole body of water, so additional force is required to move the liner against the surrounding water as well. If somehow water was getting trapped inside a closed blade then the blade would take on a wider, unbalanced shape, which would increase drag and possibly cause tumbling.

This loss of energy is evident from analysis of the blades recovered from the LSCs fired under water without a target. The 600 gr/ft liner did not close completely. The 1200 and the 2000 gr/ft liners did close. However, upon closer inspection the liners appear not to be pressed/welded together so as to form an effective cutting blade. The results of the tests of the LSCs fired under water are evidence that the liner does not completely compress and is an ineffective cutting object, which leads to a severe loss of performance.

4.2. CHANGING STANDOFF IN WATER

As mentioned in Section 4.1, changing the standoffs underwater yielded two interesting observations. First, LSCs at smaller standoffs created small, smooth indentations in the target. Second, there were small cuts into the target in the spots where the foam was providing standoff.

The first observation indicates a blunt force impact into the target. This blunt force is from the hydraulic effect in the water, not the liner, impacting the target; and reinforces the fact that the incompressibility of water has a detrimental effect on LSC performance. This effect is seen in the military's use of a door-breaching charge known as a water-impulse charge. A water-impulse charge is constructed of two bags of water sandwiching an explosive charge. The explosive force on the water is translated through the hydraulic effect of the water and pushes into the door, thus knocking the entire door off its hinges. This is preferred to the explosive charge by itself, which would instead create a hole in the door not large enough for personnel to enter through.

The second observation was an early indication that foam would be a good material to use in the later tests. In the two spots where pieces of foam were providing standoff, as illustrated in Figure 4.10, the liner had a greater impact on the target and created the small cuts even though the foam did not fill the entire standoff volume. This result was not an intended part of the experiment, but noteworthy nonetheless.

Figure 4.10: Diagram of Standoff Material in Non-Foam Tests.

One individual test result stood out from the others. The 600 gr/ft LSC set directly onto the target's surface (standoff = 0") yielded a rough penetration that was 0.236" deep along the entire length of the LSC, as shown in Figure 4.11. This penetration was shallow and slightly wider than the benchmark tests and appeared not to be the result of a cutting blade but rather the blunt force of the explosives mashing the liner into the target. There was no identifiable run-up or run-down. The recovered liner had a chunky appearance, as if the liner was all smashed into a single line rather than into a blade.

4.3. FOAM VS AIR VS WATER

The LSCs with a foam-filled standoff performed very similar to the LSCs fired in the air. Depth of penetration was equal to or better than the benchmark tests shown in Table 4.1 and Figure 4.13. A supplementary diagram better explains the data in Figure 4.12. Results of the 600 gr/ft LSC tests prior to cutting into profile halves are shown in Figure 4.14. Cut profiles are shown in Figure 4.15. Results of the 1200 gr/ft and the 2000 gr/ft are proportionally similar to the 600 gr/ft results and are shown in Appendix B.

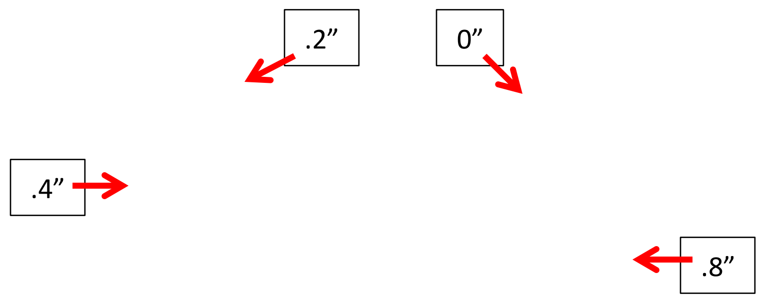

Figure 4.11: Underwater Standoff Comparison Results. 600 gr/ft LSC fired underwater at standoffs of 0.4”, 0.2”, 0.0” and 0.8” (left to right). Their respective copper liners are displayed in corresponding order. (Note: the hole in the target is from an unrelated test.)

A visual inspection of the target cross section from the foam tests revealed that the LSC appeared to perform in a manner similar to that observed in the air tests. A number of the cuts, however, were not as clean. More specifically, penetration was less consistent. In a few cuts, the majority of the profile is close to the comparable profile in air, but in a few places the profile shows a lapse in penetration. These lapses are not present in every profile and vary in size; they are likely due to the poor quality of LSC. These lapses were not a concern, because all of the cut profiles that had lapses still had sufficient lengths of maximum penetration for taking measurements.

Table 4.1: Comparison of Penetration through Various Media. (“Max” column is the maximum penetration point. “3-Max” is the minimum depth of the three deepest penetration points followed by the length across which these points spanned. “5-Max” is the same for five deepest points. Rank indicates deepest to shallowest penetration)

600 gr/ft			Penetration (inches)					
Medium	Standoff	Foam	Max	3-Max	3-Length	5-Max	5-Length	Rank
Air	.6"	No Foam	0.555	0.555	1.247	0.555	1.247	4
Water	.6"	No Foam	0	0		0		5
Water	.6"	White	0.593	0.569	0.858	0.563	1.104	3
Water	.6"	Styrofoam	0.691	0.665	2.112	0.665	2.112	1
Water	.6"	Green	0.661	0.659	0.66	0.627	1.379	2

Figure 4.12: Diagram of Measurements Used in Data Tables. These measurements intend to account for results where penetration was not as deep or complete across the length of the cut.

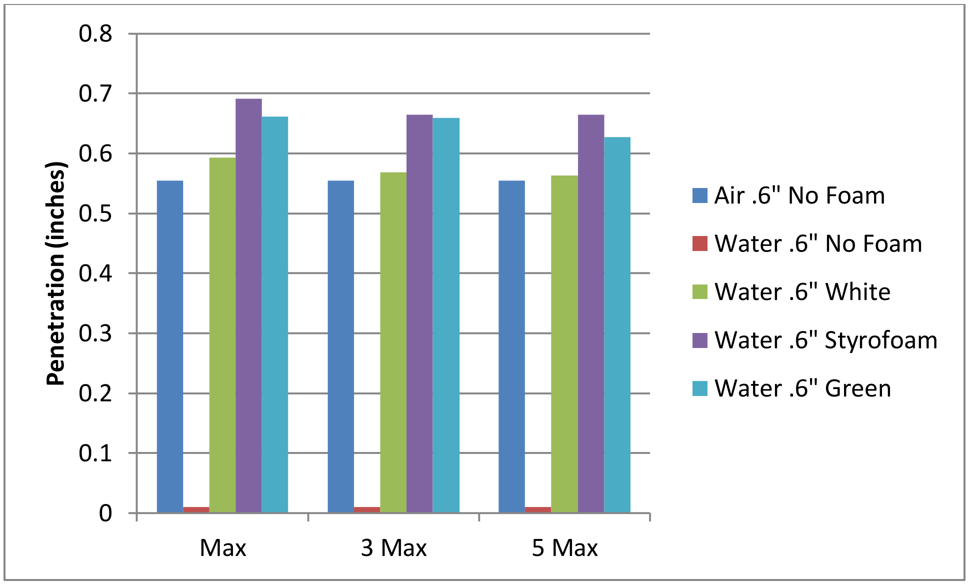

Figure 4.13: Comparison of Penetration Depths through Different Media. This graph represents data in Table 4.1.

Water

Air

Foam

Figure 4.14: Air vs. Water vs. Foam Results. Results of the 600 gr/ft LSC tests at 0.6" standoff underwater (top left), in air (top right) and underwater with a foam-filled standoff (bottom).

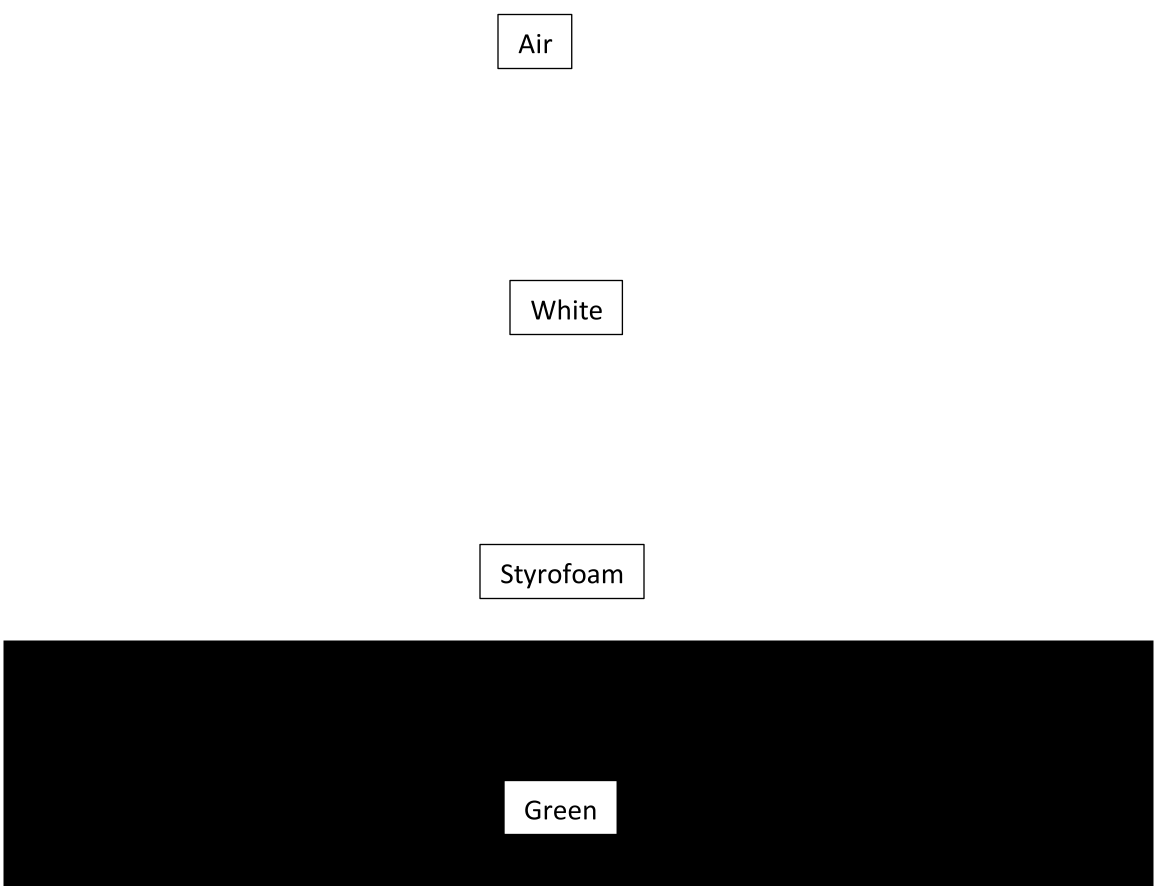

Figure 4.15: Penetration Profiles of Air vs. Water vs. Foam Results. (Left and right are each side of the same cut after cutting with a band saw.) Results of the 600 gr/ft LSC fired in the air (top) and underwater with the following foam-filled standoffs: white foam (2nd from top), Styrofoam (3rd) and green foam (bottom) all at 0.6” standoff.

4.4. CHANGING STANDOFF WITH FOAM

Small changes in the height of the foam-filled standoff had little impact on performance. However, penetration was degraded at standoffs smaller than 0.3”. The target block was cut in half along the cut to better analyze the cut profile. Cut profiles of the 600 gr/ft tests using the white foam are shown in Figure 4.16 and Figure 4.17. Measured results are shown in Table 4.2 and in a chart in Figure 4.18.

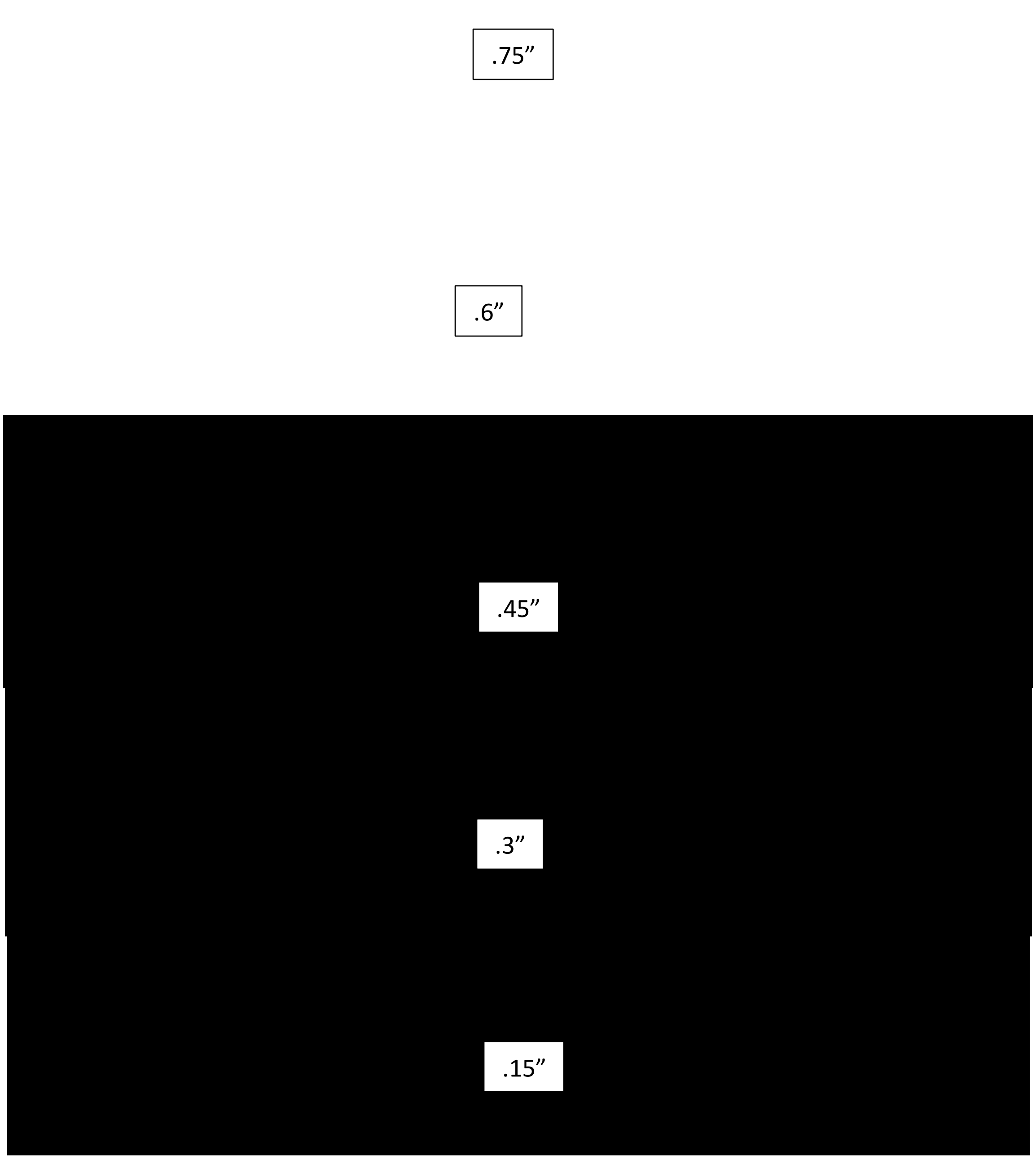

Figure 4.16: Penetration Profiles of Different Sized Foam-filled Standoff Results. 600 gr/ft under water with foam-filled standoff using white foam. From top to bottom: 0.75”, 0.6”, 0.45”, 0.3” and 0.15”. Both sides of the same cut are displayed side by side.

[redacted]

Figure 4.17: Result of Foam-filled Cavity with No Standoff. 600 gr/ft LSC placed underwater with a white foam-filled standoff that was set directly onto target (standoff = 0”). No profile was cut for this test because the penetration was so shallow. This result resembled the zero standoff test conducted without the foam.

Table 4.2: Comparison of Penetration through White Foam at Different Standoffs.

600 gr/ft			Penetration (inches)					
Medium	Standoff	Foam	Max	3-Max	3-Length	5-Max	5-Length	Rank
Water	.75"	White	0.485	0.47	0.675	0.461	1.464	4
Water	.6"	White	0.593	0.569	0.858	0.563	1.104	1
Water	.45"	White	0.503	0.484	0.781	0.475	2.469	3
Water	.3"	White	0.516	0.506	0.634	0.496	1.532	2
Water	.15"	White	0.402	0.396	0.619	0.351	0.814	5
Water	0"	White	0.243	0.243	all	0.243	all	6

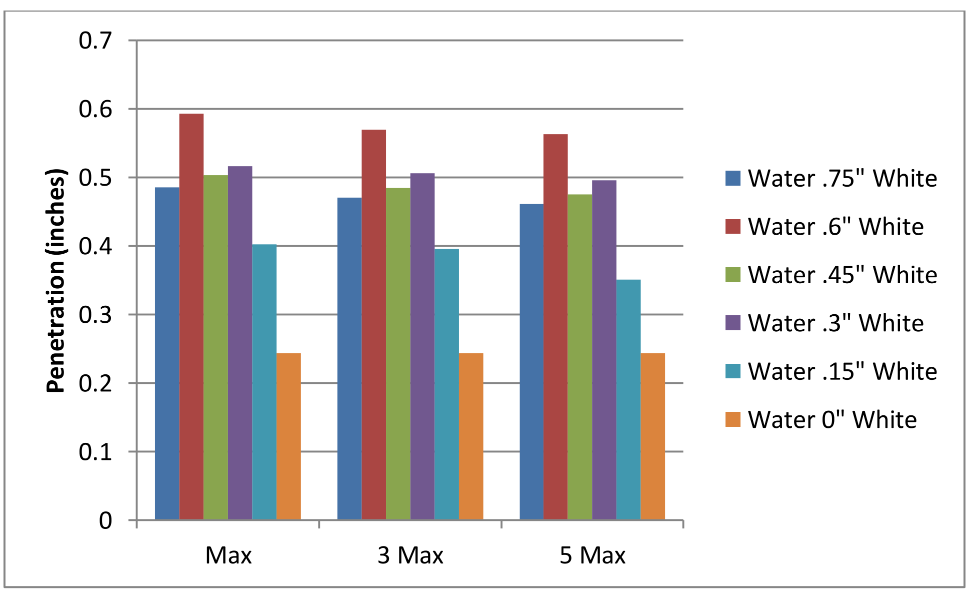

Figure 4.18: Comparison of Penetration Depth through White Foam under Water at Different Standoffs. This graph represents data in Table 4.2.

4.5. CHANGING FOAMS

The performance seemed to be impacted very little by the type of foam used. All the foams performed similarly regarding penetration and consistency, which means the difference in density between the foams was insignificant. The biggest issue identified was ease of use. The white foam was hardest to cut smoothly. Large chunks were removed if the material was bumped accidentally or the saw was moved imprecisely. The green foam was easiest to cut and shape.

The blue insulation foam was not tested because its specifications were similar to those already tested. The spray foam was not tested either; it was not only similar to the other foams, but also incredibly difficult to manipulate. Spraying it into the assembled standoff between the charge and the target meant waiting for the foam to harden, a process which was time-consuming and impractical.

Measured results of the Styrofoam and green foam tests are shown in Table 4.3 and Table 4.4. Pictures and charts of the results of the Styrofoam and green foam tests are shown in Figures 4.19 – 4.22.

Table 4.3: Comparison of Penetration through Styrofoam at Different Standoffs.

600 gr/ft			Penetration (inches)					
Medium	Standoff	Foam	Max	3-Max	3-Length	5-Max	5-Length	Rank
Water	.75"	Styrofoam	0.644	0.629	0.949	0.619	0.949	2
Water	.6"	Styrofoam	0.691	0.665	2.112	0.665	2.112	1
Water	.45"	Styrofoam	0.579	0.562	1.233	0.553	1.223	3

.75”

.6”

.45”

Figure 4.19: Styrofoam Results. Results of the 600 gr/ft LSC underwater with Styrofoam-filled standoff. The standoff from top to bottom was 0.75”, 0.6” and 0.45”. Both sides of the same cut are displayed side by side.

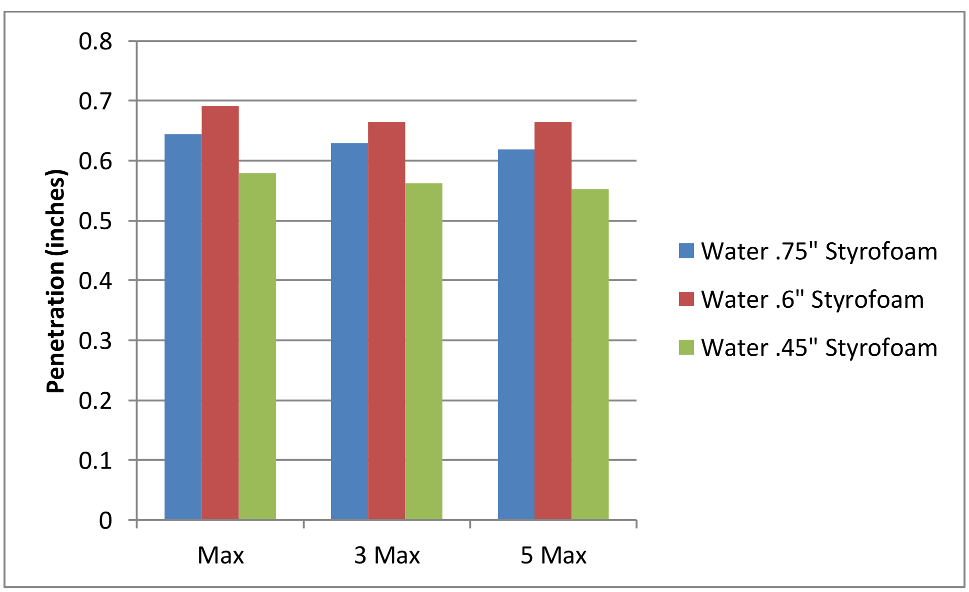

Figure 4.20: Comparison of Penetration Depth through Styrofoam under Water at Different Standoffs. This graph represents data in Table 4.3.

.75”

.6”

.45”

Figure 4.21: Green Foam Results. Results of the 600 gr/ft LSCs under water with a green foam-filled standoff. The standoff from top to bottom was 0.75”, 0.6”, and 0.45”. Both sides of the same cut are displayed side by side.

Table 4.4: Comparison of Penetration through Green Foam at Different Standoffs.

600 gr/ft			Penetration (inches)					
Medium	Standoff	Foam	Max	3-Max	3-Length	5-Max	5-Length	Rank
Water	.75"	Green	0.583	0.473	2.903	0.473	2.903	3
Water	.6"	Green	0.661	0.659	0.66	0.627	1.379	2
Water	.45"	Green	0.708	0.687	0.688	0.68	0.791	1

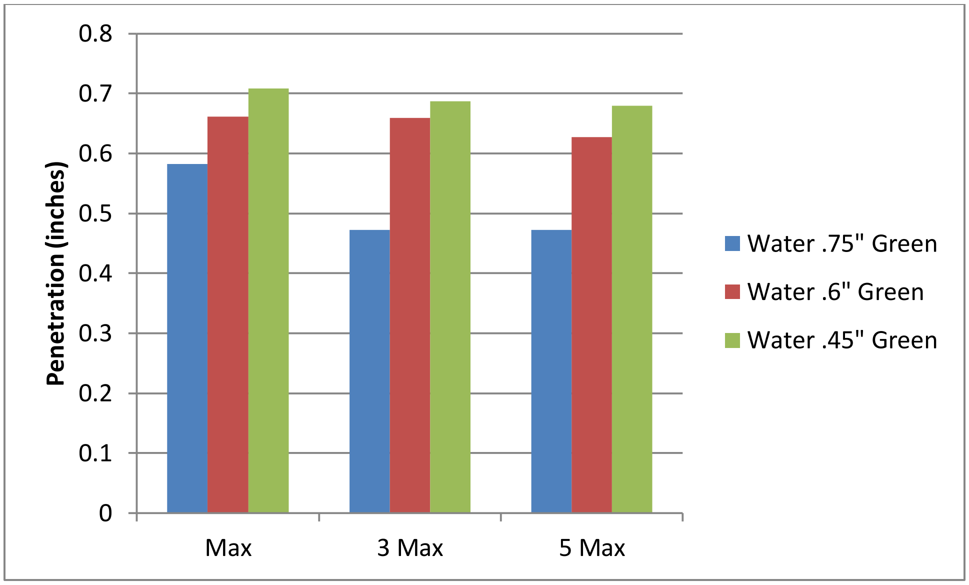

Figure 4.22: Comparison of Penetration Depth through Green Foam under Water at Different Standoffs. This graph represents data in Table 4.4.

4.6. CHANGING FOAM SHAPES AND OTHER VARIATIONS

Several additional tests were conducted with different shapes of foam inside the standoff, as illustrated in Figure 4.23. The purpose of these tests was to determine if water around the standoff, not just inside the standoff, had any significant effect on performance. These tests yielded no significant results. For one test the entire charge with foam was sealed inside cellophane, and for another it was sealed inside a plastic bag, as illustrated in Figure 4.24. The purpose of these two tests was to determine if water seeping inside the standoff area had any effect. These tests also yielded no significant differences in results.

Figure 4.23: Two Foam Shapes Tested. (Left) Foam was cut to fit inside the standoff. (Right) Foam was cut to fit inside and around the standoff to better displace the water.

Figure 4.24: Plastic Seal around Charge and Foam. A couple of methods attempted to determine if water seeping inside the standoff area was affecting performance. The foam shapes were square blocks. A small air gap was present between the foam and the LSC. Cellophane wrap (top) and a plastic bag (bottom) prevented water from filling this area.

5. DISCUSSION

The LSCs' performance was severely reduced when fired under water. The evidence in the results is in line with the stated hypothesis that the greater density and the incompressibility of water are what reduced the performance. In most of the underwater tests without foam the target appears only smoothly dented. This dent indicates a blunt force rather than a cutting force. In the tests with no standoff there was some penetration. While this penetration was not a smooth dent, it was shallow and a little wider than a standard penetration profile. The shallow depth and increased width indicate that the penetration is more due to the proximity of the explosive than from any kind of blade. Unlike the blades recovered from the foam tests, the recovered liner from the zero-standoff underwater test was mashed into a line, which also indicates the liner did not have enough space to form.

In the underwater tests with no target the recovered blades did not completely close to form an effective cutting edge. The water inside the standoff could not be pushed out of the way because it is incompressible, so the closing liner had to push not only the water inside the standoff, but all of the water in the path between the standoff and the edge of the body of water. This larger affected volume coupled with water's significantly greater mass required more explosive force from the closing liner to be moved, so the liner had a significantly lower acceleration and final velocity.

The foam tests showed that LSCs can be effectively employed in an underwater environment. The volume of the foam displaced the water. The foam was both less dense and compressible, so the liner no longer had to act against the larger, denser body of water.

The results of the foam tests were consistently slightly better than the measured result in air. This is likely due to the surrounding water having a tamping effect on the LSC against the foam as mentioned earlier in this thesis.

In comparing the foams, all the foams provided acceptable results, as shown in Figure 5.1. The Styrofoam on average had a slightly deeper penetration and slightly fewer gaps, but these measurements were not significant. Further testing would be needed in order to determine what type of foam would be best.

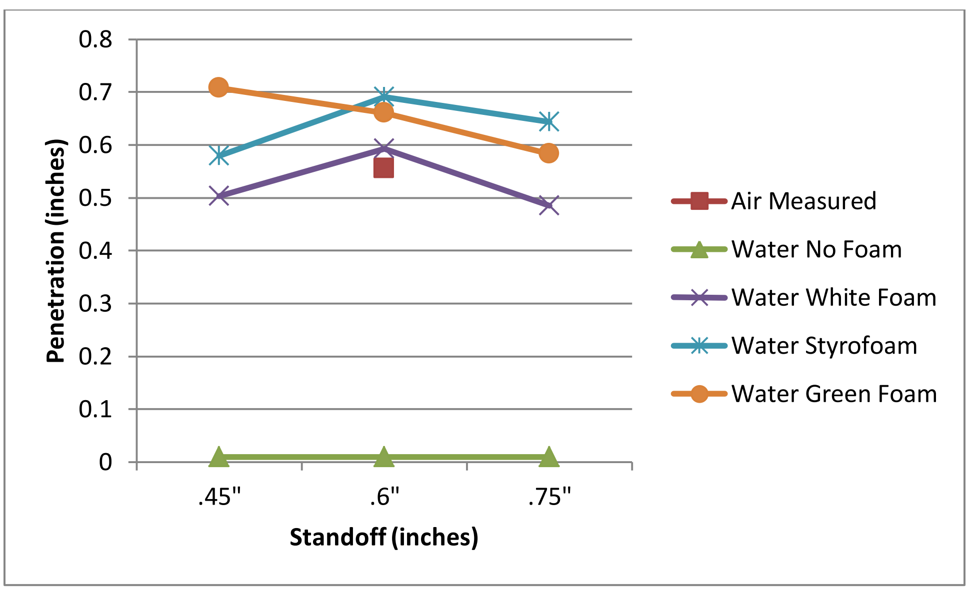

Figure 5.1: Comparison of LSC Penetration through Air vs Water vs Foam.

6. CONCLUSION

The experiments showed that water negatively affected the performance of LSCs. It also showed that displacing the water with less dense and compressible material allowed the LSC to function as designed when under water.

Although various foams were tested and different cross-sectional shapes were used to supply standoff, the difference in the foams' performances was not significant.

With some additional testing, a foam material used to displace water in the standoff area could provide a reliable way to effectively employ LSCs in an underwater environment.

7. FURTHER STUDIES

While the study yielded satisfactory results for the original problem, some additional testing could be done to further understand this topic. The available testing environment could not support testing the effect of using an LSC at a sizable depth. It is possible that different foams or other containment devices would be necessary to withstand the hydrostatic pressure at an increased depth.

Specific foams could be more rigorously tested to determine the cause of the intermittent gaps in the cut profile and to determine a way of preventing these gaps. The cut must be consistent before the industry will accept this method for use.

Different materials and methods of waterproofing could lead to a more reliable setup. Foam was a good starting point, but may not be the best material. One proposed idea that was not tested was encapsulating the LSC in a PVC pipe or some kind of thin container. This would allow the LSC to fire through air and possibly be easier to handle and transport.

APPENDIX A:

TABLE OF TEST RESULTS

No.	gr/ft	Medium/Foam	Standoff	Max	3-Max	3-Length	5-Max	5-Length
1	600	Air	.6"	0.555	0.555	1.247	0.555	1.247
2		Under Water	.8"	0				
3		"	.6"	0				
4		"	.4"	0				
5		"	.2"	0				
6		"	0"	0.236	0.236	all	0.236	all
7		White Foam	.75"	0.485	0.470	0.675	0.461	1.464
8		"	.6"	0.434	0.395	0.739	0.380	0.853
9		"	.45"	0.503	0.484	0.781	0.475	2.469
10		"	.3"	0.516	0.506	0.634	0.496	1.532
11		"	.15"	0.402	0.396	0.619	0.351	0.814
12		"	0"	0.243	0.243	all	0.243	all
13		Green Foam	.75"	0.583	0.473	2.903	0.473	2.903
14		"	.6"	0.661	0.659	0.660	0.627	1.379
15		"	.45"	0.708	0.687	0.688	0.680	0.791
16		Styrofoam	.75"	0.644	0.629	0.949	0.619	0.949
17		"	.6"	0.691	0.665	2.112	0.665	2.112
18		"	.45"	0.579	0.562	1.233	0.553	1.223
19		Triangle taped on sides	.6"	0.593	0.569	0.858	0.563	1.104
20		Square/Air pocket (sealed)	.6"	0.641	0.631	2.237	0.631	2.237
21		Square/Water pocket	.6"	0				
22	1200	Air	.75"	0.821	0.810	0.589	0.775	1.603
23		Water only	1.0"	0				
24		"	.75"	0				
25		"	.6"	0				
26		"	.4"	0				
27		"	.2"	0				
28		"	0"	0				
29		White Foam	.75"	0.597	0.560	0.730	0.523	2.798
30		Styrofoam	.75"	0.909	0.859	0.633	0.818	1.500
31		Green Foam	.75"	0.745	0.664	0.805	0.617	0.805
32	2000	Air	.75"	1.303	1.245	0.764	1.156	1.157
33		Water only	1.0"	0				
34		"	.75"	0				
35		"	.5"	0				
36		"	.25"	0				
37		"	0"	0				
38		White Foam	.75"	1.118	1.001	0.714	0.847	2.691
39		Styofoam	.75"	1.079	1.048	0.601	1.013	1.403
40		Green Foam	.75"	1.282	1.257	1.509	1.257	1.509

Table A.1: Complete List of Tests. The five rightmost columns are a customized method of determining effectiveness. All are measured in inches. The “Max” column is a measure of the single point of maximum penetration. The “3pts” and “5pts” columns are the minimum of the three and five deepest points of penetration. The “Length” column is the measure of the length between the three and five points. The higher the numbers in the points column, the deeper the penetration. The higher the number in the length column, the better the penetration was throughout the length of the LSC.

APPENDIX B:

ADDITIONAL PICTURES OF TEST RESULTS

Figure B.1: 1200 gr/ft LSC at 1.0” Standoff under Water.

Figure B.2: 1200 gr/ft LSC at .6” Standoff under Water.

Figure B.3: 1200 gr/ft LSC at .4” Standoff under Water.

Figure B.4: 1200 gr/ft LSC at .2” Standoff under Water.

Figure B.5: 1200 gr/ft LSC at 0” Standoff under Water.

Figure B.6: 2000 gr/ft LSC at 1.0” Standoff under Water.

Figure B.7: 2000 gr/ft LSC at .5” Standoff under Water.

Figure B.8: 2000 gr/ft LSC at .25” Standoff under Water.

Figure B.9: 2000 gr/ft LSC at 0” Standoff under Water.

Figure B.10: 1200 gr/ft LSC at .75” Standoff under Water through White Foam.

Figure B.11: 1200 gr/ft LSC at .75” Standoff under Water through Styrofoam.

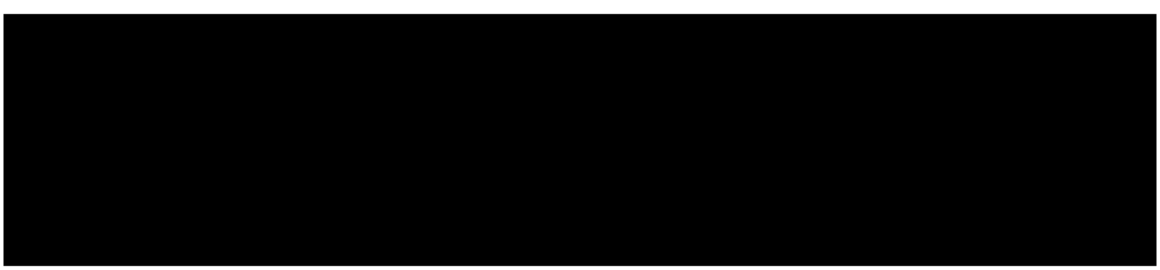

Figure B.12: 1200 gr/ft LSC at .75” Standoff under Water through Green Foam.

Figure B.13: 2000 gr/ft LSC at .75” Standoff under Water through White Foam.

Figure B.14: 2000 gr/ft LSC at .75” Standoff under Water through Styrofoam.

Figure B.15: 2000 gr/ft LSC at 75” Standoff under Water through Green Foam.

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VITA

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