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A modified initiation and cut profile study of the 10500 grain per foot linear shaped charge

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A MODIFIED INITIATION AND CUT PROFILE STUDY OF THE 10500 GRAIN PER FOOT LINEAR SHAPED CHARGE

By

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ABSTRACT

A 10,500 grain per foot (gr/ft.) linear shaped charge (LSC) was developed to cut targets that were too thick for smaller LSC. The manufacturer observed shallower penetration from the 10,500 gr/ft. LSC than was expected. This prompted investigations to uncover the cause of the perceived reduced performance.

A study performed at the Missouri University of Science and Technology changed the initiation method of the 10,500 gr/ft. charge to increase the cut performance of the charge. A modified two point, single end initiation method was devised and tested. This initiation method was termed “dual initiation” and focused on creating a planar detonation wave in the LSC earlier than standard initiation methods.

A series of tests cut steel cuboids to gather cut depth information used to define; maximum penetration and the zones of run-up, cut and run-down. Additional analysis of the target data was performed to find the total cut area achieved by the 10,500gr/ft. LSC. A second series of tests used a pipe as a witness plate to determine failure characteristics of the 10,500 gr/ft. liner.

The results showed the dual initiation method obtained a deeper maximum penetration and greater overall cut area than standard initiation methods. However, the dual ignition method also increased the undesirable cut zone of run-up. The shrapnel characterization tests exemplified the significance of manufacturing defects on the performance of the dual initiation system. Based on the result it was concluded that dual initiation system improved the overall cut performance of the 10,500gr/ft. LSC.

ACKNOWLEDGMENTS

The author would like to thank his advisor, Dr. Jason Baird, for his valuable instruction and guidance in developing and completing this thesis. The author also wishes to express his gratitude to his committee members Dr. Paul Worsey and Dr. John Hogan for their valuable input.

The author gives a special shout out to Dominique Nolan who provided unique insight and a foundational understanding of the 10,500 gr/ft. Similarly this thesis could not have been successful without the experimental assistance of Kevin Phelps, who was continually called upon even once the author left Rolla. The beginning of Kevin’s work as a hand model can be seen in Appendix A.

Finally the author would like to thank all his friends and family for their continued support through the writing process for their valued edits and inputs on the document. (This includes you Dr. Ross!)

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1. INTRODUCTION

Linear shaped charges (LSC) are specialized copper lined explosive devices primarily used in the civilian demolition industry to cut metal targets such as I-beams or steel concrete reinforcement (Diven 2010). The predictable depth of the cut profile of an LSC allows contractors to demolish structures remotely and in a controlled manner. LSCs are manufactured in a variety of sizes.

Accurate Energetic Systems (AES) produces a 10,500 grain per foot (gr/ft.) LSC that is limited to a maximum length of one foot, due to manufacturing restrictions. This created a need to maximize the cut performance over the charge's entire length as AES believed this particular charge was not preforming optimally. A study was undertaken by Missouri University of Science and Technology's (MS&T) Explosive Research Group to identify ways to improve the overall cut performance of the 10,500 gr/ft. LSC.

Figure 1-1 shows the typical geometry of several LSCs, with the 10,500 gr/ft. charge on the far right.

Figure 1-1. Typical LSCs (10,500gr/ft. far right) (AES Linear Shaped Charge Flyer 1/27/05)

The LSCs are generally initiated using a standard blasting cap or small booster. As the geometry of LSCs increase the relative initiation area will decrease. Due to the significant size difference of the 10,500 gr/ft. LSC it was decided that changing the initiation method could improve the overall cutting performance directly after detonation. This decision was also influenced by previous explosive initiation work performed for the initiation of geophysical explosive charges (Ortel 2012). The focus of this research was to develop a two point "dual" initiation method to improve the cut profile of the 10,500 gr/ft. The limited number of LSCs restricted this study to 4 dual initiation tests.

A method developed by SeokBin Lim in 2003 at Missouri Science and Technology was used to characterize the shrapnel pattern of an LSC. These tests utilize a steel pipe to catch the projected copper liner from an LSC detonation. The damage on the pipe illustrates how the explosion propagated. Following Bin Lim's methods a series of shrapnel pattern tests were planned and conducted. The results of the 10,500gr/ft. LSC shrapnel pattern tests were compared to Bim Lim's results to determine the effectiveness of the dual initiation method. Only 2 tests were conducted in this manner as a result of the available number of 10,500gr/ft LSCs.

2. FUNDAMENTAL SHAPED CHARGE THEORY

Two main explosives effects are responsible for the different penetration techniques observed for conical shaped charges (CSC) and LSCs. CSCs advantageously use a hollow cavity effect to form a jetting stream to perforate targets, known as the Monroe Effect (Walters & Zukas, 1989). The formation of a LSC cutting blade is best described by the Misznay-Schardin effect, defined in the following section. The observation that LSCs do not form a jet was published at Missouri University of Science and Technology (Lim, 2006).

Despite the results presented by Bin Lim (Lim, 2006), manufacturers of LSCs continue to advertise that LSCs cut using the “Monroe effect” and form a “plasma jet” (Accurate Energetic Systems, LLC, 2014). Due to the standing misperception of LSC cutting dynamics a description of both processes is provided.

2.1. THE CONICAL SHAPED CHARGE

CSCs are cylinders of explosives with detonators located at one end and cavities at the other, this is depicted in Figure 2-1.

When detonated, the cone shaped cavity experiences an intense localized force that is focused out the bottom of the cone. This is commonly known as the Monroe effect, after Charles E. Monroe who rediscovered the process in 1888. In his experiments he cut cavities in gun cotton (nitrocellulose) and observed different penetration profiles in iron targets based on the shape of their cavities. (Munroe 1887) The process is also commonly known as the von Foerster effect after a German Army officer who is credited with the first demonstration of the shaped charge phenomena (Kennedy 1990)

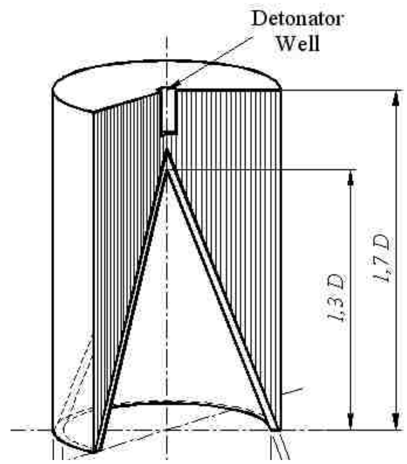


Figure 2-1. Conical shaped charge (http://commons.wikimedia.org/wiki/File:Conical_Shaped_Charge_2.png).

Figure 2-2 shows a sectional view of a computer simulation of the collapse of a CSC; the explosive is colored green and the liner is colored red. The copper liner is symmetrically compressed and pushed out as a fluid jet.

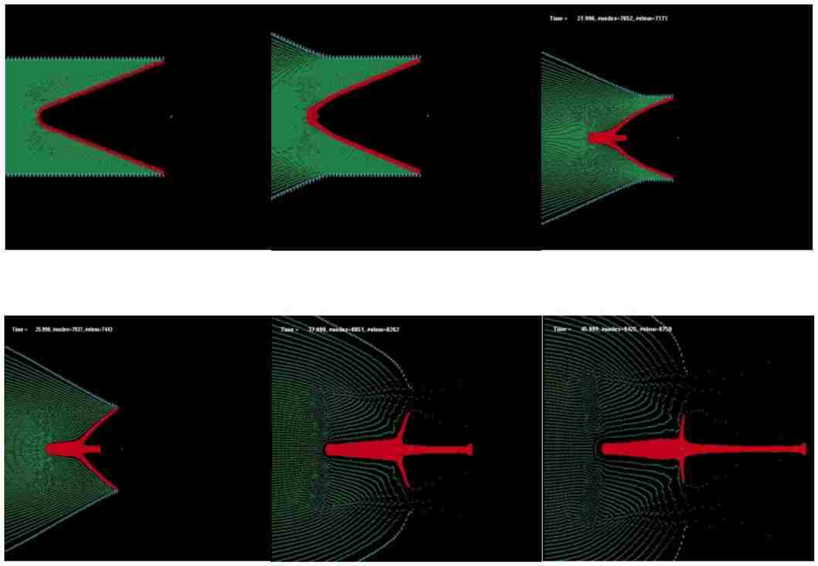


Figure 2-2 Computer simulation of CSC collapse (www.warheadanalysis.com/).

2.2. THE LINEAR SHAPED CHARGE

LSCs use the Miszany-Schardin effect to project a copper liner off of a central explosive charge. In 1944, Hungarian explosives expert József Misznay and German expert Dr. Hubert Schardin demonstrated this effect to in order to develop more effective anti-tank weapons. (Schardin 1954) Upon the conclusion of World War II, they continued their research in the United States, which eventually lead to the development of the M18 Claymore antipersonnel mine pictured in Figure 2-3. (Lim 2006)

Figure 2-3. Claymore mine (http://www.imfdb.org/wiki/M18A1_Claymore).

The Miszany-Schardin effect describes how a sheet of explosive material, when detonated, will always create a force perpendicular to the original face of the explosives.

A typical LSC has six flat faces where the Miszany-Schardin effect describes the observable phenomena (Vigil 1996). The 10,500 gr/ft. charge has an extra surface on the top as shown in Figure 2-4; manufacturing restrictions lead to this deviation in the design of the 10,500 gr/ft. LSC. It was worth noting that during a visit to the AES LSC manufacturing facility in 2013 the 600 gr/ft. LSC was identified by AES personnel as an LSC that performs optimally.

Figure 2-4. Typical LSC (left) 10,500 gr/ft. LSC (right).

When detonated, the copper liner is projected normal to each of the 6 planes resulting in the collapse of the “V” shaped” bottom as the legs are pushed together. The resulting interaction of the two legs will cause the interface of the impacting legs to become unstable (Hammerberg 2009) which ultimately welds the legs together. This is illustrated by an isometric view of an LSC model run in AUTODYN (Lim 2006). Figure 2-5 shows the charge liner (green) 13 microseconds (μsec) after detonation and Figure 2-

6 shows the position of the copper liner (green) 27μsec after detonation. This simulation was run assuming that shocked copper deforms elastically.

Hydrodynamic computer simulations are dependent on equations of state for the defined materials and have successfully reproduced stress and velocity measurements from shock wave experiments (Steinberg 1979). This modeling technique was advantageously used by Lim in his work at Missouri University of Science and Technology.

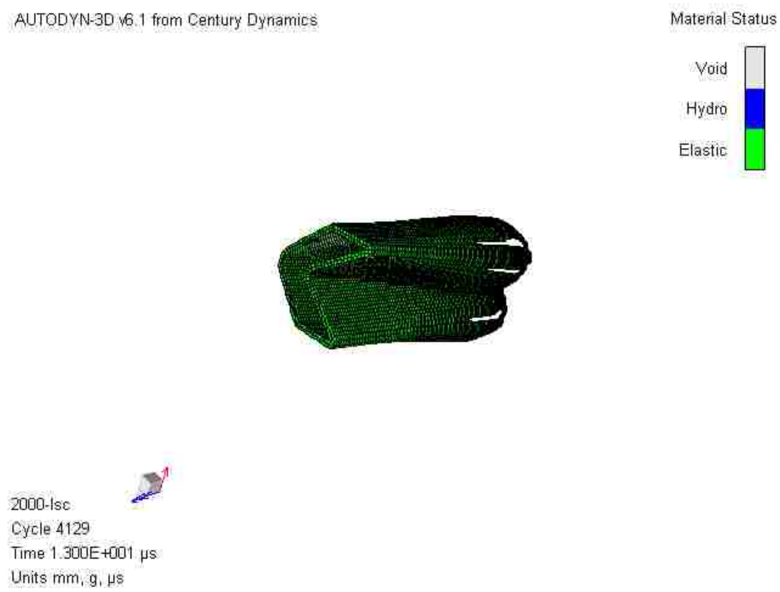


Figure 2-5. LSC 13μsec after detonation (Lim, 2006) The LSC liner was the only material that was displayed in this simulation. Notice the deformation of the liner as the explosive core detonates. This causes the legs of the LSC to start to collapse inward and the sides be projected perpendicularly off the charge.

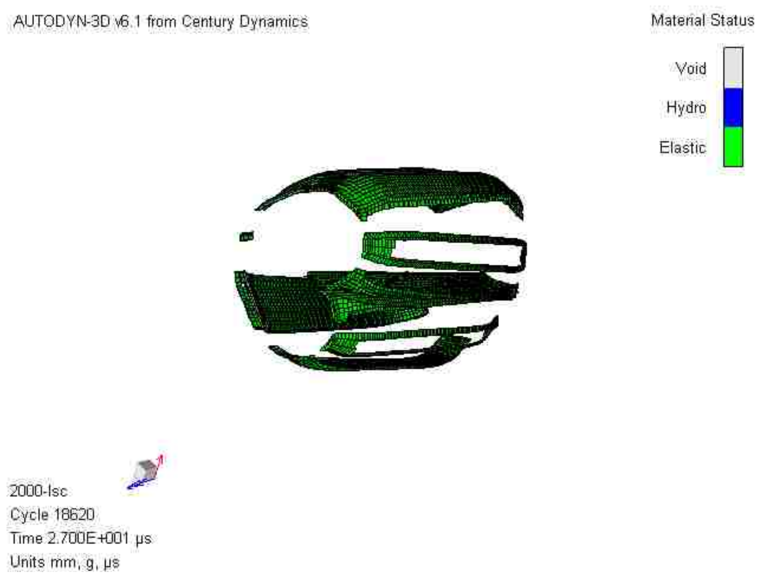


Figure 2-6. LSC 27µsec after detonation (Lim, 2006). By this time the explosive has accelerated the entire length of the LSC liner. Notice how all the faces have been projected outwards (when compared to figure 2-5) and the blade has almost completely formed from the collapse of the LSC legs.

The fragment formed from the collapse of the bottom of an LSC is used to cut targets and has been referred to as a carrot, ribbon, or blade. The blade travels at about half the velocity of a CSC jet (Hayes 1984) and can be captured with minimal deformation or damage by shooting an LSC into a body of water. Examples of captured blades are illustrated in Figure 2-7.

Figure 2-7. Recovered LSC blade segments using a water catch system (Tabacchi, 2014).

3. PREVIOUS WORK WITH LINERAR SHAPED CHARGES

In the early 2000's tests to cut reinforced concrete made the knowledge gap between CSCs and LSCs apparent at Missouri University of Science and Technology. Research was performed to fill the knowledge gaps. The studies applicable to the dual initiation research of this thesis are reviewed in the following subsections.

3.1. PERFORMANCE EVALUATION AND EFFECTS OF STANDOFF ON 10,500 GRAIN PER FOOT LINEAR SHAPED CHARGE

Previous work performed by the Explosives Research Group at MS&T investigated the cutting performance of Accurate Energetic Systems' 10500 gr/ft. LSC at different distances from a target. The distance between the bottom of an LSC and a target was referred to as a standoff distance (Hayes 1984). Standoff distance is usually defined as a function of the charge diameter multiplied by a constant. Figure 3-1 defines common terms used to describe the physical dimensions of LSCs.

The standoff distances used by Nolan varied between 0.5-2.0 charge diameters. The targets used in this test series were blocks of A36 steel with dimensions of 14in long by 4in wide by 4.5 in high. (Nolan 2013)

Each standoff distance was tested 4 times, obtaining an eighty percent confidence of bounding the mean value. This data set is too small to provide a standard deviation, however, the decision to use only 4 tests was justified by the limited availability of charges and the large number of proposed tests.

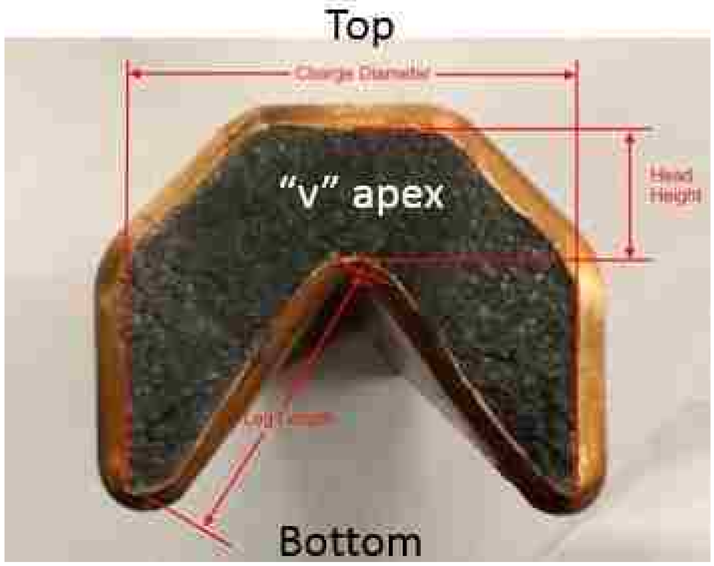


Figure 3-1. Parameters of an LSC (Nolan, 2013). The charge diameter is the width of the explosive core of the LSC. The Head height is the distance in the explosive from the top of the inner V apex

The cut profile of an LSC was defined by three different zones; run-up, cut and run-down zones. The run-up zone was described as the area of suboptimal cut depth on the side of the target where the LSC was initiated. The cut zone was the area where there was a stable almost horizontal cut depth. The run-down zone occurred on the side of the target opposite to the initiation point. This was where the cut depth decreased from the cut zone to a point where there was no longer any cut. Figure 3-2 shows the cross section of a cut target with the different cut zones labeled.

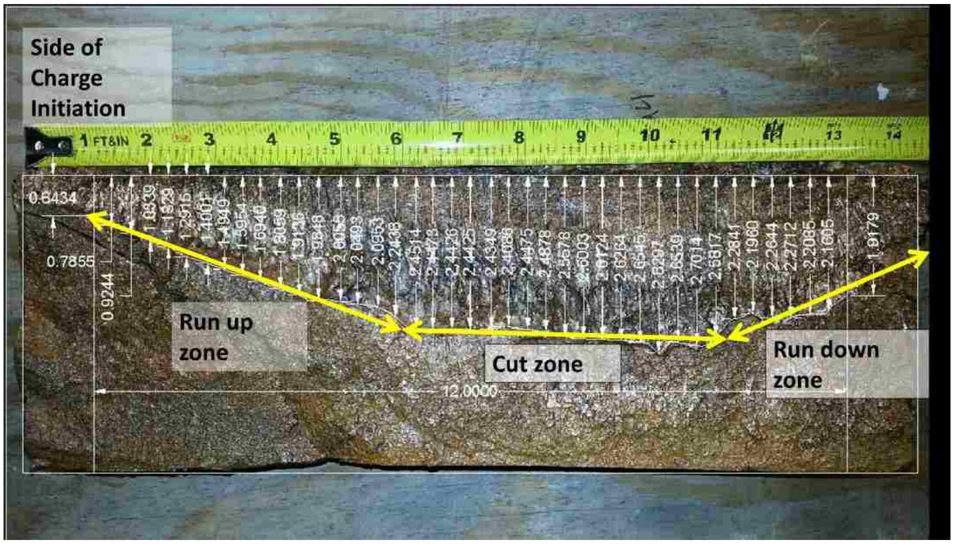


Figure 3-2. 10,500 gr/ft. target and the defined cut profile zones with depth measurements.

The performance evaluation, led by Nolan, provided data not only concerning the different cut zones but also the maximum penetration data. The following table summarizes the findings from the performed research.

Table 3-1 Summary of Nolan's Data (units cm) (Nolan, 2013).

Series	Shot #	Run Up	% Length Run Up	Run Down	% Length Run Down	Optimum Penetration	% Length Optimum Penetration	Max. Pen.	Average Max. Pen.
0.5 CD	1	8.382	27.50	0.000	0.00	22.098	72.50	5.6902	5.7364
	2	7.620	25.00	0.000	0.00	22.860	75.00	5.2531	
	3	4.572	15.00	0.000	0.00	25.908	85.00	5.1932	
	4	7.620	25.00	0.762	2.50	22.098	72.50	6.8089	
1.0 CD	1	6.858	22.50	2.286	7.50	21.336	70.00	7.2847	6.0427
	2	8.382	27.50	1.524	5.00	20.574	67.50	5.9863	
	3	8.382	27.50	1.524	5.00	20.574	67.50	5.5608	
	4	9.906	32.50	0.000	0.00	20.574	67.50	5.3391	
1.5 CD	1	8.382	27.50	0.000	0.00	22.098	72.50	4.8642	4.8737
	2	9.906	32.50	2.286	7.50	18.288	60.00	3.8562	
	3	10.668	35.00	0.000	0.00	19.812	65.00	6.1466	
	4	9.144	30.00	1.524	5.00	19.050	62.50	4.6277	
2.0 CD	1	7.620	25.00	0.000	0.00	22.860	75.00	4.7381	5.5050
	2	7.620	25.00	0.000	0.00	22.860	75.00	4.8627	
	3	10.668	35.00	0.762	2.50	19.050	62.50	5.2801	
	4	12.192	40.00	0.000	0.00	18.288	60.00	7.1392	

The zero values recorded for cut run-down occur when the cut abruptly stopped without a gradual decay in the depth of the cut. This research concluded that the most effective standoff distance was equal to the charge diameter. These results were in accordance with the approximation of 0.9 times the charge diameter as defined by Cooper (Cooper, 1996) but is smaller than the 1.04 times the charge diameter (2.5 in) recommended by Accurate Energetics Systems. (Accurate Energetic Systems 2014)

It was noted by the authors that the cut depth for half a charge diameter was on average 30mm less than the cut depth at 1 charge diameter standoff. However, all the targets were separated into two unique halves during the 0.5 charge diameter test series whereas the one charge diameter tests did not always separate into two halves. This phenomenon was also observed during the dual initiation test.

The test setup used in the performance evaluation of 10500gr/ft. LSC (Nolan, 2013) was used in the dual initiation tests and will be thoroughly outlined in Section 4.2.

3.2. LSC INITIATION

The point of initiation on an LSC can greatly affect the proper formation of an LSC cutting blade and significantly affect the performance of an LSC. In a 2003 study (Lim 2003) published through the International Society of Explosives Engineers, 4 different initiation positions were investigated. Tests using 500gr/ft. LSCs investigated single end, mid-point, linear and dual end initiation methods. An overview of these initiation methods is presented in Figure 3-3. The dual initiation method was previously discussed is described in Section 4. Note all figures in the following Subsections are direct excerpts from Lim's study.

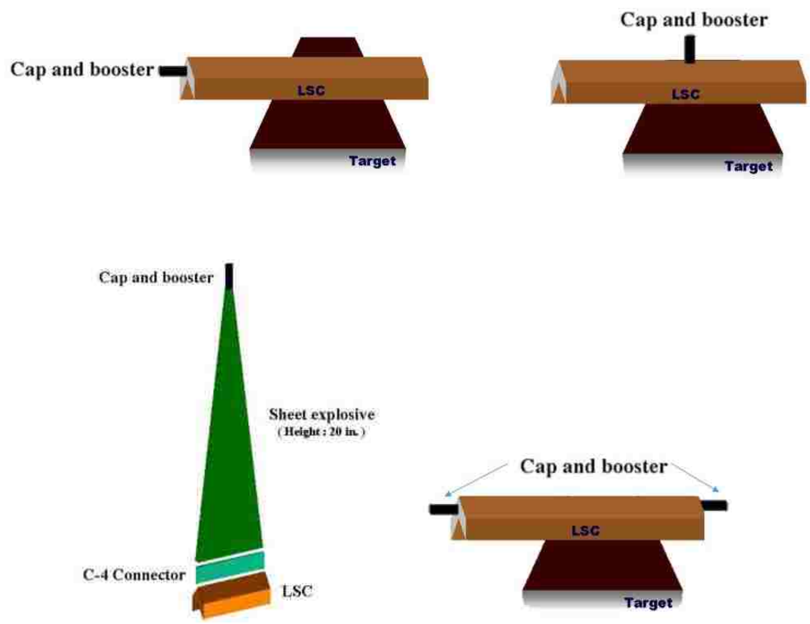


Figure 3-3. Single end initiation (upper left), mid-point initiation (upper right), linear initiation (bottom left) and dual end initiation (bottom right) (Lim, 2003) These initiation methods will be discussed further in the following Subsections.

3.2.1. Single End (Standard) Initiation. A single blasting cap was attached to a piece of wood molding and placed at the apex of the explosive of the LSC. Which was positioned over a steel target. After the charge was fired, the target was mechanically sectioned (cut with a band saw) and the cut profile was manually inspected. Researchers noted that the run-up zone had a smooth penetration slope of 30^{o} and was 1.35 inches long. This set up is shown in Figure 3-4 along with the sectioned target in Figure 3-5.

Figure 3-4. Single end initiation test setup (Lim, 2003). This initiation method places a cap at one end of a LSC aiming to start the detonation at one side of the LSC and have it progress to the other.

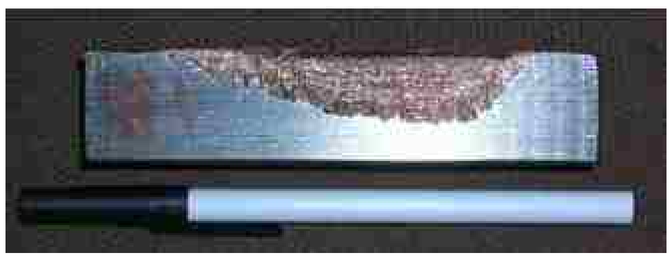


Figure 3-5. Observed cut profile of single end initiation (pen for scale) (Lim, 2003. The cut profile observed in this target block is a fairly representative cut profile. The zones of run-up, cut and run-down are clearly visible. This initiation method performed as hoped and is recommended by Lim as viable initiation method that produces an acceptable cut profile.

3.2.2. Midpoint Initiation. A blasting cap was inserted into a hole drilled in the liner of the LSC. The hole was located at the midpoint of the apex of the charge, seen in Figure 3-6. The cut profile directly under the initiation point was very shallow with the depth increasing in both directions away from the initiation point. Moving out from the initiation point, the cut profile was almost identical to a single end initiation. Figure 3-7 images the cut profile of the midpoint test.

Figure 3-6. Midpoint initiation test setup (Lim, 2003). For this initiation method started the detonation in the center of the LSC via a hole that was drilled through the liner. This method was developed based on the idea that cut dynamics of a LSC was similar to a CSC.

Figure 3-7. Midpoint initiation cut profile. This cut profile show that the midpoint initiation method did not increase the cut performance of the LSC instead it nearly doubled the zone of run up.

This initiation method was not recommended because it doubles the amount of run-up for a charge. The charge did not perform optimally in the center of a cut which is usually where a deeper cut is preferred.

3.2.3. Linear Initiation. LSCs were initiated along their entire length using a purpose build primer designed to create a planar detonation wave along the entire apex of the LSC. A channel was cut out of the top of the copper liner to allow intimate contact between the explosive core of the LSC and the priming device. Figure 3-8 depicts the test setup and Figure 3-9 shows a comparison of the resulting cut profile of the linear initiation (top) and single end initiation (bottom).

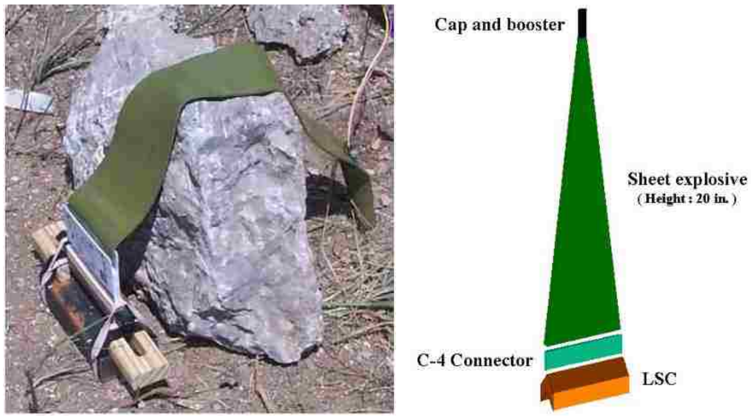


Figure 3-8. Linear initiation test setup (Lim, 2003). Similar to the midpoint initiation method this was developed with the belief that LSCs performed similar to CSC. A slit was cut in the LSC liner and explosives were inserted into the cut. A cap was placed at the end of a high explosive sheet to try and achieve a completely simultaneous initiation of the top of the LSC.

Figure 3-9. Linear initiation cut profile (top) single end initiation (bottom) (Lim, 2003). The cut profile of the linear initiation method shows that is performed worse than the single end initiation. There was no run-up observed and only a small amount of run-down on each end of the cut profile however the maximum cut depth was far less than the single point initiation method.

It is apparent in Figure 3-9 that the linear initiation method reduced the total cut depth but created a more uniform cut profile. This method was not recommended because a reduction in cut depth is equivalent to a reduction in performance.

3.3. LSC DATA ACQUISITION STUDIES

Researchers have several methods of data acquisition available for to obtain experimental data. Three different methods used to obtain cut depth data were explored in "New Methodology in Measuring Experimental Results of Linear Shaped Charges Using Digital Software" (Phelps 2013). An overview of the three measurement methods as described by the Phelps and his contributing authors is provided.

All three measurement methods required the target block to be separated into two halves. The LSC often separated the target completely. However, targets that did not separate were cut in half using an oil-cooled band saw, Figure 3-9 pictures targets that were cut using a saw.

3.3.1. Hand Measurement. This was the first of the three methods used to measure the cut depth of LSCs. Researchers used mensuration tools to gather the run-up, optimal cut, and run-down lengths. Three measurements were usually taken along the optimal cut zone on both halves of the target; at the maximum, minimum and at an additional randomly chosen point within the optimal cut zone. This method was highly subjective because it required researchers to visually choose a point along the cut and hand measure it. The distortion of targets from the force during separation required researchers to approximate the beginning and ending of the different cut zones. This method was the most rapid and simplistic method, which compromised the accuracy and reliability of the gathered data.

3.3.2. Digital Analysis. Digital analysis required both halves of a target to be positioned with the cut end facing upward. A camera was positioned above the targets and pictures were taken with a scale in the frame. The photo was uploaded to a computer and manipulated with a Photoshop-like program called GIMP. This software was used to remove distortion from the camera lens which. This effect is known as barrel distortion and causes the center of a target to appear distorted closer to the camera than the target's edges would appear.

Barrel distortion was removed from the image and the scale function in AutoCAD was used to define points along the scale in the image to measure distances. The points at the beginning of each cut zone were subjectively chosen and measured. This method was more time intensive than measuring by hand however it increased the accuracy of the measurements. Digital analysis also provided a way to document cut depth photographs so that, if needed, another study can use and reanalyze the data.

3.3.3. Digital Analysis and Excel. The final method was built off of the aforementioned digital analysis method. Once the target photograph was imported and scaled in AutoCAD, the cut profile was measured along the entire length on a constant interval. This study recommended measuring the depth of cut every 0.3 inches.

Using Microsoft Excel, depth measurements are analyzed using a series of logic functions to define the run-up, cut and run-down zones. The tool requires user defined acceptable deviation and maximum penetration to determine a maximum penetration range. The tool identified if the cut depth was increasing or decreasing, i.e. the run-up zone. By comparing consecutive averages, run-up was determined if successive values were greater than the previous two. Values that overlapped with the maximum penetration zone were re-categorized as the zone of maximum penetration.

The advantage of the “data analysis and excel” method was the clear cut divisions along a sample and the removal of bias. Additionally, output data was easily stored and archived for future analysis using different techniques.

The original spreadsheet tool defined the cut zones based on a user defined accepted deviation from max penetration in centimeters (Phelps 2013). When the author, Phelps, was contacted, the spreadsheet tool had been updated to allow the user to enter acceptable deviation as a percent of the max penetration and minor updates were made to the underlying algorithms. Note if future research requires the excel tool contact Phelps (Phelps, 2013) for the most current version of the tool.

3.3.4. Shrapnel Characterization. Additional data on the failure characteristics of the copper liner of LSCs can be gathered by a pipe test (Lim 2003). These tests can provide qualitative information on the failure pattern of the LSC copper liner.

In Lim’s tests an LSC was placed in the center of a ¼in. thick steel pipe with an interior diameter of 6in. The pipe was used as a witness plate to show the impact pattern from the copper liner of the LSC. A 5in section of a 500gr/ft. LSC was held in the center of the pipe by copper wire with a piece of wood molding attached to each end of the LSC to stop any swinging. The pipe section was long enough to capture the entire shrapnel pattern of the LSC (10in. long). The LSC was initiated using the single point end initiation method described in Section 3.2.1. After it was fired, the inside of the pipe was closely examined.

This test setup provided an excellent shrapnel pattern with five distinct and major impacts on the pipe. The resulting pattern from Lim’s tests is presented in Figure 3-10.

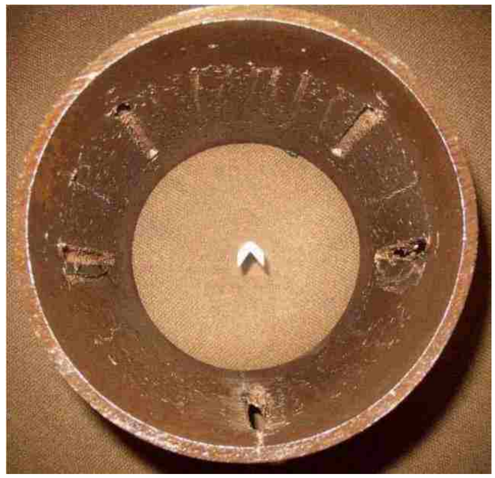


Figure 3-10. Result of pipe test (Original orientation of LSC at center) (Lim, 2003) notice how there was a significant impact that perforated the pipe from the bottom of the LSC. This was a result of the blade impact. It was also worth noting the right most impact also perforated the pipe, this fragment originated from the leg of the LSC.

Out of the five major impacts, the bottom and largest impact was produced by the LSC blade. The other four impacts were oriented perpendicular to the four flat faces of the LSC this was a direct representation of the Misznay-Schardin effect. The width of the indentations roughly matches the original length of the LSC face, which can be approximated in Figure 3-10. The smaller shrapnel patterns, between significant impacts, resulted when the corners were pulled apart.

4. DUAL INITIATION THEORY AND EXPIRIMENTAL TEST SETUP

Run-up and run-down were not usually significant issues with LSCs because the charges are manufactured in long lengths that can be cut on site to any desired size. The manufacturing process of the 10,500gr/ft. charge limited the total length to 12 inches. This is because the 10,500gr/ft. LSC is too large to fit in the roller and dye machines used to make smaller LSCs and has do be shaped with a mechanical press. This created a need to maximize the cut depth over the entire length of the charge. As shown by Nolan in "Performance Evaluation and Effects of Standoff on 10,500 grain per foot Linear Shaped Charge" anywhere from 22.5% to 32.5% of the cut was lost to the zone of run-up. Another 0 to 7% of the cut can be lost in the zone of run-down. Potentially 40% (4.8 in) of the cut profile for a 10,500gr/ft. LSC was less than the desired cut depth resulting in nearly half of the charge not performing as designed.

4.1. DUAL INITIATION THEORY

Based on the results of the initiation work described in the Section 3.2. a modified single end initiation method was devised by the Author, referred to as the dual initiation method. This method focused on creating a planar detonation wave in the LSC earlier (i.e., closer to the end of the LSC) by increasing the area initiated on the face of an LSC. In initiated explosives the detonation wave travels spherically outward at a constant velocity (detonation velocity) from the point of initiation (Cooper 1996). The charge diameter/face area of the 10,500gr/ft. was significantly larger than that of other LSCs, resulting in a larger time and distance requirement for the detonation wave to become planar.

Figure 4-1 shows a simplistic idealized representation of a planar shock wave and compares it to an expanding shockwave with the initiation point represented by a red dot. The arrows represent potential velocity vectors. It is important to notice that the wave traveled into the page and was constrained by the shape of the LSC.

Figure 4-1a. has constant velocity vectors along the entire leg length because the wave was planar and equally accelerated the entire copper liner. Whereas

Figure 4-1b. shows a velocity gradient along the leg length because the explosive has had more time to accelerate the apex of the “V”.

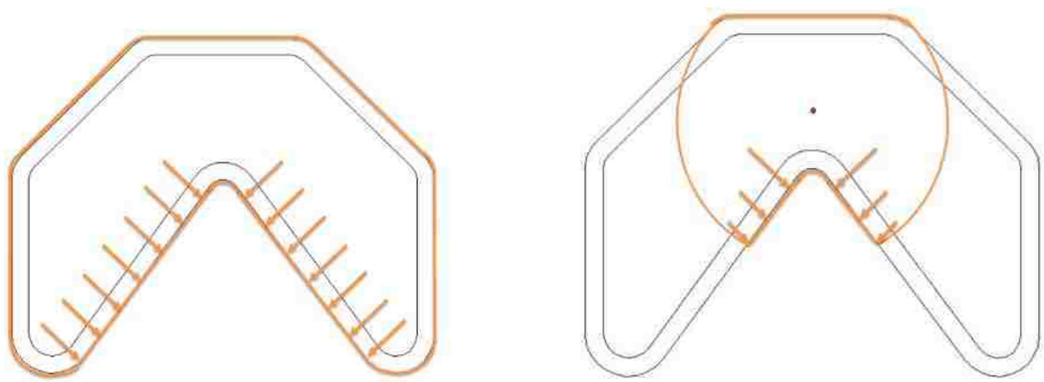


Figure 4-1. Planar shock wave (left) non-planar shock wave (right). The non-planar shockwave diagrams assume the initiation took place as a point initiation (marked in the head height of the LSC). The shock wave has progressed from the initiation point and accelerated the LSC legs at the apex but has not accelerated the leg further down the charge. Whereas when the detonation wave is planar (left) the entire leg length is uniformly accelerated.

The interaction of a non-planar detonation wave and metallic sheath was known to cause stress fractures in the metal (Baird) which likely contributed to the large amount of run-up observed with the 10,500gr/ft. LSC. When the detonation wave was not planar it resulted in the inner “V” of the LSC legs to collapse progressively from top down as the detonation wave progressed down the leg of the LSC. When the detonation wave became planar, it uniformly forced the copper liner inward along the entire leg length of the charge. The single point top initiation method discussed in Subsection 3.2.2 exemplifies the negative cutting effects of the non-planar shock wave because it resulted in twice the amount of run-up as seen in Figure 3-7.

In reality, the shock reflections and gas expansion from detonation create a significantly more complex shock wave shape than is depicted in Figure 4-1. However, the figure provides a good diagram to help visualize the effect of the expanding shock wave on the collapse of the inner liner (e.g. blade formation).

The dual initiation theory assumes a significant cause of the run-up observed in the 10,500gr/ft. LSCs was due to the time (distance) necessary for the shockwave to become planar. Therefore, the dual initiation method used two simultaneous detonations in the “wings” of the 10,500gr/ft. charge to initiate it. Figure 4-2 illustrates shockwave propagation from the two initiation points.

It was crucial for the initiation to happen simultaneously, or the blade would not collapse symmetrically, which would reduce the penetration performance of the LSC. As part of a study presented at the 7th International Symposium on Ballistics (Held 1983) researchers noted that a single initiation point must be set precisely at the mid-point of the cross section or, the explosive core would not be initiated symmetrically and decrease penetration performance.

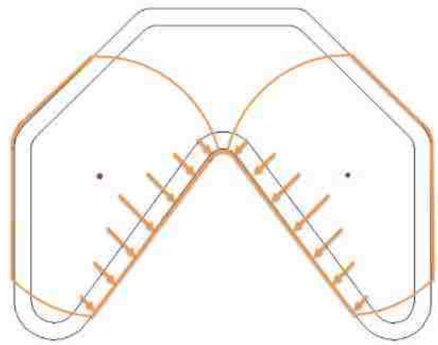


Figure 4-2. Dual initiation theoretical shock wave. This representation assumes the initiation started in the marked points and has had time to progress through the charge. The arrows represent the hypothetical velocity magnitudes along the length of the leg of the inner liner. The position of the initiation points was selected so that the detonation wave could accelerate the entire leg length of the LSC and produce a planar detonation wave earlier in the charge.

Non-symmetric initiation likely caused the legs to collide with different velocities at some off-center angle. The non-symmetric collision either broke apart or rotated the blades and impacted a target at a random angle. This effect was observed during testing, however, non-symmetric initiation is not the focus of this thesis and is not explored further.

Both initiation points in Figure 4-2 were below the apex of the “V”. This theory assumed that the downward velocity of an LSC blade was not dependent on the head height of the charge. Instead, the downward velocity resulted from the sum of the velocity vectors imparted to the legs by the explosive directly behind the copper liner. The symmetry of the LSC caused a cancelation of the horizontal component of the velocity vector and a summation of the vertical components.

4.2. EXPERIMENTAL TEST SETUP

Electronic systems can achieve the precise timing required for the dual initiation method. However, the net explosive weight of the 10,500gr/ft. LSC exceeded the limit of the indoor test facilities at the University of Science and Technology Explosive Research Lab. The initiation device also needed to be portable or easily constructed, which leaned the focus away from sophisticated electronics. The following section details the initiation system developed for this research. The charge standoff and target were kept consistent with the procedures used by Nolan. This allowed for a direct comparison of the standard initiation method and the dual initiation method when applied to a 10,500gr/ft. LSC.

4.2.1. Initiation System. A multi-step explosive initiation system was devised and employed to achieve the dual initiation of the 10,500gr/ft. LSCs. An electric blasting cap initiated two 6-8in lengths of 25gr/ft. detonating cord (det-cord). Only one blasting cap was used in this initiation method to remove any variation introduced by multiple pyrotechnic delays. The Det-cord detonated two aluminum cased 0.2734oz RDX AAP3 boosters connected in series with 0.2822oz Dyno Noble stingers comprised of mechanically pressed Pentolite. This method relied on the constant detonation velocity of; det-cord (25,000ft/s), mechanically pressed RDX (28,700ft/s), and Pentolite (25,600ft/s). The precise lengths of the explosives in the different stages of this initiation method allowed for essentially simultaneous initiation in the wings of the 10500gr/ft. charge. A diagram of this initiation method is presented in Figure 4-3.

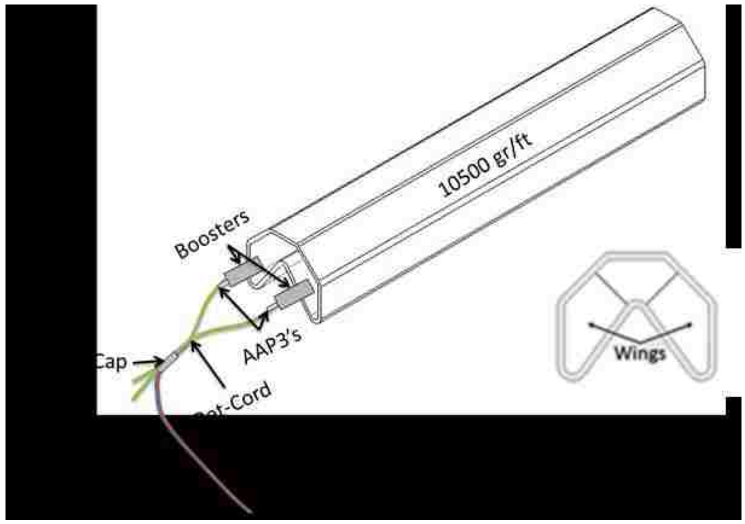


Figure 4-3. Diagram of the dual initiation method.

Detonation velocities were taken from product specification sheets (Dyno 2013) and detonation velocity tables (Cooper 1996). The process of constructing a dual initiation device is outlined in the following bulleted list:

- Two identical lengths of det-cord were cut. Special attention was paid to not pour explosive out of the freshly cut end.
- Electrical tape was wrapped around the end of the AAP3. This ensured that AAP3 was secure when inserted into the booster.
- The det-cord was held horizontal and the newly cut end was inserted into an AAP3.
- The end of the AAP3 was crimped twice, turning it 90 degrees between each crimp.
- The AAP3 was inserted into the booster.

- The above process was repeated to make the second half of the dual initiation device.

The step by step process of manufacturing the dual initiation system is archived in appendix A.

After manufacturing the dual initiation system, it was secured to the charge. The inner “V” of the LSC shouldn’t be obscured when the boosters were attached. In this study, tongue depressors were secured to the outside of the LSC legs and used as anchors for the boosters. The boosters were positioned on the 10,500gr/ft. LSC so that the top of the booster was in line with the apex of the inner “V”. The distance between the booster and the copper on the inside of the LSC leg was held constant when possible. Once in position the boosters were secured to the tongue depressors using electrical tape,

Figure 4-4 shows this placement. The tongue depressors on either side can’t be easily seen because they were oriented perpendicular to the camera lens.

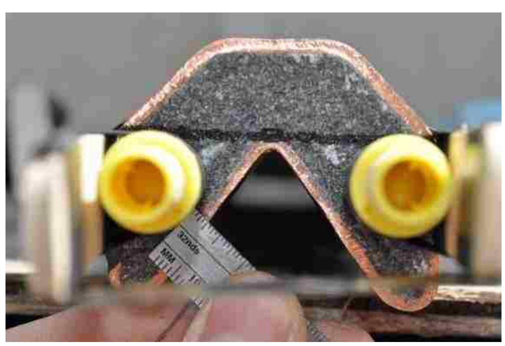


Figure 4-4. Position of the initiation device. The inner V of the LSC was not obstructed when boosters were attached and the position of the boosters was symmetric about the center of the charge. The boosters were lined up with the apex of the inner V and the distance from the booster to the inner liner was kept constant.

The booster was in intimate contact with the explosive face of the LSC. If there were no defects in the end of the charge then the booster would sit perpendicular to the explosive face.

Once the initiation system was secured to the 10,500gr/ft. LSC, the range was cleared so that the blasting cap could be attached to the det-cord. The length of det-cord from the end of the blasting cap to the AAP3 were kept equal for both sides of the initiation system. A distance from the AAP3 was measured and marked on the det-cord, usually 6 to 8 inches. Then the tip of the blasting cap was lined up with the marks and taped to both lengths of det-cord. Note: the blasting cap should only be attached when the charge is ready to fire. Figure 4-5 shows the final charge setup including the initiation system, blasting cap and 10,500gr/ft. LSC.

Figure 4-5. Final charge setup. When the initiation system was attached to the charge it was important to ensure the length of explosives from the cap to the LSC was kept the constant. This would ensure a simultaneous initiation of the LSC.

4.2.2. Charge Placement and Target. The target was a rectangular cuboid of A36 structural steel with dimensions 14in by 4in by 4.5 in. (length, width, height). A36 is a widely used low carbon steel with a density of 0.28lbs/in^3, specific gravity of 7.8, maximum yield strength of 36ksi, and tensile strength between 58-80ksi. A36 structural steel specifications were taken from 46 CFR 160.035-3(b) (2) 1999. This target material was chosen because of its wide use in the construction industry, its high probability of becoming target material for a 10,500gr/ft. LSC, and its historical use in previous 10,500gr/ft. research allowed for a direct comparison between cut depths.

Following the results presented by Nolan, all the charges were positioned one charge diameter from the surface of the target. Standoff distances were achieved by stacking lengths of low density foam (8.9E*10^{-4}lbs/in^3) under the charge. The foam was approximately 20 times denser than air and 360 time less dense than copper and did not impede the formation and subsequent travel of the LSC blade. Figure 4-6 shows a 10,500gr/ft. LSC attached to the target with one charge diameter of standoff.

Figure 4-6. 10,500gr/ft. LSC and target with one charge diameter standoff

Two test sites were available at Missouri University of Science and Technology, an above ground test site named “the quarry” and an underground test site named “the WOMBAT”. The quarry test site was prone to flooding leaving small “islands” where charges and targets were placed for testing. Two factors led to a minor last minute adjustment in the final Dual Initiation (DI 4) test plan. After the first test shot was fired one half of the target was lost in the flooded portion of the quarry for several weeks until the quarry was drained. After shots in the quarry were fired the center of the “island” was cratered out. This left an uneven pile of crushed stone. The decision was made to place the target in the crater and loosely pack sand around the target to stabilize it and ensure that half the target would not be lost in the flooded area. The sand provided additional confinement which added boundary constraint on the target. This confinement could cause the run-down zone to increase. The variation to the test plan added resistance to the movement of the target halves which could have reduced the final cut depth. This is discussed in further length in Section 5.2 and is pictured in appendix A Figure A. 10 for reference.

The position of the LSC in this type of test was crucial to obtaining worthwhile data. If the charge was not positioned along the center axis of the target then test results could be lost by part of the blade missing the target losing valuable run-up or run-down data. The Charge must also be level so that the cut depth isn’t affected by a varied stand-off distance. The distance from the face of the LSC to the end of the target averaged 1 in and the distance from the sides of the LSC to the side of the target averaged 1in. The charges did not always have the same dimensions which lead to slight variations in test set-ups between the shots. The one-charge-diameter stand-off was adjusted to match each individual 10,500gr/ft. LSC whose distance averaged around 2.3in (± .05 inches). The head height, charge diameter, left and right leg were measured and recorded for all the 10,500 gr/ft. LSCs used in the dual initiation tests.

Significant defects in the charges were recorded. For example, the explosive face of the some of the 10,500gr/ft. LSCs were not flush to the end of the liner. This is pictured in Figure 4-7a. When possible, a booster with extra Pentolite extruded from the end of the yellow plastic liner was paired with the disfiguration, as shown in Figure 4-7b. This was done to keep the initiation of the LSC legs as close to simultaneous as possible.

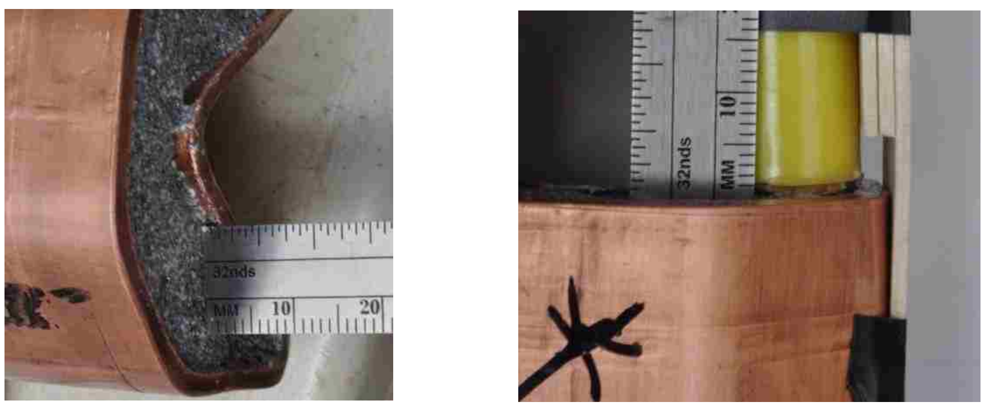


Figure 4-7. Explosive face disfiguration (left) extruded Pentolite used to match face disfigurations (right). The boosters were paired with the disfigurations to attempt to keep the length of explosives from the blasting cap to the LSC equivalent. This would ensure the LSC wings were initiated simultaneously.

Both ends of each 10,500gr/ft. LSC were inspected and the face where the explosive was most flush with the end of the copper was chosen as the side of initiation and marked with an asterisk.

4.2.3. Pipe Test Experimental Setup. Shrapnel characterization tests were planned to compare the liner failure of a 10,500gr/ft. LSC to that observed in "An Investigation of the Characteristics of Linear Shaped Charges Used in Demolition" (Lim 2003). The first test mimicked with the standard LSC initiation method described in Section 3.2.1. Another test utilized the dual initiation method described in Section 4.2.1. The limited supply 10,500gr/ft. charges restrained the total number of pipe tests to one for the standard and one for the dual initiation method.

The 10,500gr/ft. LSC is substantially larger than the 500gr/ft. LSC used in Lim's study and would likely deform a ¼in. thick 6in. inner diameter pipe beyond recognition. For this reason the pipe was scaled up from Lim's test setup to a 7/8thin. thick 3ft inner diameter pipe. The large charge weight of this LSC generated concerns about steel debris being generated from spallation off of the outside of the pipe due to the shock from the impact of the liner with the pipe. For this reason, the pipe was placed upright so that any debris would impact the rock walls of the test site. A blast mat was positioned on the pipe so that the personnel firing the shot were afforded an extra level of protection. 4X4 timbers were positioned around the pipe to keep it upright after the shot. This setup is shown in Figure 4-8. The lines spray painted on the pipe represent quick estimations of where impacts would occur on the pipe.

Figure 4-8. Pipe test general setup. The pipe was positioned vertically and covered with a blast mat to reduce hazards from pipe debris. The spray painted lines (green), on either end of the horizontal timber, were rough order of magnitude predictions of where the LSC liner fragments would impact the pipe.

The LSC was elevated off of the ground and held in place using lengths of the low density foam. Any preexisting marks in the pipe were colored out with green marking paint to avoid confusion with new impact points. Figure 4-9 shows the charge placement inside the pipe, this figure pictures the charge with the dual initiation system attached.

The charge was centered with all the flat faces equidistant from the pipe walls. The tip of LSC legs were offset by the same distance. This preserved the symmetry of the failing liner and the impacts on the pipe correctly reflected the liner failure. If the charge was off-center, the differences in the impact pattern were interpreted as a failure in the design or manufacture of the LSC.

Figure 4-9. Charge position inside pipe. The foam standoffs were used the keep the sides of the charge, the top of the charge and the lower tips of the charge legs equidistant from inside of the pipe. This setup was meant to ensure the LSC fragments traveled the same distance before impacting the pipe.

5. EXPERIMENTAL RESULTS AND DISCUSSION

Due to the limited amount of 10,500gr/ft. LSC specimens, a total of 4 dual initiation shots and 2 shrapnel characterization shots were fired. A few charges remained for the investigation of 10,500gr/ft. LSCs after these tests but were not included due to disfigurations in the explosives faces.

5.1. DUAL INITIATION TEST RESULTS

An increase in the average of the maximum charge penetrations was noted when compared to the single charge diameter (1.0 CD) standoff tests (Nolan). Nolan's data provides a good benchmark for comparison because all the 10,500gr/ft. LSCs used in his tests were initiated using the standard single point initiation method presented in Section 3.2.1. In defining the parameters used to calculate the zones of run-up, run-down and cut, Nolan's data was calculated using an older form of the spreadsheet tool (Phelps). In the older tool, "accepted deviation from the max" was defined by a set distance in centimeters. Nolan's data used an accepted deviation of 1cm (0.3937in) which equates to almost 16.55% of average max penetration (6.0427cm or 2.379in) recorded from his tests. The acceptable deviation was rounded to 17 percent and input into the new spreadsheet tool. The results from the dual initiation tests (DI) are presented in Table 5-1. For comparison Nolan's 1.0 CD data was converted to English units and is presented in Table 5-2.

Table 5-1. Dual initiation test results

Test name	Run-up zone (in.)	Run-up zone (% total cut length)	Cut zone (in.)	Cut zone (% total cut length)	Run-down zone (in.)	Run-down zone (% total cut length)	Max Penetration (in.)
DI 1	4.5	37.5	6.9	57.5	0.6	5	2.7695
DI 2	3.3	27.5	5.1	42.5	3.6	30	2.6665
DI 3	5.1	42.5	6.9	57.5	0	0	2.4091
DI 4	4.5	37.5	3.6	30	3.9	32.5	2.4063
Test Series Averages	4.35	36.25	5.63	46.88	2.03	16.88	2.56285

Table 5-2. 1.0 CD tests (Standard initiation) (Nolan, 2013)

Test name	Run-up zone (in.)	Run-up zone (% total cut length)	Cut zone (in.)	Cut zone (% total cut length)	Run-down zone (in.)	Run-down zone (% total cut length)	Max Penetration (in.)
1.0 CD (1)	2.7	22.5	8.4	70	0.9	7.5	2.8680
1.0 CD (2)	3.3	27.5	8.1	67.5	0.6	5	2.3568
1.0 CD (3)	3.3	27.5	8.1	67.5	0.6	5	2.1893
1.0 CD (4)	3.9	32.5	8.1	67.5	0	0	2.1020
Test Series Averages	3.30	27.50	8.18	68.13	0.53	4.38	2.3790

A 7.7% increase in the max penetration was observed in the dual initiation test. However, the accepted deviation (17%) from the maximum penetration lead to a decrease in the cut zone. The dual initiation method saw a decrease in the cut zone from 68% for the single initiation method to almost 47% (dual initiation.) This left the extra 21% of the cut to be defined as either run-up or run-down.

5.2. DISCUSSION OF DUAL INITIATION TEST RESULTS

The zone of run-up and zone run-down were defined to be dependent on the difference between the measured cut depth at a point and the max penetration. Since the max penetration increased, the zones of run-up and run-down also increased. This is because the charge in the dual initiation test now cut past the bench mark (observed optimum cut depth) set by the 1.0 CD tests. The increased cut depth performance causes points that would have been flagged in the cut zone to now be classified as either run-up or run-down. There are no published standards for how to measure run-up and run-down in an LSC until the development of the spreadsheet tool discussed in section 3.3.3. Before this tool all definitions of these zones were subjective.

LSC performance defined by the length of run-up and run-down shows that the dual initiation method actually reduced the performance of the 10,500gr/ft. LSC even though a deeper max penetration was observed. Therefore the data from the 1.0 CD test was plotted on the same graph as the DI data series. The specific tests in the two test series do not correspond to each other based on test number i.e. 1.0 CD (1) does not correlate to the DI 1 test other than they were the first shots fired. For this reason, the average of the 4 1.0 CD tests is plotted against the average of the DI tests in Figure 5-1.

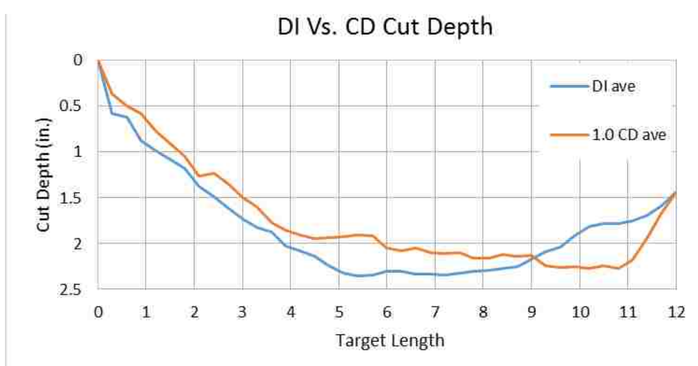


Figure 5-1. Comparison of cut depth DI test vs. 1.0 CD tests. Note, the curve that initially tracks lower is the plot is the DI data (A difference between the curves' colors may only be apparent in color copies of this document).

The area of the cuts was computed using the trapezoid method of integration. The average cut area for the DI test series was 21.9in.^{2} and the average area of the 1.0 CD cuts was 20.8in.^{2}. Using cut area to compare the results reported an increase in the performance of 1.1in.^{2} when using the dual initiation method. Upon visually inspecting the two cut profiles, the DI method consistently outperformed (cut deeper) than the standard initiation method until approximately 9in. into the cut. This was likely the product of poor test results obtained from DI 4. The last minute adjustment to the DI 4 test setup possibly affected the cut depth. More notably, the target was highly deformed and the band saw cut slightly off-center with when preparing the target for analysis. Figure 5-2 excludes the DI 4 data and compares the average of DI 1-3 with the average of 1.0 CD tests 1-4.

Figure 5-2. Comparison of cut depth DI tests vs. 1.0 CD tests (no DI 4 data). Note, the curve that initially tracks lower is the plot for the DI data (a difference between the curves' colors may only be apparent in color copies of this document).

The cut profile of the DI test no longer trends suddenly upward after 9in. of cut length and the overall cut area increased to 23.4in.^{2}. This preliminary study suggests that dually initiating 10500gr/ft. LSCs will improve the overall cut area of the charge. As a consequence, the zones of run-up and run-down will also increase because they are defined using the maximum penetration. Figures 5-1 and 5-2 show that even though the run-up zone is longer for the DI tests the overall cut depth in this zone (and the cut zone) is deeper than the cut depth measured for the 1.0 CD tests in these zones.

5.3. RESULTS AND DISCUSSION OF PIPE FAILURE TESTS

The pipe failure tests provided qualitative descriptions of the shrapnel patters of LSC. These tests determined if observed inadequacies in the cut depth of 10,500gr/ft. LSC were due to a general failure caused by the deviation in the geometric shape of the charge.

In order to compare to past pipe failure tests of optimal LSCs all the faces of the 10,500gr/ft. LSC must project perpendicularly to the face of the explosive core. One noticeably larger impact must also be observed from the cutting blade. The larger impact provided a preliminary assessment the 10,500gr/ft. LSC blade integrity. Figure 5-3 (before) shows the initial charge setup with arrow pointing to where the notable impacts should be observed on the pipe. Figure 5-3 (after) shows the posttest impacts.

Figure 5-3. Pipe test before (left) and pipe test (after) charge detonation. The impact profile on the pipe shows the liner was directly projected off of the faces of the LSC.

Overall, the pipe test showed that the geometry of the charge performed as expected. The green lines pained on the outside of the pipe were able to predict the position of the impacts with fairly high accuracy. Five major impacts were observed directly in line with the 5 faces of the 10,500gr/ft. LSC and a sixth, more significant impact can be seen were the blade perforated the pipe. Note, the impacts from the sides of the LSC breached the pipe whereas the other three faces did not.

Figure 5-4 illustrates how the liner impacted in the predicted areas. One mark impacted dead center and the other impact occurred an inch off center, which removed about half the thickness of the painted line.

Figure 5-4. Prediction markers and impacts. The rough order of magnitude predictions actually predicted where the liner fragments would impact the pipe.

The lines only aimed to mark a position on the circumference of the pipe, not height of the impact. This was a perfect example of the Misznay-Schardin effect and how it describes the direction of the applied force from a detonation. One potentially significant peculiarity was noted about this shrapnel pattern. The shrapnel from the top face of the 10,500gr/ft. LSC split down the middle forming an oblong toroid-like shape. The impact from this toroidal shape is shown in Figure 5-5.

Figure 5-5. Impact from the top of a 10,500gr/ft. LSC. This impact was not expected but could be a product of shock reflections off of the top of the inner liner.

This could be evidence that the head height of the 10,500gr/ft. LSC was too short, causing shock reflections from the tip of the inner “V” to interact with the top face of the LSC and split down the middle. This could imply that shock reflections from the top of the LSC are also affecting the blade and causing a reduction in penetration.

The dual initiation pipe test was the first test where the deformations of explosive at the end of the 10,500gr/ft. could not be corrected for by selecting a booster with extra Pentolite. The better of the two faces still had a rough recessed face pictured in Figure 5-6 (left). Besides a difference in depth, this also caused the boosters to angle outward as shown in Figure 5-6 (right).

These asymmetries caused concern about the performance of the dual initiation system, however no data supported the idea that this could cause the charge to malfunction. The charge was positioned in the pipe identically to the first pipe test

(Figure 5-3a). The dual initiation achieved the same circumferential impact distribution as the first pipe test (comparable to Figure 5-3b).

Figure 5-6. DI pipe face deformations (left) and asymmetric booster angles (right) note that this changed the distance from the blasting cap to the LSC and could cause one side of the LSC to initiate before the other.

Several oddities were observed in the debris strikes on the pipe. For instance, the toroidal impact that was expected from the top of the LSC was highly deformed and almost split into two unique debris impacts. Deeper penetrating impacts were observed at the top and bottom of almost all the debris strikes. This is likely due overhanging copper liner that was accelerated with the rest of the copper liner instead of being explosively driven. Finally the impact from the blade, if a blade formed, likely had the shallowest penetration depth. Two deep lines cut in the pipe amidst what could only have been the impact of a debris cloud of copper fragments. Figure 5-7 shows the impact from the top of the LSC liner, this is pictured furthest left. An impact with an unexpected perforation is pictured in the center of Figure 5-7, this perforation is likely caused by the excess copper at the end of the charge. Finally the impact from the “blade” is pictured on the right, notice that the blade impact looks similar to a debris cloud impact with indicates that the charge did not perform as expected and was unable to form a cutting blade. This means that when the dual initiation method did not perform correctly the charge failed catastrophically and did not produce a cutting blade.

Figure 5-7. Top impact (left) unexpected perforation (center) debris cloud impact (right).

It is worth noting that preliminary computer models were ran and showed that the 10,500 gr/ft. LSC blade forms a thin profile which differs from blades caught from smaller charges (the 600gr/ft charge shown on the left in the Figure 5-8.) The Figure 5-8 shows the approximate outline of typical blades. Keep in mind the charge and blade on the left have been enlarged to show how their cross sections differ from the 10500gr/ft charge. This elongated blade may be more sensitive to a poor initiation than then other LSCs.

This was discussed at length to emphasize how important the quality control is when manufacturing LSCs. The failed performance of this specific charge was exacerbated by non-symmetric detonation from the dual initiation system resulting from uneven contact with the explosive face. This also confirmed that no further DI test could be performed with the remaining 10,500gr/ft. LSCs because the remaining charges were of similar quality to the charge used in the dually initiated pipe failure test.

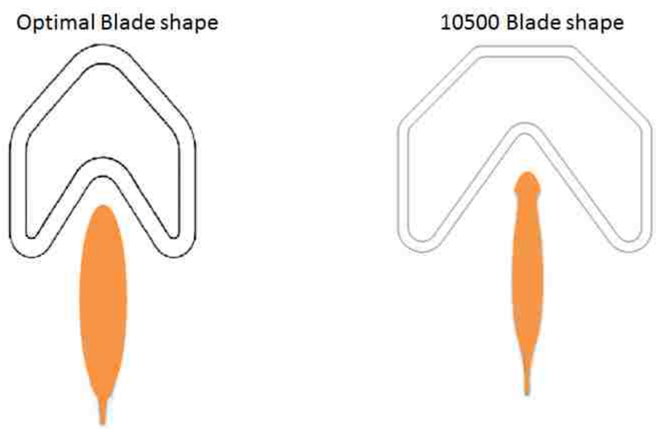


Figure 5-8. LSC blade cross sections. This figure is meant to show how the blade from the 10500gr/ft charge was different than the blade of the optimal charges. This means the extra amount of explosive behind the leg lengths may affect the integrity of the blade.

6. CONCLUSIONS

The dual initiation method increased the length of the undesirable cut zones (run-up and run-down) measured from steel targets. This initially meant that the dual initiation method reduced the effectiveness of the 10,500gr/ft. LSC. However, the cut zones are primarily defined by comparing the local trend in the cut with maximum cut depth. The reduced effectiveness (as defined by cut zones) of the dual initiation method was a product of the increased maximum cut depth. Furthermore, when the cut area was calculated, the dual initiation method increased the maximum cut depth and increased the total area cut of the 10,500gr/ft. LSC.

The single-point initiation method of the 10,500gr/ft. LSC caused the detonation wave to advance down the head of the LSC before it progressed through the legs. This caused the top of the inner “v” to be accelerated first whereas the dual initiation method caused the detonation wave to progress down the legs first (which accelerated the middle of the leg length before the top or bottom). The dual initiation method aimed to develop a planer detonation wave sooner in the LSC. A planar detonation wave would uniformly accelerate the entire leg length of an LSC. It was perceived that the cut zone observed in LSC targets was a product of the detonation wave reaching a planar state therefore causing the optimal penetration.

The increased performance observed with the dual initiation method combined with the position of the boosters led researchers to believe that head height was not a charge dimension important to the design and performance of LSCs. Instead the depth of explosive behind the copper leg length likely contributes more to LSC cut performance, this builds off of the basic definition of the Miszany-Schardin effect stating that sheet of explosives will expand perpendicularly to the face of the explosives. This was also based on the Gurney equations which assume fragment velocity is dependent, in part, on the mass of the explosive charge behind a metal liner.

The vector sum concept developed to describe the velocity of the LSC blade was not completely verified in this study due to the few charges available and resulting small number of tests. However, since the zone of run-up saw an increased cut depth it is likely that this hypothesis is correct. To prove or disprove this theory the amount of explosive in the head height of the LSC would need to be varied and the effect on the cut profile recorded. If a decrease in the head height did not negatively affect the cut profile then the vector sum concept for LSC blade velocity would be proven. It is likely that some head height would be necessary in order to avoid edge effects and spalling from shock interaction at the copper air interface. To further investigate this concept the amount of explosive behind the inner “v” could also need to be varied to obtain different blade velocities.

The 10,500gr/ft. LSC had a significantly larger amount of explosive behind the copper liner than smaller LSCs. This resulted in decreased confinement on the explosive core of the LSC and was a likely cause for the reduced performance, as compared with smaller charges. An addition of more mass on the outside of the 10,500gr/ft. LSC would increase the confinement and could advantageously affect the cut profile. The extra mass could be achieve by thickening the copper liner on the outside of the charge or attaching a “cap” to the charge. The sole purpose of the cap is to provide confining mass therefore it could be comprised of any low cost high density material. The mass of a cap for a

10,500gr/ft. LSC should be calculated to emulate the explosive to copper mass ratio observed in smaller LSCs.

Adding copper to the inside of the 10,500gr/ft. LSC could improve the cut profile by increasing the amount of mass available to cut the target. The extra mass might also increase the integrity of the 10,500gr/ft. LSC blade if the blade was compromised by the increased net extra explosive weight to copper ratio. The addition of extra mass will cause a decrease in the velocity of the blade which could negatively affect the cut profile. Current fragment penetration models are kinetic energy dependent, 1/2 mass times velocity squared, meaning the velocity component is more significant than the mass component. Again, if more mass was added to the inside of the 10,500gr/ft. LSC then the outside confinement of the LSC should also be increased; to save on cost a cap could be used as discussed.

The pipe failure tests proved that a properly manufactured 10,500gr/ft. LSC initiated in the standard manner has a predictable shrapnel pattern. Predictions basis on Lim’s (2003) pipe failure testing correctly anticipated the shrapnel pattern of the 10,500gr/ft. LSC. The DI pipe test failed to perform correctly because the explosive face was irregular and not smooth. In this failure insights were gained into the behavior of a substandard dual initiation and the importance of quality control while manufacturing these charges. This also shows the importance of precisely and methodically constructing the dual initiation devise to ensure a symmetric initiation. If the dual initiation method failed to perform optimally then the LSC would catastrophically fail which would lead to either the blade not forming or the blade turning and impacting the target at a skew angle. It is worth noting that a suboptimal initiation (initiation on a rough/uneven explosive face) using the single-point initiation method did not cause such a significant failure of the LSC. The sensitivity to construction quality could result in reduced field utility of the dual initiation method.

7. FURTHER STUDIES

It was previously felt that the head height of an LSC greatly affected the charges performance. However, the theory behind the dual initiation method largely ignores head height. This theory assumed the vertical velocity of the LSC blade was a vector sum from the movement of the inner lining. The dual initiation method increased the cut performance of the 10,500 gr/ft. LSC therefore the effects of charge head height on cut depth should be investigated. This could lead to a redesign of LSCs that focused on the triangular area of influence behind the legs of the inner "V" instead of head height. If half the head height of the 10,500gr/ft. LSC was removed, then the charge weight could be reduced by nearly 1,050gr/ft. or approximately 1/10 the charge weight. To test this theory different LSCs would need to be designed with decreasing head heights. These charges would likely need to be initiated using the dual initiation method due to a lack of initiation area in the head height. Custom LSCs could be manufactured by backing ribbons of copper with explosive, the inner angle between the ribbons should be 72 degrees (the recommended interior angle by AES). The two explosively backed segments would then be initiated simultaneously, after providing some form of confinement of the explosive. The cut profile should then be analyzed using both the digital analysis and excel method and the cut area method.

Another area identified for further research is the effect of an increased thickness of copper liner. The 10,500 gr/ft. LSC has approximately four times the amount of explosive behind the liner as the 600 gr/ft. LSC variant. The 600 gr/ft. charge was recognized by AES as one of the most effective LSC's in terms of the ratio of cut depth to charge diameter. A preliminary comparison of the 10500 gr/ft. LSC fragments collected during testing lead researchers to believe the copper liner thickness on the 10500 gr/ft. charges were too thin.

Three different methods for increasing the liner thickness are recommended for testing. Increase the thickness of copper inside the “v” to add mass and potentially improve blade integrity. Keep in mind that the penetration of the blade is kinetic energy dependent and highly reliant on blade velocity. Second, increase the confinement around the outside of the charge either through using a low cost “cap” or laminating on extra copper. Finally, increase the total liner thickness (both inside the “v” and along the outside perimeter) to obtain a copper/explosive ratio similar to smaller LSCs. An increased liner thickness will increase the amount of mass available to cut and increase the confinement of the charge which could increase the performance of large LSCs such as the 10,500gr.ft. LSC. The additional liner thickness could be achieved by cutting and pressing a second pipe around the LSC or by laminating different thicknesses of sheet metal or foils on the LSC.

APPENDIX A:

CONSTRUCTION AND PLACEMENT OF DUAL INITIATION SYSTEM

This appendix archives the construction process of the dual initiation in great detail with high resolution photographs to aid any future work that might be performed using the dual initiation test setup.

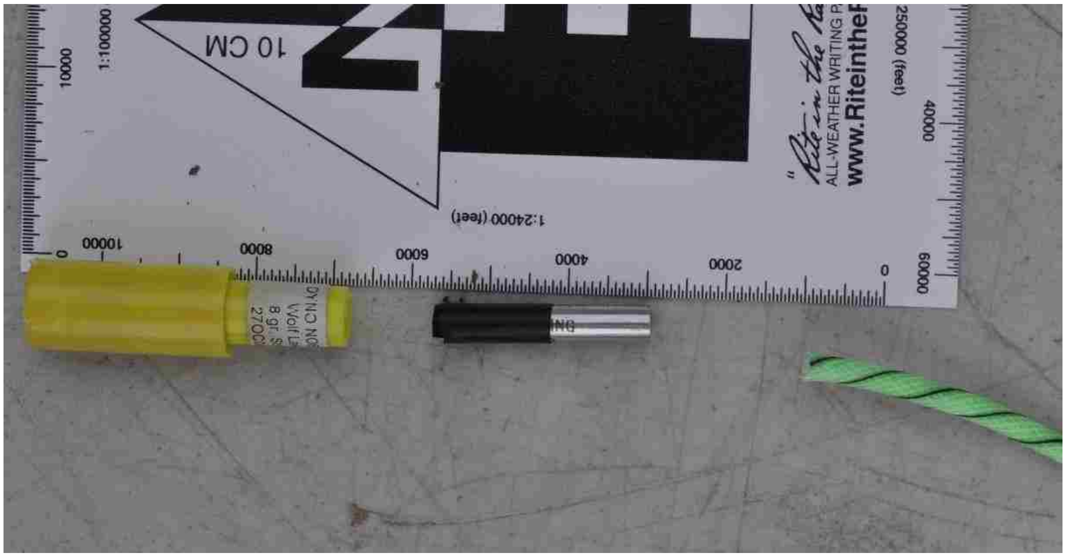


Figure A. 1: Booster (yellow), AAP3 (black/silver) with one thickness of electrical tape and det-cord (green with black stripe)

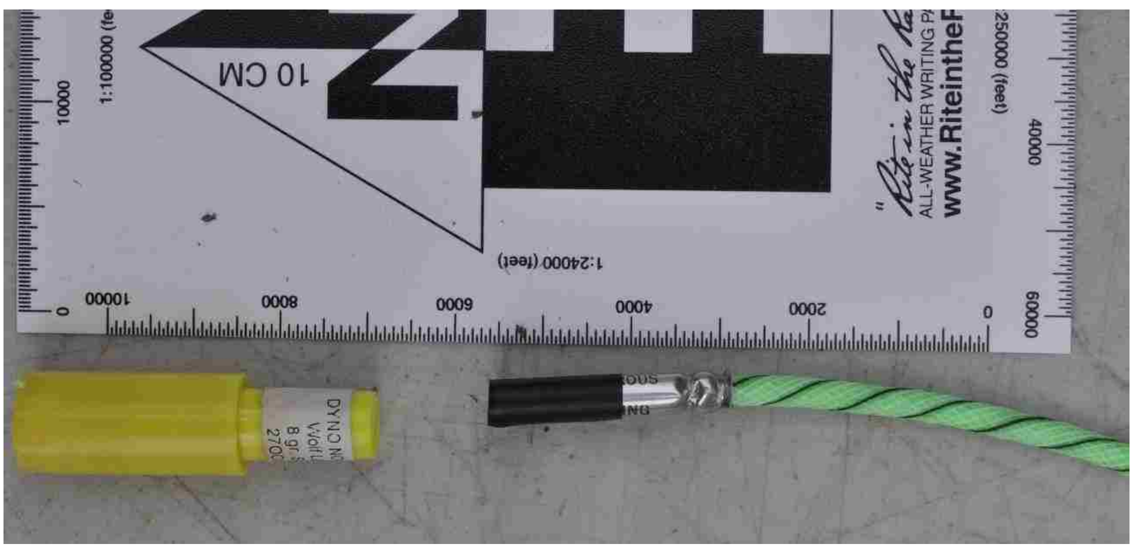


Figure A. 2: AAP3 crimped onto det-cord

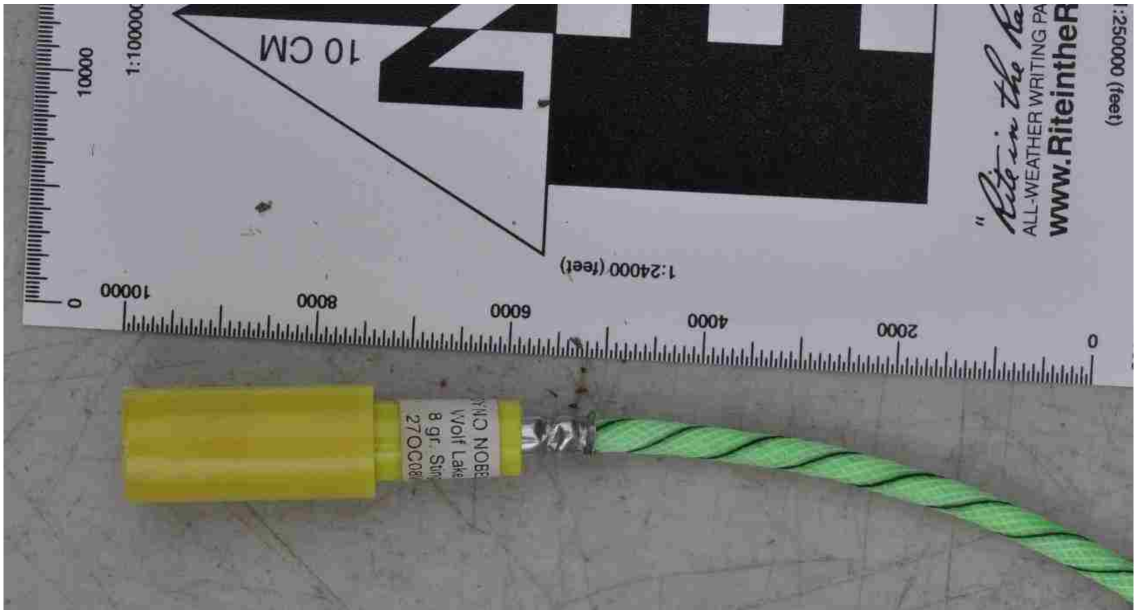


Figure A. 3: AAP3 and de-cord inserted into the booster

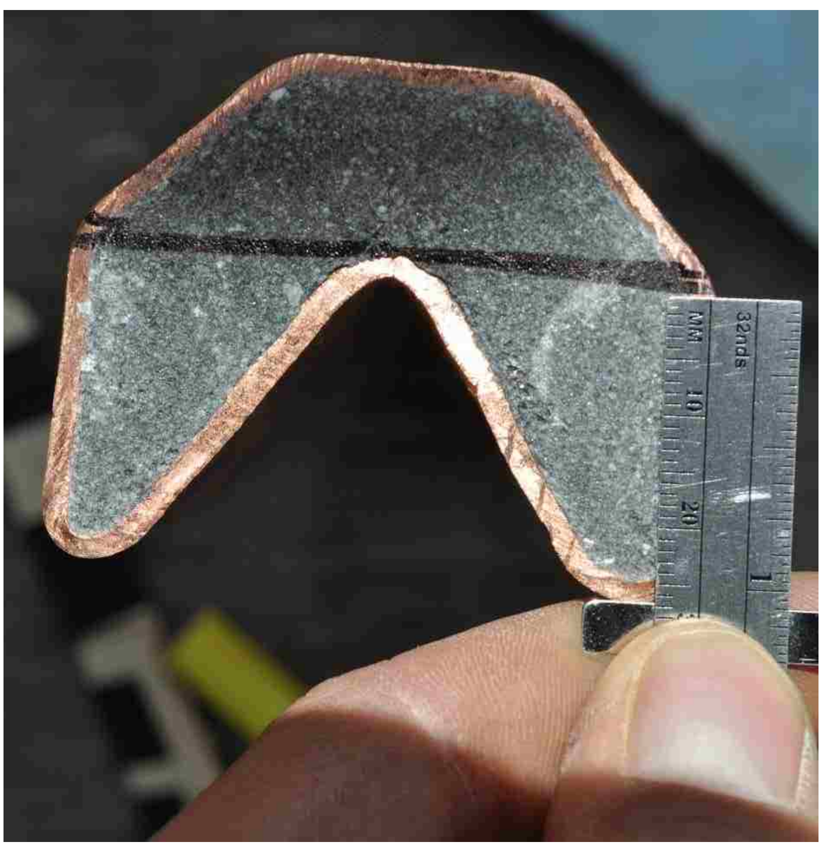


Figure A. 4: Mark the 10,500 gr/ft. LSC to ensure symmetry of dual initiation system

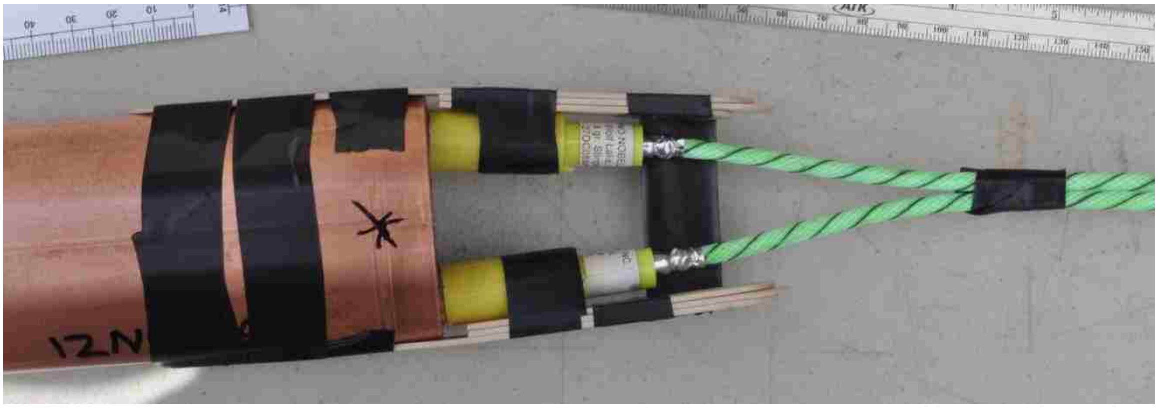


Figure A. 5: Secure both side of the dual initiation system to the 10,500 gr/ft. LSC and tape the ends of det-cord together

Figure A. 6: Secure the dual initiation system and LSC to the target at the desired stand-off distance

Figure A. 7: Mark the sections of det-cord so that length of det-cord from the booster to the mark is equal on both sides

Figure A. 8: Securely attach the blasting cap so that it is in line with the measured marks

Figure A. 9: Final test set-up

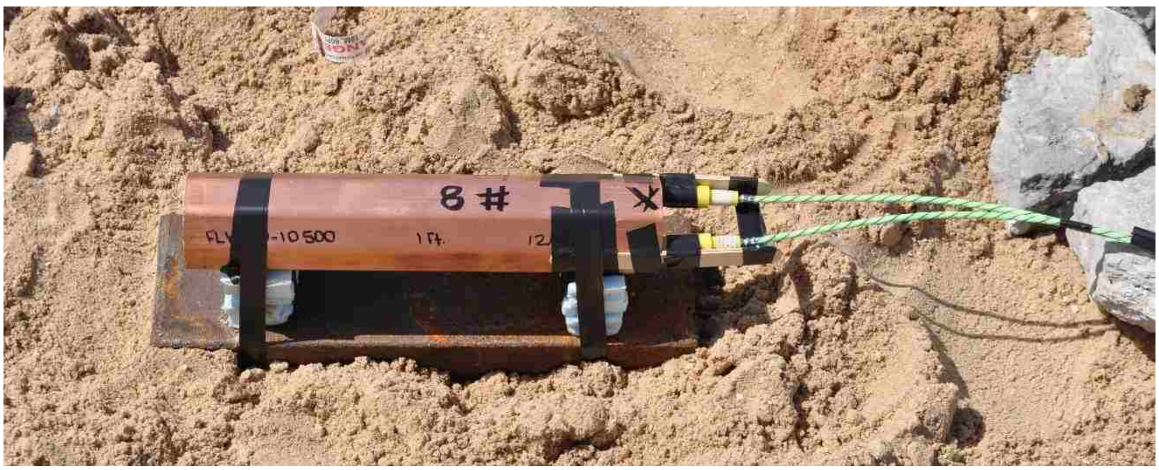


Figure A. 10: Final test set-up variant (DI-4)

APPENDIX B:

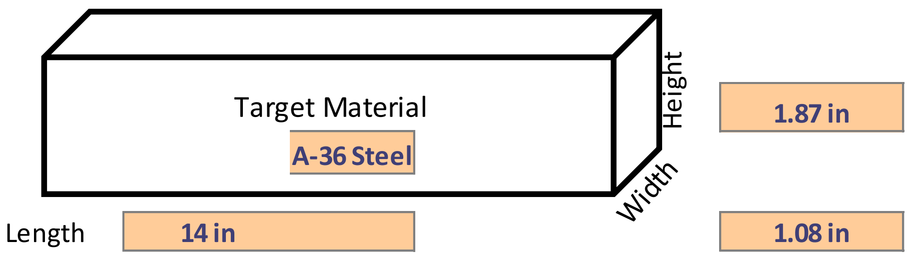
TEST RESULTS:

Cut depth measurements exported from the Excel tool including target information and a cut profile plot.

This appendix presents all of the data from the DI 1-4 tests that was gathered in AUTOCAD and then input into the Excel tool for analysis. This data was also used to plot and integrated to find the total cut area of the different tests. It also provides a target description, an overview of the cut zone lengths and percentages and provides a plot of the cut profile.

DI 1		10500
Acceptable Deviation (% of Max Penetration)	17	0.470815
Max Penetration (in)		2.7695
Target Penetration (in)		3
Data Point	*Penetration Value (in.)*	*Cut Type*
1	1.1385	Run-Up
2	1.2087	Run-Up
3	1.268	Run-Up
4	1.3398	Run-Up
5	1.4845	Run-Up
6	1.6144	Run-Up
7	1.7265	Run-Up
8	1.8386	Run-Up
9	1.9508	Run-Up
10	2.0629	Run-Up
11	2.175	Run-Up
12	2.1505	Run-Up
13	2.1911	Run-Up
14	2.1857	Run-Up
15	2.2447	Run-Up
16	2.3452	Penetration Range
17	2.5366	Penetration Range
18	2.6567	Penetration Range
19	2.6635	Penetration Range
20	2.6491	Penetration Range
21	2.5968	Penetration Range
22	2.5809	Penetration Range
23	2.6601	Penetration Range
24	2.7117	Penetration Range
25	2.7032	Penetration Range
26	2.6787	Penetration Range
27	2.6498	Penetration Range
28	2.667	Penetration Range

29	2.759	Penetration Range
30	2.7695	Penetration Range
31	2.7029	Penetration Range
32	2.7052	Penetration Range
33	2.5447	Penetration Range
34	2.3044	Penetration Range
35	2.292	Penetration Range
36	2.385	Penetration Range
37	2.385	Penetration Range
38	2.3421	Penetration Range
39	2.2042	Run-Down
40	2.089	Run-Down



Charge Standoff: **1 CD**

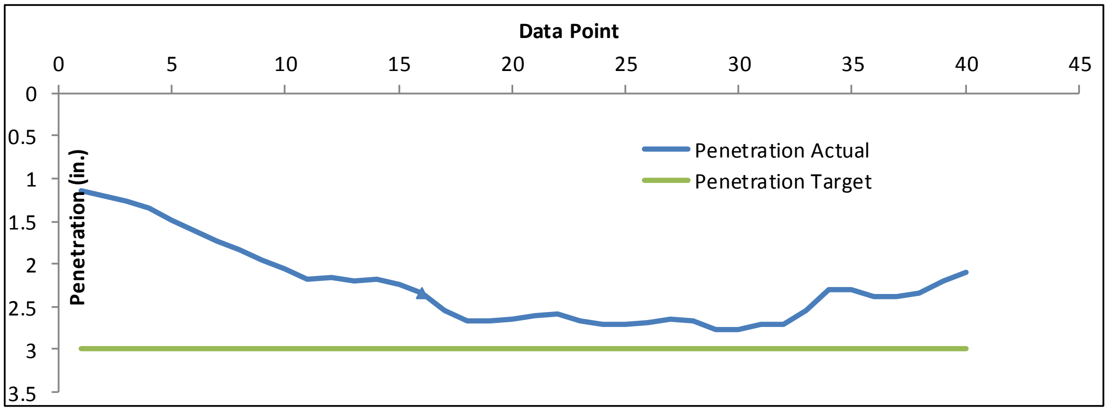
Initiation Method: **Dual Point**

Charge Length: **12 Inches**

Charge Weight: **10500 gr/ft**

	Run-Up	*Penetration Range*	*Run-Down*
Percent	37.5 %	57.5 %	5 %
Length	4.5 in.	6.9 in.	0.6 in.

Average Penetration Range Depth	2.577786957



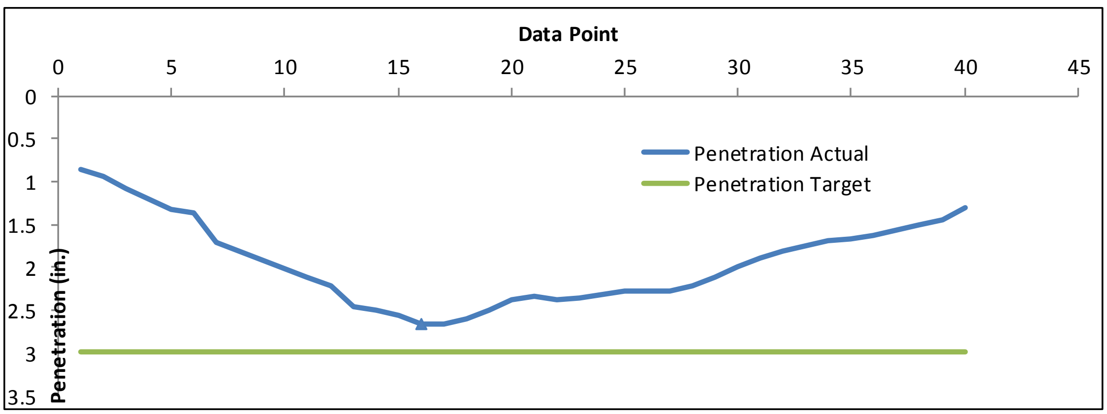
DI 2		10500
Acceptable Deviation (% of Max Penetration)	17	0.453305
Max Penetration (in)		2.6665
Target Penetration (in)		3

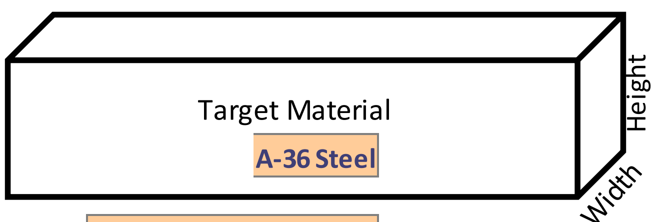
Data Point	*Penetration Value (in.)*	*Cut Type*
1	0.8652	Run-Up
2	0.9334	Run-Up
3	1.0723	Run-Up
4	1.2112	Run-Up
5	1.3276	Run-Up
6	1.3671	Run-Up
7	1.7128	Run-Up
8	1.813	Run-Up
9	1.9132	Run-Up
10	2.0134	Run-Up
11	2.1136	Run-Up
12	2.2138	Penetration Range
13	2.4567	Penetration Range
14	2.5089	Penetration Range
15	2.5711	Penetration Range
16	2.6665	Penetration Range
17	2.6665	Penetration Range
18	2.596	Penetration Range
19	2.5076	Penetration Range
20	2.3758	Penetration Range
21	2.3487	Penetration Range
22	2.3878	Penetration Range
23	2.3529	Penetration Range
24	2.3187	Penetration Range
25	2.2864	Penetration Range
26	2.2786	Penetration Range
27	2.2708	Penetration Range
28	2.2292	Penetration Range
29	2.1122	Run-Down
30	1.9952	Run-Down
31	1.8959	Run-Down

32	1.8209	Run-Down
33	1.7458	Run-Down
34	1.7002	Run-Down
35	1.6665	Run-Down
36	1.6239	Run-Down
37	1.5635	Run-Down
38	1.5031	Run-Down
39	1.4427	Run-Down
40	1.2971	Run-Down

	Run-Up	*Penetration Range*	*Run-Down*
Percent	27.5 %	42.5 %	30 %
Length	3.3 in.	5.1 in.	3.6 in.

Average Penetration Range Depth	2.413882353





1.87 in

Length 14 in

1.08 in

Charge Standoff: 1 CD

Initiation Method: Dual Point

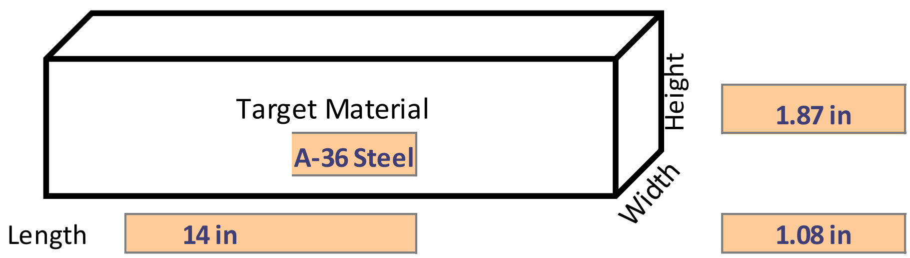
Charge Length: 12 Inches

Charge Weight: 10500 gr/ft

DI 3		10500
Acceptable Deviation (% of Max Penetration)	17	0.409547
Max Penetration (in)		2.4091
Target Penetration (in)		3

Data Point	*Penetration Value (in.)*	*Cut Type*
1	0.3066	Run-Up
2	0.3382	Run-Up
3	0.4053	Run-Up
4	0.4855	Run-Up
5	0.5861	Run-Up
6	0.7081	Run-Up
7	0.7384	Run-Up
8	0.8436	Run-Up
9	0.9942	Run-Up
10	1.1452	Run-Up
11	1.265	Run-Up
12	1.3901	Run-Up
13	1.5914	Run-Up
14	1.6534	Run-Up
15	1.7464	Run-Up
16	1.8668	Run-Up
17	1.9299	Run-Up
18	2.0038	Penetration Range
19	1.9972	Penetration Range
20	1.9776	Penetration Range
21	1.9572	Penetration Range
22	1.957	Penetration Range
23	2.0233	Penetration Range
24	2.0487	Penetration Range
25	2.1022	Penetration Range
26	2.1235	Penetration Range
27	2.1396	Penetration Range
28	2.2463	Penetration Range
29	2.3845	Penetration Range
30	2.3499	Penetration Range
31	2.3979	Penetration Range

32	2.4091	Penetration Range
33	2.2635	Penetration Range
34	2.2572	Penetration Range
35	2.3346	Penetration Range
36	2.374	Penetration Range
37	2.374	Penetration Range
38	2.3468	Penetration Range
39	2.2546	Penetration Range
40	2.0901	Penetration Range



Charge Standoff: **1 CD**

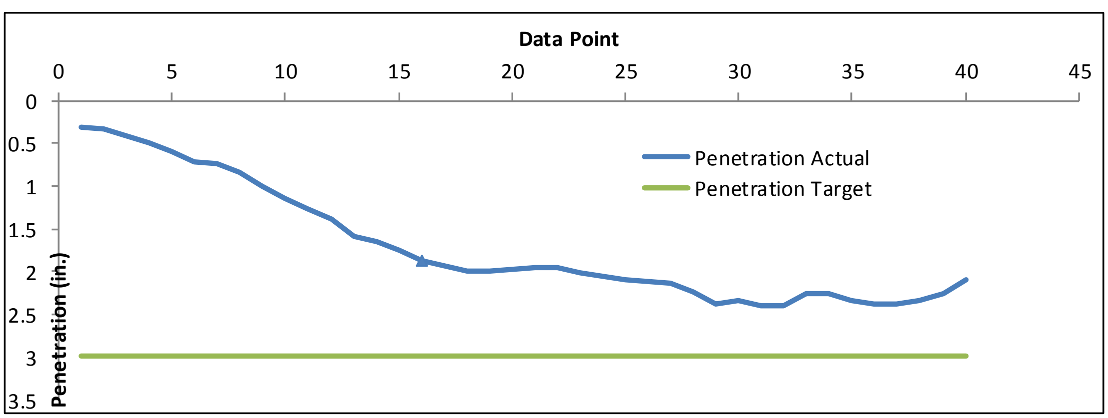
Initiation Method: **Dual Point**

Charge Length: **12 Inches**

Charge Weight: **10500 gr/ft**

	Run-Up	*Penetration Range*	*Run-Down*
Percent	42.5 %	57.5 %	0 %
Length	5.1 in.	6.9 in.	0 in.

Average Penetration Range Depth	2.191852174



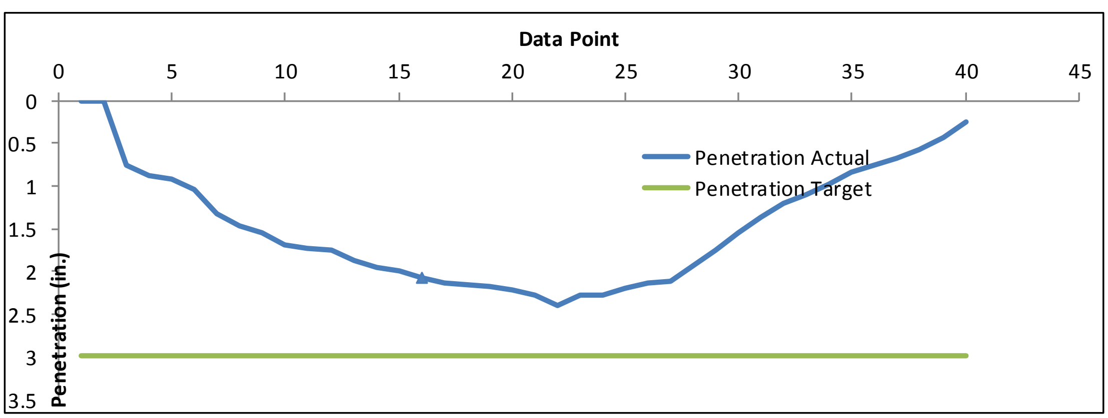
DI 4		10500
Acceptable Deviation (% of Max Penetration)	17	0.409071
Max Penetration (in)		2.4063
Target Penetration (in)		3

Data Point	*Penetration Value (in.)*	*Cut Type*
1	0	Run-Up
2	0	Run-Up
3	0.7535	Run-Up
4	0.8849	Run-Up
5	0.9111	Run-Up
6	1.0451	Run-Up
7	1.3268	Run-Up
8	1.463	Run-Up
9	1.5567	Run-Up
10	1.6874	Run-Up
11	1.7268	Run-Up
12	1.7529	Run-Up
13	1.8791	Run-Up
14	1.9574	Run-Up
15	1.9963	Run-Up
16	2.081	Penetration Range
17	2.136	Penetration Range
18	2.1579	Penetration Range
19	2.1875	Penetration Range
20	2.2148	Penetration Range
21	2.2822	Penetration Range
22	2.4063	Penetration Range
23	2.2722	Penetration Range
24	2.2782	Penetration Range
25	2.1999	Penetration Range
26	2.1413	Penetration Range
27	2.1146	Penetration Range
28	1.9296	Run-Down
29	1.7444	Run-Down
30	1.5523	Run-Down
31	1.3695	Run-Down

32	1.2129	Run-Down
33	1.0938	Run-Down
34	0.9822	Run-Down
35	0.839	Run-Down
36	0.7521	Run-Down
37	0.6781	Run-Down
38	0.5669	Run-Down
39	0.4323	Run-Down
40	0.2525	Run-Down

	Run-Up	*Penetration Range*	*Run-Down*
Percent	37.5 %	30 %	32.5 %
Length	4.5 in.	3.6 in.	3.9 in.

Average Penetration Range Depth	2.205991667



BIBLIOGRAPHY

Diven, R. J., & Shaurette, M. (2010). "Demolition Practices, Technology and Management." West Lafayette: Purdue University Press

Accurate Energetic Systems, LLC. (2014). *Demolition Charges*. Retrieved from Linear Shaped Charge Product Data Sheet: http://www.aesys.biz/products/fabricated-explosives/demolition-products/ May 2013

Ortel, M.A., McCullough, E., Preece, D., Tawadrous, A. "Optimizing the Initiation Position of Geophysical Exploration Charges" *International Society of Explosives Engineers 39th Annual Conference on Explosives and Blasting Techniques*. February 2013

Lim, S., MS thesis. "An Investigation of the Characteristics of Linear Shaped Charges Used in Demolition." *International Society of Explosives Engineers.* niversity of Missouri Rolla, Mining Engineering, 2003

Walters, W. P., & Zukas, J. A. (1989). *Fundamentals of Shaped Charges* . New York: Wiley-Interscience.

Lim, S., Ph.D dissertaion. *A Preliminary Investigation of the Blade Formation and Cutting Process of the Linear Shaped Charges.* University of Missouri Rolla, Mining Engineering, Rolla. 2006

Munroe, Charles, "On Certain Phenomena Produced by the Detonation of Gun Cotton" *Newport Natural History Society, Proceedings* 1887, Report No. 6.

Kennedy, D. R. "The History of the Shaped Charge Effect, The First 100 Years" MBB Schrobenhausen, west Germany, 1990

Schardin, Hubert, "Development of the Shaped Charge" *Wehrtechnische Hefte*, Hefte 4, 1954.

Vigil, Manuel G., P*recision Linear Shaped Charge Designs for Severance of Metals*. Sandia National Laboratory. Albuquerque, NM. 1996

Steinberg, D.J., Cochran, S.G., Guinan, M.W. "A Constitutive Model for Metals Applicable at High-Strain Rate" Lawrence Livermore Laboratiory November 1979

Hayes, G. A. Linear shaped-charge (LSC) collapse model. *Journal of materials science 19*, (1984) 3049-3058.

Hammerberg, J.E., Holian, B.L., Germann, T.C., Ravelo, R. "High Velocity Properties of the Dynamic Frictional Force between Ductile Metals." *APS Topical Conference on Shock Compression*, June 2008 Nashville.

Tabacchi, D., *The Effects of coupling Linear Shaped Charge (LSC) Segments.* December 2014. Explosives Engineering 498. Presentation

Nolan, D., Phelps, K., Mulligan, P., & Baird, J. P., "Performance Evaluation and Effects of Standoff on 10,500 grain per foot Linear Shaped Charge," *Proceedings of the Thirty-Ninth Annual Conference on Explosives and Blasting Technique.* (2013)

Cooper, P. W., & Kurowski, S. R. (1996). *Introduction to the Techonlogy of Explosives.* New York: Wiley-VCH, Inc.

Phelps, K., Nolan, D., Mulligan, P., Baird, J., "New Methodology in Measuring Experimental Results of Linear Shaped Charges Using Digital Software," *Proceedings of the Thirty-Ninth Annual Conference on Explosives and Blasting Technique* (2013)

Baird, Jason, Ph.D dissertation, "Shock Wave Interactions at Explosive/Metallic Interfaces." 2001

Sternberg, H.M., Piacesi, D., "Interaction of Oblique Detonation Waves with Iron" U.S. Naval Ordnance Laboratory, White Oak, Silver Spring Maryland 1965

Held, M., "Characterizing Shaped Charge Performance by Stand-Off Behavior", *7th International Symposium on Ballistics,* (1983): 331-339

Dyno Nobel, (2013) "Detonation Cord" Technical Information and Product Specification Sheet

American Society for Testing and Materials, "ASTM A36: Standard Specification for Carbon Structural Steel", Sept. 1999 (46 CFR 160.035-3(b)(2))

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Matthew A. Ortel was born in West Palm Beach Florida in 1989. He graduated Mahomet-Seymour High School in 2008. In May 2012, he received his B.S. in Mining Engineering from the Missouri University of Science and Technology. While at while working a summer internship between semesters at Missouri University of Science and Technology he also authors and coauthored conference papers for the 2012 conference of the International Society of Explosives Engineers. These papers were titled “Seismic Wave Frequency Filtering during Computer Modeling of Geophysical Explosive Charges” and “Optimizing the Initiation Position of Geophysical Exploration Charges” respectively.