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The Effects of Water on Sympathetic Detonation and Dead Pressing of Dynamite and Emulsions

by

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A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN EXPLOSIVE ENGINEERING

2012

Approved by

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Dr. Leslie Gertsch

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ABSTRACT

Dynamite and emulsions are very effective explosives in blasting; however they do have some shortcomings. Dynamite is prone to sympathetic detonation whereas emulsions are prone to dead pressing. While this does not happen all the time, the conditions in which the explosives are used do have an effect on whether or not they will sympathetically detonate or dead press.

Numerous researchers have investigated sympathetic detonation for a relationship between the distance between charges, hole separation distance, and size of explosive. This research aimed to look at how hole separation distance was affected when water was introduced into the boreholes for sympathetic detonation of dynamite. Also this research looked at the same setup for the dead pressing of emulsions.

To investigate sympathetic detonation, dynamite acceptor charges were placed at various distances from the donor charge. These distances were used for dry and wet holes. The same setup was used to study dead pressing in emulsions.

For sympathetic detonation, the author discovered that the hole separation distance nearly doubled when the boreholes were filled with water versus when the boreholes were dry. A similar relationship was found for the emulsion that was used. The range in which dead pressing occurred, nearly doubled in distance when the boreholes were filled with water versus when the boreholes were dry.

This is important because the conditions in which an explosive is used should be a significant consideration when loading holes. For example, when the ground is saturated, a pattern may have to be redesigned to prevent either sympathetic detonation or dead pressing from occurring.

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NOMENCLATURE

Symbol	Description
′	Foot/Feet
°	Degrees
″	Inches
A	Cross-sectional Area
C_0	Bulk Sound Speed
dBA	Decibels
e	Specific Internal Energy
E	Total Internal Energy
Ft	Feet
GPa	Gigapascal
km	Kilometers
L	Length
m	Meter
mm	Millimeter
N	Newton
P	Pressure
ρ	Density
R	Distance between Acceptor and Donor
s	Empirical Constant
sec	Second

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U	Shock Velocity
u	Particle Velocity
W	Donor Mass

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1. INTRODUCTION

The ability to predict sympathetic detonation and dead pressing in different environments is advantageous for safety concerns, production of product, ground vibrations, and property protection. These safety concerns include dead pressed explosives left after detonation, unsafe ground conditions after a blast, and increased fly rock. Some production concerns would be incomplete shots and unsafe ground condition leading to delays in the sequence of shots. Having sympathetic detonation of holes could result in an increase in ground vibrations, potentially exceeding the legal limit or result in an increase in the amount of explosive detonated per 8ms delay.

Sympathetic detonation occurs when an explosive that is sensitive to shock receives a shock wave from another blast hole that is large enough to cause premature initiation of the explosive. Many factors affect sympathetic detonation including the type of both the donor and the acceptor explosive, dimensions of the explosive column, hole separation distance between the explosives, and presence of water (Stiehr 210). An example of an explosive that is susceptible to sympathetic detonation is dynamite because of the nitroglycerin that is present in it. This is because nitroglycerin is a very shock sensitive compound.

On the other side, dead pressing occurs when a shock wave from another blast hole increases the explosive density to a point where it can no longer function as originally intended. This is also known as a desensitization process. There are many ways for dead pressing to happen, one of which is with water (Stiehr 199-200). Basically in simpler terms, the explosive is pressed until it no longer functions. An example of an explosive that is susceptible to dead pressing is emulsion because of the void spaces that

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are present in emulsions that are there to sensitize the emulsion. When the emulsion is dead pressed, these void spaces are crushed out, thereby removing the sensitization of the emulsion.

This research evaluated the effect of water on both sympathetic detonation and dead pressing to better understand sympathetic detonation and dead pressing in dolomite rock. There has been much research done on sympathetic detonation with respect to hole separation distance and explosive size, however, this research focuses on the effect of ground saturation on sympathetic detonation and dead pressing.

There are two possible setups that can be looked at. One is the head-on setup, which has two sticks of explosives in the same hole separated by an air deck or a stemming deck, while the other is a side-on configuration, which is two sticks of explosive, one stick in each of two different holes that are separated by a barrier such as the ground. The experimental data that was gathered from this thesis research will help better understand the effect that water plays in both sympathetic detonation and dead pressing. A possible reason that water increases the range of propagation is that it reduces impedance mismatch, which increases the transmission of shock between holes. Another possible reason that water increases the range of propagation is because of the hydraulic conductivity in the rock. Through the knowledge of the pre-shocked density, along with the velocity of the wave travelling through the material, the impedance can be found. The change in impedance between water and rock is less than the change in impedance between air and rock. This reduced impedance mismatch creates the wider range of shock propagation.

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In order to investigate sympathetic detonation, an experiment was devised using dynamite. Holes were drilled in a crucifix like pattern with different distances between donor and acceptor holes. Half the time the holes were left dry, while the other half of the time the holes were filled with water. A similar experimental setup was used for the investigation of dead pressing in emulsions.

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2. LITERATURE REVIEW

The effects of sympathetic detonation and dead pressing have been known for over a hundred years, involving dynamite and detonators respectively (Walke) (Watson). Ever since these effects were discovered, researchers have been trying to quantify their effects. Today, the majority of research focuses on different shock distances with respect to shock pressure. The following literature review is presented in chronological order, starting with the oldest first.

2.1. SYMPATHETIC DETONATION AND INITIATION BY IMPACT (Eichelberger and Sultanoff, 1958)

Eichelberger and Sultanoff used a sympathetic detonation experiment to look at shock initiation of solid explosives and the conditions that led to the detonation after the shock. Eichelberger and Sultanoff used multiple high speed cameras of different types to photograph the shock waves from both the donor and receptor [acceptor] explosives. The dimensions and type of the explosives were varied. From their measurements, Eichelberger and Sultanoff were able to find a linear relationship for depth within the acceptor explosive of initiation and time.

Eichelberger and Sultanoff used 50/50 pentolite, 60/40 cyclotol, and tetryl. Figure 2-1 shows sympathetic detonation of pentolite across a steel barrier. From this picture and others, the authors came to numerous conclusions, one of these being that the acceptor explosive sympathetically detonated from within itself instead of at the surface of the explosive, and the initiation of the acceptor took place at the shock front, not over the entire explosive at once.

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Another conclusion was that the shock velocity had an initial drop after initiation, which then remained constant afterwards. From the second conclusion, the authors decided to look at quantitative measurements of pressure and gap distance. Gap distance is the separation of the charges. Eichelberger and Sultanoff found that gap distance versus time was a linear relationship. This can be seen in Figure 2-2. Figure 2-2 graphed the gap distance as time changed for the three different sizes of the explosive tested. The best fit line through these coordinates did not go through the origin of the graph; this proved that shock velocity had an initial drop. The slope of the best fit line was linear, proving that the shock was constant after the initial drop in velocity. Eichelberger and Sultanoff's research on gap distance found a linear relationship. A similar relationship should be able to be found for other explosives.

The project described in this thesis researched hole separation distance for sympathetic detonation. The initial setup that was used in Eichelberger and Sultanoff's research was similar to the research described in this thesis. The difference in the setup is that dolomite and water were used as a barrier instead of steel, and dynamite was used instead of pentolite. Using the linear relationship that Eichelberger and Sultanoff found, a similar relationship for dolomite, water, and dynamite for sympathetic detonation were found.

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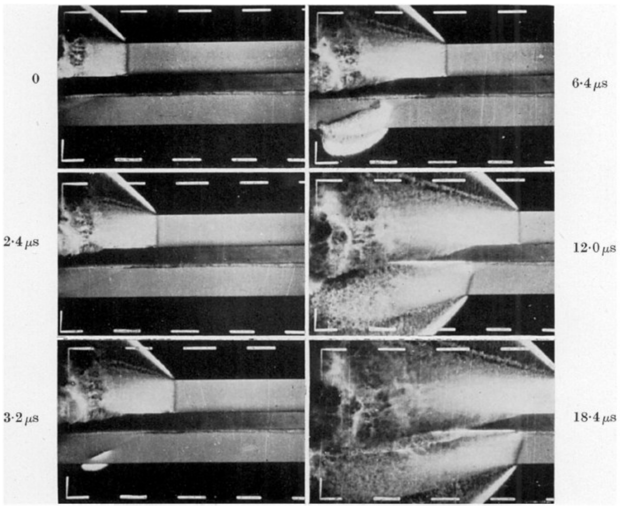

Figure 2-1: Sympathetic Detonation across Steel Barrier (Eichelberger and Sultanoff)

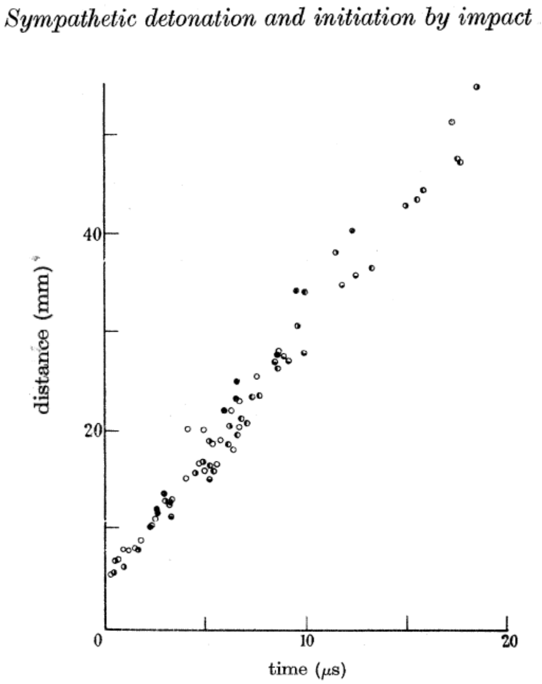

Figure 2-2: Gap Distance Versus Time (Eichelberger and Sultanoff)

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2.2. SUPPRESSION OF SYMPATHETIC DETONATION (Fosters, Gunger and Craig, 1984)

Fosters, Gunger and Craig looked at the prevention of sympathetic detonation of high explosives by varying distance to investigate pressure. One of the ways they did this was by looking at shock sensitivity. Experiments included explosives with and without endplates in the setup. The endplates that were used by Fosters, Gunger and Craig were made of steel. These plates were used to control the strength of the shock wave that is transmitted into the acceptor. Using these endplates, along with concrete and Plexiglas barriers, they were able to calculate pressure as a function of gap distance. Along with this, they observed a pressure profile of the received shock in the acceptor explosive with respect to the distance from the donor explosive. Fosters, Gunger and Craig concluded that the pressure decayed slower with endplates than without endplates. This can be seen in Figure 2-3. Here the calculated pressure was graphed as a function of distance for both with and without endplates. They also found that the shock velocity in the acceptor increased slowly as the length of the cylinder of explosive increased. This can be seen in Figure 2-4. The shock velocity increase seen in the graph was observed even when a strong shock was used for initiation. Fosters, Gunger and Craig concluded that increasing the donor shock increased the acceptor explosive reaction velocity.

Fosters, Gunger and Craig investigated pressure at different distances. It is this pressure that causes sympathetic detonation and dead pressing, both of which this thesis investigates. This research was similar to the research presented later in this thesis. The difference between Fosters, Gunger and Craig's research and this research is that the shots were performed in the ground with rock as the barrier instead of concrete and Plexiglas.

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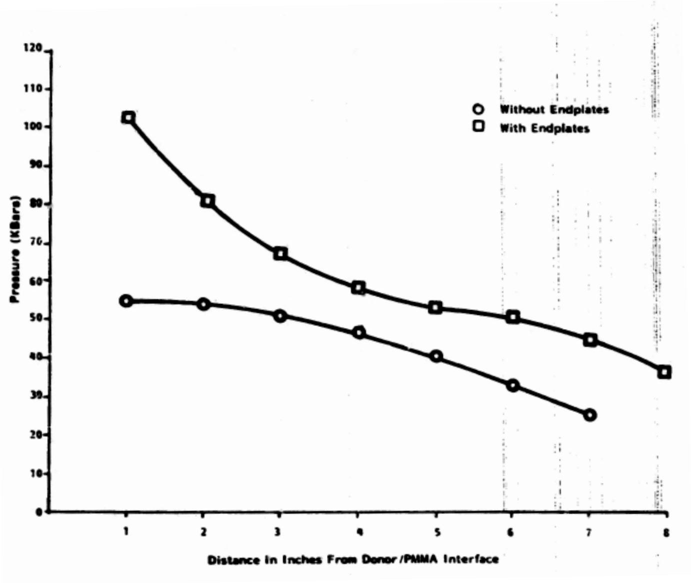

Figure 2-3: Pressure Decay With and Without Endplates (Fosters, Gunger and Craig)

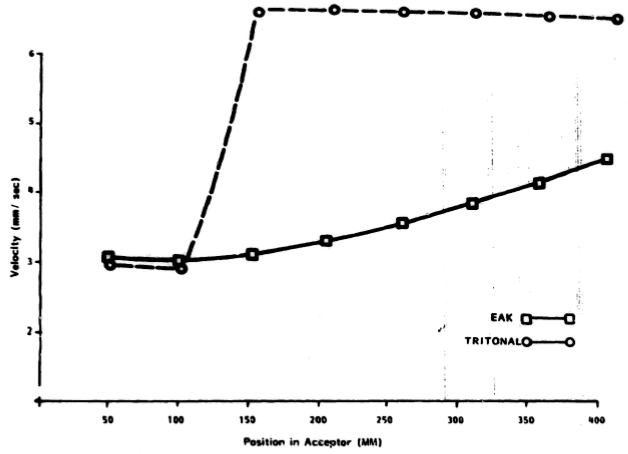

Figure 2-4: Shock Velocity versus Length of Cylinder (Fosters, Gunger and Craig)

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2.3. EXPERIMENTAL AND THEORETICAL STUDIES OF SYMPATHETIC DETONATIONS IN BLASTHOLES (Katsabanis, 1992)

Katsabanis investigated sympathetic detonation in blast holes. He observed that the pressure decreased in the stemming and increased in the acceptor charge and stated that the shock waves that travel through the host rock can induce the detonation in the acceptor.

One of the experiments that Katsabanis ran used a slurry explosive. From this, he found that the pressure was less for the reaction to start than for the explosive to detonate. This means it takes less pressure to start the explosive deflagrating than to start it detonating. The shock wave may be less than what was needed to have the explosive detonate, but may have been enough to cause the explosive to deflagrate, which could have led to a detonation. This is shown in Figure 2-5. This figure shows the particle velocity thresholds for both detonation and reaction for slurry explosives. The reactions start at pressure much lower than what is required for the explosive to detonate due to shock. The initiation of sympathetic detonation had the practical criterion of the critical energy of the acceptor explosive. Katsabanis said that the majority of the time the cause of sympathetic detonation was really caused by deflagration to detonation instead of sympathetic detonation. The pressures needed for deflagration would change when the dimensions of either the donor or acceptor charges changed.

Also, Katsabanis claimed that deflagration to detonation caused what most people consider sympathetic detonation. The research in this thesis did not look at deflagration to detonation but instead looked at the timing of the explosives detonation versus the time of intended detonation. The study of deflagration to detonation versus normal sympathetic detonation would be a good topic for future research.

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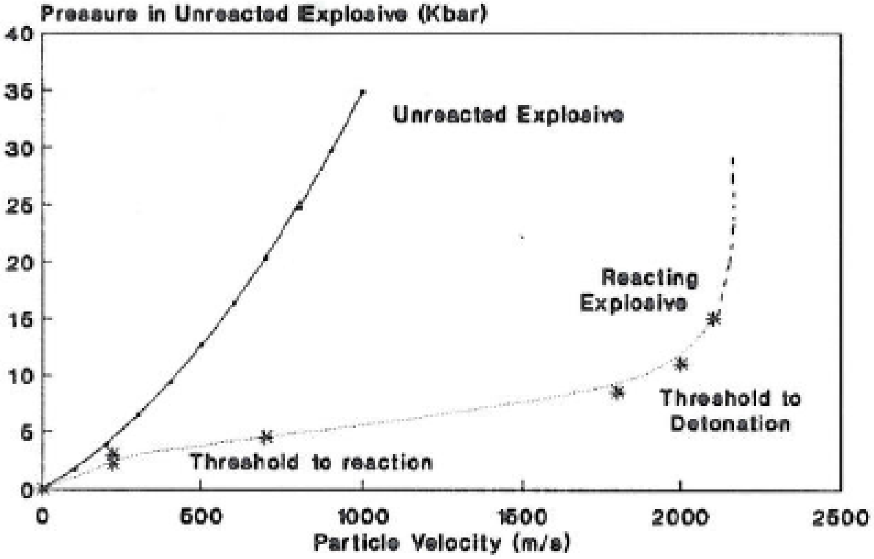

Figure 2-5: Pressure vs. Particle Velocity in a Slurry Explosive (Katsabanis)

2.4. CONDITION FOR SYMPATHETIC INITIATION OF EXPLOSIVES IN SMALL DIAMETERS (Mohanty and Deshaies, 1992)

Mohanty and Deshaies investigated external pressure in inter-hole situations. They discovered that pressure was dependent on the charge weight and distance the explosives were from each other; that incident shock pressure depends on factors too numerous to be named; at short distances, the pressure can easily exceed the pressure needed for sympathetic detonation; and the incident shock pressure is a poor indicator of sympathetic detonation in the receptor [acceptor]. Pressure was studied in an underwater environment via water gel slurries and emulsions of equal densities.

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By placing the donor charge of a two meter long detonating cord underwater, the pressure profile that is given off when detonated was recorded at a distance of two meters horizontally to the donor charge. Mohanty and Deshaies placed the pressure sensors at different depths to represent the top, middle, and bottom of the explosive, both inside the explosive cartridge and outside the explosive cartridge facing the donor. This experiment was repeated with the pressure sensor inside both a water gel slurry cartridge and an emulsion cartridge.

The first experiment that Mohanty and Deshaies did with a two-meter long detonating cord and the water gel slurry, resulted in a Doppler Effect pressure profile similar to a spherical donor charge. The second experiment Mohanty and Deshaies did with the emulsion cartridge showed a much smaller peak pressure. This was due to impedance mismatch between the emulsion and the water.

Using the results from experiment one and experiment two that showed pressure differences, Mohanty and Deshaies decided to repeat the experiment at different distances for primed and unprimed acceptor charges. Using the results from the primed and unprimed acceptor charges at differing distances Mohanty and Deshaies came up with numerous results. The pressure in the explosive column varies from continuous and low at the bottom, to short and high pressure at the top when the donor hole was part of a multi-hole blast initiated from the bottom of the column. The amplitude of the pressure depended on the ratio of the velocity of detonation in the donor to stress wave velocity in the rock, explosive height, and the distance between donor and acceptor charges. However, Mohanty and Deshaies found that the most important relationship was not only the distance between the charges but also the properties of the explosive matrix. It was

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found that when the stress wave encountered a different impedance than the material it was traveling though, there was a loss in amplitude. Therefore, if the shock pressure induced in any part of the explosive setup was greater than the critical energy of that item, sympathetic detonation occurred. Using these results, Mohanty and Deshaies came to four conclusions.

These four conclusions are discussed below. First, that the pressure acting on the acceptor explosive when the donor was underwater was difficult to model because of numerous variables. These variables were velocity of detonation, length, initiation type of donor explosive, distance between explosives, shock wave propagation velocity, and pressure measurement locations. Second, at large distances, the initial shock pressure did not adequately indicate if the acceptor explosive would sympathetically detonate. Third, for explosives at small distances, the pressure needed for sympathetic detonation could be reached easily. Fourth, when the explosive and detonator were in water, the pressure was at least ten times greater than if they were out of the water. These conclusions are important for understanding real world applications and the research presented in this thesis.

This research investigated sypathetic detonation at small distances between materials with differing impedances: rock, water, and explosive. Mohanty and Deshaies' research on impedance mismatch helps to explain why the safe distance to prevent sympathetic detonation, presented later in this thesis, is different for wet holes verses dry holes. Water has a better coupling than air, which helps to reduce the impedance mismatch. By this reduction of impedance mismatch, the shock that is transmitted is greater than without this water. Also, Mohanty and Deshaies found that that at small

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distances, the energy for sympathetic detonation was easily reached. This research found that over small distances, sympathetic detonation occurred, but not over larger distances. Overall, Mohanty and Deshaies' research helps to explain the effect seen later in this thesis.

2.5. DEAD-PRESSING PHENOMENON IN AN ANFO EXPLOSIVE (Nie, Deng and Persson, 1993)

Nie, Deng and Persson investigated dead pressing of ANFO to find an equation to predict whether or not the ANFO will dead press. This equation involves the density of the dead pressed explosive. Nie, Deng and Persson defined dead-pressing density as "… the critical density at which a reaction induced by an incident steady detonation… cannot be sustained for a defined distance" (Nie, Deng and Persson). Using this definition, along with an experiment using ANFO as a donor explosive, Nie, Deng and Persson found their equation to predict whether or not an explosive would sympathetically detonate. This equation can be seen in Equation 1 (Nie, Deng and Persson) where ρ is the density of the compressed ANFO, ρ_{max} is the maximum possible density for ANFO, ρ_c is the critical density beneath which dead pressing does not occur, L_{max} is the maximum length that the ANFO can be without having dead pressing occur and L is the length of the compressed ANFO.

Nie, Deng and Persson used this equation to predict when dead pressing would occur. They found that when F was greater than one, dead pressing occurred, and when F was less than one, dead pressing did not occur. Nie, Deng and Persson state that this equation can be applied to other areas, such as rock blasting, as long as L_{max} is

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predetermined. Using this information, a similar relationship can be found for other explosives, including emulsions.

$$\boldsymbol{F} = \frac{(\rho - \rho_c)}{(\rho_{max} - \rho_c)} * \left(\frac{L}{L_{max}}\right)^2 \qquad \text{Equation 1}$$

2.6. IMPACT SENSITIVITY OF DETONATORS (Franklin and Worsey, 2004)

Franklin and Worsey tested the impact sensitivity of commercial detonators. They did this by testing how much force the detonators could withstand without accidently firing. This was done by using a modified BAM Fallhammer test. The BAM Fallhammer test, in this case, is used to test the response of the substance to impact. They found that a Nonel LP required 60 to 78.5 Nm to accidently detonate depending upon manufacturer of the cap. They found that a shock tube requires more than 78.5 Nm to accidently fire. The research presented later in this paper used Nonel LP caps.

Franklin and Worsey's research is important when looking at sympathetic detonation. Sympathetic detonation can be caused by either the detonator sympathetically detonating or the explosive sympathetically detonating. Using the energy found by Franklin and Worsey along with the Hugoniot equations from Paul Cooper's Book (Cooper), and physically testing the caps, the caps were ruled out as the likely cause of sympathetic detonation in this thesis research, Sections 4.3 and 5.1.

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2.7. INFLUENCE OF PRESSURE WAVE PROPAGATING IN COMPRESSED EMULSION EXPLOSIVES ON DETONATOR (Fumihiko, Hirosaki and Kato, 2005)

Fumihiko, Hirosaki and Kato's experimented with glass microballoon emulsions (GMB), resin microballoon emulsions (RMB) and plain emulsions to study peak pressure and pressure applied to the acceptor explosive, to clarify the dead pressing occurrence. This was done by looking at pressure profiles of the explosives and the deformation of the explosives. First, pressure was investigated.

Pressure profiles were studied by placing both the donor charge and acceptor charge underwater at a set distance apart. This setup can be seen in Figure 2-6. Here the donor was placed two meters underwater while at fifty or eighty centimeters away from the acceptor. It was with this experiment that Fumihiko, Hirosaki and Kato found the pressure profiles for RMB, GMB, and plain emulsion.

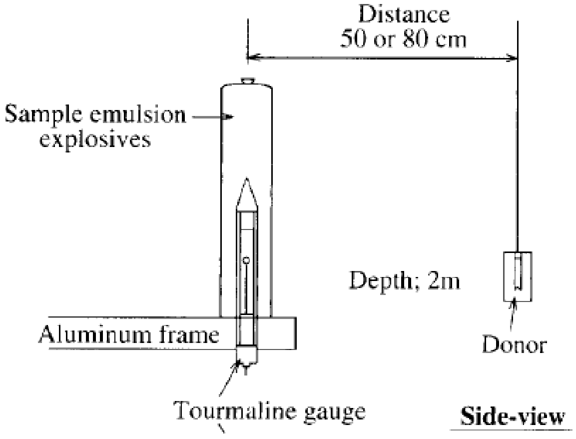

Figure 2-6: Side-View of Setup (Fumihiko, Hirosaki and Kato)

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The results from Fumihiko, Hirosaki and Kato experiment at a distance of eighty centimeters showed different peak pressure levels for the different explosives. These pressure levels can be seen in Figure 2-7. From this graph, it can be seen that RMB had the highest peak pressure, followed by plain emulsion, with GMB having the lowest peak pressure. Also, it is important to note that RMB had a higher peak pressure than the incident shock wave. With this information, Fumihiko, Hirosaki and Kato came up with two results.

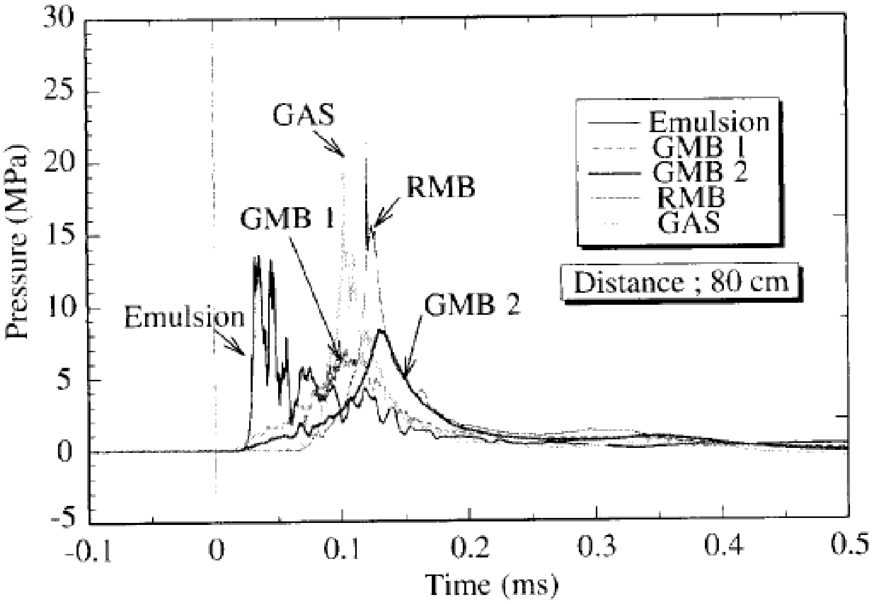

Figure 2-7: Pressure Profiles Inside Sample Explosives (Fumihiko, Hirosaki and Kato)

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The two results that Fumihiko, Hirosaki and Kato came up with follow. First, the pressure in the middle of the explosive charge was 1.5 times higher than the applied pressure. Second, an increased charge diameter does not affect the peak pressure for GMB, only for RMB. When Fumihiko, Hirosaki and Kato were finished looking at pressure profiles, they investigated deformation of the emulsions.

Fumihiko, Hirosaki and Kato performed a deformation test on the explosives to observe how pressure caused the shells to deform. This was done by placing both the donor and the acceptor charge two meters underwater at differing distances apart. Using the data they collected, they calculated a squeeze ratio. The equation used can be seen in Equation 2 (Fumihiko, Hirosaki and Kato). The squeeze ratio was found for GMB emulsion, RMB emulsion, and plain emulsion. With this information, Fumihiko, Hirosaki and Kato came up with the following results.

$$\boldsymbol{Squeeze\ Ratio} = \frac{(\boldsymbol{Inital\ shell\ volume - Shell\ volume\ after\ deformation})}{(\boldsymbol{Inital\ shell\ volume - Shell\ volume\ after\ fully\ deformed})} \tag{Equation 2}$$

The two results that Fumihiko, Hirosaki and Kato concluded using the squeeze ratio information are as follows. First, RMB had the greatest squeeze ratio and plain emulsions had the smallest squeeze ratio. Second, a linear realtionship exists between the squeeze ratio and the scaled distance. From these results and the results of the pressure profiles, Fumihiko, Hirosaki and Kato came up with several conclusions.

Three of the important conclusions that Fumihiko, Hirosaki and Kato found are as follows. First, the presence of microballoons or microbubbles did not affect the incoming

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stress wave. Second, the pressure inside the explosive is 1.5 times higher than the pressure applied. Third, emulsions don’t deform easily when under shock pressure.

This thesis research looked at dead pressing of emulsions and sympathetic detonation of dynamite. Using the pressure profiles and the fact that the pressure is 1.5 times higher inside the explosive than the applied pressure, a maximum pressure on the explosive was calculated in this thesis, to show that the caps were not sympathetically detonating. Also, using the deformation data on emulsion, it can be seen that the emulsions in this thesis research did not damage the detonators. If the detonators had been damaged and did not fire as a result of the pressure wave, the result would look identical to if the emulsion had dead pressed. Overall, the research by Fumihiko, Hirosaki and Kato helps to show that the caps were not the cause of sympathetic detonation or dead pressing in this thesis research.

2.8. DESIGN METHODOLOGY FOR UNDERSTANDING THE SYMPATHETIC DETONATION CHARACTERISTICS OF INSENSITIVE HIGH EXPLOSIVES (Raghavan, 2005)

The purpose of Raghavan’s research was to determine the best configuration for storing artillery shells to prevent a chain reaction if one shell were to accidentially detonate. In other words, Raghavan wanted to find the distance and orientation that would prevent other shells from sympathetically detonating if a neighboring shell where to detonate. Raghavan began his project by looking at mathematical methodology for blasting. Next, he completed a small scale study on the effect of donor size. Finally, he completed a large scale study, looking at head on configuration versus side on

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configuration. Using his results, he determined that side on configuration would be the best orientation for storage of shells.

First, Raghavan mathmatically modeled sympathetic detonation for artillary shells to look at detonation velocity. He used the shock equations of state including the Hugoniot Equations, the Chapman-Jouguet State, the Lee-Tarver Ignition and Growth Model and the JWL approximation. The author then performed numerical simulations including the Kubota Gap Test and the NPS Gap Test. These two tests were done to determine the shock sensitivity of an explosive. The results of these tests showed that the theoretical detonation velocity was slightly higher than the observed detonation velocity in Composition B. Using the fact that the detonation velocity is lower than the theoretical value, Raghavan next completed a small scale experiment to verify this.

The emphasis of his small scale study was to find the effect of donor sizing on sympathetic detonation. The results from the small scale simulation showed that a high pressure wave over a long period time would cause sympathetic detonation in the acceptor. Another find was that the donor charge weight was directly related to the incident pressure wave, and for a larger mass explosive a larger gap distance was needed to avoid sympathetic detonation. In other words, the larger the donor charge is, the further away an acceptor charge will sympathetically detonate.

Using the fact that larger shells need to be further apart to prevent sympathetic detonation, Raghavan completed a large scale experiment. This experiment studied the likelihood of the sympathetic detonation of two artillery shells in storage. He studied both head-on orientation and side-on orientation to one another. Raghavan concluded that the distance of safe separation was reduced by 25% when the artillery shells were

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store side by side versus head-on. He deduced that a pressure wave that was expanding in a circular manner decreased faster than a pressure wave traveling along an axis.

Overall, the paper and research showed that artillery shells had the greatest chance of sympathetic detonation when they were in a side-on configuration.

The research that is presented later in this thesis is similar to Raghavan's in the fact that the tests that are preformed are in the side-on configuration. This should cause sympathetic detonation to occur more often.

2.9. ALL ABOUT WATER HAMMER (Pelikan, 2009)

Pelikan says that there are four different conditions that must be present in a system before water hammer can take place. The first item that must be present is a fluid flowing through a medium at a high enough velocity. This means that the fluid velocity must be higher than five feet per second. The next thing that must be present is a change in velocity that is fast enough to shock the system. This can be a slowing of the fluid velocity or a speeding up of the fluid velocity. The third item that must be present is a pipe system that is long enough for this to take place over. The fourth item that must be present is a ridge pipe system. When all of these things are present, a pressure approximately ten times larger than the normal pressure in the system can build up. The pressure keeps traveling through the system, until it finds a way to release the excess pressure or drops due to different losses in the system.

This is imporant in blasting because you have an very rapid change in the fluid velocity, in wet holes. When hydraulic conductivity is present in the rock, this provides a ridgid system for the fluid to travel through. With this information, on the water

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hammering effect, a possible explanation as to why sympathetic detonation and dead pressing occur out to further distances, when water is present in the holes than when the holes are dry, can be explained.

2.10. STUDY ON THE SHOCK SENSITIVITY OF AN EMULSION EXPLOSIVE BY THE SAND GAP TEST (Ishikawa, Abe and Kubota, 2006)

Ishikawa, Abe and Kubota studied the gap distances of different size explosives in order to find a relationship between gap distance and size of explosive. They used mortar and sand as a separator in the gap between the explosives. Figure 2-8 shows the results from their tests, which show a log-log relationship between gap thickness and explosive weight.

While Figure 2-8 shows a liner relationship for the specific explosive that was tested with a sand gap, a similar relationship should be able to be found for other explosives in a different type of gap material. The relationship that they found will not hold true for all other explosives with different types of material in the gap between them, although, it is a good starting point to show that there is a relationship to be found.

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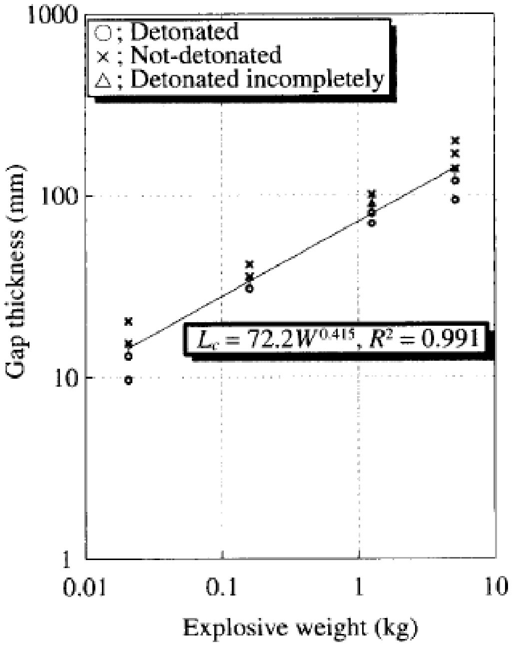

Figure 2-8: Relationship of Explosive Weight to Gap Thickness (Ishikawa, Abe and Kubota)

2.11. INTRA-HOLE AND INTER-HOLE EFFECTS IN TYPICAL BLAST DESIGNS AND THEIR IMPLICATIONS ON EXPLOSIVES ENERGY RELEASE AND DETONATOR DELAY TIME—A CRITICAL REVIEW (B. Mohanty, 2010)

Mohanty investigated sympathetic detonation, specifically decking and firing times. Mohanty looked at pressure for explosives, mainly pentolite, for donor explosives. Mohanty was able to calculate the incident shock pressure for different receptor [acceptor] explosives at different distances. During the experiment, the researcher made voids in the explosive matrix. From the results, he found that the voids amplified the

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pressure and that air bubbles were better amplifiers than glass micro-balloons. This amplified pressure led to deflagration and sympathetic detonation of some of the explosives. The study also found that gas doped emulsions needed twenty borehole diameters in length to prevent misfires while non-gassed slurries only needed sixteen borehole diameters in length of stemming. This was inter-hole, which is between two different holes. The final concept that the researcher looked at was decking. This was intra-hole which is within the same hole. He found that for both decked and non-decked blasts, that the energy released was affected by the mode of initiation.

When priming a stick of explosive, it is hard to not introduce voids into the explosive. The voids that are introduced do have an effect on the amplification of the pressure wave in the explosive. Emulsions naturally have voids in them, which is what sensitizes the emulsions, and what is crushed out when they dead press. Emulsions are used in this thesis research to investigate dead pressing.

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3. EXPERIMENTAL PROCEDURE

In this section, the experimental procedures for setup, instrumentation, measurements, and inspections are discussed.

3.1. PROCEDURE FOR SETUP

In order to maintain consistency between the different tests, it was important to setup the experiment in the same way every time. This was done by drilling the holes in the same pattern and setting up the equipment in the same way every time including loading the holes and priming the shot. Measurements were also taken to account for deviations in the drilling. The rock the patterns were drilled in was Jefferson City Dolomite. The description of the setup procedure follows.

3.1.1. Geology of Site. All of the holes were drilled at Missouri S&T's Experimental Mine in the dolomite rock present. The locations for the shots were in the quarry and in the creek next to the quarry. The reason for doing the shots close to each other was to try to minimize the amount of differences between the rocks being blasted. The further apart the patterns are being blasted, the greater the chances are that the rock is not identical to what was blasted in previous shots. All of the dry holes were done in the quarry because the quarry was mostly dry with no running water. The creek was used for the wet shots as it had running water which ensured that the holes were wet and stayed wet after drilling.

The dolomite rock has a density of between 89 and 178 pounds per cubic foot depending on porosity, up to 50% (Missouri Department of Natural Resources). The

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higher the porosity is, the lower the density is. Dolomite is rarely a pure dolomite rock; it usually has a mixture of other materials with it to give it its consistency. Some of these other materials are quartz, clay and pyrite (Missouri Department of Natural Resources). Because the sites are not normally perfectly homogenous, it is recommended that a site survey be done before blasting takes place. This will help to find voids and cracks that are present that are not easily seen from the surface.

3.1.2. Design of Boreholes. The pattern for the tests was designed to show how far out from the center hole sympathetic detonation or dead pressing would occur after the donor hole had been detonated.

This was done in a cruciform pattern that can be seen in Figure 3-1. The donor charge was placed in the middle of the diamond, and the acceptor charges were placed at the corners, where the distance between the donor and the acceptor charges increased by two inches as the acceptor holes moved further away from the donor hole. The nominal distances ranged from two inches to eight inches. In order to prevent the acceptor hole to acceptor hole distance being less than the acceptor hole to donor hole distance, the acceptors were placed at right angles to each other with respect to the donor hole.

The distances were measured from edge of donor hole to edge of acceptor hole. The acceptor holes were placed at 2″, 4″, 6″, and 8″ distances. The 2″ hole will be called hole 1, the 4″ being called hole 2, the 6″ hole being called hole 3, the 8″ hole being called hole 4, and the center hole being called hole 0. A top view of what this looked like is shown in Figure 3-1.

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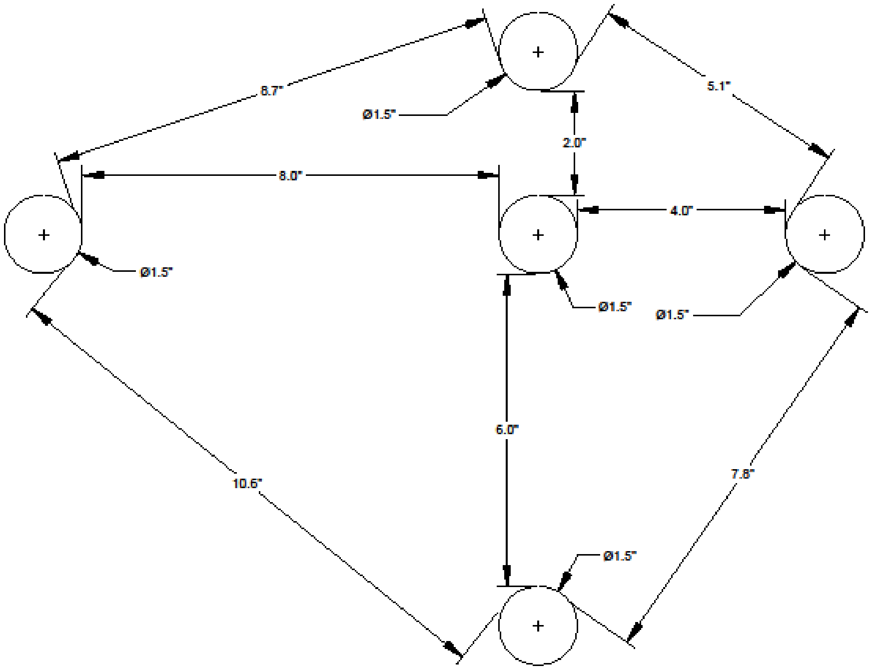

Figure 3-1: Layout of Holes

3.1.3. Drilling of the Holes. The first step in the testing process was to drill the holes. During the drilling of the holes, there were at least three people present. One person operated the drill, shown in Figure 3-2, while the other two people stood at ninety degrees to each other and in line with the drill operator to make sure that the drill remained level during the drilling. Also, they were in charge of informing the drill operator when the depth of the hole had been reached. The dimensions of the holes were 1½″ by 24″. After each hole was drilled, it was checked to make sure that it was at the proper depth, and if it was found not to be, it was corrected by either drilling, if found to

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be short, or backfilling to the correct depth using stemming, if found to be too deep. The stemming size that was used for both the back filling and for stemming the holes was $^{3}/_{8}''$ minus. This size is large enough that the stemming cannot go down past the explosive, even if the explosive is completely on one side of the hole, as there is only ¼″ which is less than $^{3}/_{8}''$. The depth was checked by using a rigid pole with a flat bottom that was lowered into the hole until it reached the bottom. Once the rigid pole reached the bottom, the pole was marked and then removed from the hole. The length of the pole from the bottom to the mark yielded the depth of the hole. This pole was also used to make sure that there were no major voids or major cracks in the hole. This was done by running the pole up and down the sides of the borehole to see if any voids could be felt with the pole.

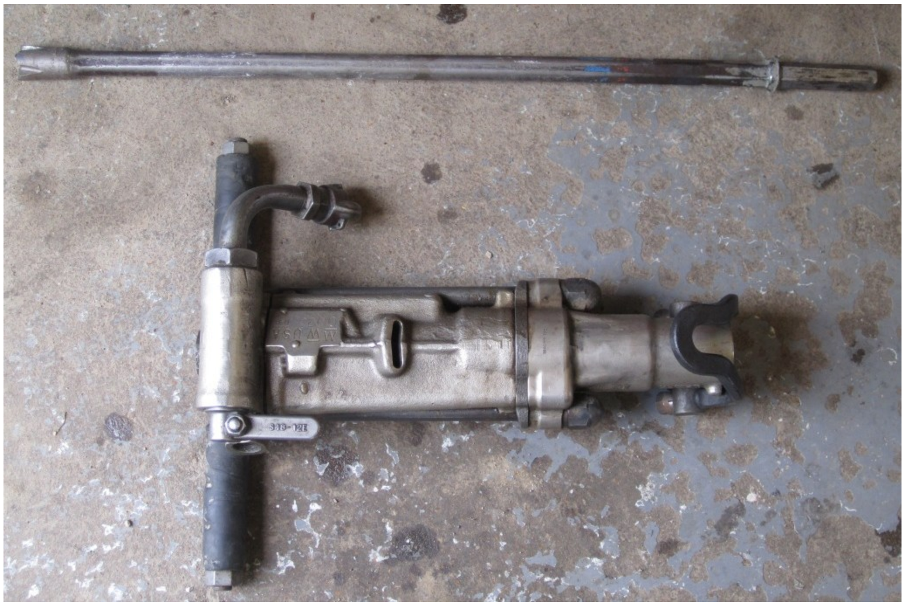

Figure 3-2: Drill and Drill Bit

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Each of the drill patterns was set at least ten feet from any previous pattern. This was important to prevent the possibility of fractures in the rock, due to the previous blasts, intersecting the rock for the other patterns. Fractures would cause an abnormality in the rock, which could cause more of the holes to either sympathetically detonate or dead press than would normally.

3.1.4. Measurement of the Holes. The measurements of the holes took place before, during and after the holes were drilled. During the drilling process, the distance between the holes was measured from the edge of the donor hole to the edge of the acceptor hole. This was done with the same tape measure that was used to measure the depth of the holes, to mitigate error due to equipment.

3.1.5. Setup of Recording Equipment. Once the pattern was drilled but before the holes were loaded, the seismograph was set up. The seismograph was placed twenty-five feet from the outside of hole 4. The seismograph and geophone were pointed towards the blast pattern to make sure the results were properly recorded.

The high speed camera was set up inside a blast shelter, shown in Figure 3-3. The camera was positioned so that both the shock tube stand and the blast were visible in the recording. Once the camera was set up and focused on the stand, the holes were then loaded.

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Figure 3-3: Camera in Blast Shelter

3.1.6. Loading of Holes. The holes were loaded in a similar fashion for both the sympathetic detonation of dynamite, Dyno Nobel Unimax, and dead pressing of emulsions, Orica Senatel Ultrex. The size of the explosive used was 1¼ x 8″ with one stick in each hole. The holes were loaded in the following order: hole 0, hole 1, hole 2, hole 3, and hole 4. Loading the holes the same way each time, helped to prevent the wrong delay from being put in a hole. The caps were first laid out starting with the lowest number delay being placed next to the donor hole, hole 0. The next lowest numbered delay was then placed next to hole 1, then hole 2 and so on.

After the caps had been placed next to the holes, loading began. First, the explosive charge was primed with the proper delay cap. After it had been primed, the tail

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end of the cap lead line was taped to the stick. Then a length of shock tube was measured out to be three feet longer than the distance between the borehole and the stand. The extra three feet was to account for the two feet in the hole and one foot wrapped around the stand. The shock tube stand was used to hold the loops of shock tube so that the high speed video camera could record the flashes of the shock tube. This allows us to see when the hole detonated. The shock tube ends were then taped over to ensure that nothing could get into the tube during the loading process and anytime till the pattern was shot. The end that was going in the hole was then taped to the whole length of the explosive charge. The finished product can be seen in Figure 3-4. This ensured proper contact with the explosive, and when the charge went off, the shock tube should go off along with it. Then the charge was lowered into the hole with the aid of a loading pole to make sure that the charge was placed completely at the bottom of the hole. The lead line of the cap was cast off to the side to make sure that it did not get in the way of loading other holes. After the charge was lowered into the hole, the shock tube line from the charge was then taped to the stand. After this, the next hole was done in the same way. Each hole had a cap to make sure that the explosive was shot and that no live explosive was left in the ground. This was for the safety of this blast and future people to make sure no explosive was in the ground or elsewhere that someone could encounter. This is realistic to field conditions. Figure 3-5 shows how a hole looked after it is loaded. An example of the stand tapped up is shown in Figure 3-6.

The primed stick of dynamite shown below shows both the LP cap lead line along with the shock tube that is taped to it that goes to the shock tube stand. This extra shock tube is what the high speed camera sees.

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After all of the holes were loaded with explosives, water was added to the holes for patterns that were designated wet. If the holes were to be dry, no water was added. The next task was adding the stemming to each hole until there was a little stemming above each hole, to make sure that the holes were completely filled. During the loading of stemming, the stemming was pushed in at the top by hand. This was to prevent the shock tube or the cap line from being cut, while still filling the hole completely with stemming. The lines were taped to the stand in the same fashion every time. It was always taped starting on the left with the donor hole and moving across the stand to the right, with hole 1, 2, 3, and 4 in order. This provided consistency with every shot. When viewing the video footage, the flashes went off from left to right on the stand so one knew what one was seeing each time. Figure 3-7 shows a typical shot of fully loaded holes with the shock tube running to the stand, seen in the bottom left of the picture, and the cap lead lines, seen in bottom right of picture.

Figure 3-4: Primed Stick of Dynamite

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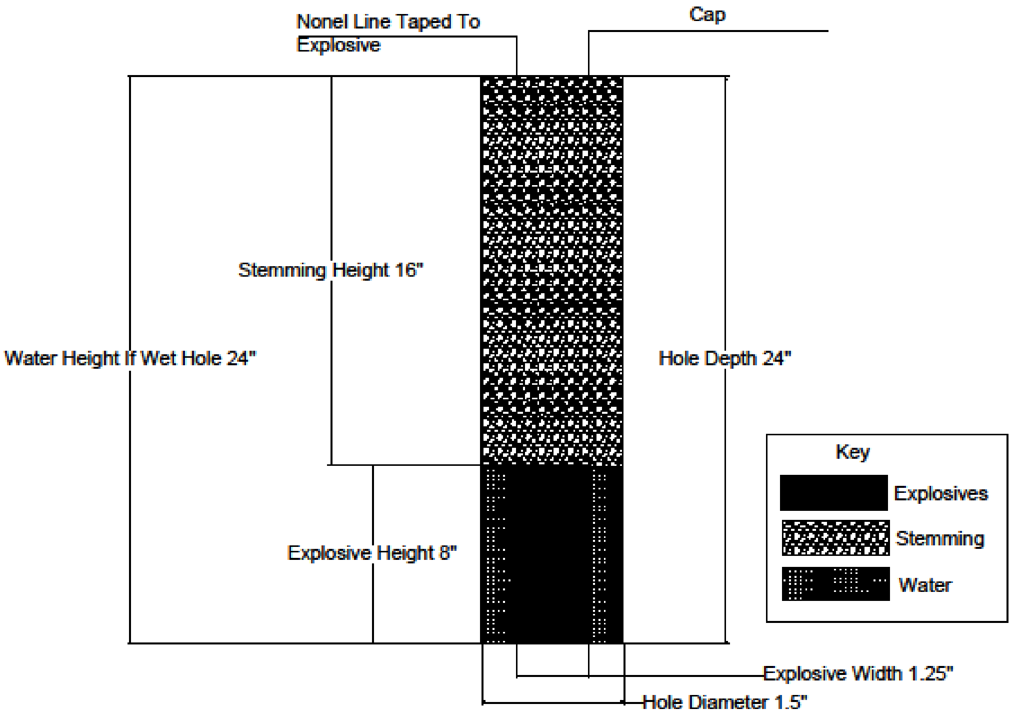

Figure 3-5: Column Layout

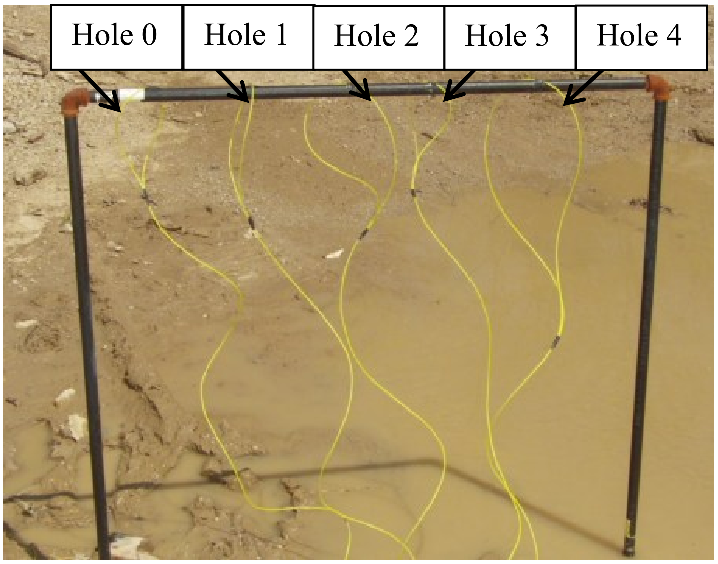

Figure 3-6: Shock Tube Stand Layout

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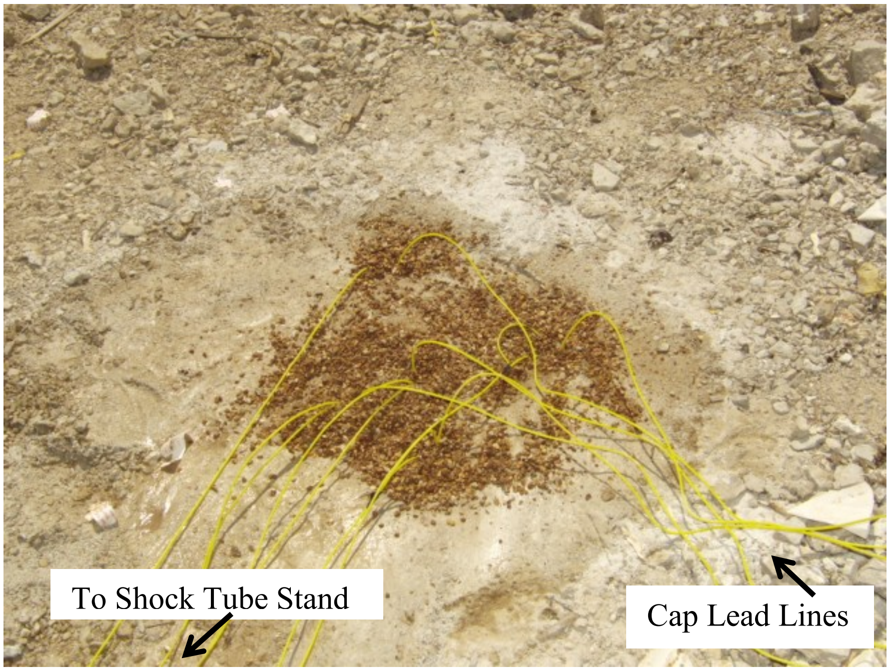

Figure 3-7: Top View of Loaded Holes

3.1.7. Verifying Setup. Once the setup was finished, the shot was checked again to verify everything was setup properly. Every shock tube line was checked to make sure that the proper cap was in each hole and that the shock tube line was attached to the proper spot on the stand. After the check was done, the shot pattern was primed with a starter cap.

3.1.8. Priming the Shot. The shock tube lines attached to the caps from each stick were gathered up on the side of one pattern as illustrated in Figure 3-7. These tubes were brought to a slight tension to try to make sure that there were no cutoffs when the pattern was blasted and that each cap in each hole was initiated at the same time. Then each of the tubes was taped to the starter cap so that all of the tubes would be started by

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the starter cap at the same time. After this was done, everyone left the shot pattern site as the explosives were ready to be blasted. As the blaster left the site, the blaster checked the seismograph and the high speed camera, and then started the high speed camera to capture the shock tube flashes when the pattern was blasted.

3.2. INSTRUMENTATION

In order to record data to get accurate measurements of if sympathetic detonation or dead pressing occurred, a high speed camera and seismograph were employed.

3.2.1. High Speed Camera. A Casio Exilim EX-FH25 high speed camera, shown in Figure 3-8, recorded each of the sixteen shots to obtain the flashes of the shock tube. These flashes were used to tell when each hole detonated. By recording the blast, the author was able to view the video later and observe what actually happened.

The blast was visible, in the camera video, from behind the shock tube stand in order to obtain high quality video without objects blocking the flashes. The camera was placed approximately 100 feet from the location of the shock tube stand. A metal box with Plexiglas viewports shielded the camera from any sizeable fragments that resulted from the blast. The camera had a speed of 1000 frames per second that was used for each shot. The resolution of the recorded shots was 224 x 64. The focus and zoom of the camera varied from shot to shot but were selected to give the best recorded video based on outside conditions.

3.2.2. Seismograph and Geophone. A White Industrial Seismology, Inc. Mini-Seis seismograph was used to record the ground vibration and air blast of each shot. It was with this data, that detonation of the different sticks of explosives could be observed

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with respect to time of the first arrivals for each detonation. This can be done by looking at the report that the seismograph generates of the ground vibration. When looking at this report, the peaks in the graphs represent the detonation of explosives. The seismograph was place approximately twenty-five feet from the location of the 8″ hole. A sandbag was placed on top of the seismograph's geophone to ensure that it had constant contact with the ground during the blast. This can be seen in Figure 3-9. The same seismograph was used each time and the settings were not changed. The settings of the seismograph are shown below:

Seis. Trigger: 0.060 in/sec
Air Trigger: 148 dBA (Off)
Pre-Trigger: 0.25 Seconds
Duration: 5.0 Seconds
Sample Rate: 2048/second

The Air Trigger was set to "off" to prevent the seismograph from prematurely starting due to wind and other sounds of nature. This premature start would cause the seismograph to record only part of the blast. The seismograph recorded a 0.25 second pre-trigger so that nothing was lost.

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Figure 3-8: Casio Exilim EX-FH25 High Speed Camera

Figure 3-9: Seismograph Setup

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3.3. PRE-BLAST INSPECTION: MEASURING OF HOLES

The distances between the holes were measured to account for deviation between the shots. Before the loading of the holes commenced, the holes were checked for collar separation distance and deviation to find how close each of the acceptor hole explosives were to the donor hole explosive. The distance was checked by placing two rigid poles along the inside of the donor and acceptor boreholes to assume the best case scenario for the location of the explosives. The deviation was calculated from the distance between the poles at both the ground level and two feet off the ground to see if the holes were convergent or divergent. From that, the top and the bottom of the explosive could be calculated to find which part of the acceptor hole explosive was the closest to the donor hole explosive. An example of how this was done is shown in Figure 3-10 and Figure 3-11. These values can been found in Appendix B.

Figure 3-10: Measurement of Hole Separation on Surface

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Figure 3-11: Measurement of Hole Deviation at Two Feet Above Ground Surface

3.4. POST-BLAST INSPECTION

After each blast, the high speed video data was collected and compared to the seismograph data to determine what actually happened.

3.4.1. Checking of Shock Tube. After each pattern was shot, the shock tubes were checked to make sure that the whole pattern had been shot. If any of the tubes were not shot, then time was spent to make sure the pattern was safe to approach before checking the shock tubes more closely. This mostly happened on shots when the rock and debris from the blast either cut or ripped the shock tubes from the holes above the ground before they had a chance to detonate. This check was mainly to make sure that the pattern was safe to approach after the blast and that no explosive was left in the

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ground. The shock tubes always shot in order of detonation except for when there was sympathetic detonation in the holes.

3.4.2. Checking of High Speed Video. After the pattern had been cleared, the video of the shock tube stand was downloaded and viewed. This was done by slowing the high speed video down to a frame by frame speed. When this was done, the individual flashes of the different shock tube lines could be viewed easily, thus showing the order and the time of each detonation. Each of the shock tubes was the same approximate length, twenty-five feet, which fires at 6500 ft/sec. The small error in time difference is systematic and due to LP caps being used and was not important.

When reviewing the data from the high speed video and the seismograph, the flashes on the video from the shock tube were matched to the peaks on the seismograph. This data was used to see when each hole went off in case a shock tube did not flash due to a cutoff from the movement of the rock. With this knowledge, the seismograph data could be viewed and interpreted with more clarity.

3.4.3. Checking Of Seismograph Data. After the camera data had been reviewed, the seismograph data was viewed with Seismograph Data Analysis V10. This showed the ground vibrations and air blast resulting from the shot pattern. The vibration traces showed the timing of when each blast happened but did not reveal which hole detonated at which time. The camera data was needed for that, but data gathered from the shock tubes and looking at the blast afterwards, helped. A sample excerpt of a shot seismograph data is shown in Figure 3-12 below.

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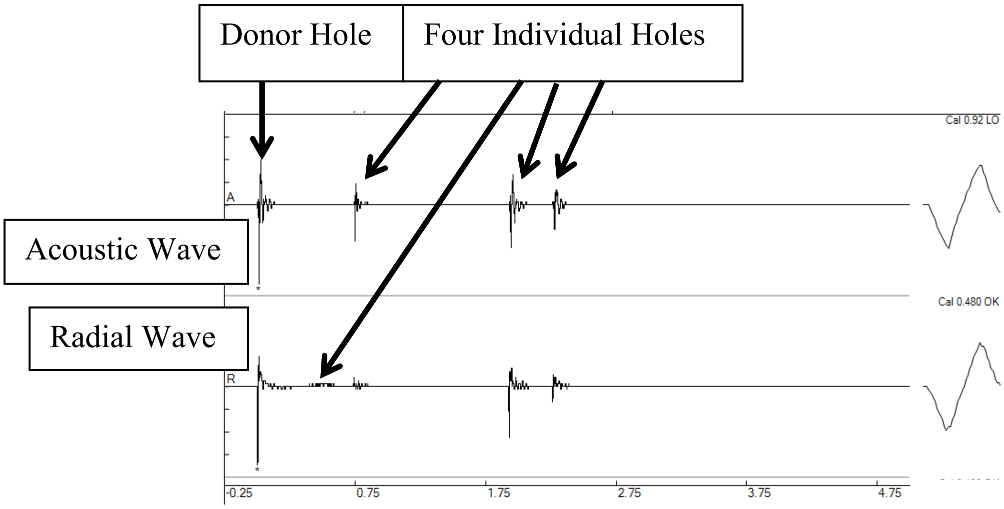

Figure 3-12: Sample Excerpt of Seismograph Data

Figure 3-12 shows the starting cap and all five holes. This is a sample from a dead pressing test. The peaks of interest were only the first arrivals. The figure shows that the hole one and hole two dead pressed while hole three and hole four did not. This can be seen from the larger vibrations recorded for the radial waves, as told by the program. Hole three and hole four had larger radial waves than hole one and hole two. Hole three had the largest radial wave of the four holes, showing that it was moving more material than the other holes. This, combined with hole three and hole four having larger radial waves, shows that hole three and hole four did not dead press while hole one and hole two did.

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The reason for the donor hole having the largest ground vibration is because when the hole was detonated, it had no relief to blast to. This caused a larger vibration as it had to move the rock out of the way. The rest of the holes had a relief to blast to which reduced the amount of work that they had to do, which in turn reduced the ground vibration. This explains why hole 0 had a larger ground vibration peak on the seismograph than holes 1 through 4.

3.4.4. Verifying Data. After the data from both the camera and seismograph had been reviewed, the data was checked to make sure that the information found was consistent between the camera and seismograph. If there was a discrepancy between the seismograph and the high speed camera, the problem was thought out as to a possible reason for it, and then the pattern was checked to see if the holes showed support of this.

3.5. TESTING OF CAPS

The caps were tested to see if the caps were the cause of sympathetic detonation. By ruling the caps out, the cause can be concluded to be the explosive.

The procedures and setup for the tests, done as wet holes, were used with the exception of the acceptor holes. The acceptor holes just had a cap in the hole, no stemming or explosive. The caps were placed in the acceptor holes by themselves. These caps were taped to a dowel rod, which can be seen in Figure 3-13, to make sure that the caps were lowered to the bottom of the hole and placed at the proper depth.

By only having the cap in the acceptor hole, the impedance mismatch that is present when the donor charge is detonated is reduced. By reducing this mismatch, it improves the probability that the cap will sympathetically detonate. This was repeated

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four times. Three of the times were with the holes at two, four, six, and eight inches while the fourth time had all the holes at three inches.

Figure 3-13: Cap Test Setup

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4. EXPERIMENTAL RESULTS

In the experimental results, the high speed camera and seismograph were compared to find at what distance sympathetic detonation and dead pressing occurred out to. Hole 0 refers to the donor hole, while hole one, two, three, and four refer to the acceptor holes at two, four, six and eight inches respectfully from the donor hole. The actual distance is the distance the acceptor explosive was from the donor explosive in the experiments. The Nominal delay is the delay as would be seen by the seismograph. The shock tube time represents the time at which the shock tube flash could be seen on the video. The following column notes if a flash was not seen in the shock tube but an explosion was on the video. The seismograph time is the time the seismograph saw a vibration. The following column shows whether or not the explosive sympathetically detonated or dead pressed.

4.1. SYMPATHETIC DETONATION

Sympathetic detonation was investigated in both dry holes and wet holes to represent different environmental conditions. Three trials were completed for each set. When looking at the seismograph, if there was no peak where a cap delay was supposed to be, this showed that the hole may have sympathetically detonated. This was also checked against the high speed camera to see if the shock tube for the hole flashed at the same time as the donor hole to show that it sympathetically detonated.

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4.1.1. Dry Holes. The sympathetic detonation of dynamite was found to occur when the donor hole charges and acceptor hole charges were 3.92 inches or less apart when the holes were dry. Following is more detail on the error in the placement of the holes, a summary of the seismograph data, and a summary of the high speed video. It was with this information that the 3.92 inch range was found.

4.1.1.1. Blast one. A summary of the results from the seismograph and camera for shot number one of sympathetic detonation of dry holes is shown in Table 4-1 below.

Table 4-1: Sympathetic Detonation Dry Hole Shot #1

Sympathetic Detonation Dry Holes Shot #1						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Sympathetic Detonation
0	-	0.0 Secs	0.0 Secs		0.9 Secs	-
1	1 3/4 inches	0.4 Secs	0.0 Secs		-	Yes
2	3 1/3 inches	0.8 Secs	0.0 Secs		-	Yes
3	6 11/24 inches	1.7 Secs	-		2.8 Secs	No
4	9 2/3 inches	2.2 Secs	2.0 Secs	No Flash	3.1 Secs	No

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Based on the seismograph data and the high speed camera summarized above, both hole 1 and hole 2 sympathetically detonated. By looking at the times for holes 3 and 4 from the seismograph, it can be seen that they matched closely to the nominal delay of the caps when the time is offset by the starting time of hole 0.

4.1.1.2. Blast two. A summary of the results from the seismograph and camera for shot number two of sympathetic detonation of dry holes is shown in Table 4-2 below.

The seismograph data, summarized in the table below, was only able to record two spikes. These spikes corresponded to hole 0 and hole 2. It was concluded that holes 1, 3, and 4 sympathetic detonated when the center hole went off according to the seismograph data.

Table 4-2: Sympathetic Detonation Dry Hole Shot #2

Sympathetic Detonation Dry Holes Shot #2						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Sympathetic Detonation
0	-	0.0 Secs	0.0 Secs		0	-
1	2 1/6 inches	0.4 Secs	0.0 Secs		-	Yes
2	4 1/2 inches	0.8 Secs	-		0.9 Secs	No
3	7 1/6 inches	1.7 Secs	-		-	Yes
4	9 1/6 inches	2.2 Secs	-		-	Yes

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The high speed camera was able to record that hole 1 sympathetically detonated but none of the other holes. This could be caused by the rock debris cutting the shock tube after the donor hole went off or water leaking into the shock tube in the ground before the pattern was detonated. The seismograph was only able to see hole 0 and hole 2 detonate normally. When combining high speed camera data with the seismograph data, it was reasoned that sympathetic detonation occurred out to hole 1 and that hole 3 and hole 4 misfired.

4.1.1.3. Blast three. A summary of the results from the seismograph and camera for shot number three of sympathetic detonation of dry holes is shown in Table 4-3 below.

The seismograph data summarize in the table below, shows that hole 1 sympathetically detonated while the other holes did not. The seismograph recorded holes 2, 3, and 4 detonating. It recorded hole 2 detonating at a time that was close to the nominal delay time for the cap however, holes 3 and 4 detonated approximately one second higher than the nominal delay time according to the seismograph. This could be due to a bad recording.

The high speed camera was able to record that hole 4 detonated normally but was unable to record that the other holes detonated because no visible flash from the shock tube was present in the recording. Overall, by comparing the camera and seismograph data, it was concluded that only hole 1 sympathetically detonated.

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Table 4-3: Sympathetic Detonation Dry Holes Shot #3

Sympathetic Detonation Dry Holes Shot #3						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Sympathetic Detonation
0	-	0.0 Secs	0.0 Secs		0	-
1	3 1/12 inches	0.4 Secs	-		-	Yes
2	5 inches	0.8 Secs	-		0.9 Secs	No
3	7 1/6 inches	1.7 Secs	-		2.9 Secs	No
4	8 3/4 inches	2.2 Secs	2.4 Secs		3.1 Secs	No

4.1.1.4. Summary of blasts. Sympathetic detonation of dry holes was important to test to give a baseline comparison when comparing the wet holes results to see the effect of water. Overall, the effect found was that sympathetic detonation occurred when the donor and acceptor charges were 3.92 inches or less apart. This result was supported by both the high speed camera and the seismograph. The graph, shown in Figure 4-1, shows a summary of the three blasts. A more detail breakdown of the percent error, deviation, and measurements by hole is shown in Appendix B. The variance in the drilling error was beneficial as it allowed for the transition zone to be narrower than at the original distances. The transition zone is the area between when the explosive sympathetically detonates and when the explosive detonates normally.

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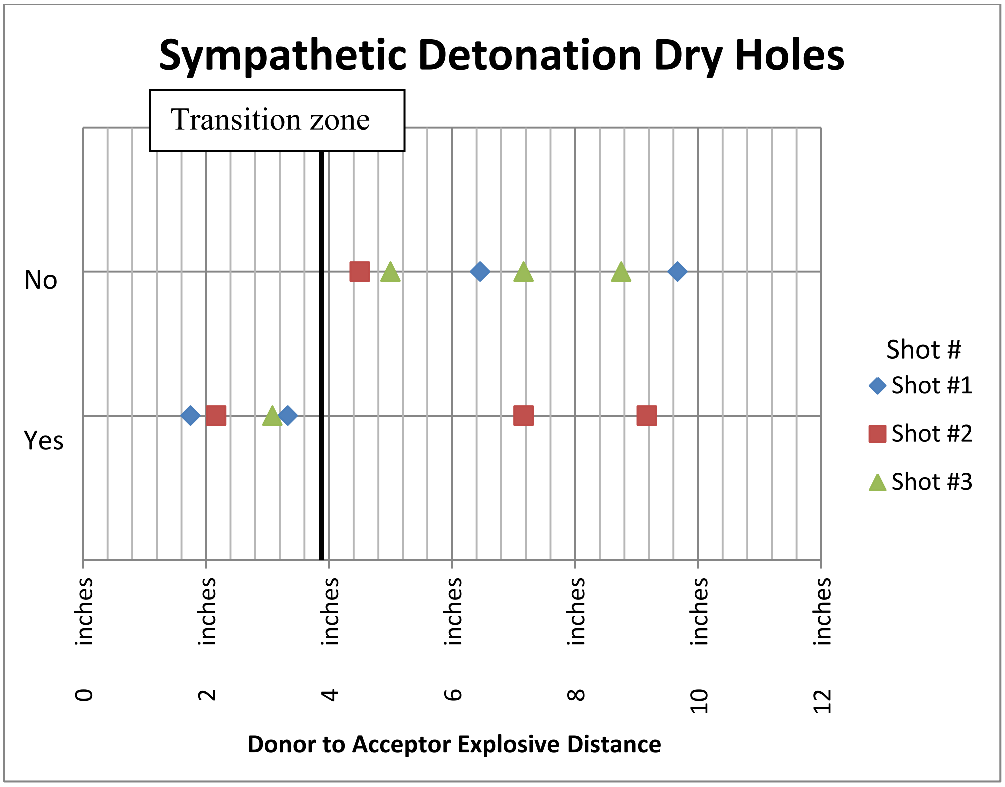

Figure 4-1: Sympathetic Detonation of Dry Holes Results

4.1.2. Wet Holes. The sympathetic detonation of dynamite was found to occur under wet conditions when the donor and acceptor charges were 5.64 inches or less apart. Following is more details on the error in the placement of the holes, a summary of the seismograph data, and a summary of the high speed video. It was with this information that the 5.64 inch range was found.

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4.1.2.1. Blast one. A summary of the results from the seismograph and camera for shot number one of sympathetic detonation of wet holes is shown in Table 4-4 below.

Table 4-4: Sympathetic Detonation Wet Holes Shot #1

Sympathetic Detonation Wet Holes Shot #1						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Sympathetic Detonation
0	-	0.0 Secs	0.0 Secs	No Flash	0	-
1	2 13/24 inches	0.4 Secs	-		-	Yes
2	5 inches	0.8 Secs	-		-	Yes
3	7 1/12 inches	1.7 Secs	1.9 Secs	No Flash	1.7 Secs	No
4	8 11/12 inches	2.2 Secs	2.5 Secs	No Flash	2.4 Secs	No

Both the seismograph and high speed camera showed precise results. The high speed camera did not record a flash for hole 3 and hole 4, although an explosion was seen for the holes. From looking at the seismograph data summarized in the table above, it can be seen that the blast sympathetically detonated hole 1 and hole 2 while hole 3 and hole 4 detonated normally. From looking at the high speed video, both holes 1 and 2

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sympathetically detonated while hole 3 and 4 did not. The times from both the seismograph and high speed camera were close to each other, thus, the data showing that hole 1 and hole 2 sympathetically detonated while holes 3 and hole 4 did not, can be seen to be correct.

4.1.2.2. Blast two. A summary of the results from the seismograph and camera for shot number two of sympathetic detonation of wet holes is shown in Table 4-5 below.

Table 4-5: Sympathetic Detonation Wet Holes Shot #2

Sympathetic Detonation Wet Holes Shot #2						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Sympathetic Detonation
0	-	0.0 Secs	-		0	-
1	4 1/12 inches	0.4 Secs	-		-	Yes
2	4 1/2 inches	0.8 Secs	-		-	Yes
3	5 1/2 inches	1.7 Secs	-		1.8 Secs	No
4	8 2/3 inches	2.2 Secs	-		2.1 Secs	No

The seismograph had the same results for blast two as blast one. Both hole 1 and hole 2 sympathetically detonated, leaving hole 3 and hole 4 to detonate normally. However, the high speed camera was not able to capture the blast. The camera cut off the

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recording before the pattern was blasted. A possible reason for this could have been a faulty camera. Another possible reason for this could have been that the shock from the blast could have interrupted the power supply of the camera. This could have been done by the shock moving the batteries inside the camera just enough to cause the power turn off. A possible way to prevent this in the future would to be use two cameras, as this would reduce the possibility that no video is captured because of one camera not working.

4.1.2.3. Blast three. A summary of the results from the seismograph and camera for shot number three of sympathetic detonation of wet holes is shown in Table 4-6 below.

Table 4-6: Sympathetic Detonation Wet Holes Shot #3

Sympathetic Detonation Wet Holes Shot #3						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Sympathetic Detonation
0	-	0.0 Secs	0.0 Secs		0	-
1	4 1/12 inches	0.4 Secs	0.0 Secs		-	Yes
2	6 1/12 inches	0.8 Secs	0.0 Secs		-	Yes
3	5 3/4 inches	1.7 Secs	2.0 Secs	No Flash	1.8 Secs	No
4	8 11/12 inches	2.2 Secs	2.6 Secs	No Flash	2.4 Secs	No

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Based on the seismograph data and high speed video of the explosion, it was determine that both hole 1 and hole 2 sympathetically detonated. Seen in the table above, the seismograph was able to record that hole 1 and hole 2 both sympathetically detonated. Hole 3 and hole 4 both detonated normally. The high speed camera was able to record that hole 1 and hole 2 sympathetically detonated while hole 3 and hole 4 detonated normally.

4.1.2.4. Summary of blasts. Overall, this set of blasts had good results. It was seen that when the holes were filled with water, they would sympathetically detonate out to 5.64 inches.

There were some issues with the seismograph and high speed camera, but because all three blasts had the same results, these issues became immaterial. Below is a graph in Figure 4-2 showing the results of the blasts.

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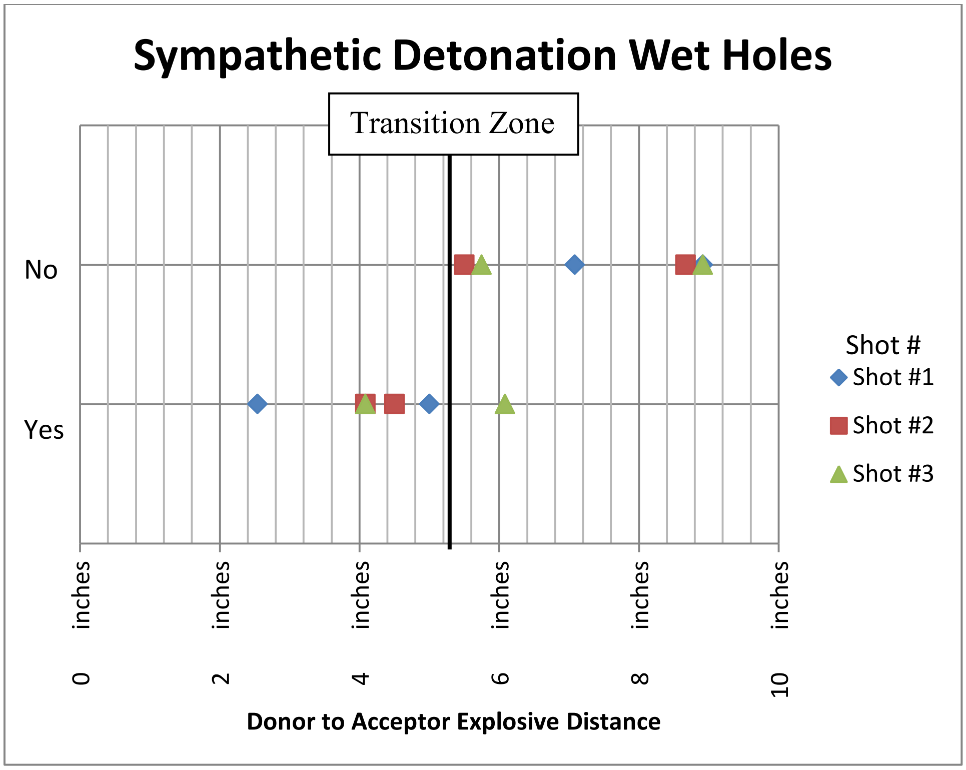

Figure 4-2: Sympathetic Detonation of Wet Holes Results

4.2. DEAD PRESSING

Dead pressing was investigated in both dry holes and wet holes to represent different environmental conditions. Three trials were completed for each set. When looking at the seismograph, if there was a smaller than normal peak where a cap delay was supposed to be, this showed that the hole may have dead pressed. This was also checked against the high speed camera to see if the shock tube for the hole flashed at the same time as the donor hole to show that it dead pressed.

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4.2.1. Dry Holes. The dead pressing of emulsion was found to occur under dry conditions when the donor charges and acceptor charges were 3.26 inches or less apart. Following is a summary of the seismograph data and a summary of the high speed video.

4.2.1.1. Blast one. A summary of the results from the seismograph and camera for shot number one of dead pressing of dry holes is shown in Table 4-7 below.

The seismograph data showed that dead pressing occurred in hole 1 but not in any of the other holes. The cap in hole 1 was able to be seen detonating on the seismograph data, but the vibration was less than that of a cap and explosive detonating, therefore the explosive dead pressed.

The high speed video was able to record that hole 1 dead pressed while hole 3 and hole 4 detonated normally. It was not able to record hole 2 detonating clearly.

Table 4-7: Dead Pressing Dry Holes Shot #1

Dead Pressing Dry Holes Shot #1						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Dead Pressed
0	-	0.0 Secs	0.0 Secs		0	-
1	2 1/8 inches	0.4 Secs	-		0.4 Secs	Yes
2	5 3/4 inches	0.8 Secs	-		0.7 Secs	No
3	7 11/48 inches	1.7 Secs	2.0 Secs		1.9 Secs	No
4	8 17/48 inches	2.2 Secs	2.4 Secs		2.3 Secs	No

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4.2.1.2. Blast two. A summary of the results from the seismograph and camera for shot number two of dead pressing of dry holes is shown in Table 4-8 below.

From looking at the seismograph data summarized in the table below, it was seen that the blast dead pressed hole 1 while hole 2, hole 3, and hole 4 did not dead press.

The high speed video recorded that hole 1 dead pressed while hole 2 did not. It did not record hole 3 or 4 detonating.

Table 4-8: Dead Pressing Dry Holes Shot #2

Dead Pressing Dry Holes Shot #2						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Dead Pressed
0	-	0.0 Secs	0.0 Secs		0	-
1	1 13/16 inches	0.4 Secs	0.0 Secs		-	Yes
2	5 13/48 inches	0.8 Secs	0.8 Secs		0.7 Secs	No
3	6 1/4 inches	1.7 Secs	-		1.8 Secs	No
4	8 inches	2.2 Secs	-		2.4 Secs	No

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4.2.1.3. Blast three. A summary of the results from the seismograph and camera for shot number three of dead pressing of dry holes is shown in Table 4-9 below.

Table 4-9: Dead Pressing Dry Holes Shot #3

Dead Pressing Dry Holes Shot #3						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Dead Pressed
0	-	0.0 Secs	0.0 Secs		0	-
1	2 11/48 inches	0.4 Secs	-		0.1 Secs	Yes
2	2 13/16 inches	0.8 Secs	0.8 Secs	No Flash	0.8 Secs	No
3	7 5/12 inches	1.7 Secs	-		1.5 Secs	No
4	10 3/16 inches	2.2 Secs	2.3 Secs		-	Yes

From looking at the seismograph data summarized in the table above, it was seen that the blast dead pressed in hole 1 and hole 4, but not in holes 2 or 3. The cap of hole 1 was able to be seen detonating on the seismograph, but the vibration was less than that of a cap and explosive detonating, therefore the explosive dead pressed.

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From looking at the high speed video, it was only able to record the hole 4 shock tube flash. It was unable to record the other holes detonating. A flash for hole 4 was seen in the video, but no explosion was noticed.

4.2.1.4. Summary of blasts. Overall, this set of blasts had good results. It was found that when the holes were dry, they dead pressed out to 3.26 inches.

There were some issues with the seismograph and the high speed camera, but because all three blasts had the same results, these issues became immaterial. Below is a graph in Figure 4-3 showing the results of the blasts. A more detail breakdown of the percent error, deviation, and measurements by hole is shown in Appendix B. From these results, it was concluded that dead pressing occurred out to 3.26 inches in dry holes.

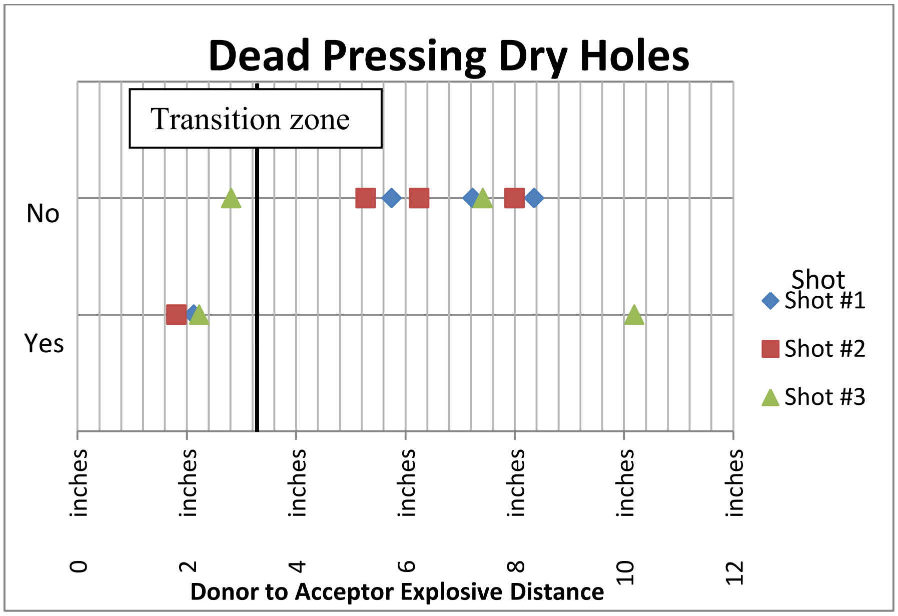

Figure 4-3: Dead Pressing of Dry Holes Results

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4.2.2. Wet Holes. The dead pressing of emulsions was found to occur under wet conditions when the donor and acceptor charges were 4.75 inches or less apart. Following is a summary of the seismograph data and a summary of the high speed video. It was with this information that a 4.75 inch range was found.

4.2.2.1. Blast one. A summary of the results from the seismograph and camera for shot number one of dead pressing of wet holes is shown in Table 4-10 below.

Table 4-10: Dead Pressing Wet Holes Shot #1

Dead Pressing Wet Holes Shot #1						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Dead Pressed
0	-	0.0 Secs	0.0 Secs		0.4 Secs	-
1	3 1/3 inches	0.4 Secs	-		1.3 Secs	Yes
2	5 1/2 inches	0.8 Secs	1.3 Secs		1.6 Secs	Yes
3	7 1/2 inches	1.7 Secs	2.4 Secs		2.6 Secs	No
4	9 1/6 inches	2.2 Secs	2.7 Secs		2.9 Secs	No

From looking at the seismograph data, it was found that the blast dead pressed hole 1 and hole 2 while hole 3 and hole 4 detonated normally. The seismograph vibration

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chart shows that holes 1 and 2 had smaller vibration than that of holes 3 and 4, which shows that the holes dead pressed.

From looking at the high speed camera video, it can be seen that hole 1 and hole 2 dead pressed while hole 3 and hole 4 detonated normally. Hole 2 showed a flash from the cap detonating inside the explosive and setting off the shock tube taped to the explosive. The movement seen on the video is not consistent with the other holes detonating on the video, which leads to the conclusion that hole 2 dead pressed.

4.2.2.2. Blast two. A summary of the results from the seismograph and camera for shot number two of dead pressing of wet holes is shown in Table 4-11 below.

Table 4-11: Dead Pressing Wet Holes Shot #2

Dead Pressing Wet Holes Shot #2						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Dead Pressed
0	-	0.0 Secs	0.0 Secs	No Flash	0.9 Secs	-
1	3 1/12 inches	0.4 Secs	-		-	Yes
2	5 1/6 inches	0.8 Secs	0.7 Secs	No Flash	1.6 Secs	No
3	6 inches	1.7 Secs	2.0 Secs	No Flash	2.6 Secs	No
4	8 1/8 inches	2.2 Secs	2.4 Secs	No Flash	3.2 Secs	No

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From looking at the seismograph data summarized in the table above, it could be seen that hole 1 dead pressed while hole 3 and hole 4 both detonated normally. Hole 2 seemed to have a partial detonation, as the vibrations were not as strong as hole 3 and 4, but there was still a detonation.

The high speed camera video was able to record that hole 1 dead pressed while holes 2, hole 3 and hole 4 all detonated normally.

4.2.2.3. Blast three. A summary of the results from the seismograph and camera for shot number three of dead pressing of wet holes is shown in Table 4-12 below.

From looking at the seismograph data it was seen that hole 1 dead pressed while holes 2, hole 3, and hole 4 detonated normally.

The high speed camera video was able to record that hole 1 dead pressed while holes 2, hole 3, and hole 4 all detonated normally.

Table 4-12: Dead Pressing Wet Holes Shot #3

Dead Pressing Wet Holes Shot #3						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Dead Pressed
0	-	0.0 Secs	0.0 Secs		0	-
1	2 23/24 inches	0.4 Secs	0.0 Secs		-	Yes
2	4 19/24 inches	0.8 Secs	0.8 Secs		0.7 Secs	No
3	6 7/16 inches	1.7 Secs	2.0 Secs		1.8 Secs	No
4	8 19/48 inches	2.2 Secs	2.5 Secs	No Flash	2.3 Secs	No

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4.2.2.4. Summary of blasts. Overall, this set had good results. It was seen that when the holes were filled with water, they would dead pressed out to 4.75 inches.

There were some issues with the seismograph and high speed camera, but because of consistency between the blasts, these issues became immaterial. A more detailed breakdown of the percent error, deviation, and measurements by hole is shown in Appendix B. Below is a graph in Figure 4-4 showing the results of the blasts.

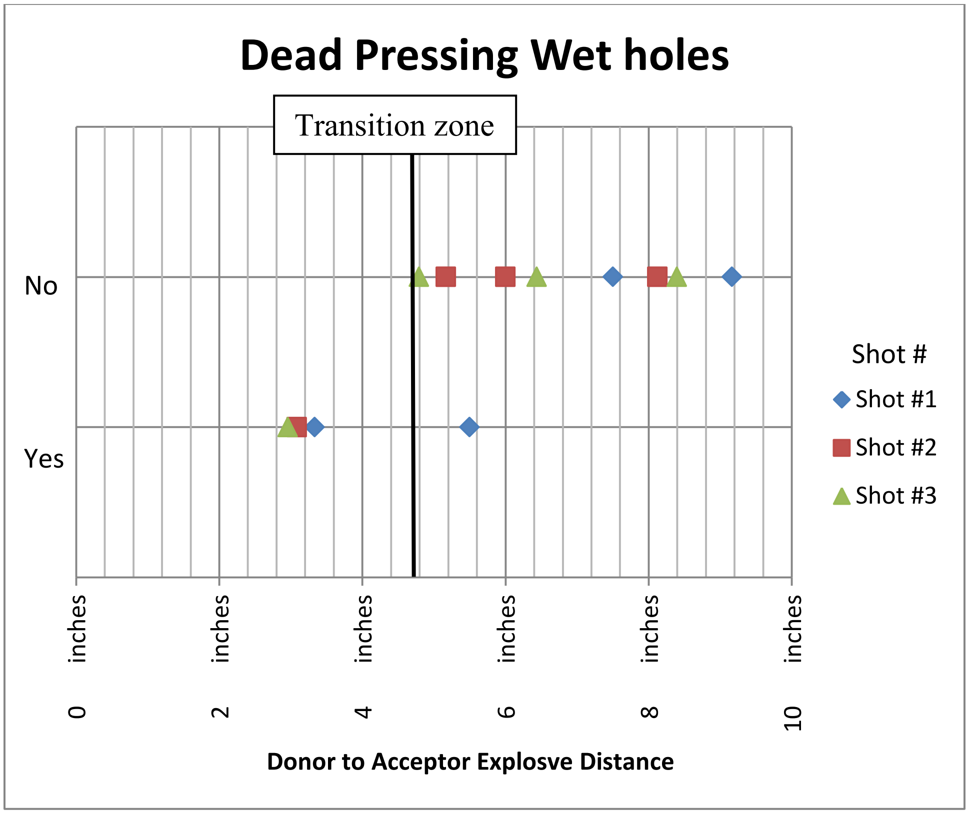

Figure 4-4: Dead Pressing of Wet Holes Results

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4.3. CAP TESTS

The purpose of testing the caps was to rule them out as a cause of sympathetic detonation. The caps were tested in the wet hole conditions. The wet hole conditions were used to give the caps the best chance of sympathetic detonation. The caps were also tested alone, not in an explosive except for the donor hole, to reduce impedance mismatch overall to give them the greatest chance of sympathetically detonating. This removed the interface of the water and explosive along with the explosive and cap. By removing these two interfaces, the impedance mismatch is reduced and the shock propagation is increased. This reduction in interfaces provides a theoretical harsher environment than if the cap was in the explosive.

4.3.1. Blast One. A summary of the results from the seismograph and camera for shot number one of caps in wet holes is shown in Table 4-13 below.

Table 4-13: Cap Test Blast #1

Cap Test Holes Shot #1						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Sympathetic Detonation
0	-	0.0 Secs	0.0 Secs		0	-
1	2 3/4 inches	0.4 Secs	-		-	-
2	4 1/2 inches	0.8 Secs	0.9 Secs		0.9 Secs	No
3	5 5/8 inches	1.7 Secs	2.2 Secs	No Flash	2.9 Secs	No
4	9 inches	2.2 Secs	2.8 Secs	No Flash	3.1 Secs	No

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From the seismograph data, it can be seen that the caps in holes 2, 3, and 4 did not sympathetically detonate. This is also confirmed by the high speed camera. Hole 1 is unknown.

4.3.2. Blast Two. A summary of the results from the seismograph and camera for shot number two of in wet holes is shown in Table 4-14 below.

From the seismograph data, it can be seen that the caps in holes 2, 3, and 4 did not sympathetically detonate. This is also confirmed by the high speed camera. Hole 1 is unknown.

Table 4-14: Cap Test Blast #2

Cap Test Holes Shot #2						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Sympathetic Detonation
0	-	0.0 Secs	0.0 Secs		0	-
1	2 7/8 inches	0.4 Secs	-		-	-
2	4 5/8 inches	0.8 Secs	0.8 Secs		0.9 Secs	No
3	6 9/16 inches	1.7 Secs	2.1 Secs		2.9 Secs	No
4	8 inches	2.2 Secs	2.6 Secs		3.1 Secs	No

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4.3.3. Blast Three. A summary of the results from the seismograph and camera for shot number three of caps in wet holes is shown in Table 4-15 below.

Table 4-15: Cap Test Blast #3

Cap Test Holes Shot #3						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Sympathetic Detonation
0	-	0.0 Secs	0.0 Secs	No Flash	0	-
1	2 7/8 inches	0.4 Secs	-		-	-
2	4 5/8 inches	0.8 Secs	-		0.8 Secs	No
3	6 7/8 inches	1.7 Secs	-			-
4	8 3/8 inches	2.2 Secs	2.2 Secs	No Flash	2.0 Secs	No

From the seismograph data, it can be seen that the caps in holes 2 and 4 did not sympathetically detonate. This is also confirmed by the high speed camera. Holes 1 and 3 are unknown.

4.3.4. Blast Four. A summary of the results from the seismograph and camera for shot number four of caps in wet holes is shown in Table 4-16 below.

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Table 4-16: Cap Test Blast #4

Cap Test Holes Shot #4						
Hole #	Actual Distance	Nominal Delay	Shock Tube Time		Seismograph Time	Sympathetic Detonation
0	-	0.0 Secs	0.0 Secs		0.0 Secs	-
1	3 3/8 inches	0.4 Secs	-		0.5 Secs	No
2	3 3/8 inches	0.8 Secs	2.7 Secs		0.9 Secs	No
3	3 1/2 inches	1.7 Secs	-		-	-
4	3 1/8 inches	2.2 Secs	2.7 Secs		2.6 Secs	No

From the seismograph data, it can be seen that the caps in holes 1, 2, and 4 did not sympathetically detonate. This is also confirmed by the high speed camera. Hole 3 is unknown.

4.3.5. Summary of Blasts. From test one, test two, and test three, where the caps were tested without any explosives, it was easily seen that holes 2, 3, and 4 did not sympathetically detonate. Seismograph data from some of the blasts showed hole 1 detonating normally, which lead to the conclusion that the caps were not sympathetically detonating. In test four, a series at three inches was also looked at to try to understand hole 1 better from the first three tests. This test showed that the caps did not sympathetically detonate. Hole 3 was not seen detonating by seismograph. There are many different possible reasons for this. One possible reason includes the caps being crushed to a point where they can no longer function. Another possible reason includes

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the explosive element of the cap being separated from the rest of the cap. Therefore, it can be concluded that the caps are not the cause of the explosive sympathetically detonating.

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5. DISCUSSION

5.1. HUGONIOT CALCULATIONS

The Hugoniot calculations and energy calculations are based on Paul Coopers' book, Explosive Engineering (Cooper). These calculations should be considered simpler than what was actually happening in the system because they do not take into account energy lost in the form of heat, energy in the flying rock fragments, and the distance the blast waves traveled through the water and dolomite.

Assuming that the detonation of the explosive in the center hole produced a spherical shockwave and that there are no reflections off of any impurities in the rock, then the calculations could be made for finding the shock velocity at the explosive in the acceptor hole. The equations used for this are shown in Equation 3 and Equation 4 (Cooper). Since it is known that these two equations are equal to each other, one can solve for "u", particle velocity. By solving for "u" in each of the different medium interfaces, the pressure at the explosive front in the acceptor hole was found, assuming that the particle velocity had trivial loss through each medium. With the pressure, the specific internal energy acting upon the explosive can be found and then the total internal energy can be found from that. The equations used to find specific internal energy and total internal energy are shown in Equation 5 and Equation 6 (Cooper) respectively. The initial values used for 3 and Equation 4 are shown in Table 5-1. The calculations are shown in Appendix C.

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$$\boldsymbol{P_{right} = \rho_0 C_0 u + \rho_0 s u^2} \qquad \text{Equation 3}$$

$$P_{left} = \rho_0 C_0 (u_0 - u) + \rho_0 s (u_0 - u)^2 \qquad \text{Equation 4}$$

$$\boldsymbol{e_1 - e_0 = \frac{P_1 u_1 - p_0 u_0}{\rho_0 (U - u_0)} - \frac{1}{2}(u_1^2 - u_0^2)} \qquad \text{Equation 5}$$

$$E = \rho A L e \qquad \text{Equation 6}$$

The values in Table 5-1 come from numerous sources. The $C_{0\ \mathrm{Explosive}}$ and $S_{0\ \mathrm{Explosive}}$ are not the values listed in the book, but a percentage of the value was taken to match the density of the explosive tested. This does not yield a true $C_{0\ \mathrm{Explosive}}$ and $S_{0\ \mathrm{Explosive}}$ but values that are close enough to run a basic test to rule out the caps. The velocity of detonation for the dynamite was used for the $U_{\mathrm{Exploisve}}$ which is not the true particle velocity but still a close value. Another assumption was that $u_0=U_{\mathrm{Explosive}}$. Using these values, a close representation can be found to give a basis for ruling out the caps. The u_0 was selected as the detonating velocity of the explosive. These are not a true value, but the closest that could be made within reason.

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Table 5-1: Initial Values Used in Equation 3 and Equation 4

Variable	Value	Unit
$\rho_{Explosive}$	1.51	g/cm[1]
ρ_{Water}	0.998	g/cm^3[2]
$\rho_{Dolomite}$	2.848	g/cm^3[3]
$C_{0\ Explosive}$	2.127	km/s[4]
$C_{0\ Water}$	1.647	km/s[5]
$C_{0\ Dolomite}$	5.3	km/s[6]
$s_{Explosive}$	1.576	None[7]
s_{Water}	1.921	None[8]
$s_{Dolomite}$	1.16	None[9]
$U_{Explosive}$	5.3	km/s[10]

Using the values from Table 5-1 along with Equation 3 and Equation 4, the particle velocity at the explosive interface in the acceptor hole was 0.2834 km/s. Plugging that back into either Equation 3 or Equation 4, this yielded pressure at the

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[1] (Dyno Nobel Inc.)

[2] (Cooper)

[3] (Missouri Department of Natural Resources)

[4] (Dobratz and Crawford)

[5] (Dyno Nobel Inc.)

[6] (Rogers)

[7] (Dobratz and Crawford)

[8] (Cooper)

[9] (Rogers)

[10] (Dyno Nobel Inc.)

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interface to be 1.1018 Gpa. With this value found, Equation 5 was used to find the specific internal energy. This was found to be 0.245 km^2/s^2. Plugging this into Equation 6, gave the energy to be 7.573 Nm. The least amount of impact shock that was found to set off a Nonel LP cap due to impact was 60 Nm at a fire rate of 50% found in Table 1 (Franklin and Worsey). The shock impact needed to detonate the caps was found to be ten times higher than what was actually in play for this research. This leads to showing that the caps were not sympathetic detonating and that it was in fact the explosive that was doing so. The same table also showed that shock tube, has an impact sensitivity that was greater than 54 Nm. This showed that the shock tube did not flash from the shock generated from the donor hole but only from the explosive that it was taped to actually going off. This allowed for the conclusion that the shock tube was giving accurate information that the explosive had shot when the shock tube flashed. If it is taken into account that in some explosives, there is an increase in pressure in the middle of the explosive, where the cap is placed, according to Fumihiko, Hirosaki and Kato's paper, they found that 7.573 Nm should be multiplied by 1.5 that was found in their research to get a new force of 11.981 Nm. This force is still much less than the force of 60 Nm. Overall, this still shows that the caps were not the likely cause of sympathetic detonation.

5.2. SYMPATHETIC DETONATION

Sympathetic detonation was investigated for two different environmental situations. One of the situations was when the holes were wet and the other situation was when the holes were dry. The explosive used in this this series of tests were Unimax. It has 40 % nitroglycerin by weight. The range of sympathetic detonation was found for

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each situation to determine how you would need to change your design in the field if the ground was saturated with water.

To begin, the dry holes were tested to get a baseline. Here it was found that sympathetic detonation occurred out to 3.92 inches. This distance was found by using a logistic regression[11] after removing the two outliers at 7 $^{1}/_{6}$ and 9 $^{1}/_{6}$ inches that sympathetically detonated during the tests. This equates to 3.14 explosives diameters because the explosives used in this research were 1.25 inches in diameter. There are two outliers, however because of extenuating circumstances, they can be ruled out. These were ruled out through looking at the rest of the data from the tests of the series. The other holes had data points that showed that the holes did not make sense since holes both closer and further away, did not do the same as the outlier. There was also a void seam that was found that gave a possible explanation for this. This 3.92 inch range is the baseline for sympathetic detonation of dry holes.

Next, the wet holes were tested to investigate how water affected the range for sympathetic detonation. It was found that sympathetic detonation occurred out to 5.64 inches. This was found by using logistic regression including what was thought to be the outliers. This equated to 4.51 explosives diameters. The one outlier can be ruled out based on its location from looking at the other data of the series. The other holes had data points that showed that the holes did not make sense since holes both closer and further away, did not do the same as the outlier. Therefore, it was found that the distance

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[11] A logistic regression was used instead of a Gaussian distribution based on advice from Dr. Gayla Olbricht.

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of sympathetic detonation increased 43.9% when the environment supports saturated ground. These conclusions can be seen in Figure 5-1.

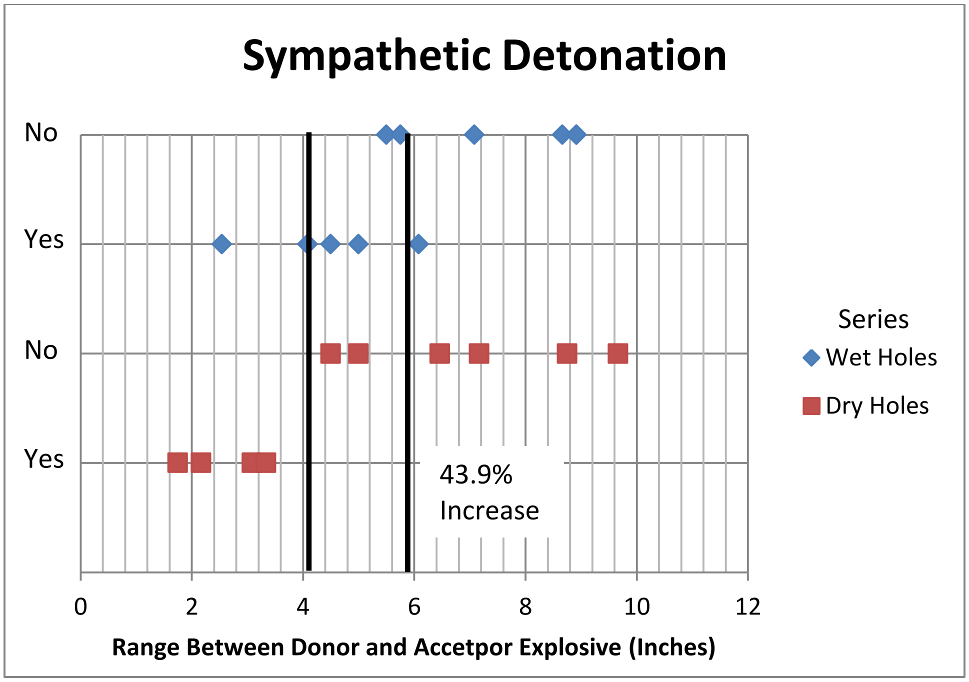

Figure 5-1: Sympathetic Detonation Comparison of Holes

These values were taken from the good data; however, there were three outliers. These outliers are concluded to be because of a void seam. A void seam allows the shock

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to transmit straight through the void seam and not go through the rock. This would reduce the impedance mismatch by reducing the different number of materials that it would go through. Upon inspection, after the blast, a void seam was found in dry hole blast #2 and wet hole blast #3. This void seam can be seen in Figure 5-2. A void seam was not found in any of the other blasts in the sympathetic detonation patterns. For the dry hole blast, the reason these holes sympathetically detonated could be blamed on the possibility of water leaking into the hole, even after the holes were cleared and checked to make sure that no water was present in the holes. Another possible reason could be due to the rock not being perfectly homogeneous in density and consistency. The explosives also could have been resting in the bottom of the hole slightly differently than the rest of the shots. This is just a theory because the inspection of the blast after the shot showed no water present, but any wet rock could have been moved away by the blast and out of sight. For the wet hole blast, the reason this hole sympathetically detonated could be because of reduced impedance mismatch from the voids. These voids are common in the dolomite that is present at the Missouri S&T mine. It does contain some planes and cracks. As best as possible prior to the tests, sections of rock that were used for these tests were found to have no major discontinuities between planes or cracks between holes. If major cracks or discontinuities were found, a new pattern was drilled in a different location. This was in an attempt to get the best data, but this was not always the case as some discontinuities were not found until after the blast was done. These void spaces could cause an influence in the data from the hydraulic conductivity, which could cause an increase in the shock transmission. This is a possible explanation of why there

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are outliers in the data. Overall, the void seams in the dolomite provided a real life situation because not all blasts were in virgin rock.

This research showed that sympathetic detonation would occur out to 5.64 inches (4.51 explosive diameters) when the holes were wet. This could be used in many different applications where the holes are close together. With this knowledge, a company could save the cost of caps and use sympathetic detonation to set off each stick with another. This could only be done when the total weight of the shot would still be below the legal limit. Two possible reasons for the wet holes sympathetically detonating further out than the dry holes could be that the water in the holes could be providing a better coupling with the explosive, which reduced the shock loss when traveling from the donor hole to the acceptor hole or the water could be causing a water hammer effect. The water hammer effect is when there is a sudden change in the velocity of the water, which is an incompressible fluid (Hauser 20). More careful and detailed measurements and experimental setups would need to be done to determine if one was the cause.

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Figure 5-2: Void Seam

5.3. DEAD PRESSING

Dead pressing was investigated for two different environmental situations. One of the situations was when the holes were dry and the other situation was when the holes were wet. The explosive used for this series of tests was Senatel Ultrex. It is sensitized by using microballoons. The range of dead pressing was found for each situation to determine how one would need to change their design in the field if the ground was saturated with water.

To begin, the dry holes were tested to get a baseline. Here it was found that dead pressing occurred out to 3.26 inches. This was found by using logistic regression including what was thought to be the outliers. This equates to 2.61 explosives diameters because the explosives used in this research were 1.25 inches in diameter. There was one outlier, however because of extenuating circumstances, it can be ruled out. The other

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holes had data points that showed that the outlier hole did not make sense since numerous holes closer that did not do the same. This 2.61 inch range is the baseline for dead pressing of dry holes.

Next, the wet holes were tested to investigate how water affected the range for dead pressing. Here it was found that dead pressing occurred out to 4.75 inches. This was found by using logistic regression including what was thought to be the outliers. This equates to 3.80 explosives diameters because the explosives used in this research were 1.25 inches in diameter. The one outlier can be ruled out based on its location from looking at the other data of the series. The other holes had data points that showed that the outlier hole did not make sense since holes both closer and further away, did not do the same. Therefore, it was found that the distance of dead pressing increased 45.7% when the ground was saturated with water. These conclusions can be seen in Figure 5-3.

Based on the data collected for dead pressing, the range to prevent dead pressing was found, however there were two outliers, one for the dry hole tests and one for the wet hole tests. A possible cause of the outlier in the wet hole test dead pressing is because of a void space that was not detected. This would cause a reduction in the impedance mismatch, which would cause a higher shock transmission. The reason this could not be verified was because after the blast, the rock around the blast was not in the same state that it was in before the blast happened. The outlier for the dry hole blast could have been crushed by the movement of some rock, which would have artificially dead pressed the explosive due to the rock instead of the donor charge. Overall, these outliers represent what could happen in the real world.

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The importance of this research is that dead pressing will occur out to 4.75 inches (3.80 explosive diameters) when the holes are wet. With this knowledge, the situations to use a different explosive or a different burden and spacing can be known. This will help in the prevention of shots not being completely shot or having partially shot patterns. Two possible causes of this increased range of dead pressing are the water hammer effect and the water coupling effect. More careful and detailed measurements and experimental setups would need to be done to determine which one or neither is the cause.

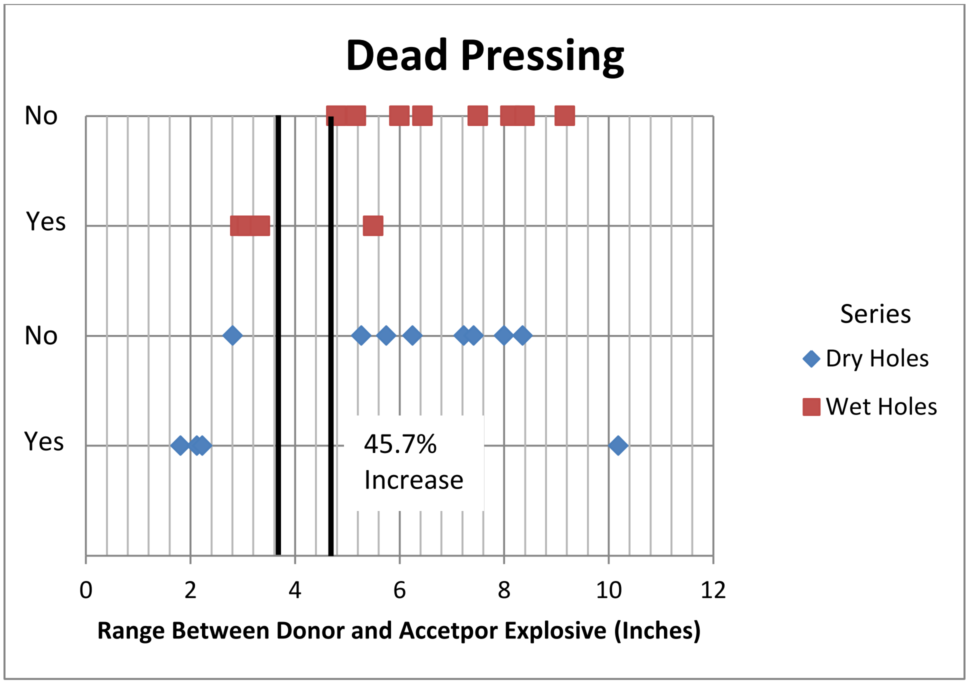

Figure 5-3: Dead Pressing Comparison of Holes

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5.4. CAP TESTS

In order to determine whether sympathetic detonation was caused by the caps or by the explosives sympathetically detonating, a cap test was performed. This was done by placing the caps in the wet holes without explosives where the acceptor charges went. In this test, none of the caps sympathetically detonated. This was seen in the seismograph data where all of holes 2, 3, and 4 were clearly detonated at their intended time. The caps in hole 1 were ruled out as sympathetically detonating because, in the test blasts with explosives, the seismograph was able to record the cap detonate. Overall, sympathetic detonation was caused by the explosives, not by the caps. From the seismograph data, the detonations of the caps and the explosives can be easily seen. The spikes in the seismograph data corresponded to the caps detonating, showing that the caps detonated whether or not the explosive detonated or dead pressed.

5.5. MEASUREMENTS

The drilling of the holes was an important factor to consider when taking into account the results of the data. The drilling was a possible source of error because this was the main part of the setup. This controlled how close the holes were not only to the center hole, but to each other. Care was taken when drilling the holes to make sure the best drilling possible was done. This included having two people watch the driller to make sure that the drill was level at all times during the drilling. This was a hard task as the drill tended to bounce during the drilling which was the cause of the deviation of the holes. Corrections were made to the drilling to try to level the drill and make the holes

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parallel to the other holes. Corrections made at the beginning of the drilling process made a bigger difference. However, error in the drilling made at the end of the holes also had a large impact because that was where the explosive was located in the pattern.

Another source of error was the wear of the drill steel. This was minor due to the small amount of use the drill steel saw when compared to the life of the drill steel. However, the wear on the drill steel will result in the holes becoming smaller over time compared to the original size of the drill steel.

A more likely cause of error is in the measuring of the holes. This had multiple parts to it. These different parts included the tape measure used for measuring, the person doing the measuring, and the poles used to measure the holes. This could cause a smaller or larger deviation in the measurement of the distance between the holes. The same tape measure was used each time to make sure that the error inherit in the tape measure was consistent and did not vary from measurement to measurement. This is just as important as the person taking the measurement. The person who was taking the measurements might have been looking at it from a different angle than a different person would. This would have resulted in a different reading which would change the error. To minimize this, the same person took the same measurements each time. This did not eliminate the error, but kept it to a minimum and systematic, which was the best that can be done. The last big part of the potential error was the measuring poles. These were made rigid to help reduce the bending of the poles to give a more accurate reading of the distance, however, the poles still had some flex because the diameter of the hole did not allow for a perfectly rigid pole to fit into the hole to be used for measuring.

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6. CONCLUSIONS

This research focused on two of the factors that affect whether or not an explosive will sympathetically detonate or dead press. These two factors were distance between boreholes and presence of water. First sympathetic detonation was investigated, and then dead pressing was studied.

Sympathetic detonation of dynamite in dry holes was tested and the safe distance to prevent sympathetic detonation was determined. This range was found to be 3.14 explosive diameters out from the donor hole for normal blasting conditions. The explosives used in this research were 1.25 inches in diameter; which equated to 3.92 inches in range. This was important because it provided a baseline to compare how the range changed when the environmental conditions were different, for example, if the holes were filled with water.

The next step in this research was to fill the holes with water and repeat the above experiment and analysis. It was found that the safe distance to prevent sympathetic detonation was 4.51 explosive diameters. This equated to 5.64 inches. By comparing the ranges to each other, the boreholes filled with water needed to be 1.439 times farther apart than the holes without water to prevent sympathetic detonation. After studying dynamite and sympathetic detonations, the next step was to study emulsions and dead pressing. This was again done for both dry and wet holes, to simulate different environmental conditions.

When studying dead pressing, the goal was to find the distance at which dead pressing of the explosive did not occur, or in other words, to find the distance at which the explosive detonated. For dry conditions, this range was found to be 2.61 explosive

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diameters. Since the emulsion explosives that were used in this research were 1.25 inches in diameter, this equated to 3.26 inches in range. This was important because it provides a baseline at which the safe distance could be compared for other environmental conditions, such as wet holes.

The next step was to find the safe distance at which dead pressing of emulsions did not occur, when the holes were filled with water. The range from these tests was found to be 3.80 explosive diameters. Since the emulsion explosives that were used in this research were 1.25 inches in diameter, this equated to 4.75 inches in range. When the different conditions were compared, wet verses dry, it was seen that the range had increased more than 45.7% times further for the wet boreholes. The safe distance to prevent dead pressing came out to be 1.457 times larger for wet holes. Despite this being a large increase, the range being so small for dead pressing to occur, shows that the emulsion is very dead press resistant but is still able to be dead pressed. This is very important when it comes to burn cuts as this is when you have explosives close together and they are likely to dead press. This also is important for poor drilling as holes can deviate which will bring holes closer or further apart than designed for. The holes may even intersect.

After the experiments were completed, a mathematical model was created to investigate how the dynamite was detonating in the sympathetic detonation tests. This mathematical model looked at the pressure on the caps. The Hugoniot equations were used to determine the pressure on the caps in the acceptor hole. By ruling the caps out, this allowed for the conclusion that the explosive was sympathetically detonating. The equations in section 5.1 showed that the energy on the detonators was much less than the

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detonators sensitivity to impact, showing that the detonators were not a cause of sympathetic detonation. This was also confirmed via a cap test experiment.

The presence of water in the ground has an effect on how far sympathetic detonation will reach. However, open seams and channels connecting holes have an even larger effect in sympathetic detonation. Thus, there is no easy way to predict how far out sympathetic detonation will occur because blasts rarely take place in ideal rock.

Overall, it is important to take into account the environmental conditions, such as water present in the holes, to make sure one is blasting safely. Sympathetic detonation and dead pressing have many factors that affect their results. Two of these factors are distance between the charges and water present in the bore holes. If the charges are too close together, a charge might sympathetic detonate instead of detonating normally or it might dead press and not detonate. Sympathetic detonation and dead pressing can cause higher ground vibrations, air blast, and/or fly rock. If water is present in the holes, the safe distance to prevent sympathetic detonation and dead pressing increases. This is important as one the places that you can expect to have the most problems is when there is high hydraulic conductivity.

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7. FUTURE WORKS

There are many different possible expansions for this project. Some possible topics for further study are the same experiment done with different amounts of water in the holes, different types of fluid in the holes, different sizes of holes, different grades of dynamite and emulsion, different amounts of explosives in the hole, and determining if water coupling or water hammer is playing a part on the change in range of the shock wave prorogation.

Testing various water levels in the holes is a topic of interest because a hole is not always completely full of water in the real world. Chances are the water level in the holes is not always going to be the same. Another possible derivative from this would be to change the type of fluid that is in the hole. This could lead to the finding of a new way to prevent both sympathetic detonation and dead pressing.

Different size holes using the same amount and size explosive are also an interesting topic. This is because sometimes it might be beneficial to use up some old leftover explosives that are not in the original design, but are still able to get to the desired result.

The position of the holes with respect to gravity would be interesting to see. This would take a look at loading in a face instead of loading that takes place on the ground. This would be beneficial because some operations use loading of a face instead of blasting the ground.

Another option would be to see if water coupling or water hammer is causing the increase in range for sympathetic detonation and dead pressing. This would be a close look at the mechanisms that are causing both sympathetic detonation and dead pressing.

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Hydraulic conductivity would be another topic of interest. Seeing how different hydraulic conductivity would affect sympathetic detonation and dead pressing would be interesting to see since this is something that is in the real world that one cannot control easily.

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APPENDIX A.

SEISMOGRAPH DATA

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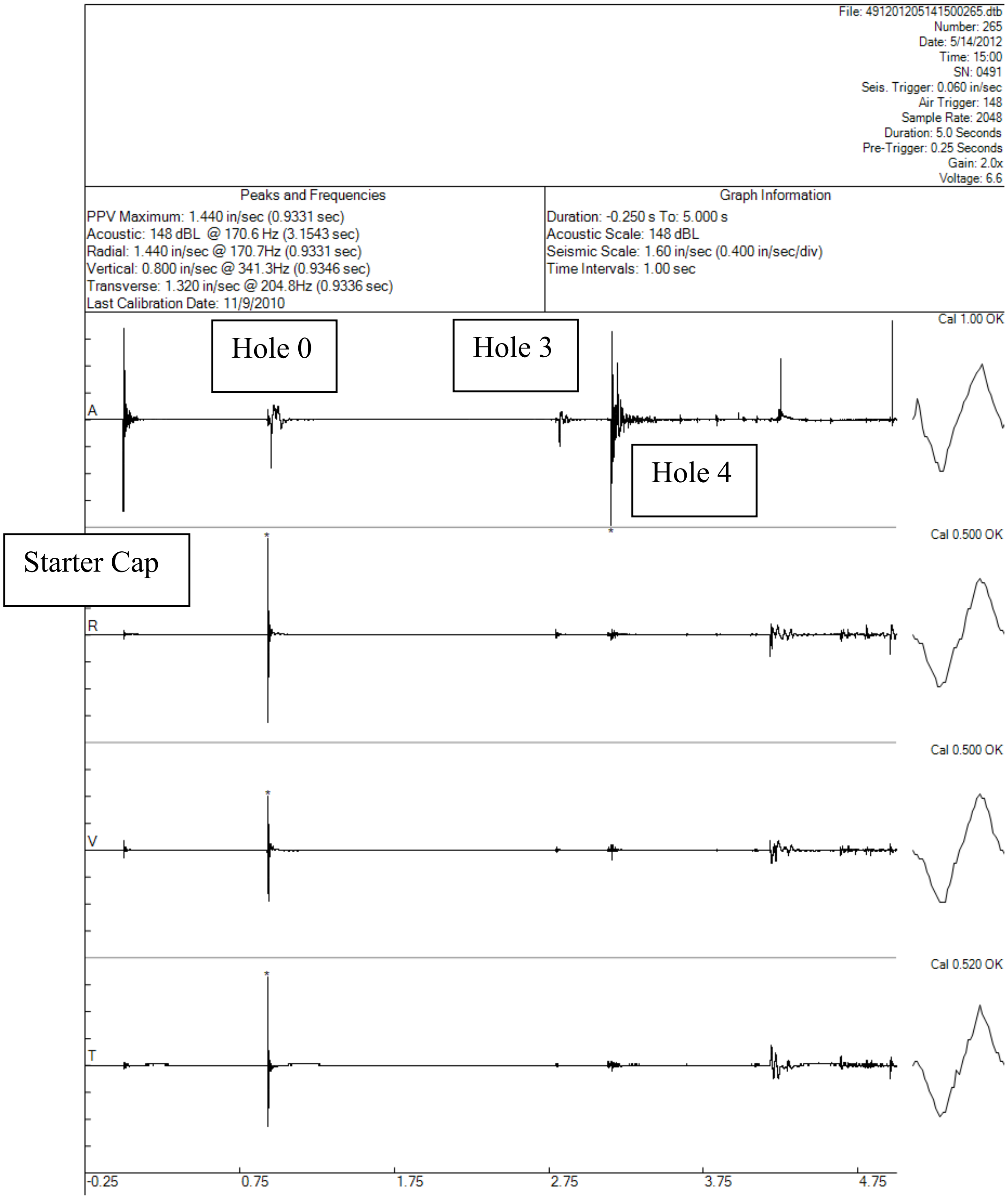

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Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.6

Peaks and Frequencies

PPV Maximum: 1.440 in/sec (0.9331 sec)
Acoustic: 148 dBL @ 170.6 Hz (3.1543 sec)
Radial: 1.440 in/sec @ 170.7Hz (0.9331 sec)
Vertical: 0.800 in/sec @ 341.3Hz (0.9346 sec)
Transverse: 1.320 in/sec @ 204.8Hz (0.9336 sec)
Last Calibration Date: 11/9/2010

Graph Information

Duration: -0.250 s To: 5.000 s
Acoustic Scale: 148 dBL
Seismic Scale: 1.60 in/sec (0.400 in/sec/div)
Time Intervals: 1.00 sec

Sympathetic Detonation Dry Shot #1

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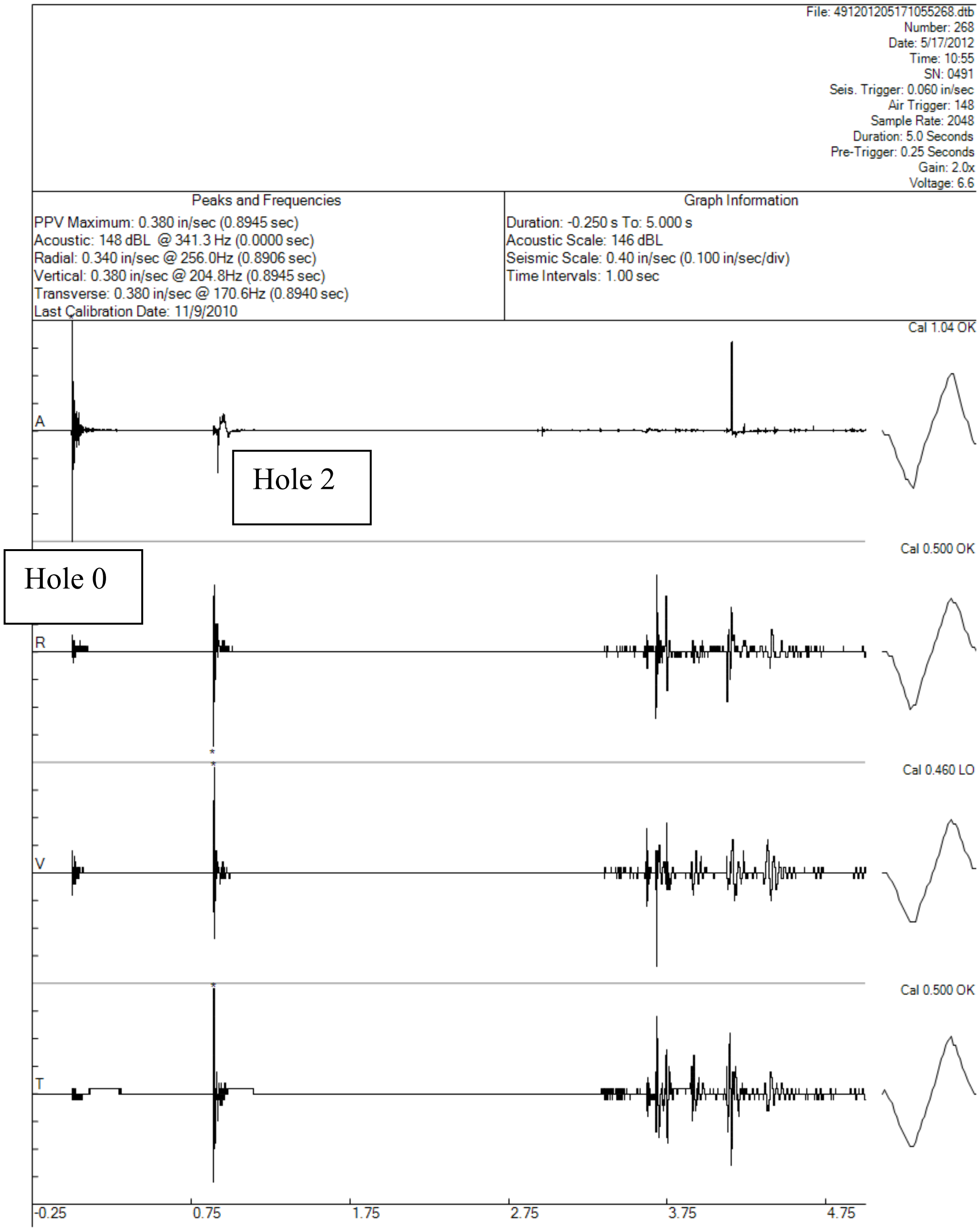

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Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.6

Peaks and Frequencies

PPV Maximum: 0.380 in/sec (0.8945 sec)
Acoustic: 148 dBL @ 341.3 Hz (0.0000 sec)
Radial: 0.340 in/sec @ 256.0Hz (0.8906 sec)
Vertical: 0.380 in/sec @ 204.8Hz (0.8945 sec)
Transverse: 0.380 in/sec @ 170.6Hz (0.8940 sec)
Last Calibration Date: 11/9/2010

Graph Information

Duration: -0.250 s To: 5.000 s
Acoustic Scale: 146 dBL
Seismic Scale: 0.40 in/sec (0.100 in/sec/div)
Time Intervals: 1.00 sec

Sympathetic Detonation Dry Shot #2

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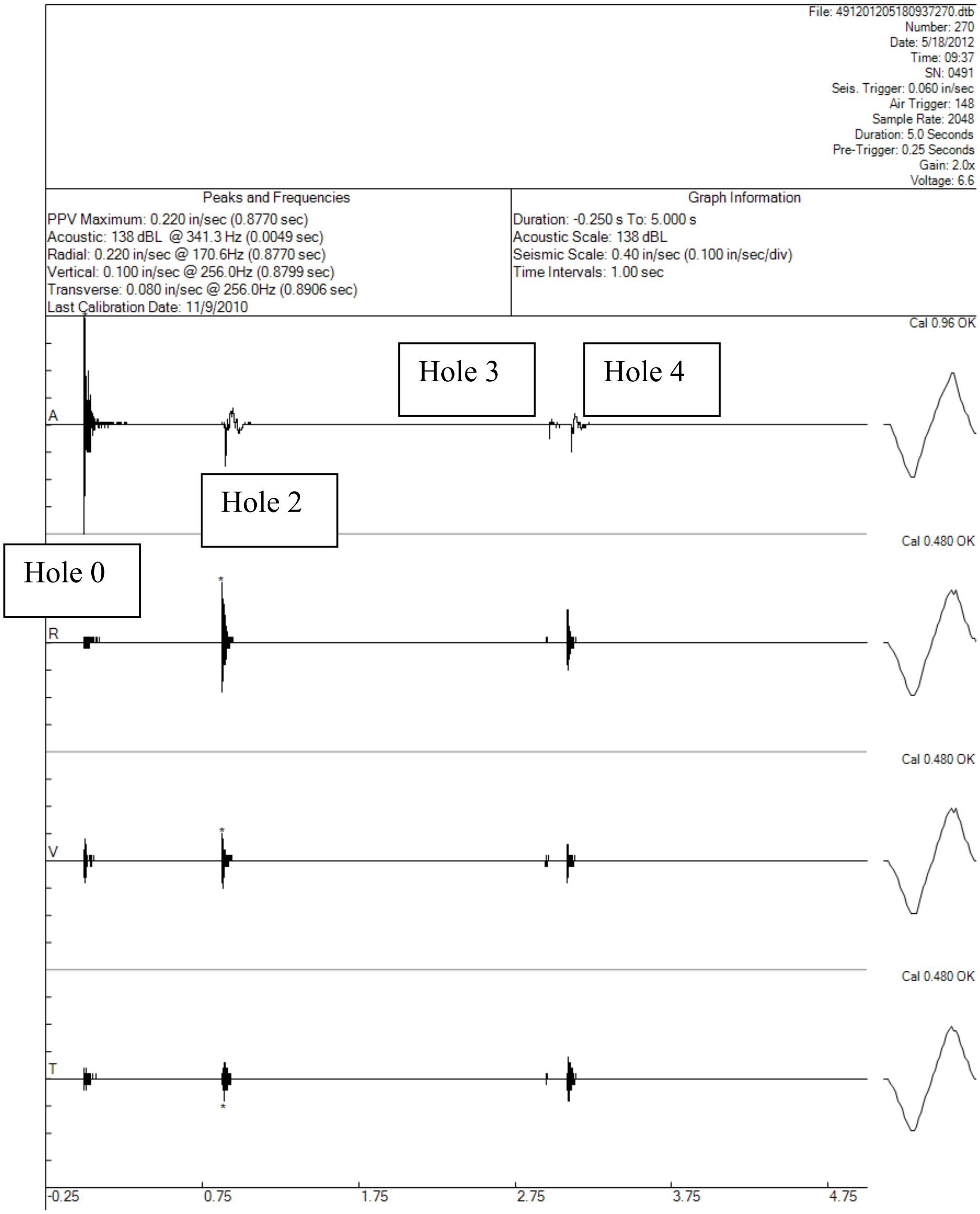

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Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.6

Peaks and Frequencies
PPV Maximum: 0.220 in/sec (0.8770 sec)
Acoustic: 138 dBL @ 341.3 Hz (0.0049 sec)
Radial: 0.220 in/sec @ 170.6Hz (0.8770 sec)
Vertical: 0.100 in/sec @ 256.0Hz (0.8799 sec)
Transverse: 0.080 in/sec @ 256.0Hz (0.8906 sec)
Last Calibration Date: 11/9/2010

Graph Information
Duration: -0.250 s To: 5.000 s
Acoustic Scale: 138 dBL
Seismic Scale: 0.40 in/sec (0.100 in/sec/div)
Time Intervals: 1.00 sec

Sympathetic Detonation Dry Shot #3

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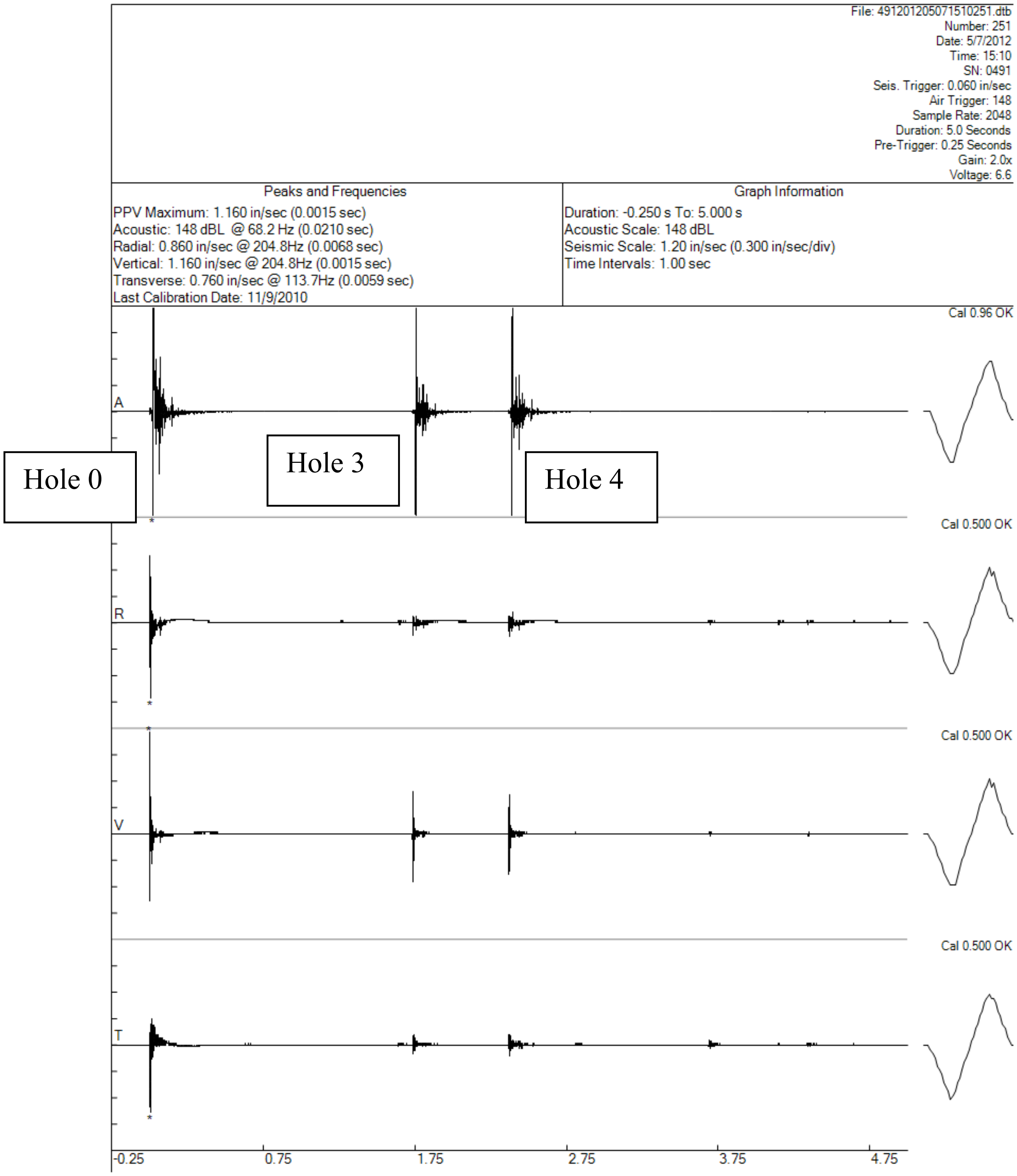

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Date: 5/7/2012
Time: 15:10
SN: 0491
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Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.6

Peaks and Frequencies	Graph Information
PPV Maximum: 1.160 in/sec (0.0015 sec) Acoustic: 148 dBL @ 68.2 Hz (0.0210 sec) Radial: 0.860 in/sec @ 204.8Hz (0.0068 sec) Vertical: 1.160 in/sec @ 204.8Hz (0.0015 sec) Transverse: 0.760 in/sec @ 113.7Hz (0.0059 sec) Last Calibration Date: 11/9/2010	Duration: -0.250 s To: 5.000 s Acoustic Scale: 148 dBL Seismic Scale: 1.20 in/sec (0.300 in/sec/div) Time Intervals: 1.00 sec

Sympathetic Detonation Wet Shot #1

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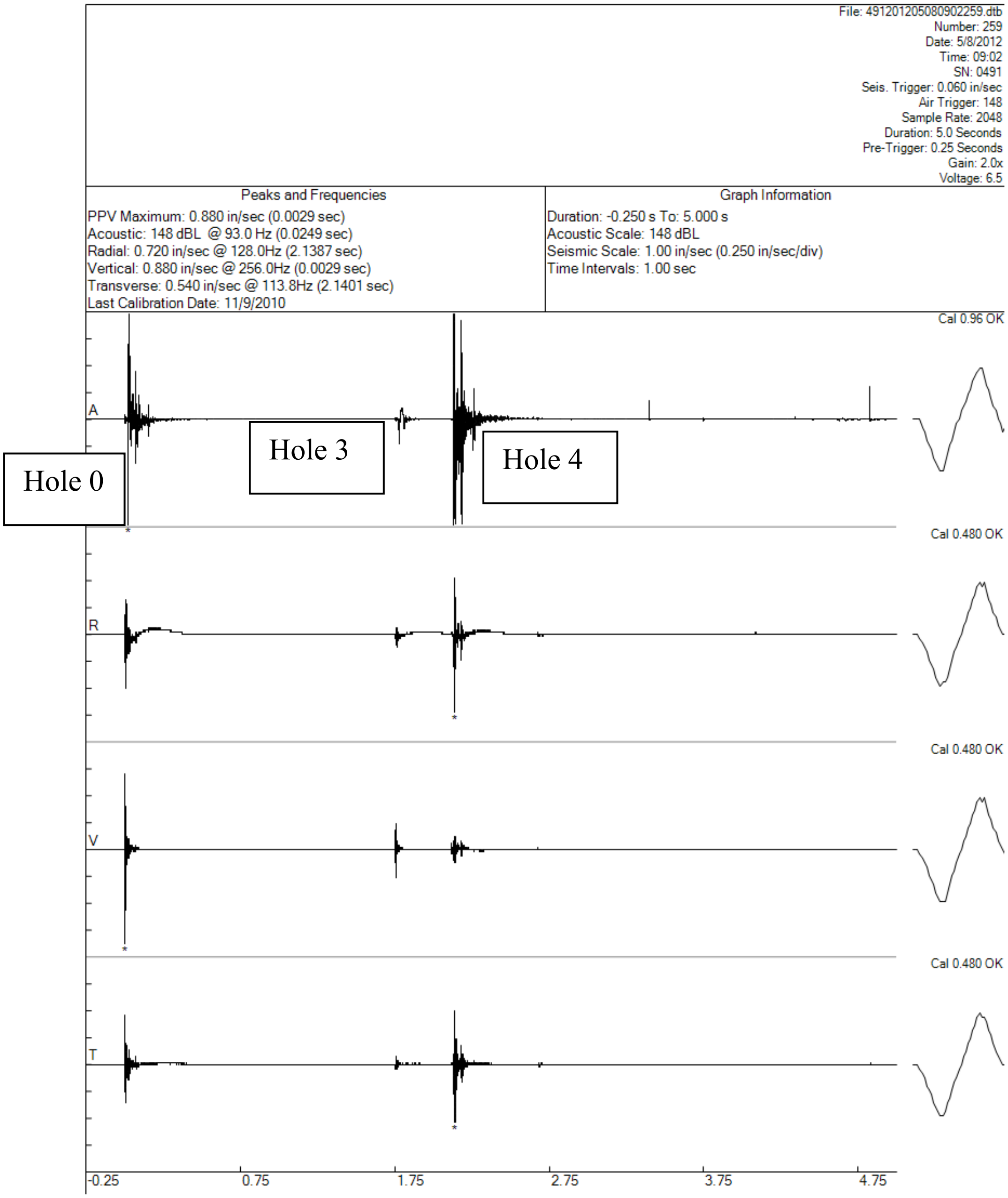

File: 491201205080902259.dtb
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Date: 5/8/2012
Time: 09:02
SN: 0491
Seis. Trigger: 0.060 in/sec
Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.5

Peaks and Frequencies

PPV Maximum: 0.880 in/sec (0.0029 sec)
Acoustic: 148 dBL @ 93.0 Hz (0.0249 sec)
Radial: 0.720 in/sec @ 128.0Hz (2.1387 sec)
Vertical: 0.880 in/sec @ 256.0Hz (0.0029 sec)
Transverse: 0.540 in/sec @ 113.8Hz (2.1401 sec)
Last Calibration Date: 11/9/2010

Graph Information

Duration: -0.250 s To: 5.000 s
Acoustic Scale: 148 dBL
Seismic Scale: 1.00 in/sec (0.250 in/sec/div)
Time Intervals: 1.00 sec

Sympathetic Detonation Wet Shot #2

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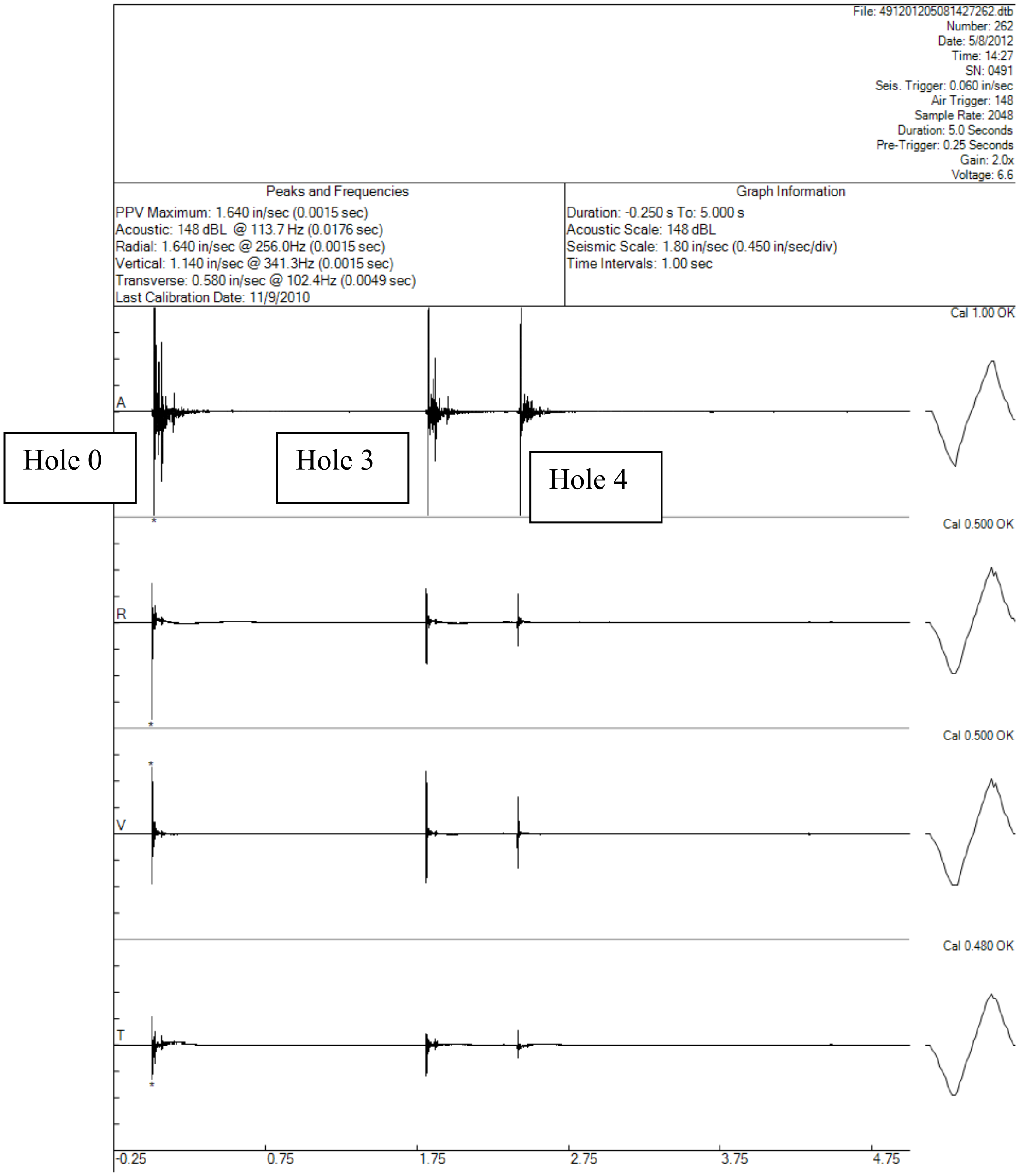

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Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.6

Peaks and Frequencies

PPV Maximum: 1.640 in/sec (0.0015 sec)
Acoustic: 148 dBL @ 113.7 Hz (0.0176 sec)
Radial: 1.640 in/sec @ 256.0Hz (0.0015 sec)
Vertical: 1.140 in/sec @ 341.3Hz (0.0015 sec)
Transverse: 0.580 in/sec @ 102.4Hz (0.0049 sec)
Last Calibration Date: 11/9/2010

Graph Information

Duration: -0.250 s To: 5.000 s
Acoustic Scale: 148 dBL
Seismic Scale: 1.80 in/sec (0.450 in/sec/div)
Time Intervals: 1.00 sec

Sympathetic Detonation Wet Shot #3

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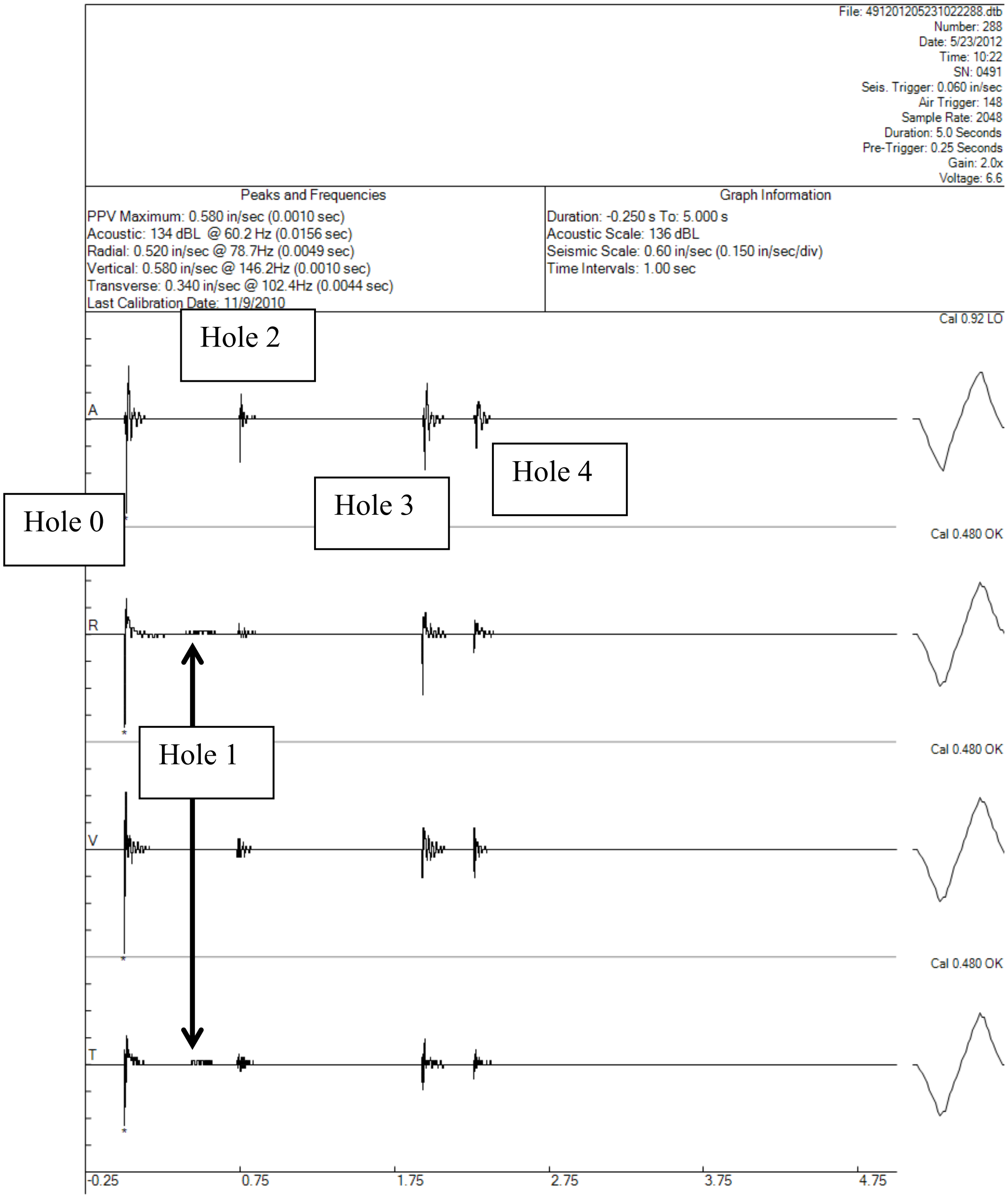

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Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.6

Peaks and Frequencies
PPV Maximum: 0.580 in/sec (0.0010 sec)
Acoustic: 134 dBL @ 60.2 Hz (0.0156 sec)
Radial: 0.520 in/sec @ 78.7Hz (0.0049 sec)
Vertical: 0.580 in/sec @ 146.2Hz (0.0010 sec)
Transverse: 0.340 in/sec @ 102.4Hz (0.0044 sec)
Last Calibration Date: 11/9/2010

Graph Information
Duration: -0.250 s To: 5.000 s
Acoustic Scale: 136 dBL
Seismic Scale: 0.60 in/sec (0.150 in/sec/div)
Time Intervals: 1.00 sec

Dead Pressing Dry Shot #1

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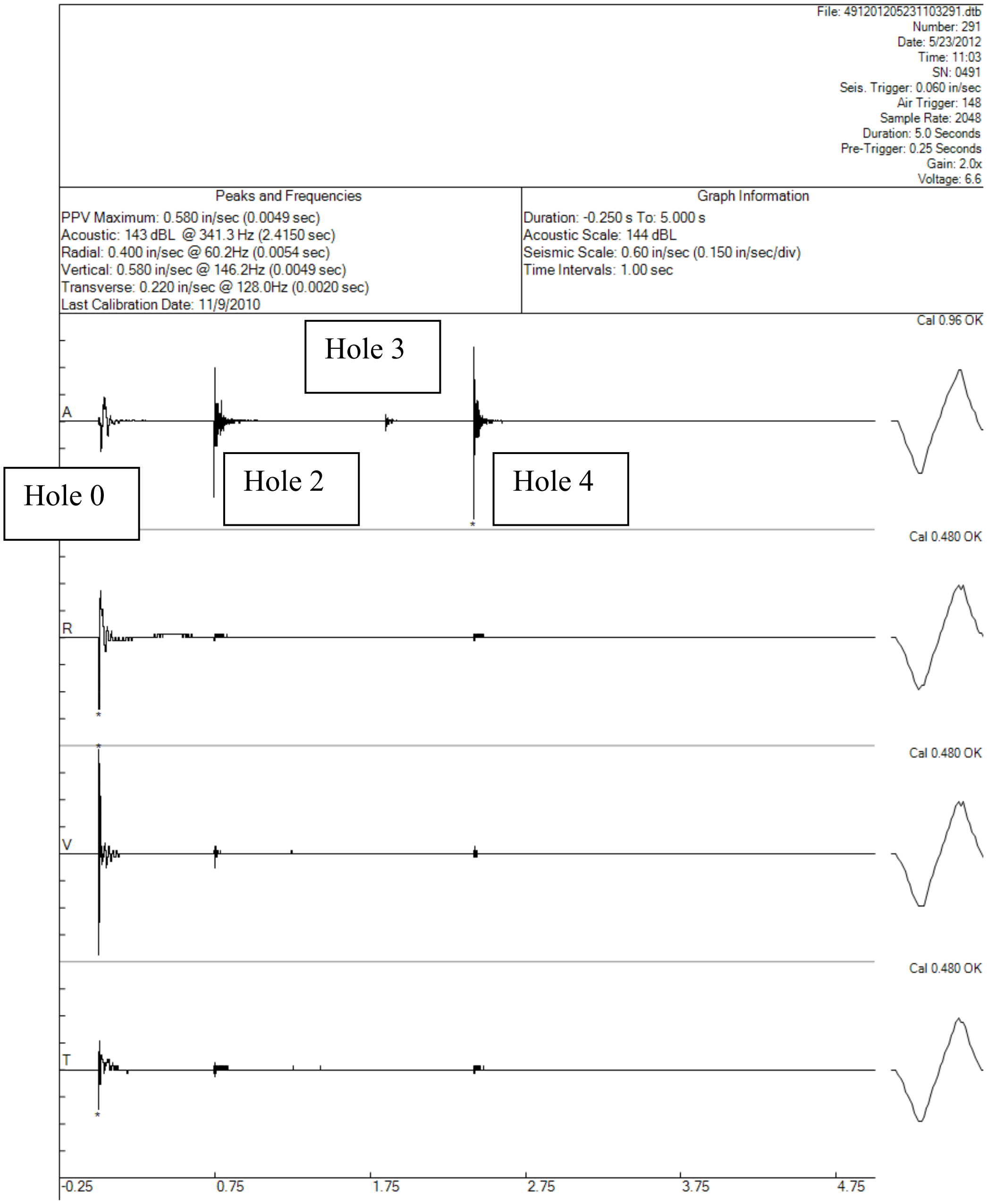

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Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.6

Peaks and Frequencies

PPV Maximum: 0.580 in/sec (0.0049 sec)
Acoustic: 143 dBL @ 341.3 Hz (2.4150 sec)
Radial: 0.400 in/sec @ 60.2Hz (0.0054 sec)
Vertical: 0.580 in/sec @ 146.2Hz (0.0049 sec)
Transverse: 0.220 in/sec @ 128.0Hz (0.0020 sec)
Last Calibration Date: 11/9/2010

Graph Information

Duration: -0.250 s To: 5.000 s
Acoustic Scale: 144 dBL
Seismic Scale: 0.60 in/sec (0.150 in/sec/div)
Time Intervals: 1.00 sec

Dead Pressing Dry Shot #2

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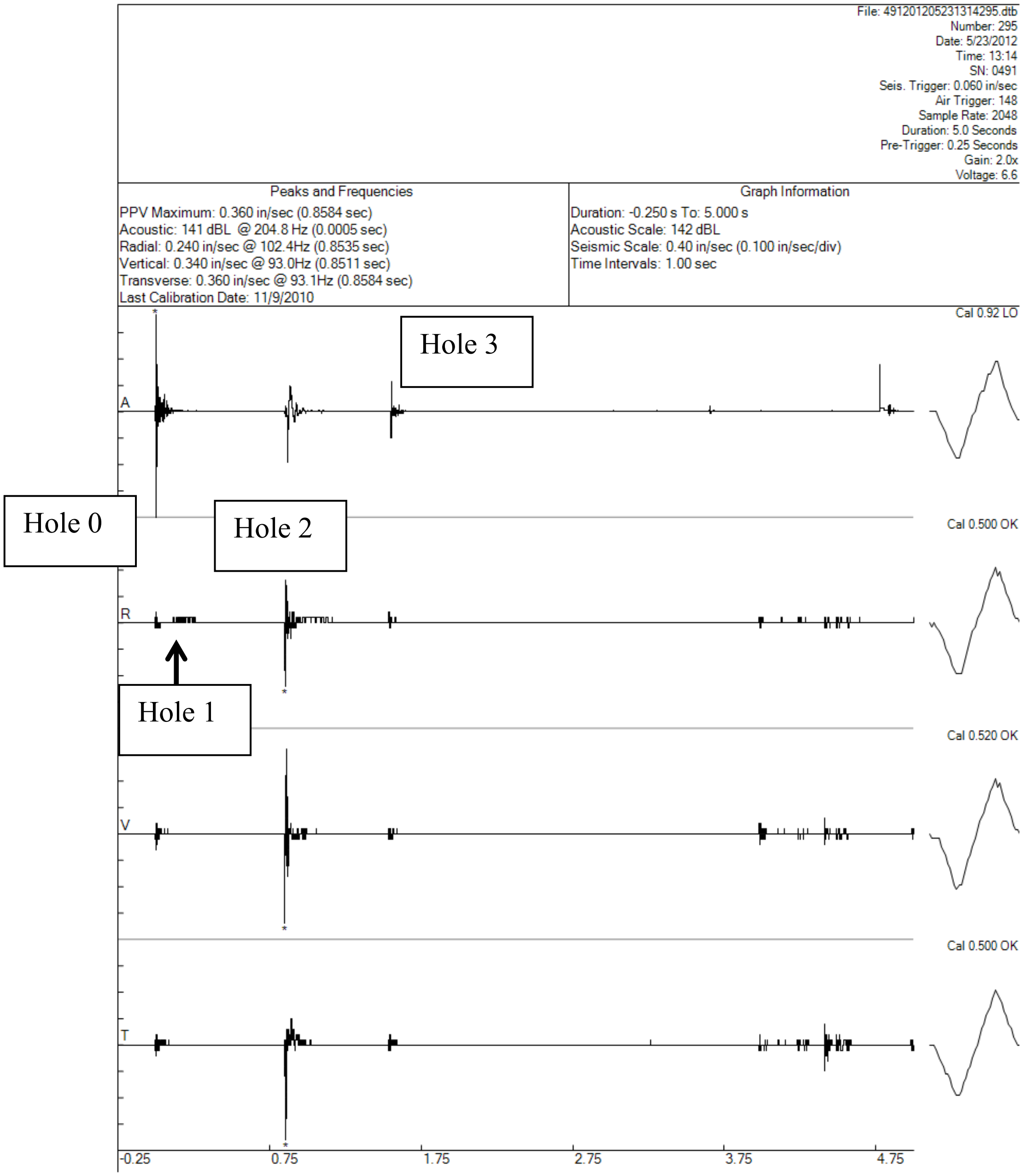

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Time: 13:14
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Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.6

Peaks and Frequencies
PPV Maximum: 0.360 in/sec (0.8584 sec)
Acoustic: 141 dBL @ 204.8 Hz (0.0005 sec)
Radial: 0.240 in/sec @ 102.4Hz (0.8535 sec)
Vertical: 0.340 in/sec @ 93.0Hz (0.8511 sec)
Transverse: 0.360 in/sec @ 93.1Hz (0.8584 sec)
Last Calibration Date: 11/9/2010

Graph Information
Duration: -0.250 s To: 5.000 s
Acoustic Scale: 142 dBL
Seismic Scale: 0.40 in/sec (0.100 in/sec/div)
Time Intervals: 1.00 sec

Dead Pressing Dry Shot #3

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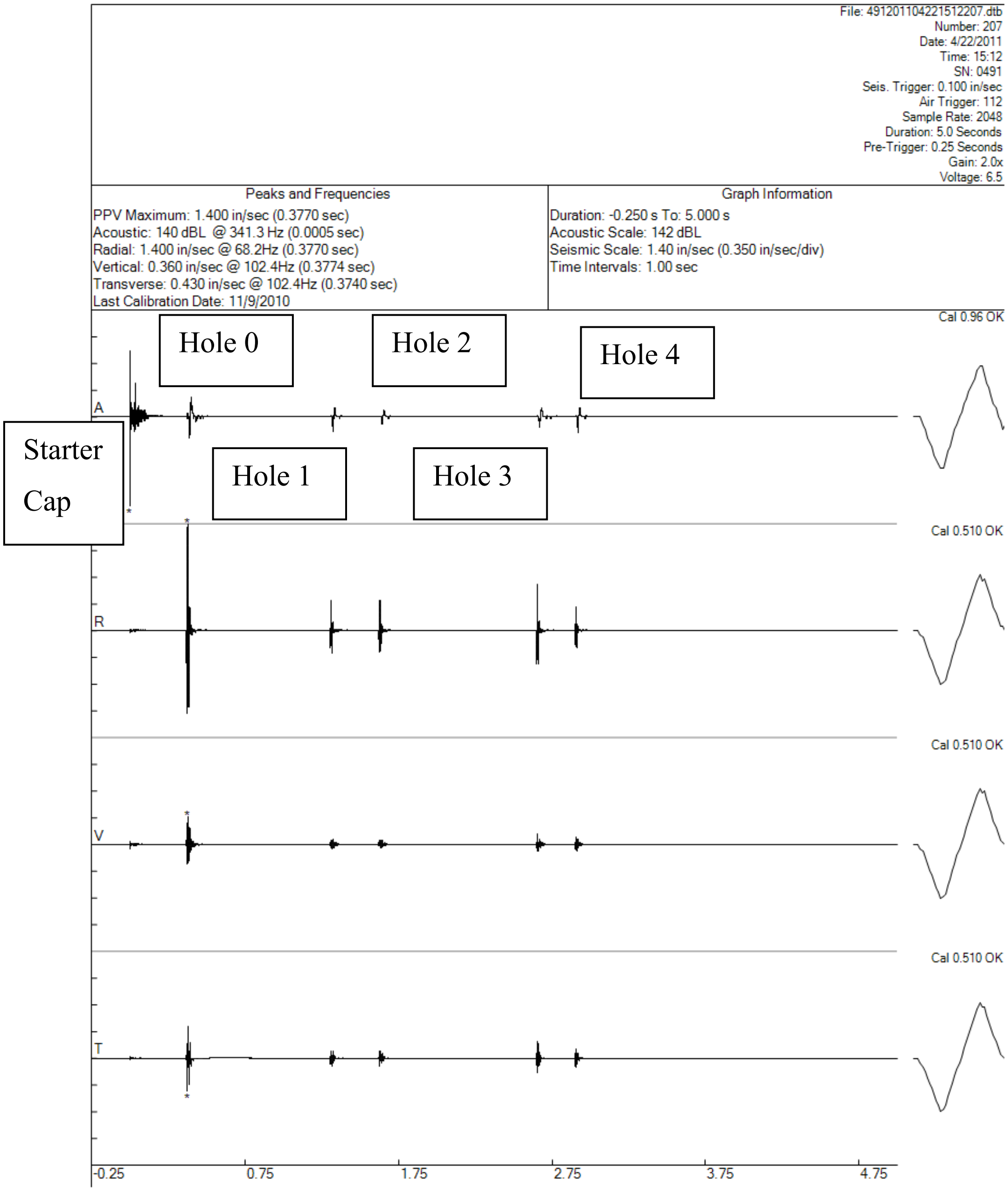

File: 491201104221512207.dtb
Number: 207
Date: 4/22/2011
Time: 15:12
SN: 0491
Seis. Trigger: 0.100 in/sec
Air Trigger: 112
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.5

Peaks and Frequencies

PPV Maximum: 1.400 in/sec (0.3770 sec)
Acoustic: 140 dBL @ 341.3 Hz (0.0005 sec)
Radial: 1.400 in/sec @ 68.2Hz (0.3770 sec)
Vertical: 0.360 in/sec @ 102.4Hz (0.3774 sec)
Transverse: 0.430 in/sec @ 102.4Hz (0.3740 sec)
Last Calibration Date: 11/9/2010

Graph Information

Duration: -0.250 s To: 5.000 s
Acoustic Scale: 142 dBL
Seismic Scale: 1.40 in/sec (0.350 in/sec/div)
Time Intervals: 1.00 sec

Dead Pressing Wet Shot #1

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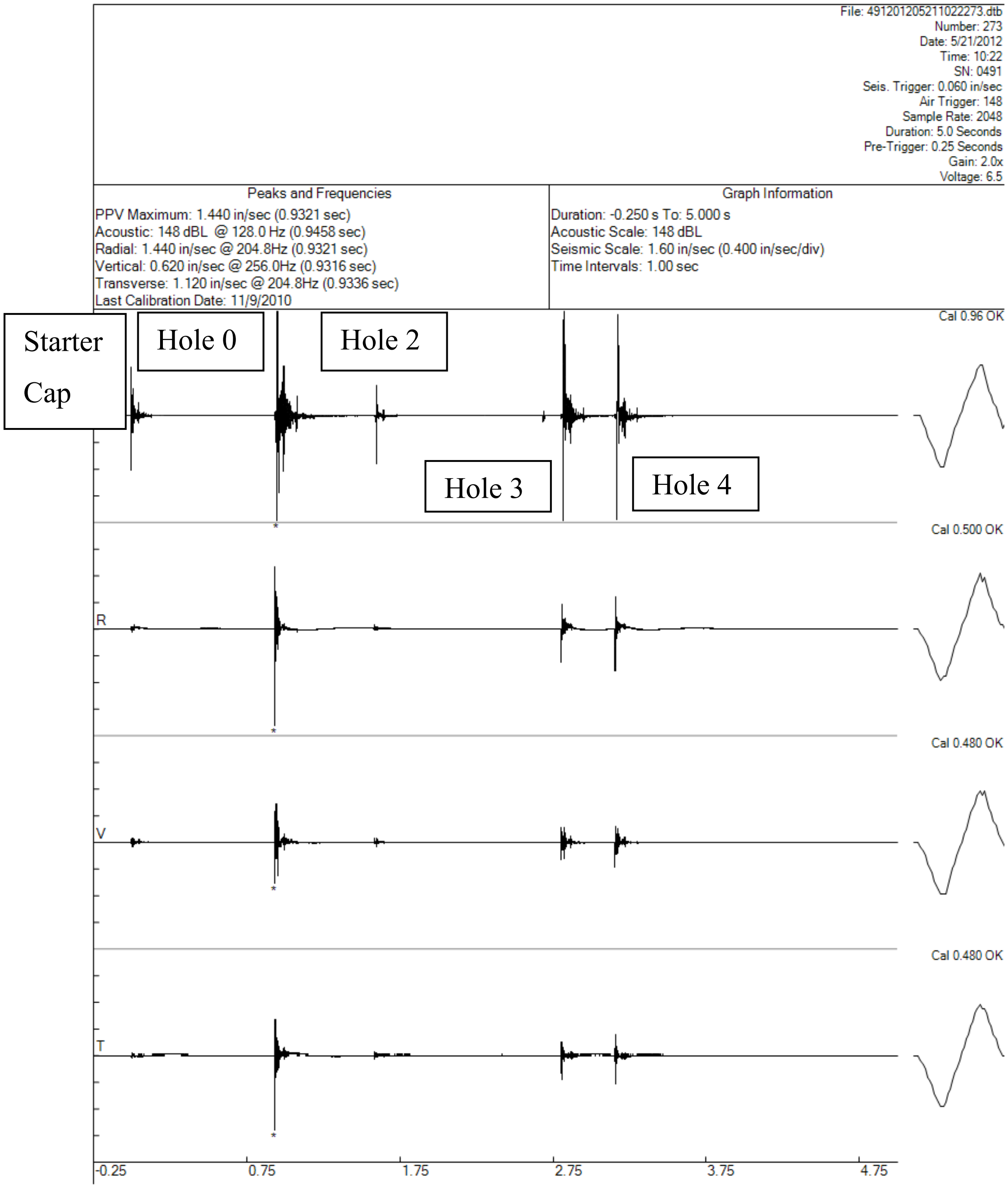

File: 491201205211022273.dtb
Number: 273
Date: 5/21/2012
Time: 10:22
SN: 0491
Seis. Trigger: 0.060 in/sec
Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.5

Peaks and Frequencies

PPV Maximum: 1.440 in/sec (0.9321 sec)
Acoustic: 148 dBL @ 128.0 Hz (0.9458 sec)
Radial: 1.440 in/sec @ 204.8Hz (0.9321 sec)
Vertical: 0.620 in/sec @ 256.0Hz (0.9316 sec)
Transverse: 1.120 in/sec @ 204.8Hz (0.9336 sec)
Last Calibration Date: 11/9/2010

Graph Information

Duration: -0.250 s To: 5.000 s
Acoustic Scale: 148 dBL
Seismic Scale: 1.60 in/sec (0.400 in/sec/div)
Time Intervals: 1.00 sec

Dead Pressing Wet Shot #2

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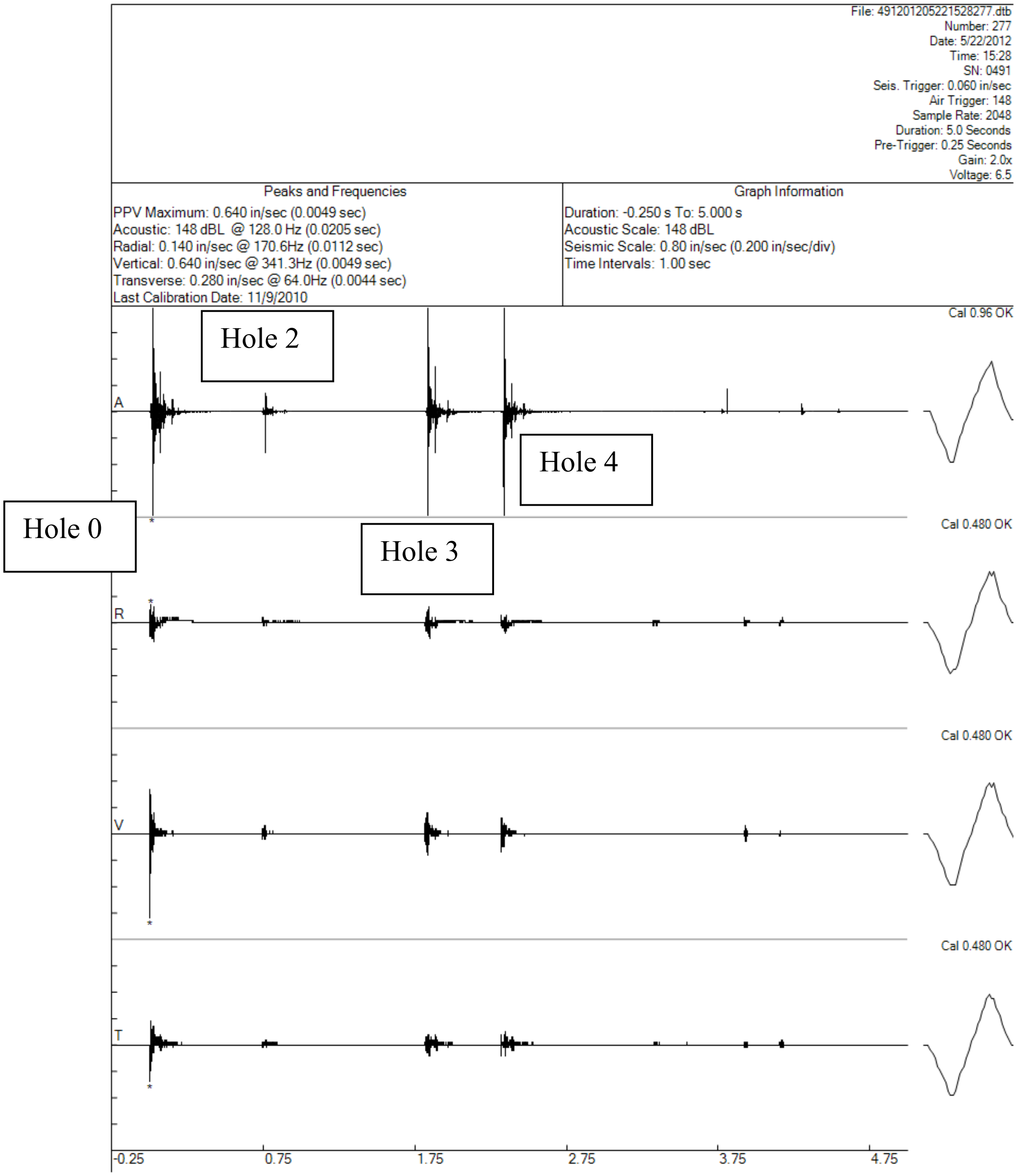

File: 491201205221528277.dtb
Number: 277
Date: 5/22/2012
Time: 15:28
SN: 0491
Seis. Trigger: 0.060 in/sec
Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.5

Peaks and Frequencies
PPV Maximum: 0.640 in/sec (0.0049 sec)
Acoustic: 148 dBL @ 128.0 Hz (0.0205 sec)
Radial: 0.140 in/sec @ 170.6Hz (0.0112 sec)
Vertical: 0.640 in/sec @ 341.3Hz (0.0049 sec)
Transverse: 0.280 in/sec @ 64.0Hz (0.0044 sec)
Last Calibration Date: 11/9/2010

Graph Information
Duration: -0.250 s To: 5.000 s
Acoustic Scale: 148 dBL
Seismic Scale: 0.80 in/sec (0.200 in/sec/div)
Time Intervals: 1.00 sec

Dead Pressing Wet Shot #3

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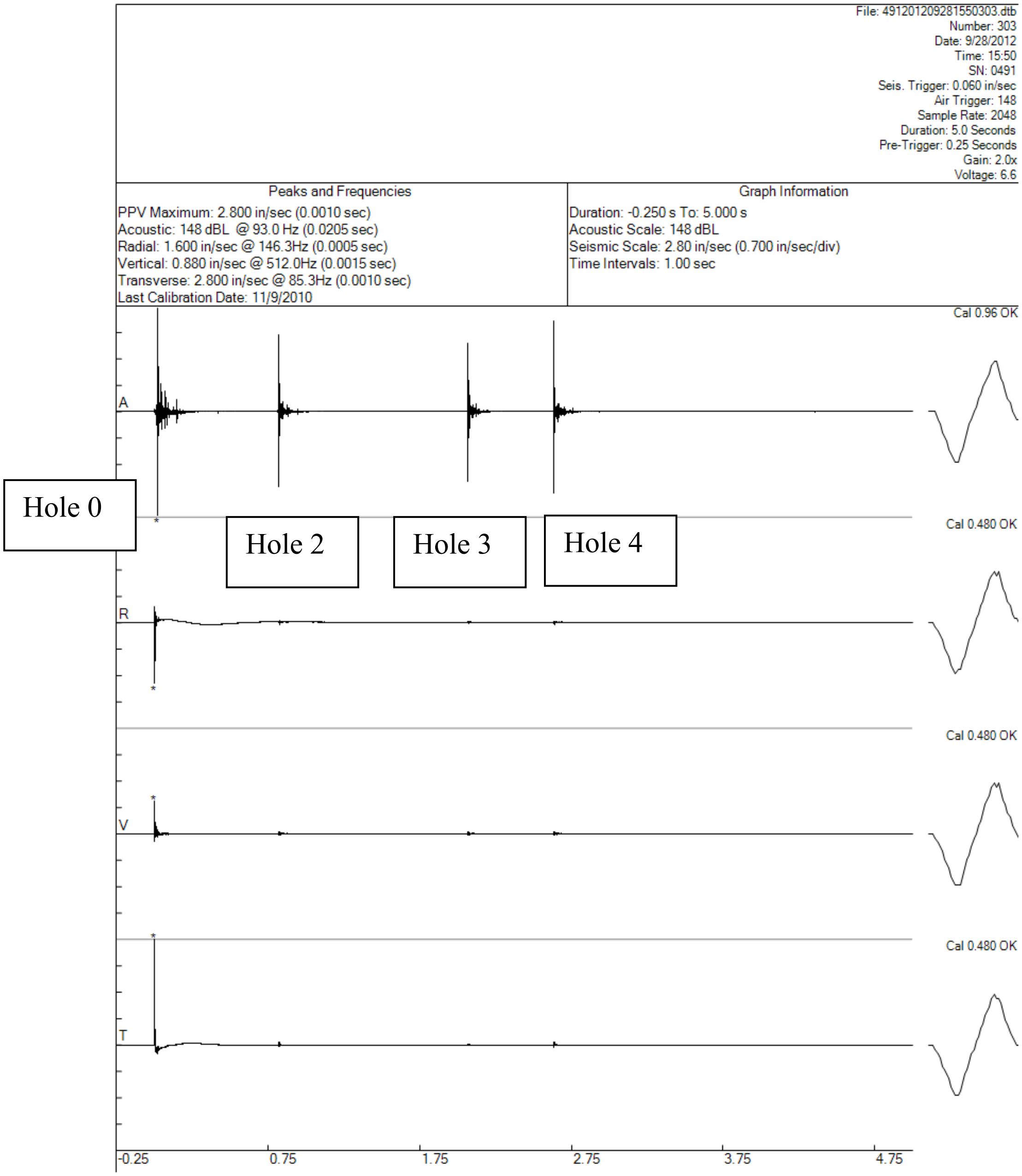

File: 491201209281550303.dtb
Number: 303
Date: 9/28/2012
Time: 15:50
SN: 0491
Seis. Trigger: 0.060 in/sec
Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.6

Peaks and Frequencies
PPV Maximum: 2.800 in/sec (0.0010 sec)
Acoustic: 148 dBL @ 93.0 Hz (0.0205 sec)
Radial: 1.600 in/sec @ 146.3Hz (0.0005 sec)
Vertical: 0.880 in/sec @ 512.0Hz (0.0015 sec)
Transverse: 2.800 in/sec @ 85.3Hz (0.0010 sec)
Last Calibration Date: 11/9/2010

Graph Information
Duration: -0.250 s To: 5.000 s
Acoustic Scale: 148 dBL
Seismic Scale: 2.80 in/sec (0.700 in/sec/div)
Time Intervals: 1.00 sec

Cap Test Shot #1

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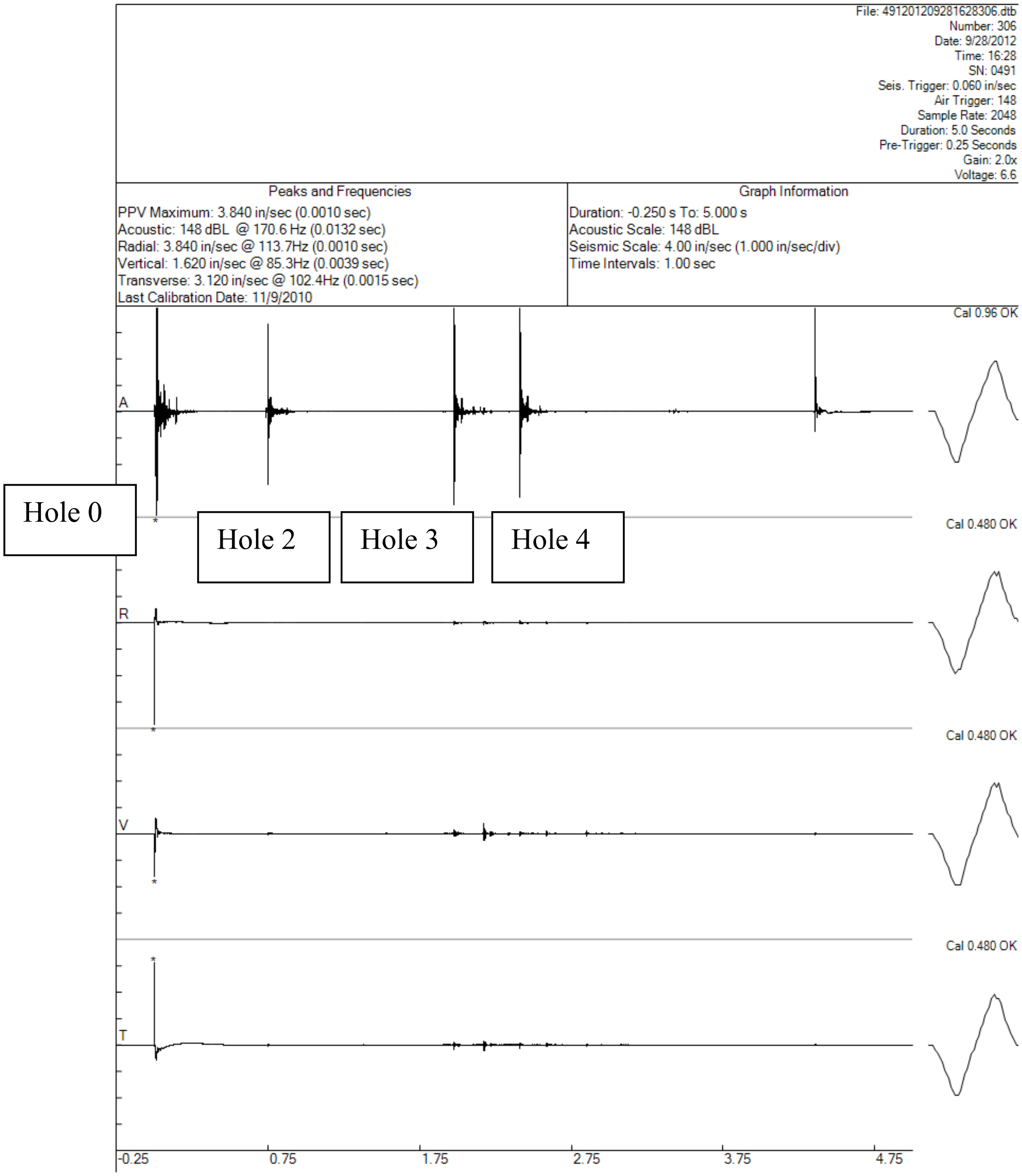

File: 491201209281628306.dtb
Number: 306
Date: 9/28/2012
Time: 16:28
SN: 0491
Seis. Trigger: 0.060 in/sec
Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.6

Peaks and Frequencies

PPV Maximum: 3.840 in/sec (0.0010 sec)
Acoustic: 148 dBL @ 170.6 Hz (0.0132 sec)
Radial: 3.840 in/sec @ 113.7Hz (0.0010 sec)
Vertical: 1.620 in/sec @ 85.3Hz (0.0039 sec)
Transverse: 3.120 in/sec @ 102.4Hz (0.0015 sec)
Last Calibration Date: 11/9/2010

Graph Information

Duration: -0.250 s To: 5.000 s
Acoustic Scale: 148 dBL
Seismic Scale: 4.00 in/sec (1.000 in/sec/div)
Time Intervals: 1.00 sec

Cap Test Shot #2

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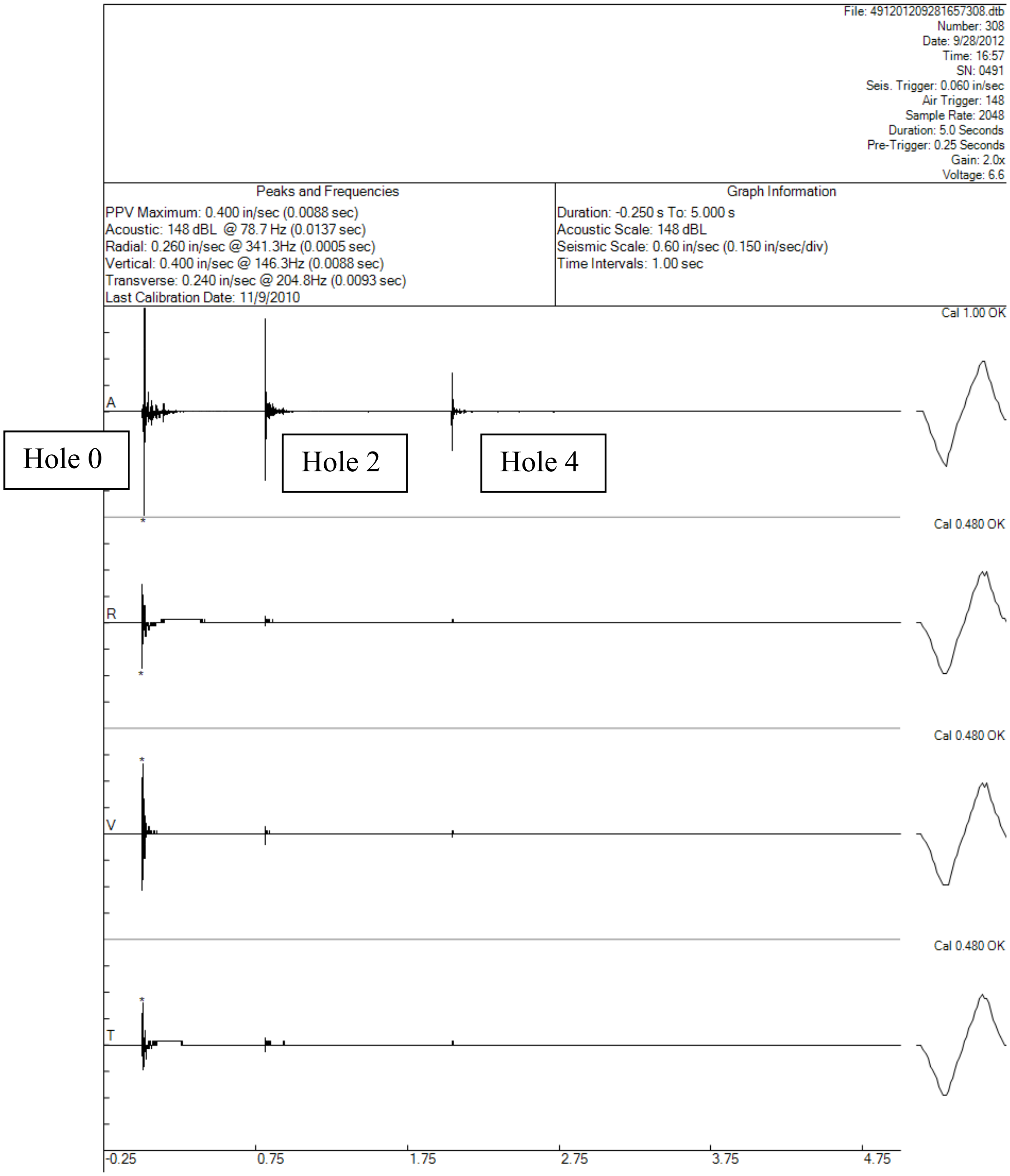

File: 491201209281657308.dtb
Number: 308
Date: 9/28/2012
Time: 16:57
SN: 0491
Seis. Trigger: 0.060 in/sec
Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.6

Peaks and Frequencies
PPV Maximum: 0.400 in/sec (0.0088 sec)
Acoustic: 148 dBL @ 78.7 Hz (0.0137 sec)
Radial: 0.260 in/sec @ 341.3Hz (0.0005 sec)
Vertical: 0.400 in/sec @ 146.3Hz (0.0088 sec)
Transverse: 0.240 in/sec @ 204.8Hz (0.0093 sec)
Last Calibration Date: 11/9/2010

Graph Information
Duration: -0.250 s To: 5.000 s
Acoustic Scale: 148 dBL
Seismic Scale: 0.60 in/sec (0.150 in/sec/div)
Time Intervals: 1.00 sec

Cap Test Shot #3

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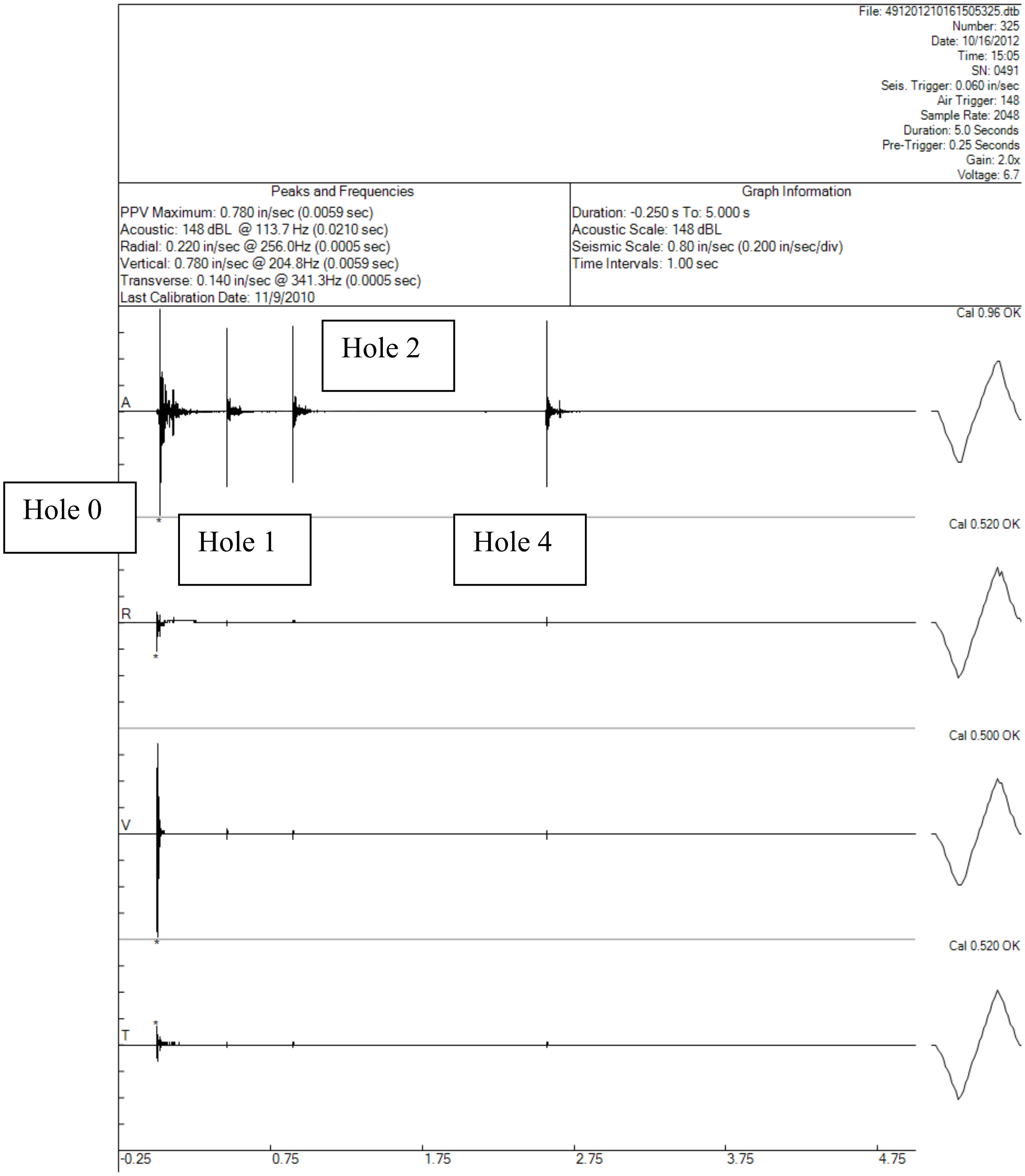

File: 491201210161505325.dtb
Number: 325
Date: 10/16/2012
Time: 15:05
SN: 0491
Seis. Trigger: 0.060 in/sec
Air Trigger: 148
Sample Rate: 2048
Duration: 5.0 Seconds
Pre-Trigger: 0.25 Seconds
Gain: 2.0x
Voltage: 6.7

Peaks and Frequencies

PPV Maximum: 0.780 in/sec (0.0059 sec)
Acoustic: 148 dBL @ 113.7 Hz (0.0210 sec)
Radial: 0.220 in/sec @ 256.0Hz (0.0005 sec)
Vertical: 0.780 in/sec @ 204.8Hz (0.0059 sec)
Transverse: 0.140 in/sec @ 341.3Hz (0.0005 sec)
Last Calibration Date: 11/9/2010

Graph Information

Duration: -0.250 s To: 5.000 s
Acoustic Scale: 148 dBL
Seismic Scale: 0.80 in/sec (0.200 in/sec/div)
Time Intervals: 1.00 sec

Cap Test Shot #4

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APPENDIX B.

PATTERN DATA

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Sympathetic Detonation Dry Holes

Shot #1	Measurements at		Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
Distance	Ground	2'								
2 inches	1 3/4 inches	1 3/4 inches	1 3/4 inches	1 3/4 inches	Top	1 3/4 inches	1/4 inches	12.50%	73/96 inches	14.41%
4 inches	3 1/2 inches	3 3/4 inches	3 1/4 inches	3 1/3 inches	Top	3 1/3 inches	2/3 inches	16.67%		
6 inches	6 1/8 inches	5 5/8 inches	6 5/8 inches	6 11/24 inches	Top	6 11/24 inches	11/24 inches	7.64%		
8 inches	8 1/4 inches	6 1/8 inches	10 3/8 inches	9 2/3 inches	Top	9 2/3 inches	1 2/3 inches	20.83%		

Shot #2	Measurements at		Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
Distance	Ground	2'								
2 inches	2 inches	1 3/4 inches	2 1/4 inches	2 1/6 inches	Top	2 1/6 inches	1/6 inches	8.33%	3/4 inches	13.72%
4 inches	4 inches	3 1/4 inches	4 3/4 inches	4 1/2 inches	Top	4 1/2 inches	1/2 inches	12.50%		
6 inches	6 1/2 inches	5 1/2 inches	7 1/2 inches	7 1/6 inches	Top	7 1/6 inches	1 1/6 inches	19.44%		
8 inches	8 1/2 inches	7 1/2 inches	9 1/2 inches	9 1/6 inches	Top	9 1/6 inches	1 1/6 inches	14.58%		

Shot #3	Measurements at		Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
Distance	Ground	2'								
2 inches	2 1/4 inches	1 inches	3 1/2 inches	3 1/12 inches	Top	3 1/12 inches	1 1/12 inches	54.17%	1 inches	27.00%
4 inches	4 1/4 inches	3 1/8 inches	5 3/8 inches	5 inches	Top	5 inches	1 inches	25.00%		
6 inches	7 inches	6 3/4 inches	7 1/4 inches	7 1/6 inches	Top	7 1/6 inches	1 1/6 inches	19.44%		
8 inches	8 1/4 inches	7 1/2 inches	9 inches	8 3/4 inches	Top	8 3/4 inches	3/4 inches	9.38%		

Distance	Overall Per Hole Deviation	Overall Per Hole Percent Error	Overall Average Deviaton	Overall Average Percent Error
2 inches	1/2 inches	25.00%	41/49 inches	18.37%
4 inches	13/18 inches	18.06%		
6 inches	67/72 inches	15.51%		
8 inches	1 7/36 inches	14.93%		

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Sympathetic Detonation Wet Holes

Shot #1 Distance	Measurements at Ground	2'	Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	2 3/8 inches	2 1/8 inches	2 5/8 inches	2 13/24 inches	Top	2 13/24 inches	13/24 inches	27.08%	85/96 inches	20.40%
4 inches	4 1/4 inches	3 1/8 inches	5 3/8 inches	5 inches	Top	5 inches	1 inches	25.00%		
6 inches	6 inches	4 3/8 inches	7 5/8 inches	7 1/12 inches	Top	7 1/12 inches	1 1/12 inches	18.06%		
8 inches	8 1/4 inches	7 1/4 inches	9 1/4 inches	8 11/12 inches	Top	8 11/12 inches	11/12 inches	11.46%		

Shot #2 Distance	Measurements at Ground	2'	Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	3 1/4 inches	2 inches	4 1/2 inches	4 1/12 inches	Top	4 1/12 inches	2 1/12 inches	104.17%	15/16 inches	33.33%
4 inches	4 inches	3 1/4 inches	4 3/4 inches	4 1/2 inches	Top	4 1/2 inches	1/2 inches	12.50%		
6 inches	5 3/8 inches	5 1/4 inches	5 1/2 inches	5 11/24 inches	Bottom	5 1/2 inches	1/2 inches	8.33%		
8 inches	8 inches	7 inches	9 inches	8 2/3 inches	Top	8 2/3 inches	2/3 inches	8.33%		

Shot #3 Distance	Measurements at Ground	2'	Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	3 3/4 inches	3 1/4 inches	4 1/4 inches	4 1/12 inches	Top	4 1/12 inches	2 1/12 inches	104.17%	1 1/3 inches	42.97%
4 inches	5 3/4 inches	5 1/4 inches	6 1/4 inches	6 1/12 inches	Top	6 1/12 inches	2 1/12 inches	52.08%		
6 inches	6 1/4 inches	7 inches	5 1/2 inches	5 3/4 inches	Top	5 3/4 inches	1/4 inches	4.17%		
8 inches	8 1/4 inches	7 1/4 inches	9 1/4 inches	8 11/12 inches	Top	8 11/12 inches	11/12 inches	11.46%		

Distance	Overall Per Hole Deviation	Overall Per Hole Percent Error	Overall Average Deviaton	Overall Average Percent Error
2 inches	1 41/72 inches	78.47%	1 5/96 inches	32.23%
4 inches	1 7/36 inches	29.86%		
6 inches	11/18 inches	10.19%		
8 inches	5/6 inches	10.42%		

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Dead Pressing Dry Holes

Shot #1 Distance	Measurements at Ground	 2'	Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	1 3/4 inches	1 3/16 inches	2 5/16 inches	2 1/8 inches	Top	2 1/8 inches	1/8 inches	6.25%	83/96 inches	18.73%
4 inches	4 3/4 inches	3 1/4 inches	6 1/4 inches	5 3/4 inches	Top	5 3/4 inches	1 3/4 inches	43.75%		
6 inches	5 15/16 inches	4 inches	7 7/8 inches	7 11/48 inches	Top	7 11/48 inches	1 11/48 inches	20.49%		
8 inches	7 9/16 inches	6 3/8 inches	8 3/4 inches	8 17/48 inches	Top	8 17/48 inches	17/48 inches	4.43%		

Shot #2 Distance	Measurements at Ground	 2'	Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	1 3/4 inches	1 11/16 inches	1 13/16 inches	1 19/24 inches	Bottom	1 13/16 inches	3/16 inches	9.38%	41/96 inches	11.33%
4 inches	4 1/16 inches	2 1/4 inches	5 7/8 inches	5 13/48 inches	Top	5 13/48 inches	1 13/48 inches	31.77%		
6 inches	7 3/16 inches	8 1/8 inches	6 1/4 inches	6 9/16 inches	Bottom	6 1/4 inches	1/4 inches	4.17%		
8 inches	7 5/8 inches	7 1/4 inches	8 inches	7 7/8 inches	Bottom	8 inches	0 inches	0.00%		

Shot #3 Distance	Measurements at Ground	 2'	Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	1 13/16 inches	1 3/16 inches	2 7/16 inches	2 11/48 inches	Top	2 11/48 inches	11/48 inches	11.46%	1 12/47 inches	23.03%
4 inches	2 1/2 inches	2 3/16 inches	2 13/16 inches	2 17/24 inches	Bottom	2 13/16 inches	1 3/16 inches	29.69%		
6 inches	6 1/2 inches	5 1/8 inches	7 7/8 inches	7 5/12 inches	Top	7 5/12 inches	1 5/12 inches	23.61%		
8 inches	9 1/16 inches	7 3/8 inches	10 3/4 inches	10 3/16 inches	Top	10 3/16 inches	2 3/16 inches	27.34%		

Distance	Overall Per Hole Deviation	Overall Per Hole Percent Error	Overall Average Deviaton	Overall Average Percent Error
2 inches	13/72 inches	9.03%	45/53 inches	17.69%
4 inches	1 29/72 inches	35.07%		
6 inches	28/29 inches	16.09%		
8 inches	61/72 inches	10.59%		

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Dead Pressing Wet Holes

Shot #1 Distance	Measurements at Ground	Measurements at 2'	Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	3 inches	2 1/2 inches	3 1/2 inches	3 1/3 inches	Top	3 1/3 inches	1 1/3 inches	66.67%	1 3/8 inches	35.94%
4 inches	5 3/4 inches	6 inches	5 1/2 inches	5 7/12 inches	Bottom	5 1/2 inches	1 1/2 inches	37.50%		
6 inches	8 inches	8 1/2 inches	7 1/2 inches	7 2/3 inches	Bottom	7 1/2 inches	1 1/2 inches	25.00%		
8 inches	9 inches	8 3/4 inches	9 1/4 inches	9 1/6 inches	Top	9 1/6 inches	1 1/6 inches	14.58%		

Shot #2 Distance	Measurements at Ground	Measurements at 2'	Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	2 3/4 inches	2 1/4 inches	3 1/4 inches	3 1/12 inches	Top	3 1/12 inches	1 1/12 inches	54.17%	19/32 inches	21.22%
4 inches	4 1/4 inches	2 7/8 inches	5 5/8 inches	5 1/6 inches	Top	5 1/6 inches	1 1/6 inches	29.17%		
6 inches	5 7/8 inches	5 3/4 inches	6 inches	5 23/24 inches	Bottom	6 inches	0 inches	0.00%		
8 inches	7 5/8 inches	6 7/8 inches	8 3/8 inches	8 1/8 inches	Top	8 1/8 inches	1/8 inches	1.56%		

Shot #3 Distance	Measurements at Ground	Measurements at 2'	Bottom of Explosive	Top of Explosive	Cloest Point to Donor Hole	Distance to Explosive	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	2 5/8 inches	2 1/8 inches	3 1/8 inches	2 23/24 inches	Top	2 23/24 inches	23/24 inches	47.92%	31/48 inches	19.99%
4 inches	3 7/8 inches	2 1/2 inches	5 1/4 inches	4 19/24 inches	Top	4 19/24 inches	19/24 inches	19.79%		
6 inches	5 11/16 inches	4 9/16 inches	6 13/16 inches	6 7/16 inches	Top	6 7/16 inches	7/16 inches	7.29%		
8 inches	8 1/16 inches	7 9/16 inches	8 9/16 inches	8 19/48 inches	Top	8 19/48 inches	19/48 inches	4.95%		

Distance	Overall Per Hole Deviation	Overall Per Hole Percent Error	Overall Average Deviaton	Overall Average Percent Error
2 inches	1 1/8 inches	56.25%	61/70 inches	25.72%
4 inches	1 11/72 inches	28.82%		
6 inches	31/48 inches	10.76%		
8 inches	9/16 inches	7.03%		

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Caps Wet Holes

Shot #1 Distance	Measurements at Ground	 2'	Bottom of Explosive	Distance to Cap	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	1 3/4 inches	3/4 inches	2 3/4 inches	2 3/4 inches	35/66 inches	37.50%	13/28 inches	17.19%
4 inches	4 1/8 inches	3 3/4 inches	4 1/2 inches	4 1/2 inches	35/99 inches	12.50%		
6 inches	5 3/4 inches	5 7/8 inches	5 5/8 inches	5 5/8 inches	13/49 inches	6.25%		
8 inches	8 1/8 inches	7 1/4 inches	9 inches	9 inches	70/99 inches	12.50%		

Shot #2 Distance	Measurements at Ground	 2'	Bottom of Explosive	Distance to Cap	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	1 3/4 inches	5/8 inches	2 7/8 inches	2 7/8 inches	13/21 inches	43.75%	35/96 inches	17.19%
4 inches	3 5/8 inches	2 5/8 inches	4 5/8 inches	4 5/8 inches	19/43 inches	15.63%		
6 inches	5 3/4 inches	4 15/16 inches	6 9/16 inches	6 9/16 inches	35/88 inches	9.38%		
8 inches	8 inches	8 inches	8 inches	8 inches	0 inches	0.00%		

Shot #3 Distance	Measurements at Ground	 2'	Bottom of Explosive	Distance to Cap	Deviation	Percent Error	Average Deviation	Average Percent Error
2 inches	1 5/8 inches	3/8 inches	2 7/8 inches	2 7/8 inches	13/21 inches	43.75%	35/72 inches	19.66%
4 inches	4 inches	3 3/8 inches	4 5/8 inches	4 5/8 inches	19/43 inches	15.63%		
6 inches	6 1/8 inches	5 3/8 inches	6 7/8 inches	6 7/8 inches	13/21 inches	14.58%		
8 inches	7 1/2 inches	6 5/8 inches	8 3/8 inches	8 3/8 inches	13/49 inches	4.69%		

Shot #4 Distance	Measurements at Ground	 2'	Bottom of Explosive	Distance to Cap	Deviation	Percent Error	Average Deviation	Average Percent Error
3 inches	2 5/8 inches	1 7/8 inches	3 3/8 inches	3 3/8 inches	13/49 inches	12.50%	9/37 inches	11.46%
3 inches	3 inches	2 5/8 inches	3 3/8 inches	3 3/8 inches	13/49 inches	12.50%		
3 inches	2 1/2 inches	1 1/2 inches	3 1/2 inches	3 1/2 inches	35/99 inches	16.67%		
3 inches	3 1/4 inches	3 3/8 inches	3 1/8 inches	3 1/8 inches	3/34 inches	4.17%		

Distance	Overall Per Hole Deviation	Overall Per Hole Percent Error	Overall Average Deviaton	Overall Average Percent Error
2 inches	33/56 inches	41.67%	2/5 inches	16.70%
3 inches	9/37 inches	11.46%		
4 inches	33/80 inches	14.58%		
6 inches	3/7 inches	10.07%		
8 inches	12/37 inches	5.73%		

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APPENDIX C.

HUGONOIT AND ENERGY CALCULATIONS

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Step 1 Explosive into Water

$\rho_{Water}{*}\ C_{0\ Water}{*}u1+\rho_{Water}{*}\ s_{Water}{*}u_1^{\,2} = P_{right\ going\ shock\ wave}$ Cooper P.207

$\rho_{Explosive}{*}\ C_{0\ Explosive}{*}(u_0-u_1) + \rho_{Explosive}{*}\ s_{Explosive}{*}(u_0-u_1)^2 = P_{Left\ going\ shock\ wave}$ Cooper P.207

Assume $u_0 = U_{Explosive}$

Set equal to each other

$\rho_{Water}{*}\ C_{0\ Water}{*}u1+\rho_{Water}{*}\ s_{Water}{*}u_1^{\,2} = \rho_{Explosive}{*}\ C_{0\ Explosive}{*}(\ U_{Explosive} -u_1) +$

$\rho_{Explosive}{*}\ s_{Explosive}{*}(\ U_{Explosive} -u_1)^2$

Solve for u_1

$0=u_1^{\,2}{*}(\rho_{Explosive}{*}\ s_{Explosive} - \rho_{Water}{*}\ s_{Water}) +$

$+u_1{*}(-\rho_{Explosive}{*}\ C_{0\ Explosive} - 2{*}\rho_{Explosive}{*}s_{Explosive}{*}\ U_{Explosive}-\rho_{Water}{*}\ C_{0\ Water}) +$

$+(\rho_{Explosive}{*}C_{0\ Explosive}{*}\ U_{Explosive} + \rho_{Explosive}{*}s_{Explosive}{*}\ U_{Explosive}^{\,2})$

a= 0.463323761

b= -26.801617

c= 83.89247933

u_1= 54.52565084 or **3.3207608 km/s**

Step 2 Water into Rock

$\rho_{Limestone}{*}\ C_{0\ Limestone}{*}u_2+\rho_{Limestone}{*}\ s_{Limestone}{*}u_2^{\,2} = P_{right\ going\ shock\ wave}$

$\rho_{Water}{*}\ C_{0\ Water}{*}(u_1-u_2) + \rho_{Water}{*}\ s_{Water}{*}(u_1-u_2)^2 = P_{Left\ going\ shock\ wave}$

Set equal to each other

$\rho_{Limestone}{*}\ C_{0\ Limestone}{*}u_2+\rho_{Limestone}{*}\ s_{Limestone}{*}u_2^{\,2} =$

$= \rho_{Water}{*}\ C_{0\ Water}{*}(u_1-u_2) + \rho_{Water}{*}\ s_{Water}{*}(u_1-u_2)^2$

Solve for u_2

$0=u_2^{\,2}{*}(\rho_{Water}{*}\ s_{Water} - \rho_{Limestone}{*}s_{Limestone}) +$

$+ u_2{*}(-\rho_{Water}{*}\ C_{0\ Water} - 2{*}\rho_{Water}{*}s_{Water}{*}u_1-\rho_{Limestone}{*}\ C_{0\ Limestone}) +$

$+ (\rho_{Water}{*}C_{0\ Water}{*}\ u_1 + \rho_{Water}{*}s_{Water}{*}\ u_1^{\,2})$

a= -1.386522

b= -29.4709524

c= 26.59972333

u_2= -22.1225019 or **0.8671937 km/s**

$P=\rho_{Limestone}{*}\ C_{0\ Limestone}{*}u_2+\rho_{Limestone}{*}s_{Limestone}{*}u_2^{\,2}$

p= 17.204103 Gpa

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Step 3 Rock into Water

$\rho_{water} * C_{0\ water} * u_2 + \rho_{water} * s_{water} * u_3^2 = P_{right\ going\ shock\ wave}$

$\rho_{Limestone} * C_{0\ Limestone} * (u_2 - u_3) + \rho_{Limestone} * s_{Limestone} * (u_2 - u_3)^2 = P_{Left\ going\ shock\ wave}$

Set equal to each
other

$\rho_{Water} * C_{0\ water} * u_2 + \rho_{water} * s_{water} * u_3^2 = \rho_{Limestone} * C_{0\ Limestone} * (u_2 - u_3) + \rho_{Limestone} * s_{Limestone} * (u_2 - u_3)^2$

Solve for u_3

$0 = u_3^2 * (\rho_{Limestone} * s_{Limestone} - \rho_{Water} * s_{Water}) + u_3 * (-\rho_{Limestone} * C_{0\ Limestone} - 2 * \rho_{Limestone} * s_{Limestone} * u_2 - \rho_{Water} * C_{0\ Water}) + (\rho_{Limestone} * C_{0\ Limestone} * u_2 + \rho_{Limestone} * s_{Limestone} * u_2^2)$

a= 1.386522

b= -22.467967

c= 15.57421824

U_3= 15.47888005 or **0.7256713 km/s**

$P = \rho_{water} * C_{0\ Water} * u_3 + \rho_{Water} * s_{Water} * u_3^2$

P= 484.7855937 Gpa **2.2023635 Gpa**

Step 4 Water into Explosive

$\rho_{Explosive} * C_{0\ Explosive} * u_3 + \rho_{Explosive} * s_{Explosive} * u_4^2 = P_{right\ going\ shock\ wave}$

$\rho_{Water} * C_{0\ Water} * (u_3 - u_4) + \rho_{Water} * s_{Water} * (u_3 - u_4)^2 = P_{Left\ going\ shock\ wave}$

Set equal to each
other

$\rho_{Explosive} * C_{0\ Explosive} * u_3 + \rho_{Explosive} * s_{Explosive} * u_4^2 = \rho_{Water} * C_{0\ Water} * (u_3 - u_4) + \rho_{Water} * s_{Water} * (u_3 - u_4)^2$

Solve for u_4

$0 = u_4^2 * (\rho_{Water} * s_{Water} - \rho_{Explosive} * s_{Explosive}) + u_4 * (-\rho_{Water} * C_{0\ Water} - 2 * \rho_{Water} * s_{Water} * u_3 - \rho_{Explosive} * C_{0\ Explosive}) + (\rho_{Water} * C_{0\ Water} * u_3 + \rho_{Water} * s_{Water} * u_3^2)$

a= -0.46332376

b= -7.63837549

c= 2.20236351

U_4= -16.7694982 or **0.2834552 km/s**

$P = \rho_{Explosive} * C_{0\ Explosive} * u_4 + \rho_{Explosive} * s_{Explosive} * u_4^2$

P= 615.5624725 Gpa **1.1017834 Gpa**

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Energy Applied to Explosive

Assume e_0=0, P_0=0, u_0=0

Assume U=u_3, u_1=u_4, P_1=P_4

e_1-e_0=(P_1u_1-P_0u_0)/(ρ_0*(U-u_0))-1/2*(u_1^2-u_0^2) Cooper P.183

e=(P_4u_4)/($\rho_{Explosive}$*(u_3))-1/2*(u_4^2)

e= 0.24483895 Km^2/s^2

E=$\rho_{explosive}$*ALe_1 Cooper P. 182

A=Cross sectional Area of Explosives Cooper P. 181

L=Length Cooper P. 181

A= 0.0064516 m^2

L= 0.03175 m

E= 7.573011528 Nm

Assume Pressure on Explosive is 1.5 times Pressure on Cap based on article found

e= 0.387345131 Km^2/s^2

E= 11.98081084 Nm

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APPENDIX D.

TECHNICAL DATA SHEETS OF EXPLOSIVE

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UNIMAX®

Extra Gelatin Nitroglycerin Dynamite

Technical Information

Product Description

UNIMAX is an extra gelatin dynamite formulated to consistently deliver high detonation velocity and excellent water resistance. UNIMAX is designed to satisfy the vast majority of explosive applications in hard rock and may be used as the main explosive charge where high density and energy is required or as a primer for ANFO.

Application Recommendations

- UNIMAX is an excellent primer for Dynomix (ANFO), Dynomix-WR (WR ANFO) or other detonator sensitive packaged product and can be used as a secondary primer in hard seams or at the top of the explosive column.
- Minimum diameter is 25 mm (1 in).
- Minimum detonator is No. 8 strength.
- Storage at elevated temperatures and/or high humidity for 1 to 6 months can reduce the performance of Unimax depending on the diameter. Consult your Dyno Nobel representative for specific recommendations.
- Dynamites are susceptible to sympathetic detonation when applied in very wet conditions where boreholes are closely spaced and/or where geological conditions promote this effect. Consult your Dyno Nobel representative for recommendations where these conditions exist.

Properties

MSDS #1019

Density	(g/cc) Avg	1.51
Energy[a]	(cal/g)	1,055
	(cal/cc)	1,510
Relative Weight Strength[a]		1.20
Relative Bulk Strength[a,b]		2.10
Velocity[c]	(m/s)	5,300
	(ft/s)	17,400
Detonation Pressure[c]	(Kbars)	106
Gas Volume[a]	(moles/kg)	32
Water Resistance		Excellent
Fume Class		IME1 & NRCan1[d]

[a] All Dyno Nobel Inc. energy and gas volume values are calculated using PRODET™ the computer code developed by Dyno Nobel Inc. for its exclusive use. Other computer codes may give different values.

[b] ANFO = 1.00 @ 0.82 g/cc

[c] Unconfined @ 50 mm (2 in) diameter.

[d] Approved by Natural Resources Canada as Fume Class 1.

Hazardous Shipping Description

Explosive, Blasting, Type A, 1.1D, UN 0081 II

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UNIMAX®

Technical Information

Transportation, Storage and Handling

- UNIMAX must be transported, stored, handled and used in conformity with all applicable federal, state, provincial and local laws and regulations.
- For maximum shelf-life, dynamite must be stored in cool, dry and well-ventilated magazines. Dynamite inventory should always be rotated by using the oldest materials first. For recommended good practices in transporting, storing, handling and using this product, see the booklet "Prevention of Accidents in the Use of Explosive Materials" packed inside each case and the Safety Library Publications of the Institute of Makers of Explosives.

Diameter x Length		Qty / Case	Case Type	Nominal Case Weight	
mm	in			kg	lbs
25 x 200	1 x 8	140	DA	21	47
29 x 200	1 1/8 x 8	100	DA	20	45
32 x 200	1 1/4 x 8	88	DA	21	47
32 x 400	1 1/4 x 16	44	DA	21	47
40 x 200	1 1/2 x 8	60	DA	20	45
40 x 300	1 1/2 x 12	40	DA	21	47
45 x 200	1 3/4 x 8	40	DB	18	40
50 x 200	2 x 8	34	DB	20	45
50 x 400*	2 x 16*	17	DB	20	45
60 x 400*	2 1/4 x 16*	14	DB	19	42
65 x 400*	2 1/2 x 16*	10	DB	20	44
70 x 400*	2 3/4 x 16*	9	**	**	**
75 x 200	3 x 8	16	DE	21	47
75 x 400*	3 x 16*	8	DE	21	47

* Available in spiral tube shell with tapered end. • Note: all weights are approximate.

**Available upon request. Check with your Dyno Nobel representative should you have any questions.

- Product density is 1.50 g/cc for package diameters less than 50mm (2 in). Use cartridge count to determine actual explosive charge weight.
- UNIMAX is available in a wide variety of sizes. Custom sizes are subject to surcharge and may require longer than usual lead times.

Case Dimensions

DA	45 x 34 x 17 cm	17¾ x 13⅜ x 6⅝ in
DB	45 x 34 x 15 cm	17⅞ x 13⅜ x 5⅞ in
DE	45 X 34 X 17 cm	17⅝ x 13 5/16 x 6¾ in

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Technical Data Sheet

The Power of Partnership

Senatel™ Ultrex™

Description

Senatel™ Ultrex™ packaged explosive is a robust, high strength, detonator sensitive emulsion explosive. The explosive is orange in color with a firm putty-like consistency. This product is also available in High Wax (HW) formulations.

Application

Senatel™ Ultrex™ is a water resistant packaged explosive designed for use as a medium density column explosive in surface, quarry and construction, underground mining and general blasting applications.

Key Benefits

- *Senatel™ Ultrex™* delivers excellent fragmentation for easy mucking.
- *Senatel™ Ultrex™* reduces post-blast fumes and improves turnaround time.
- The tight diameter control specifications and wax formulation of *Senatel™ Ultrex™* maximizes cartridge loader performance.
- *Senatel™ Ultrex™* PMP film cartridges readily split during tamping to maximize coupling and bulk strength within a blasthole.
- *Senatel™ Ultrex™* is highly water resistant which minimizes leaching and reduces environmental impact.
- OH&S issues around the handling and storage of nitroglycerin are eliminated.
- The packaging and emulsion color of *Senatel™ Ultrex™* provides high visibility in a range of environments.
- Packaged in PMP, easy to tamp plastic film or high strength, tear resistant Valeron film cartridges that are ideal for ragged, medium size boreholes.

Technical Properties

Senatel™ Ultrex™		**Less than 50 mm (2 in.)**	**Greater than 50 mm (2 in.)**
Cartridge Density		1.13	1.19
Typical Velocity of Detonation^1		4,500 m/s^3 15,400 ft/s	5,400 m/s 17,700 ft/s
Water Resistance		Excellent	
Fume Class		1	
Relative Effective Energy (REE)^2	Relative Weight Strength (RWS)	99	
	Relative Bulk Strength (RBS)	133	

Packaging

Senatel™ Ultrex™ is packaged in white plastic film to clearly differentiate it from booster sensitive packaged explosives. Cartridges are packed in 25 kg (55 lb) fiberboard cartons. Standard cartridge sizes are as follows:

Sizes (mm)	**Sizes (in.)**	**Nominal count per case**	**Film Type**
32 x 200	1¼ x 8	159 (±5)	PMP/Valeron
32 x 400	1¼ x 16	79 (±3)	PMP
40 x 200	1½ x 8	104 (±1)	PMP/Valeron
40 x 300	1½ x12	68 (±2)	PMP
40 x 400	1½ x 16	51 (±2)	PMP
45 x 400	1¾ x 16	35 (±1)	PMP/Valeron
50 x 200	2 x 8	57(±2)	Valeron
50 x 400	2 x 16	26	Valeron
65 x 400	2½ x 16	16	PMP/Valeron
75 x 400	3 x 16	12	Valeron
90 x 400	3½ x 16	9	Valeron

Senatel™ Ultrex™

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Technical Data Sheet

The Power
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Senatel™ Ultrex™

Recommendations for Use

Priming and Initiation

An Orica high strength electric, electronic, or non-electric detonator can reliably initiate *Senatel™ Ultrex™* at temperatures higher than -15°C (5°F) in diameters less than 50mm (2 in.). In diameters greater than 50mm (2 in.) or when temperatures are below -15°C (5°F), an appropriately sized *Pentex™* Booster is recommended.

Use of detonating cord with *Senatel™ Ultrex™* is not recommended. Detonating cord will adversely affect the performance of *Senatel™ Ultrex™* and could result in misfires. Consult an Orica Technical Representative before attempting to use with detonating cord.

Charging

In small diameter blastholes the maximum energy per meter of blasthole can be achieved by tamping the explosive with a wooden tamping rod appropriate to the hole diameter. No metal instrument should be used to tamp explosives. The primer cartridge containing a detonator must not be tamped.

Sleep Time Within Blastholes

In dry blastholes, given the explosives packaging is undamaged, *Senatel™ Ultrex™* may be charged and fired several months later. If the explosive packaging is damaged, the sleep-time in a blasthole is influenced by the extent of damage to the packaging and by the nature of any water present. Even with full length slitting of cartridges, the explosive will give good performance after two weeks immersion.

Storage And Handling

Product Classification

Authorized Name:	*Senatel™ Ultrex™*
Proper Shipping Name:	Explosive, blasting, type E
Classification:	1.1D
UN No:	0241
Packing Group:	II
Class Code:	1.1D
EX Number:	2008020491 (50mm and below)

All regulations pertaining to the handling and use of such explosives apply.

Storage

Store *Senatel™ Ultrex™* in a suitably licensed magazine for Class 1.1D explosives. The cases should be stacked in the manner designated on the case.

Senatel™ Ultrex™ has a **shelf life** of up to 12 months in a well ventilated, approved magazine, even in hot and humid extremes.

Senatel™ Ultrex™ is best stored at temperatures above -15°C (5°F). This is especially important in cold weather "load and shoot" worksites where there is insufficient inhole warm-up time. *Senatel™ Ultrex™* should have an internal temperature of 0°C (32°F) or higher, before use with a pneumatic cartridge loading machine.

Transport

Senatel™ Ultrex™ should be transported between -40°C (-40°F) and +40°C (104°F).

Disposal

Disposal of explosives materials can be hazardous. Methods for safe disposal of explosives may vary depending on the user's situation. Please contact a local Orica representative for information on safe practices.

Safety

The post detonation fume characteristics of *Senatel™ Ultrex™* make the product suitable for both underground and surface blasting applications. Users should ensure that adequate ventilation is provided prior to re-entry into the blast area.

Senatel™ Ultrex™ can be initiated by extremes of shock, friction or mechanical impact. As with all explosives, *Senatel™ Ultrex™* should be handled and stored with care and must be kept clear of flame and excessive heat.

Trademarks

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Technical Data Sheet

The Power of Partnership

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Emergency Contact Telephone Numbers

For chemical emergencies (24 hour) involving transportation, spill, leak, release, fire or accidents:

Canada: Orica Canada emergency response **1-877-561-3636**

USA: Chemtrec **1-800- 424-9300**

For lost, stolen or misplaced explosives:

USA: BATFE **1-800-800-3855**. Form ATF F5400.0 must be completed and local authorities (state / municipal police, etc) must be advised.

Notes

1. VOD will depend on application including explosive density blasthole diameter and degree of confinement. The VOD range is based on minimum unconfined and calculated ideal.
2. The Relative Effective Energy (REE) of an explosive is the energy calculated to be available to do effective blasting work. All energy values are calculated using the *IDeX™* computer code owned by Orica for the exclusive use of its companies. Energy values are based on standard ANFO with a density of 0.84 g/cc and a cut-off pressure of 100Mpa. Other computer codes may give different values.
3. Unconfined at 5°C (41°F).

Senatel™ Ultrex™

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NONEL® Lead Line

Technical Information

Nonelectric Shock Tube

Product Description

NONEL LEAD LINE is NONEL shock tube spooled at the factory in 763 meter (2,500 foot) lengths for easy application and deployment. NONEL LEAD LINE shock tube is a small diameter, three-layer plastic tube coated on the innermost wall with a reactive explosive compound. When initiated, NONEL shock tube propagates a low energy signal, similar to a dust explosion, at approximately 2000 m/sec (6,500 ft/sec) along the tube's length with minimal disturbance to the outside of the tube. The signal is transmitted from one NONEL shock tube to another through field-assembled splices.

NONEL LEAD LINE provides maximum flexibility to the blaster in choosing a position of safety from which to initiate nonelectric blast rounds in either underground or surface applications. NONEL LEAD LINE is the only NONEL product that can be cut and spliced into a NONEL detonator product to construct a custom length nonelectric starter assembly.

Application Recommendations

- ALWAYS splice NONEL LEAD LINE to NONEL EZTL™ nonelectric trunkline delay detonators, NONEL EZ DET® nonelectric blast initiation system, NONEL TD or NONEL Starter detonators to make-up the nonelectric starter assembly when using

Properties

MSDS
#1124

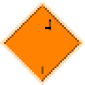
Net Explosive Content per 100 units 0.0044 kg
0.0097 lbs

Length		Spools / Case
m	ft	
762	2500	2

- **Length rounded to nearest one-half meter.**
- **See case label for exact case weight.**

Hazardous Shipping Description

Articles, Explosives, N.O.S. (HMX, Aluminum),
1.4S, UN 0349, PG II



I-28-05-02-11

See Product Disclaimer on page 2.

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NONEL® Lead Line

Technical Information

Application Recommendations (continued)

NONEL LEAD LINE as the primary initiator for NONEL blast rounds.

- ALWAYS trim at least 3 m [10 ft] of tubing before inserting into a nonelectric shock tube starting device or whenever dirt and/or moisture may have compromised the open tube ends before making a splice connection.
- ALWAYS replace the plastic tube closure over the open end of any NONEL LEAD LINE that remains on the spool and is intended to be used to make up another nonelectric starter assembly.
- ALWAYS make the final hook-up of the nonelectric starter assembly to the blast round only after all equipment and non-essential personnel are clear of the blast area.
- ALWAYS unspool NONEL LEAD LINE by hand if the starter assembly has been spliced to it and is attached to the blast round.
- ALWAYS keep any NONEL LEAD LINE tube ends sealed and free from dirt and moisture since dirt or moisture in the shock tube may cause a misfire.
- NEVER use NONEL LEAD LINE for in-hole use. NONEL LEAD LINE is for use outside the borehole only.
- NEVER attempt to knot different lengths of shock tube together. Shock tube will not initiate itself through knot connections. It must be spliced.
- NEVER remove the plastic tube closure from the NONEL LEAD LINE shock tube until just before splicing.
- NEVER attach the starter assembly to the blast round until after the LEAD LINE deployment is complete whenever NONEL LEAD LINE is to be unspooled by any method other than by hand,

Application Recommendations (continued)

- NEVER run over NONEL LEAD LINE with equipment. This may damage the shock tube and may cause a misfire. ALWAYS replace the NONEL LEAD LINE if it is damaged.
- When making a nonelectric starter assembly using NONEL LEAD LINE, ALWAYS remove the plastic tube closure and save for later use. Splice two freshly-cut ends of NONEL shock tube together (one from the NONEL LEAD LINE and the other from the NONEL detonator) by inserting them into opposite ends of the plastic connector sleeve and pushing them toward one another until they are both at least ½ cm (¼ in) in the splice.

Transportation, Storage and Handling

- NONEL LEAD LINE must be transported, stored, handled and used in conformity with all federal, state, provincial and local laws and regulations.
- For maximum shelf life (3 years), NONEL LEAD LINE must be stored in a cool, dry, well ventilated magazine. Explosive inventory should be rotated. Avoid using new materials before the old. For recommended good practices in transporting, storing, handling and using this product, see the booklet "Prevention of Accidents in the Use of Explosive Materials" packed inside each case and the Safety Library Publications of the Institute of Makers of Explosives.

Case Dimensions

51 x 25 x 28 cm 20 x 9 ¾ x 10 ¾ in

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NONEL® LP 1.1B

Nonelectric Long Period Delay Detonator

Technical Information

Product Description
NONEL® nonelectric delay detonator LP units consist of a length of yellow shock tube with a High Strength detonator attached to one end and the other end sealed. A blue J-hook, with pad-printed delay period, is affixed near the sealed end, providing easy means of connection to detonating cord. Easy-to-read, color-coded delay tags display the delay number and nominal firing time prominently.

NONEL LP units are designed to provide in-hole delay time for underground (non-coal) and special construction blasting applications that require long delay times to improve relief and fragmentation (such as drift development, raise and shaft work, as well as slope and tunnel blast rounds). They are typically used with detonating cord but can also be used with NONEL EZTL™ and NONEL TD detonators for additional timing flexibility.

Application Recommendations
For detailed application recommendations, **ALWAYS** request a copy of Dyno Nobel's *Product Manual: NONEL® and PRIMACORD®* from your Dyno Nobel representative.

- **ALWAYS** use the plastic J-hook when using a detonating cord trunkline to tie-in NONEL LP nonelectric delay detonators. A minimum 3 g/m (18 gr/ft) detonating cord trunkline is required for use with the J-hook.

Properties

MSDS
#1122

Net Explosive Content per 100 units	0.0885 kg 0.1947 lbs

Period / Delay Time (msec)	Delay Tag Color	Period / Delay Time (msec)	Delay Tag Color
0 /0	Pink	10 / 3500	Green
1 / 500	White	11 / 3900	Yellow
2 / 800	Lt Blue	12 / 4400	Red
3 / 1100	Orange	13 / 4900	White
4 / 1400	Green	14 / 5400	Lt Blue
5 / 1700	Yellow	15 / 5900	Orange
6 / 2000	Red	16 / 6500	Green
7 / 2300	White	17 / 7200	Yellow
8 / 2700	Lt Blue	18 / 8000	Red
9 / 3100	Orange		

Hazardous Shipping Description
Detonator assemblies, nonelectric,
1.1B, UN 0360 PG II

See Product Disclaimer on page 2.

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NONEL® LP 1.1B

Technical Information

Application Recommendations (continued)

- **ALWAYS** ensure the shock tube is connected at right angles to the detonating cord trunkline and that the shock tube leads returning to the hole collar do not cross over or lay near any detonating cord trunkline. If the detonating cord touches the shock tube or is closer than 6 inches (15 cm), the shock tube may be damaged and misfires may result.
- **ALWAYS** connect detonating cord using approved knots and tight connections. Place detonating cord hook-ups in closed loops and use with cross-ties.
- **NEVER** put more than 20 NONEL LP delays per bunch. A minimum 5 g/m (25 gr/ft) detonating cord is required for bunch blasting.
- **NEVER** cut or trim seals from the shock tube of a NONEL LP delay. If shock tubing is cut or is suspected of being cut or damaged during loading, **ALWAYS** reprime the borehole using a new unit of the same delay period.
- **NEVER** drive any equipment over the shock tube or detonating cord. Whenever charging from a maneuverable basket, platform or boom, **ALWAYS** make sure that no shock tube or detonating cord is entangled or can become entangled.
- **ALWAYS** make sure that no shock tube or detonating cord can be pinched between the basket, platform or boom and the face, ribs, back or floor. Rupturing or damaging shock tube or detonating cord may cause misfires.
- Where NONEL LP detonator lead lengths permit, bunch blasting provides the most efficient means of hooking up rounds in drifts, tunnels, shafts and raises.

Transportation, Storage and Handling

- NONEL LP must be transported, stored, handled and used in conformity with all federal, state, provincial and local laws and regulations.
- For maximum shelf life (3 years), NONEL LP must be stored in a cool, dry, well ventilated magazine. Explosive inventory should be rotated. Avoid using new materials before the old. For recommended good practices in transporting, storing, handling and using this product, see the booklet "Prevention of Accidents in the Use of Explosive Materials" packed inside each case and the Safety Library Publications of the Institute of Makers of Explosives.

Packaging

Length		Case Type	Quantity / Case	
m	ft		case	subpack
3.5	12	D	240	120
4.5	16	D	180	90
6	20	D	150	75
7	24	D	140	70

- Length rounded to nearest one-half meter.
- Case weight varies by length & delay; see case label for exact weight.

Case Dimensions

Detpak (D)

subpack	44 x 22 x 25 cm	17 ½ x 8 ¾ x 10 in
strapped case	44 x 45 x 25 cm	17 ½ x 17 ⅝ x 10 in

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APPENDIX E.

VIDEO FILES ON DISC

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1. INTRODUCTION

Included with this thesis is a DVD, which contains the video files of each shot from the different blasts. Each of the different video files was created by the same high speed camera. All of the video files have been prepared as an AVI file. An outline of the contents of the CD-ROM is as follows:

2. CONTENTS

Cap Test Shot 1.AVI

Cap Test Shot 2.AVI

Cap Test Shot 3.AVI

Cap Test Shot 4.AVI

Dead Pressing Dry Holes Shot 1.AVI

Dead Pressing Dry Holes Shot 2.AVI

Dead Pressing Dry Holes Shot 3.AVI

Dead Pressing Wet Holes Shot 1.AVI

Dead Pressing Wet Holes Shot 2.AVI

Dead Pressing Wet Holes Shot 3.AVI

Sympathetic Detonation Dry Holes Shot 1.AVI

Sympathetic Detonation Dry Holes Shot 2.AVI

Sympathetic Detonation Dry Holes Shot 3.AVI

Sympathetic Detonation Wet Holes Shot 1.AVI

Sympathetic Detonation Wet Holes Shot 2.AVI

Sympathetic Detonation Wet Holes Shot 3.AVI

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VITA

Adam Michael Doerfler was born on September 19, 1987 in St. Louis, MO. He graduated from Parkway South High school in Manchester, MO in 2006. After High School, he then attended University of Missouri-Rolla. He earned his B.S. degree in Mining Engineering in 2010. After completing his Bachelor's degree, Adam decided to pursue a Master's Degree in Explosive Engineering. In December 2012, Adam fulfilled the requirements to receive his M.S. in Explosive Engineering.

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