2-2017

Determine the Potential Drill Utilization Improvements and Rock Fragmentation Requirements Using Directional Drilling in a Coal Mining Overburden Highwall Application

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Recommended Citation

Dill, K.D., and Rosenthal, S.D. 2017. Preprint 17-037: Determine the potential drill utilization improvements and rock fragmentation requirements using directional drilling in a coal mining overburden highwall application. Presented at the SME Annual Meeting, Denver, CO, February 19-22.

Preprint 17-037

DETERMINE THE POTENTIAL DRILL UTILIZATION IMPROVEMENTS AND ROCK FRAGMENTATION REQUIREMENTS USING DIRECTIONAL DRILLING IN A COAL MINING OVERBURDEN HIGHWALL APPLICATION

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ABSTRACT

This project analyzed the efficiency of incorporating the use of directional drilling technology into coal overburden blasting. Directional drilling is currently in use in the petroleum industry and it is believed that it will be a valuable asset in the mining industry. This project has shown that directional drilling can be a viable technology for use in the coal overburden removal process resulting in increased drill utilization and potential for cost savings. Future work regarding blasting and geotechnical evaluation should be performed to solidify the concept.

INTRODUCTION

Determine the Potential Drill Utilization Improvements and Rock Fragmentation Requirements Using Directional Drilling in a Coal Mining Overburden Highwall Application was a project funded by Atlas Copco Drilling Solutions (Atlas Copco) based in Garland, Texas. The project was developed and researched by Montana Tech of the University of Montana. This project was intended to show how the use of directional drilling can increase drill utilization, while decreasing costs, without sacrificing overburden blasting results. This paper discusses a review of the literature, the methods performed, conclusions and future work

Background

Atlas Copco theorized that an alternative approach to drilling a cast blast pattern would be beneficial to coal mining operations by increasing drill utilization and therefore, decreasing overall costs. Increasing drill utilization results in an increase in the amount of time the drill is being productive, more drill bit time in ground. Atlas Copco's theory is that by incorporating directional drilling in the design of a cast blast pattern, a drill rig could drill multiple directional holes, which are the length of the cast blast, from a single drill set up. A drill goes through a series of steps to complete a blast pattern, these steps include: tramming to the hole location, leveling the drill, drilling the hole, cleaning the hole, and retracting the drill steel. This process is repeated hundreds of times until the whole pattern is completed. The most time intensive part of this process is drilling out the blast pattern. Integrating directional drilling into this process could decrease the overall time it takes to drill out a blast pattern by minimizing the amount of time spent tramming and setting up for each subsequent hole. Tramming and drill set up are two aspects of the drilling process where the drill tool is not engaged with the ground and, therefore, not being utilized. A cast blast pattern designed to utilize directional drilling will allow the drill tool to be "in the hole" longer and will improve drill utilization. This change in drill utilization was analyzed.

Drilling and blasting is an integral part of the mining process, without it mining would be a slower process and less material could be mined. Drilling provides holes for explosives to be loaded and then blasted. Blasting has been found to be the most cost effective method of fracturing rock in mining for material removal. Blasting is also used as a low-cost method to move the rock in open cast mines, commonly referred to as cast blasting. A cast blast is a large blast designed to allow for the maximum amount of overburden to be removed using explosives in a single blast thereby uncovering more coal at a lower cost. Not all the material is blasted to cast-to-final, which requires that material to be moved with large mining machinery. Material that is considered cast-to-final is material that has been thrown far enough to never be moved again in the coal extraction process, therefore it is in its final resting place. A typical cast profile and cast-to-final area is shown in Figure 1.

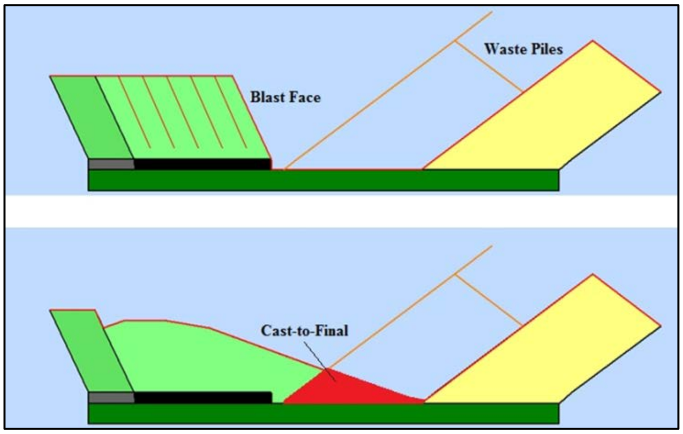

Figure 1. A cast profile shows a cast blast before and after the overburden was blasted.

Coal is one of the leading sources of energy in the world. According to the U.S. Energy Information Administration, 39% of the electricity generated in the United States in 2014 resulted from burning coal. (United States Energy Information Administration, 2016 (b)) The United States is home to both high and low quality coal deposits. In the Eastern United States near the Appalachian Mountains, coal deposits are generally mined using underground methods, such as room and pillar or longwall mining (United States Energy Information Administration, 2016 (a)). In the Western United States, specifically in the Powder River Basin, surface mining methods, such as open cast, are more prominent. In the open cast method of mining, the topsoil is removed and preserved for reclamation. The overburden or waste material is then drilled and blasted to expose the coal. A combination of draglines, trucks, shovels and other mining equipment is used to retrieve the coal. This is a continuous cycle of activity that is completed, beginning to end, every few weeks. Once the coal is removed, the reclamation process begins immediately to restore the land to the way it was before mining began. Reclamation entails restoring the natural ecosystem of the property to the way it was prior to mining the area and ensuring the environmental integrity of the land for the future. Surface mining is the most practical and cost effective method of mining for the thick, subbituminous coal seams in the Powder River Basin. The Powder River Basin was chosen as the area of study due to the large number of open cast coal mines in the area.

PROBLEM STATEMENT

This project addressed how a change in the way a cast blast pattern is drilled may positively affect the overall costs of the drilling and blasting aspect of mining. The project also focused on comparing the traditional method of drilling a cast blast to the proposed method of drilling a cast blast, using the directional drilling technique.

A typical cast blast pattern can contain 400 plus holes, requiring considerable time spent drilling the pattern. A general 3-dimensional concept of how a traditional cast blast is drilled is shown in Figure 2. A traditional cast blast consists of equally spaced holes drilled along the blast face, for the length of the blast. Typically there are 5-6 rows drilled in the same pattern. The traditional cast blast holes are vertical or angled parallel to the blast face, depending on the geologic parameters of the mine site. Figure 3 shows an angled pattern in cross-section.

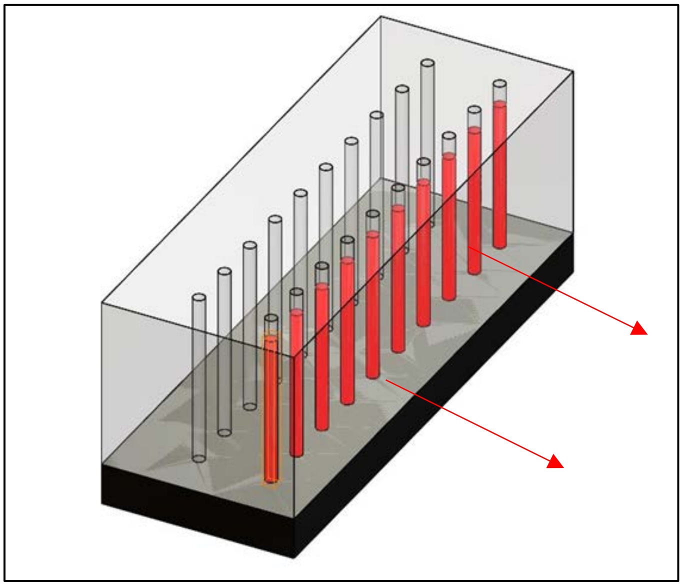

Figure 2. A 3-dimensional concept drawing of how a traditional cast blast is drilled and the relation of the drill holes to the blast face. The arrows represent the blasted material movement direction.

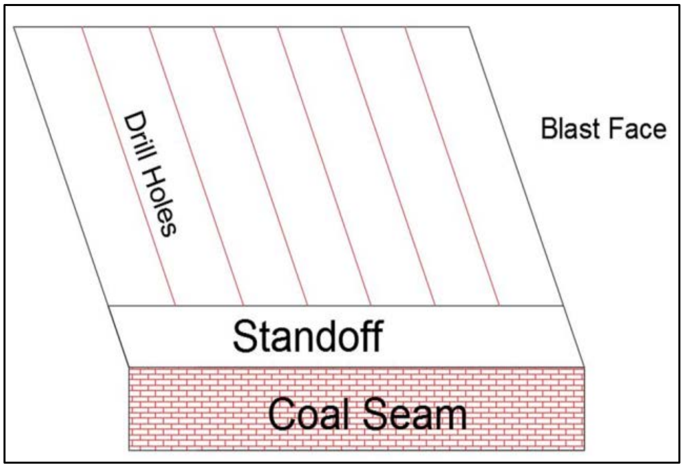

Figure 3. A cross-sectional concept drawing of how a traditional cast blast is drilled.

Once holes are drilled, an explosive product is loaded into each hole with a primer and then the whole pattern is tied in together. Using a predetermined timing sequence the blast is detonated. A cast blast typically lasts just a few seconds.

In blasting, timing is important. For example, in a cast blast the holes are timed and fired in a way that allows for each row to be peeled off and thrown away, uncovering the coal seam. This can be seen in Figure 2 and in more detail in Figure 4. The arrows in Figure 2 represent the direction of the blasted material movement. Each hole in a row is fired in sequence with a slight delay, in milliseconds (ms), between holes which helps create a peeling affect for the rows. When the first row is approximately a quarter to halfway detonated, the next row is detonated. By utilizing a domino effect of detonation, this helps overall cast results by being more efficient and increasing cast-to-final material. The movement from the second row helps push the material from the first row.

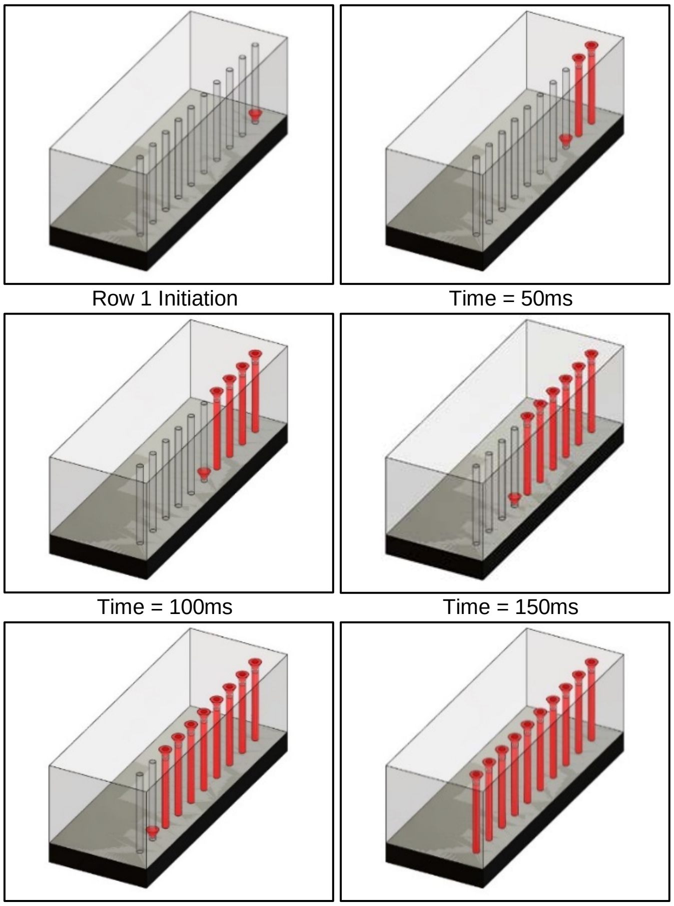

Figure 4. This series of figures shows a general timing sequence for a traditional cast blast. It should be noted that this timing sequence produces a peeling affect as mentioned above.

Atlas Copco proposed integration of directional drilling into the drilling process using a directional blast pattern theorizing that this change will improve drill utilization while lowering drilling and blasting costs, without compromising the overall blast results. The proposed method of drilling is shown in Figures 5 and 6. Figure 5 shows a conceptual 3-dimensional view of how the cast blasts will be drilled. Figure 6 shows a cross-section of the blast pattern, as if looking straight at the blast face.

The long horizontal holes in the proposed method of drilling are to be drilled from a single drill set up location thus allowing for more feet to be drilled for each time the drill is set up. The ability to drill multiple holes from a single drill set-up will significantly decrease the overall amount of time spent tramming and setting up, which in turn increases tool in-hole time and overall drill utilization.

Project Goals

The goals for this project were to present Atlas Copco Drilling Solutions with a model that determined generalized drilling and blasting costs for a directionally drilled cast blast pattern and compares it with a traditional cast blast pattern.

LITERATURE REVIEW

The literature review focused on topics of drilling and blasting in the mining industry pertaining to the topic area. The main concepts researched were explosives loading practices, directional drilling practices, blasting practices, and the utilization of equipment.

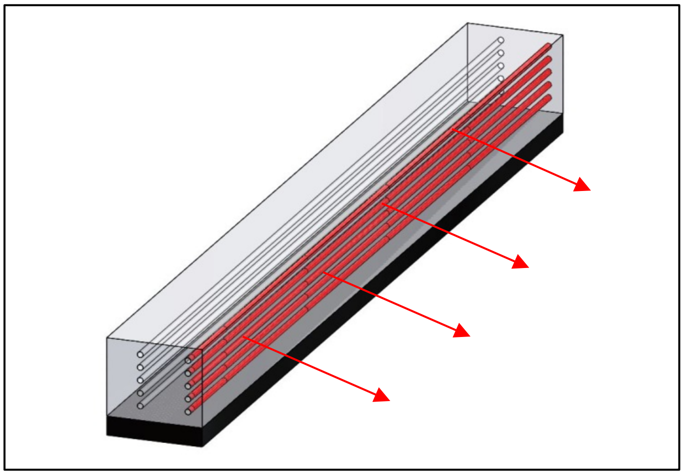

Figure 5. A 3-dimensional concept drawing of how the final drilled holes using directional drilling will be in relation to the blast face. The arrows represent the blast direction**.**

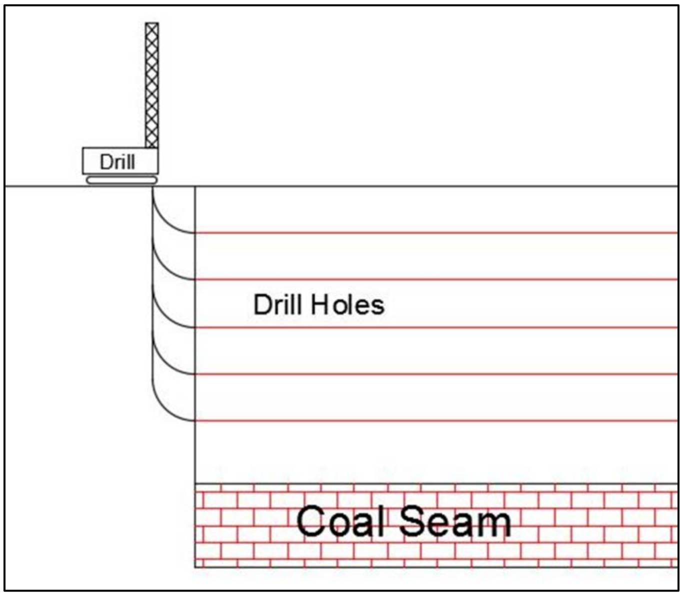

Figure 6. A cross-sectional concept drawing of how a cast blast is drilled using directional drilling.

Explosives Product Loading

In surface mining operations bulk explosive products are loaded into a blast hole by either augering (pouring) the product from the surface and letting gravity fill the hole from the bottom up or by using a loading hose to fill from the bottom of the hole up. Due to the change in geometry, from vertical to horizontal, in the proposed directional pattern, explosive loading becomes a challenge so it was important to research explosives product loading methods.

Underground blast holes being loaded with bulk explosives usually are charged with a loading hose arrangement. At the Underground Mine Education Center, an underground mine on the campus of Montana Tech, the cap and booster are placed in the end of a pneumatic hose and ammonium nitrate/fuel oil (ANFO) is blown into the end of the hole. As the hose is retracted, the hole fills with explosive product. This method has proven to be an effective way to load horizontal holes in underground mines. This method can be adapted and applied to loading a directional cast blast.

The article Explosives Loading Equipment describes multiple different types of underground explosives loading equipment and discusses how ANFO and water gel explosives are loaded into underground holes. An explosive product is placed in a "vessel or 'pot' and the vessel is then pressurized" (Champion, 1982). The vessel's hose is then placed in the blast hole and the product is blown in as the hose is extracted. Packaged products can also be loaded in a similar manner. "Using compressed air, the packages are blown quickly and safely through a hose and into the blast holes" (Champion, 1982).

Kelly Bar Loading

In addition to loading methods, literature related to Kelly Bar loading was reviewed, because with the change in geometry of the blast pattern, hole stability becomes a concern not present with vertical holes. Kelly Bars allow for explosives or a liner to be loaded into a hole without the hole collapsing while the drill steel is being extracted. The Kelly Bar is a hollow drill steel that is used in areas where the ground is not stable enough to support itself and allows a bulk or packaged explosive product to be loaded into the hole concurrent with the drill steel being extracted (Burke, 1976). After drill steel extraction, the hole can then close in on the explosive column or liner. There are two main types of Kelly Bars: one is simply a hollow drill steel used for smaller holes, less than 3" in diameter, and explosives; and, the other is used for larger holes, around 6" in diameter, with a core breaker bit inside (Argo, 2000). When loading larger holes, the core breaker bit is removed and the outer drill steel remains in place.

Before the invention of the Kelly Bar, in the late 1950's and early 1960's, "relatively short boreholes were either cased in a conventional manner or else a separate loading tube was driven down a drilled borehole through the loose material then cleaned with air or water," (Argo, 2000) the Kelly Bar combined these techniques and allowed for safer, more efficient loading practices. Kelly Bars are used in the following settings: "river crossings, drilling through excessive overburden, channel widening, seismic exploration, and stone production" especially in materials found in South Florida (Argo, 2000).

If a hole collapses before being loaded, it cuts off the ability to be loaded and blasted properly. Hercules Incorporated performed a significant amount of work with loading Kelly Bars. Most articles researched on the topic point back to Hercules' work in South Florida to develop an alternate method of Kelly Bar loading. In their paper titled "A Demonstration of an Alternate Approach to Kelly Bar Loading," (Hercules Incorporated, 1977), Hercules discusses the different trials performed and the testing of different liners that would be used in the holes to keep them from collapsing while loading an explosive product. The quarry where the Hercules tests were performed had hole stability issues, meaning the holes would not stay completely open, partially collapsing in on themselves due to ground conditions, and a solution was required to the hole charging problem. Hercules Incorporated tested various liners that were sturdy enough to keep the hole open yet did not affect the overall performance of the blast. These liners were loaded through the Kelly Bar.

Ground Vibrations

A literature review was performed on ground vibrations. Due to the change in geometry of the blast pattern, the amount of explosive loaded into each hole is increased, which would cause more vibrations each time a hole is detonated. As a part of the literature review, many articles cite extensive ground vibration work performed. Ground vibrations are an important aspect to be considered in blasting due to the impact they have on nearby structures as they can cause structural damage as well as be an annoyance, if not addressed appropriately, for people living in the area. Vibrations occur when energy is added to the ground. The Code of Federal Regulations (CFR) 30 715.19, 816.67, and 817.67 provide general guidelines to follow for surface blasting (Floyd, 2012), however, blast patterns and timing can be manipulated so that more explosives per delay interval can be detonated than the CFR's guidance.

One main concern with ground vibrations is the damage it could potentially cause to neighboring structures. In 1980, under the direction of the U.S. Bureau of Mines, three engineers and a geophysicist performed a ground vibration study that assessed "damage and annoyance potential" as well as to, "determine safe levels and appropriate measurement techniques" of ground vibrations (Siskind, 1980). Measurements were taken from 76 homes over the course of 219 production blasts. The results were combined with previous blasting studies. This study, as well as the previous studies, suggests that peak particle velocity be used to assess the damage potential of ground vibrations. A peak particle velocity of 2.0 inches per second (in/sec) was determined as a safe level for residential structures (Siskind, 1980).

This study concludes by stating that after combing all their results with previous work and using statistical methods to analyze the data, peak particle velocity is still the best "ground motion descriptor." Damage potentials are significantly higher in blasts that produce low-frequency (< 40 Hz) ground vibrations versus blasts that produce high-frequency (> 40 Hz) ground vibrations. General safe practices for particle velocity in low-frequency blasts are 0.75 in/sec for modern drywall houses and 0.5 in/sec for older plaster walled homes. For high-frequency blasts, a recommended safe peak particle velocity is 2.0 in/sec for both style homes. "Human reaction to vibration can be the limiting factor" (Siskind, 1980) as humans can feel vibrations at levels lower than those which produce structural damage. The amount of vibrations felt also depends on the duration of the blast as well as vibration level. From an annoyance standpoint, a blast could be more annoying than damaging. Similar to a small earthquake, blasts could cause enough vibration to be felt, but not enough to cause any damage. Participants from the study felt that the most serious blast vibration problems were house rattling, fear of damage or injury, being startled and possible activity interference. The report states that complaints from these causes were as high as 30% at 0.5 in/sec. Good public relations and educational programs by the blaster can help these complaints become minimized (Siskind, 1980).

Ground vibrations can be minimized by altering the blast pattern and timing of a shot. The U.S. Bureau of Mines performed another study titled, "Vibrations from Instantaneous and Millisecond-Delayed Quarry Blasts" (Duvall, 1963) and it discusses how peak particle velocity is calculated using the equation:

$$V = K * W^b * D^{-n} \quad (1)$$

where, V is the particle velocity (in/sec), D is the distance from the blast (feet), W is the charge weight per delay (lbs), and K, b and n are constants determined based off of site parameters and detonation procedure. As mentioned above, peak particle velocity is an important value to consider when blasting, as it has been found that a safe peak particle velocity is 2.0 in/sec. This report determines that blast design and timing affect the overall ground vibrations produced.

John Floyd, Blast Dynamics, has consulted many different mine sites on blasting issues concerning ground vibrations and found that altering blast design and blast timing has been a successful tool to solve ground vibration issues. One example where adjusting the blast pattern and timing fixed a vibration problem is a case study from the Trapper Mine in Colorado where there was a ground vibration problem in a new pit. When a blast was detonated, the highwall would fracture in unwanted places (known as back break or over break). Through a series of tests it was determined that the timing could be altered to minimize ground vibrations and, therefore, prevent catastrophic over break (Floyd, 2003). The Trapper Mine adjusted its timing for future blasts and has been able to avoid the over break problem that previously occurred.

At the Sasti open cast coal mine in India there was a growing issue with ground vibrations as the pit moved closer to villages. The solution to this ground vibration problem was to dig a trench between the blast and the villages. This trench acted in place of a pre-split row for the blasts. Tests were performed with varying trench depths, while the blast hole depth remained constant at 7 meters. Results from the tests showed a significant decrease in the recorded vibrations when a trench was present. The trench acted as a disruptor and was able to decrease ground vibrations. When a trench was not present ground vibrations recorded at a distance of 146 meters from the blast were 4.26 millimeters per second (mm/sec). When a 7 meter trench was dug, making the trench depth to hole depth ratio 1, the ground vibrations measured at the same distance were reduced by 55% to 1.92 mm/sec. Digging a trench might not be practical in many situations, for example, the mine site might not have enough room for an effective trench to be dug, however results from this test did show it was a successful solution in decreasing ground vibrations (Venkatesh, 2008).

Directional Drilling

Directional drilling is a common practice in the petroleum industry and is defined as "the practice of controlling the direction and deviation of a wellbore to a predetermined underground target or location" (Society of Petroleum Engineering International, 2016). Large corporations in the petroleum industry (i.e. Chevron, Exxon, and Shell) are using a directional drilling rig set up, where the drill string starts at vertical and builds angle or "turns" at very slow rates. These build rates can be as fast as 17 degrees per 100 vertical feet, but are typically around 10 degrees per 100 feet. This means that if the well is starting at vertical or zero degrees, after drilling 100 vertical feet, the well angle would be 17 degrees. Typically, in the petroleum industry, hydrocarbon bearing formations are thousands of feet deep so a build rate this slow achieves the desired result whereas in the Powder River Basin, where the overburden is approximately 150-200 feet thick, a build rate would need to be significantly faster. Directional drilling is attractive for several reasons, the main reason being that multiple holes can be drilled from a single drill set up.

Coiled tubing, or coil tube drilling, is another form of directional drilling. A coil tube drill rig is shown in Figure 7. This technology has its advantages: however, its use in the petroleum industry is significantly different than the needs of the mining industry. Applying coil tube technology to the mining industry is attractive and it would need to be adapted to a more shallow drill depth. Coil tube rigs have the ability to drill thousands of feet into the earth, where they usually operate, whereas in the Powder River Basin, drilling depths are less than 200 feet deep.

Figure 7. A typical coil tube drill rig used in the petroleum industry. This type of drill rig is loaded on a trailer and is able to be moved relatively easy (Foremost, 2016).

On a smaller scale there is another type of directional drilling similar to the petroleum industry and used for different applications. Small-scale drilling companies like Vermeer and Ditch Witch are using directional drilling to install utility lines under roads, lakes and buildings (Ditch Witch, 2015; Vermeer, 2015). The technique is similar to the petroleum industry's technique for directional drilling, however these small scale drills have a shallow angle of attack, typically between 10-15 degrees off of horizontal, which means the "turn angle", or the total amount of angle needed to build to reach horizontal, is significantly less and the turn is completed at shallower depths. Figure 8 shows a Ditch Witch directional drill rig that is used for utility line installation. Utility line installation generally occurs a few feet under the surface, according to Hidden Utilities Inc. utility lines as long as of 3,500 feet are also able to be installed (Hidden Utilities Incorporated, 2015). Ideally for this project, the directional drilling technology, either the conventional directional technology or a coil tube technology, will be combined with the small scale technology currently used to install utility lines, to create a drill rig that has the ability to successfully make a curve at shallow depths.

Figure 8. This type of drill rig is used for utility line installation (Ditch Witch, 2015).

Directional Drilling in the Mining Industry

Directional drilling in the mining industry has been predominantly applied for degassing underground mines and for mineral exploration. At the Esmeralda Coal Mine in Mexico directional drilling has been implemented as a method of degasification (Santillan, 2008). The machine that is used is capable of drilling horizontal holes up to 2,000 ft. (Acker Drill Company, 2015). Directional or horizontal drilling is also being used in New Zealand at the Huntly West Mine where long-hole directional drilling has been implemented for seam definition. Prior to the use of this drilling technique, there was uncertainty and geological risk involved with planning for a high production longwall face. In 1989 initial drilling was performed and the seam structure was redefined as the details between surface boreholes were filled in. The equipment used at the Huntly West Mine complex was similar to that of a petroleum directional drill rig consisting of a down hole motor assembly, or mud motor, attached to a bent housing and connecting rod assembly with a rotating bit assembly (Beamish, 1991). It has been concluded that the long-hole directional drilling with a down-hole motor is "the most successful and cost effective of the geological or geophysical exploration techniques tried to date at the Huntly West Mine." (Beamish, 1991). Directional drilling has proved to be a valuable tool for both degasification and seam definition.

Coil tube drilling is also being used in the mining industry for mineral exploration, particularly in Australia. An article published in the Australian Journal of Mining (Probert, 2013), discusses how coil tube technology has been adapted and modified to fill the needs of the mining industry for mineral exploration. A coil tube drill rig eliminates the need for separate joints of drill pipe, by utilizing a coil of continuous steel tubing and a down-hole motor that drives the drill bit. The Deep Exploration Technology Cooperative Research Centre (DET CRC) launched a prototype of a mobile coil tube drill rig, which allows for enhanced mineral exploration productivity (Probert, 2013). The prototype of the coil tube drill rig can be seen in Figure 9.).

Figure 9: The prototype developed by the DET CRC. This drill rig utilizes the coil tube technology for mineral exploration (Probert, 2013).

An in-depth report published by the DET CRC explains in further detail the coil tube drill rig and the coil tube technology. The report states that one of the attractive characteristics about the coil tube technology is that it has a fast operation compared to a traditional coil tube drill rig. The prototype produced by the DET CRC was mobile, which also adds to the ability to drill holes quickly and move from hole to hole at a rapid pace compared to a conventional coil tube set up. The ability to drill quickly and move quickly is attractive because it increases the time the drill is being utilized thereby decreasing overall cost per foot drilled (Roufali, 2013).

Equipment Utilization

Utilization is defined as "the act of using" or "the state of having been made use of" (The Free Dictionary, 2015). To understand the utilization of equipment in a mine one must first understand basic mine scheduling. According to the section titled "Equipment Scheduling-Including Utilization and Availability" (Sense, 1968), from the book "Open Pit Mine Planning and Design," time is broken down into four categories: mechanical availability, physical availability, use of availability, and effective utilization. These four categories help determine whether a piece of equipment is being used to its full potential. Table I is a breakdown of these four categories and helps identify where time is lost in the mining sequence (Sense, 1968).

Table I. The breakdown of the four main scheduling categories (Sense, 1968, p. 665).

Equipment Utilization & Availability				
	Mechanical Availability	Physical Availability	Use of Availability	Effective Utilization
Definition or Purpose	Time lost for mechanical reasons	Total operational availability, includes time lost for any reason	Management tool to establish effective use of equipment	Total % use relates hours worked to total hours
Equation: W = Working Hours R = Repair Hours S = Standby Hours T = Total Hours	$\frac{W}{W+R} * 100$	$\frac{W+S}{T} * 100$	$\frac{W}{W+S} * 100$	$\frac{W}{T} * 100$
Example: W = 300 R = 100 S = 200 T = 600	$\frac{300}{300+100} * 100 = 75\%$	$\frac{300+200}{600} * 100 = 83\%$	$\frac{300}{300+200} * 100 = 60\%$	$\frac{300}{600} * 100 = 50\%$

The example in Table I shows that half of the total time is lost due to repair or standby reasons. The proposed method of drilling under study here seeks to increase effective utilization by decreasing standby time or time when the bit is not drilling. Implementing directional drilling will allow multiple holes to be drilled from a single drill set up, which will result in decreased overall tram and set-up time and will allow for the drill tool to be engaged and utilized at a higher percentage than a traditional cast blast pattern.

Underground Blasting Technique

The proposed method of drilling changes the orientation of the blast holes from vertical to horizontal, similar to how blasting is performed underground. Figure 10 shows a general underground blast face. The section that is similar to a cast blast using horizontal blastholes is section "B", the stoping section. The stoping section of an underground blast is designed to heave the material into section "A" where a void was created in the first part of the blast. It is believed that a blast pattern designed to mimic section "B" would produce similar results in a cast blast as both a cast blast pattern and the stoping pattern are designed to heave material horizontally into the empty space adjacent to it. When designing a stoping pattern, the most important aspect to keep in mind is the spacing to burden (S/B) ratio. In the case of underground blasting, this ratio should be around 1.25:1 (Persson, 1964). In theory, using this ratio should produce similar results in a cast-blasting scenario. The impact of using this ratio is detailed in the solution and modeling section.

Explosives Supplier & Blasting Industry Expert Meetings

In addition to reviewing the literature, the author further explored ideas with current experts in the blasting industry and two separate contacts were interviewed. The first contact was Mr. Chris Hyle, Area Account Manager, Western Region, Orica Blasting Services. The project was discussed with an emphasis primarily focused on the blasting aspects. Mr. Hyle's professional opinions were provided in that, he voiced a few concerns to consider such as ground vibrations, hole loading, hole stability, and blast timing. As ideas about the project were discussed, Mr. Hyle thought the project being presented was interesting and could see it being successful based on what was explained. Mr. Hyle also recommended developing a blast model; however, he could not promise his organization, Orica, could perform any modeling due to a variety of factors including cost, time and existing work load (Hyle, 2015).

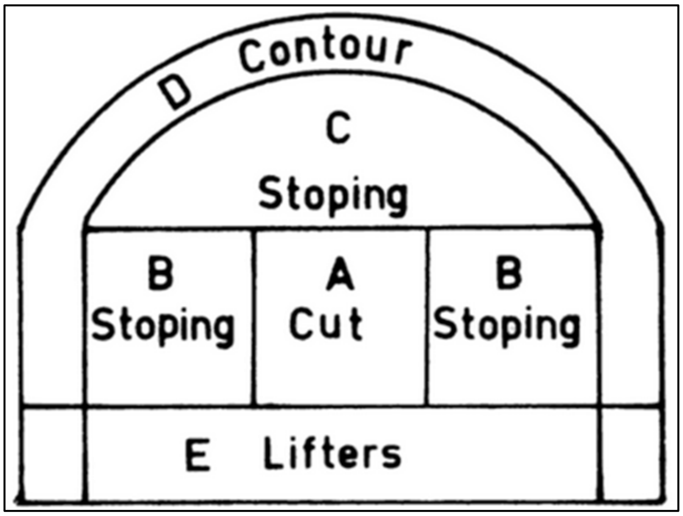

Figure 10. An underground blast face. Sections A-E represent holes with different blasting conditions. (Persson, 1964, p. 219).

The second contact interviewed was Mr. John Floyd, President, Blast Dynamics Inc. Mr. Floyd was informed on the progress of the project and was asked his thoughts about the proposed ideas based on the information provided. Mr. Floyd had similar concerns as Mr. Hyle about ground vibrations and hole loading and thought that it was an interesting idea that may have merit. Mr. Floyd was also asked about blast modeling and Mr. Floyd stated that in his professional career he does not use a blast model all that often because the models do not produce tangible results applicable to the problem. Mr. Floyd mentioned that if the full pattern or "drill face" could be utilized, especially with the use of directional drilling, the blast results could actually improve. Mr. Floyd's reasoning was that since the same amount of material is being blasted and the same amount of energy is being applied there is no reason the cast should not react similarly. Hole orientation is not factored into how far material is blasted: burden, spacing, charge weight per hole, energy, and rock properties determine blast performance (Floyd, 2015).

SOLUTION AND MODELING

Before creating any numerical models to determine an ideal directional pattern, drawings were made in AutoCAD to provide a visual representation of the different possible patterns. Using the technology currently available in the industry, drilling a directional cast blast pattern is possible. Figure 11 shows one of the drawings created using AutoCAD, this image shows a directional cast blast pattern with a shallow angle of attack, similar to a Ditch Witch style drill rig. Using a drill rig similar to a Ditch Witch would require the machine to be scaled up in size and performance, which is possible. Another issue in using a Ditch Witch style rig is that the drill would need to set up approximately 500 feet from where the blast area begins, this is depicted in Figure 11. For purposes of this project however; a more aggressive approach to drilling was taken and the assumption was made that a drill rig could make a 90 degree turn in 25 feet, shown previously in Figure 6. Once the AutoCAD images were created, a quick geotechnical analysis of sandstone was performed to understand if hole stability would be an issue. Models were then generated to better understand how a directional pattern would be laid out, for example; the number of holes the pattern would contain, the burden and spacing, and the hole diameter etc.

The geotechnical analysis was a quick way to determine whether the holes would be stable enough to remain open by themselves or if a liner was needed. This analysis assumed a hydrostatic stress was present on the hole. This means that the stress is the same all the way around the hole. Using a unit weight of 1 pound per inch squared (psi) per foot (ft.) the stress at 130 feet deep is 130 psi. Since a hydrostatic stress was assumed the stress concentration for the hole was determined to be 2. This means that the stress felt around the hole is twice as big, or 260 psi. The next step was to find the safety factor for the hole, using the factor of safety equation (2).

$$\mathrm{FS} = \frac{\text{Strength of Rock}}{\text{Stress on Rock}} \tag{2}$$

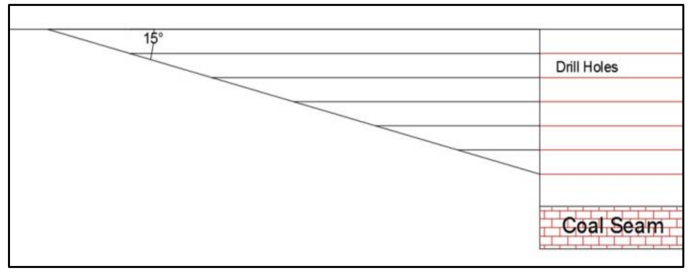

Figure 11. A directional cast blast pattern using a Ditch Witch style drill rig.

A safety factor higher than 1 is acceptable and would indicate that the hole would not need additional support. Rock data for the overburden in the Powder River Basin was not readily found during the literature search, so general sandstone data was used. For conservative measure a low strength of rock was chosen for sandstone, from the SME Mining Reference Handbook. For the "most common" sandstone a compressive strength is 7,000 psi (Society of Mining, Metallurgy, and Exploration Inc., 2002). A factor of safety of 27 was calculated, which means that the holes will be stable enough to remain open without added support (Johnson, 2016).

After determining that the holes would be stable, the models were created. It should be noted that the models are theoretical. To determine an appropriate comparison between a traditional cast blast pattern and a directionally drilled pattern, a model was created using Excel to calculate a series of outputs, seen in Table II. The outputs from the model include total feet drilled, volume of material blasted, overall powder factor for the blast, and total amount of explosives. These outputs were then used as inputs into a directional model where a new pattern was "created" horizontally. The directional model started as a rough conceptual model to form a base idea of how a directional pattern would be laid out within the overburden, and it clarified the pattern parameters, such as spacing and burden. The loading density equation (3) was used in the directional model to determine an appropriate directional pattern,

$$\rho_{ec} = 0.3405 * d_e^2 * \rho_e \tag{3}$$

where:

ρ_{ec} is the loading density (pounds/foot),
d_e is the diameter of the explosive (inches),
ρ_e is the explosive density (grams/centimeter), and
0.3405 is the English conversion factor (International Society of Explosives Engineers, 2011).

Equation 3 was rearranged into Equation 4, to solve for explosive diameter.

$$\mathrm{d_e} = \sqrt{\frac{\rho_{ec}}{0.3405 * \rho_e}} \tag{4}$$

Determining explosive diameter was important, since the holes will be fully coupled. Using the outputs from the traditional model in Table II, Equation 4 was used for a range of patterns with a varying number of holes. This was done because as the number of holes increases, total feet drilled increases and hole diameter decreases, which provided a wide variety of directional patterns. A balance was found and a directional pattern containing between 24 and 26 holes, seen in Table III, would be most reasonable to use due to the similarity to a traditional cast blast in overall total drilled feet and hole diameter.

Table II. Inputs and outputs from the traditional cast blast model.

Traditional Blast Parameters		
Height	165	feet
Width	200	feet
Length	2,240	feet
# of rows	6	
Burden	32	feet
Spacing	32	feet
Stemming	15	feet
Standoff	30	feet
Face Angle	70	degrees
Hole Diameter	12.25	inches
Explosive Density	1.21	g/cm^3

Number of Holes 420

Total Length of Drilling		
Hole Length	144	feet
Total Length	60,339	feet
Total Charge Length	54,039	feet

Volume of Material Blasted		
Total Volume	2,737,778	yard^3

Total Pounds (lbs) of Explosive Used		
English Conversion Factor	0.3405	
Load Density	62	lbs/foot
Total lbs of explosive	3,341,035	lbs

Powder Factor (P.F.)	1.22	lbs/yard^3

Table III. The directional model showing that a pattern with 24-26 holes gives a close approximation to a traditional cast blast pattern.

*Assume equal hole spacing		
# of holes	Total Feet Drilled	Hole Diameter
23	51,520	12.55
24	53,760	12.28
25	56,000	12.03
26	58,240	11.80
27	60,480	11.58

It should be noted that this model did not account for the lead-in drilling. The lead-in drilling is any drilling that is not horizontal, the lead-in drilling was added in a later version of the directional model. The absence of lead-in feet can be seen in Table IV, which compares the total drilled feet of the traditional cast blast and the directional model. The directional model was a stepping stone for further models to be developed, this model can be seen in Tables V and VI.

Table IV. Comparison of total drilled feet between the traditional model and the directional model.

	Number of Holes	Total Drilled feet
Traditional Cast Blast	420	60,339
Directional Cast Blast	24	53,760
	25	56,000
	26	58,240

Table V. Parameters used to determine a directional pattern.

Directional Blast Parameters		
Height	2,240	feet
Width	200	feet
Length	165	feet
Density	1.21	g/cm^3
Dist. From Structure	3,000	feet
Loading Density	62	lb/foot
Holes/Delay	2	

Total lbs of explosive	3,341,035	lbs

Powder Factor (P.F.)	1.22	lbs/yard^3

Table V. The directional model. Each row represents an individual pattern.

*Assume equal hole spacing		
# of holes	Total Feet Drilled	Hole Diameter (nches)
1	2,240	60.17
2	4,480	42.55
3	6,720	34.74
4	8,960	30.08
5	11,200	26.91
6	13,440	24.56
7	15,680	22.74
8	17,920	21.27
9	20,160	20.06
10	22,400	19.03
11	24,640	18.14
12	26,880	17.37
13	29,120	16.69
14	31,360	16.08
15	33,600	15.54
16	35,840	15.04
17	38,080	14.59
18	40,320	14.18
19	42,560	13.80
20	44,800	13.45
21	47,040	13.13
22	49,280	12.83
23	51,520	12.55
24	53,760	12.28
25	56,000	12.03
26	58,240	11.80
27	60,480	11.58
28	62,720	11.37
29	64,960	11.17
30	67,200	10.99
31	69,440	10.81
32	71,680	10.64
33	73,920	10.47
34	76,160	10.32
35	78,400	10.17
36	80,640	10.03
37	82,880	9.89
38	85,120	9.76
39	87,360	9.63
40	89,600	9.51
41	91,840	9.40
42	94,080	9.28
43	96,320	9.18
44	98,560	9.07
45	100,800	8.97
46	103,040	8.87
47	105,280	8.78
48	107,520	8.68
49	109,760	8.60
50	112,000	8.51

A directional model was created with a fixed number of holes, 25. A 25 hole directional pattern falls within the zone of 24 to 26 holes, seen in Table III, and results in a 5x5 pattern, with 5 directional holes for each drill set up. After completing the directional pattern model, additional review of the literature was conducted regarding underground blasting and how blasts are designed, specifically in the stoping sections. In that review, a similarity, which turned out to be significant, was noticed between how a cast blast is blasted and how a stoping section is blasted: both blasts are designed to fragment the rock and throw it horizontally into an adjacent void. Due to the similar nature of these blasts, another model for a directional cast blast was developed, using the underground stoping design parameters. This theory is based on the assumption that since a stoping section is designed to do the same thing as a cast blast using a wider burden and spacing, the results would be similar. A wider burden and spacing would require less overall drilling resulting in decreased drilling and blasting costs. Cast blasts do not throw all the overburden material to its final resting place, necessitating in well fragmented material, to be moved by large mining machinery. A hybrid pattern model was created that combined the underground technique and the directional technique. This hybrid pattern can be seen in Figure 12. The hybrid model is designed to allow the front two rows to be modeled using an underground stoping section design to throw the material far enough to a cast-to-final location and the back three rows are modeled similar to a directional cast blast for adequate fragmentation.

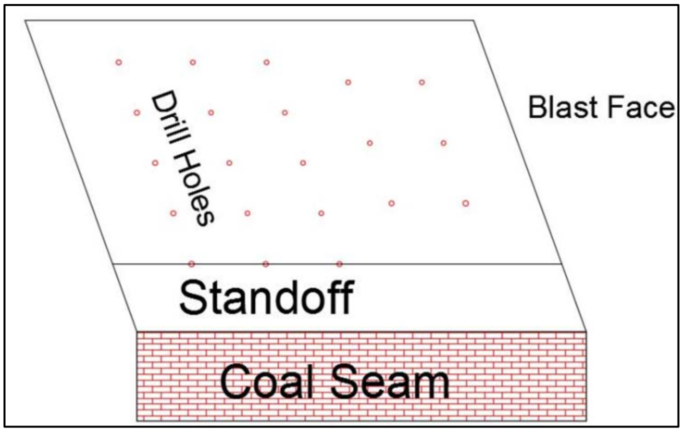

Figure 12. A cross-sectional concept drawing of how a hybrid cast blast is drilled.

Due to the given geometry of the overall blast area, it was observed that there would be blasting challenges as well as geotechnical concerns, such as ground vibrations, when detonating 2,000 plus feet, or the length of the blast, of explosive at once, so alternative loading parameters were conceived, however these methods were not modeled because they were out of the scope of the project.

Once the models were complete, general cost information for both drilling and blasting were added. The cost information was obtained from the Mine Cost Estimating handbook, from InfoMine USA (InfoMine USA, 2015). It should be noted however that this cost information is a base cost for drilling and blasting, certain drilling aspects were not accounted for, because they were not readily available. These aspects include, but are not limited to bench preparation costs, the cost of adapting a drill to include coil tube technology, etc. Table VII, shows a percent breakdown of how the costs are altered when changing from a traditional to a directional or hybrid pattern. The directional model shows that the cost/ton is increased by 3%; however, the hybrid pattern model shows that the anticipated cost/ton will be decreased by 13% from a traditional cast blast.

Table VII. Cost comparison between the three pattern types.

	Traditional	Directional	Hybrid
Total Explosives Cost	100%	103%	87%
Total Drilling Cost	100%	90%	76%
Total Cost	100%	103%	87%
Cost/Foot	100%	95%	95%
Cost/Ton	100%	**103%**	**87%**
Drill Bit in Hole	78%	82%	82%

Using the directional drilling technology can prove to be a valuable asset in the mining industry. Table VII shows that there is an increase in cost by 3% in a directional cast blast pattern, not including certain cost elements. The assumption could be made that when these costs are included, the overall cost would increase. However, once the directional drilling technology is applied to the mining industry for drilling cast blast patterns, the costs could decrease over time, especially as the technology evolves and becomes refined. According to the DTC Energy Group Inc., the average cost of a 20,000 ft. oil well in 2008 was $3.5 to $4 million. In 2013 a 21,000 ft. oil well cost $3 to $3.5 million (DTC Energy Group Inc., 2016).

CONCLUSIONS

By applying directional drilling technology for purposes of overburden removal in a surface coal mining application, it can be surmised that there is value in pursuing this option, especially relative to cost savings. The models create a generalized concept of what a directional pattern would look like and how the overall costs can change when the pattern parameters change. The results from the models are promising, because they show that there is room to improve on cost savings by an estimated 13%, which is significant in terms of a mine's drill and blast cost.

Even though the technology to directionally drill holes for a cast blast pattern is not currently available, the results of this project are promising and suggest that further research and development of this technology is worthy. If directional drilling technology were more advanced for shallower applications of large diameter holes, small scale tests could be performed allowing for more data collection and further evaluations.

FUTURE WORK

In completing this project it became apparent that more research should be performed on certain aspects of this project. Several assumptions had to be made for this project to work; for example assumptions involving blasting. More research should be performed to further explore whether the holes should be loaded completely or if there should be some sort of decking placed intermittently throughout the length of the hole to break up the powder column. It has already been determined through research and common practice in the mining industry that an explosive product can be pumped into a hole. However detonating 2,000 plus feet of explosives at once, as assumed in this study, would cause a lot of geotechnical problems, such as ground vibrations. Dividing each hole in 150 foot sections and inserting a deck of some sort between each powder column would help reduce vibrations, but the timing aspect as well as how to load the holes becomes an added challenge.

It should be noted that the drill rate used for the traditional cast blast patterns was also used for the directional cast blast patterns. This, however, is not totally accurate. When drilling a vertical hole, the weight of the drill string in addition to the pull-down force from the drill applies pressure in line with the drill bit. When drilling a directional hole, the same weight and pull-down is applied to the drill string, however these forces are not in line with the drill bit and therefore do not have the same effect. This means that the horizontal drilling rate would not be equal to the vertical drill rate. It is proposed that this be researched further to get a more accurate drilling rate.

As previously mentioned, cost information for this project was also generalized. The costs obtained were implemented to get a general idea of whether or not the costs would increase or decrease. Future research should include obtaining more accurate cost information for both traditional and directional drilling. This information was not readily available and therefore should be researched further.

When a hole is drilled, the cuttings need to be removed. In a traditional cast blast, drill hole cuttings are typically piled around the collar of the hole. Due to the increased number of holes drilled per set-up and the increased drill hole length, the amount of drill cuttings per drill set-up would significantly increase and would need to be dealt with in an alternative manner. It is proposed that further research be performed regarding the type of drilling fluid to flush the holes, as well as a location to pile the cuttings.

Another aspect of this project that has been questioned is whether the holes will naturally remain open. A quick geotechnical analysis was performed and showed that the holes would be stable enough to remain open without additional support, such as a liner. It is recommended however, that a more in depth evaluation be executed to ensure that hole stability would not be an issue. It has already been determined that Kelly bar loading is a possible solution for holes that collapse. It should also be mentioned that Atlas Copco currently produces a drill rig that has the ability to insert a liner into a vertical hole, this technology could be adapted to solve a hole stability issue, should one arise. Further exploration is needed based on the initial findings and if Atlas Copco proceeds forward, the results from this project can help open the way for others in the industry to improve technology and build off of the advancements made by Atlas Copco.

ACKNOWLEDGEMENTS

This paper is an edited version of the final academic thesis prepared by Kevin D. Dill as part of his graduate work at Montana Tech. Scott D. Rosenthal was his advisor.

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