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A novel powder factor based bench blast design method for large surface coal mines

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A NOVEL POWDER FACTOR BASED BENCH BLAST DESIGN METHOD

FOR LARGE SURFACE COAL MINES

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ABSTRACT

Large surface coal mines in Wyoming's Powder River Basin ship millions of tons of coal per annum, moving millions of cubic yards of overburden to mine the coal. Much of this volume is blasted in the form of benches, a common mining technique. Increases in production and scale of equipment in the past thirty-five years have created a paradigm shift for drill and blast personnel at these large surface mines, and the explosives industry has yet to create a blast design method specifically tailored for large surface coal mine bench blasting.

This research examines the typical scale of bench blasting at large surface coal mines, develops a new method of design tailored for these operations, and tests the new method against two widely accepted traditional blast design methods. Novel contributions of the research include a new universal scale of energy distribution known as Available Energy, and an entirely powder factor based blast design method that uses cut width as part of the design process. Numerical comparison testing is done at both small borehole diameters (corresponding to the original domain of the traditional blast design methods) and at large borehole diameters. A comparison of the new method and existing major methods of traditional blast design is monitored graphically, and linear regression is used to track the improvement of the accuracy of the match.

Finally, the new design method is presented in nomograph form to facilitate use in the field. Development of the nomograph is discussed and sample nomographs for specific design conditions are included. Recommendations for future work and broader applications of the Available Energy paradigm are given to conclude the dissertation.

ACKNOWLEDGEMENTS

One thing I have discovered is that no work is perfect. Things can always be improved, and my grammar isn't perfect always. First, I must thank He who is, was, and always will be. Faith is a challenging topic every day, and I'm thankful that the God of Abraham, Isaac, and Jacob saw fit to send His Son Jesus to die for anyone who will listen. Also, my wife Robin who patiently listened to rambles about Excel functions and nomographs (literally for *years*), and always encouraged me to pursue my goals, even if it meant delaying some of our goals. I love you, Robin. My father's work ethic and my mother's drive to excel have served me well; and the life examples of my grandparents (and Aunt Regina) have shown me how to live well when the only constant is change. Dr. Baird, thank you for your assistance and counsel, and for knowing when to speak and when to listen. Dr. Bullock, it has been an honor to have an engineer of your caliber looking over my work. Dr. Flori, thank you for modeling the intersection of faith and engineering. Dr. Lusk, I appreciate your commitment and your timely insights. Dr. Seeger, thank you for your confidence in my abilities. Barb, Judy, Shirley, and Tina, thanks. Your help is greatly appreciated. Jimmie and DeWayne, it's been great. Happy Birthday and thanks for the friendship. Dr. Paul Worsey, thank you for the life lessons; and Dr. Gillian Worsey, you didn't speak often, but when you did I listened. Finally, thanks to the people at Antelope. You taught me what it means to be an engineer (Steve W.), what leadership looks like (Greg M.), how to work as a team (Greg R., Tyler H., Rich P., Jeramie D.), the value of backup plans (Mike S.), how great shovels can be, and how to argue for the fun of it (Bob E.). The years I spent at Antelope have had a profound impact on how I conduct myself as a person and as a professional. Thank you.

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NOMENCLATURE

Special Characters

D	**Diameter**: When using bulk loaded explosive, this diameter is equal to borehole diameter
D_E	**Diameter of Explosive**: Not equal to borehole diameter if using packaged explosives; equal to borehole diameter if using bulk loaded explosive
π	**Pi**: The mathematical constant (3.14159…)
ρ	**Explosive Density**: Used to determine weight of explosives in the borehole; expressed in Grams/Cubic Centimeter, also called specific gravity of explosive
SG_E	**Specific Gravity of Explosives**: Used to determine weight of explosives in the borehole; also called explosive density
SG_R	**Specific Gravity of Rock**: Unit weight of rock expressed as a specific gravity for Konya's burden equation
St_f	**Stemming Factor**: Modifying factor used to determine length of stemming; for Ash and Konya used with respect to burden, for AE method used with respect to AE value
Su_f	**Subdrilling Factor**: Modifying factor used to determine length of subdrilling; for Ash and Konya used with respect to burden, for AE method used with respect to stemming
WT_{RK}	**Unit Weight of Rock**: Usually expressed in pounds per cubic foot.

Abbreviations and Parameter Definitions

AE	**Available Energy**: Novel energy level and distribution term introduced in this work
B	**Burden**: Shortest distance to relief – measured perpendicular to the dig face
BH	**Borehole**: Drilled into bench to hold explosives

CW — **Cut Width**: Width of material to be mined – this dimension is parallel to spacing

D&B — **Drill and Blast**: Team responsible for preparing benches for mining

EI — **Efficiency Index**: The percentage of borehole filled with explosive – powder column divided by face height – similar to Borehole Utilization without a weight component

EMM — **Existing Major Methods** (of blast design): Work done by Langefors and Kihlstrom, Ash, and Konya

FH — **Face Height**: Height of bench

LSCM — **Large Surface Coal Mine**: High tonnage (>5M tons per year) coal mine such as those in Wyoming's Powder River Basin

PC — **Powder Column**: Portion of borehole filled with explosive – equal to face height minus stemming plus subdrill

PF — **Powder Factor**: A ratio expressing quantity of explosive used to quantity of material blasted that is usually expressed in lb/cyd or kg/m^3 for terms of volume, or lb/ton and kg/tonne for terms of weight.

PRB — **Powder River Basin**: Mining area in Northeast Wyoming and Southern Montana known for thick coal beds and uranium, along with oil and gas deposits

S — **Spacing**: Perpendicular to burden – usually measured parallel to dig face – defines other sides of surface area

SA — **Surface Area**: Defined as the surface area of borehole influence – the area defined by burden times spacing

St — **Stemming**: Length of borehole filled with inert material to contain explosive energy when blast is fired

Su — **Subdrilling**: Length of borehole drilled below grade into next bench to help break the bottom of the target bench

1. INTRODUCTION

1.1. PROBLEM STATEMENT

Over the past fifty years the current mode of large-scale strip mining has been developed in the Powder River Basin (PRB) – a method dependent on the flexibility of large electric rope shovels to move between prestrip operations for draglines and full truck/shovel stripping pits. These large electric rope shovels can move well over 100,000 cubic yards of material in 24 hours, and some machines can reputedly approach 35-40 million cubic yards per year of material moved. Electric rope shovels can operate in a variety of conditions due to their relatively light weight compared to draglines and stripping shovels, and have greatly increased mobility when compared to these larger pieces of excavating equipment. Despite walking speeds of only a few miles per hour, an electric rope shovel can move from bench to bench or across the mine from one pit to another in a matter of hours. This increased mobility significantly improves operational flexibility for capital expended when compared to a dragline. Although an interesting hybrid method of cast blasting and production dozing with rope shovel excavation has been developed in recent years, the great majority of electric rope shovels usually dig shorter benches where cast blasting and production dozing are not practical.

Blasting is a part of large surface coal mine (LSCM) operations, and is scheduled based on production requirements. With dragline pits, equipment size and operating parameters allow engineers to use tall benches and methods like cast blasting or production dozing to assist with moving blasted material. Blast planning and design follows a measured pace because the dragline is committed to a particular cut in a specific pit until the coal is uncovered and work on the next cut begins – there is a rigidity of scheduling with draglines that contrasts the fluidity of electric rope shovels. The use of electric rope shovels alongside or instead of draglines has created a paradigm shift in blast planning, since the efficiency of large surface coal mines depend on well-blasted material that can be easily dug without slowing down the mining process.

The increased flexibility in excavation has presented a major challenge to LSCM operators: Accurate production scheduling is critical to fully utilize all equipment on the mine site. Fortunately, improvements in mine scheduling software have enabled engineers to provide highly detailed plans complete with alternate schedules for investigating multiple scenarios in order to provide the best plan of action for mine operators. Software packages such as XACT (Runge Pincock Minarco, 2015) allow integration of many mine operations and with reasonable care, accurate projections of materials moved and tons shipped.

However, even with increased accuracy and versatility of production scheduling, physical challenges still intervene. Many LSCM operations are sprawled out over many square miles of area, requiring considerable time to transit between operating pits.

When investigating new processes or planning new methods, designers look for critical paths – the path most likely to cause problems and delay the desired result. If one uses a practiced eye view LSCM operations, the critical path that most often presents a bottleneck to production is the Drill and Blast (D&B) group.

The D&B group create a production bottleneck because their job requires time and preparation. The typical process for preparing a bench for mining is as follows:

1. D&B Lead personnel drive out and view the bench to see if the bench is flat and smooth enough for drills to safely operate

2. D&B Lead checks with Engineering to see if a pattern design for the next bench can be completed and provided to the drillers –*repeat as necessary*
3. D&B Lead contacts Pit Lead to ask for pit equipment to build drill grade (clear the area if necessary) and build berms to demarcate the area for the next blast – *repeat as necessary*
4. D&B Lead checks to see if Pit Lead's personnel has completed the drill grade – *if not complete, return to Point 3*
5. If a drill is available, D&B Lead makes arrangements to haul to drill to the new drill grade
6. If drill is successfully hauled to new drill grade, and pattern design is complete, next available driller drills the pattern – *if not complete, return to Point 2 or Point 5 as appropriate, or repeat as necessary*
7. D&B Lead sends shot crew to newly drilled pattern to load and shoot
8. New bench is shot, and is available for mining when the shovel arrives

This process is slightly simplified compared to actual field practices, but the length of the process required for each bench immediately illustrates several locations where scheduling difficulties can drastically slow the process. One problem area often encountered concerns Point 3: Many times all available dozers will be busy in another part of the mine, perhaps production dozing in a dragline pit, or assisting a shovel, or working on a dump pushing down loads of waste material. Another critical bottleneck occurs at Point 5: Often, there is no available way to haul a drill across the mine. Usually, a lowboy trailer (TowHaul Corporation, 2012) can be used to haul drills or dozers across the mine site to minimize unnecessary wear on drill tracks and undercarriages, but occasionally the lowboy is busy or broken down. When the lowboy is unavailable, the time required to move a drill across the mine is significantly increased.

Often, several days are required to complete the first steps of the process to prepare the area for drilling, and then several days may be required to drill and shoot the bench. This time scale is difficult to condense, and easy to exacerbate by changing the production schedule for the mine. The critical path for a successful bench blast includes:

1. Timely notification of plan changes
2. Cooperation between groups for bench preparation
3. Prompt drill moves
4. Pattern designs complete and available when needed
5. Teamwork within the D&B group to safely and successfully drill and blast the bench

These five steps present constant challenges to the D&B Lead. The D&B group is the tip of the whip for mine production, and must constantly stay a step ahead of the rest of the site.

The above paragraphs outline current processes for bench blasting based on present-day mining practices. If we were to consider mine plans fifty years ago before the introduction of inexpensive calculators (let alone personal computers and software like Excel), the plans would have been much less fluid and much more rigid. D&B teams would have had plenty of time to adjust to a plan and prepare for its execution. Additionally, the scale of mining equipment was quite different fifty years ago. Ash includes a chart (Ash, 1968) showing the relative sizes of standard loading shovels (the forerunners of today's larger electric rope shovels), showing bucket sizes between three and twelve cubic yards. Today's electric rope shovels have buckets sized in the sixty and seventy cubic yard range (Orlemann, 2003). Changes in scale of equipment and speed of production scheduling have brought about a multi-dimensional shift in the planning process for D&B teams at LSCM operations. Therefore, the problem is that while equipment scale and pace of planning have drastically changed in the past fifty years, blast design has not. The last major growth in blast design methods in the United States occurred thirty to fifty years ago, and the growth spurt in design practices was aimed at quarries, not high-volume large diameter bench blasting. Work done by Richard Ash and Calvin Konya set the standard for today's scientific bench blast design practices, and the majority of this work was completed at or before the dawn of the modern personal computing era. Recently, the explosives engineering community has largely occupied themselves with applying technology to subsets of the design problem – how to improve or measure fragmentation (M. Monjezi, 2009), how to use technologically advanced methods to design blasts (Y. Azimi, 2010) (P.D. Katsabani, 2005), the public's perception of mining (Hoffman, 2013), etc. Explosives research for surface coal mining has essentially ignored bench blasting; the industry has not notably recognized the fundamental differences in scale and operational tempo that separate LSCM bench blasting from regular quarry-scale bench blasting. This research seeks to examine the differences between LSCM bench blasting and regular quarry-scale bench blasting to determine how to improve current LSCM practices.

Large surface coal mining operations are economically viable due to the large volumes mined and shipped every year. Relatively low profit margins dictate that to increase profits, either total output must be increased or costs must be cut. Maintaining profitable production is difficult, and incremental savings represent huge benefits to the operation as a whole. Many companies foster Business Improvement groups whose sole purpose is to determine safer and more efficient ways to do business. LSCM operators are generally technologically advanced, and open to new technologies to improve their businesses, as evidenced by the development of radio dispatching (Modular Mining Systems, 2015) and GPS tracking of equipment (Caterpillar, 2014) (Caterpillar, 2014). Essentially, to survive as a LSCM operator, companies must be willing to continually re-examine their business methods to improve their safety and profitability.

1.2. DESIGN METHODS IN LIGHT OF ENGINEERS

It has been said that there are two main modes of mining (Worsey, 2012) – in good times (or market expansions), total tons mined is the goal, with cost control second. In bad times (market contractions), cost control is critical, and production is driven by the company's market share and ability to absorb lower revenues.

This author's personal experience in the PRB confirms the above statement, and adds the following challenges: Within the engineering group, good times often mean additional staff positions, and reasonably detailed plans – any good plan will deliver adequate profits. When markets contract, the engineering group may lose positions through layoffs or attrition, and many highly detailed plans are required to enable management to determine the best route to carry the company through the difficult time. Therefore, during market contractions the engineering group is doing more work in greater detail in less time with fewer people. In the hurry to complete multiple long- and mid-range plans for mine management, group focus on short-term detail is often lost. Thus develops a paradox in mining: At the times when immediate cost control is most critical, the engineering group is least likely to have the time to focus on immediate cost control.

1.3. SCALE CHANGES

Bench blasting is a common form of blasting in the world (Gustafsson, 1973), and has been in use in surface coal mining for many years. The primary difference between historic bench blasting and LSCM bench blasting is scale. The following chart, Figure 1.1, shows surface coal mining statistics in Wyoming from 1960-2013 (Wyoming State Geological Survey, 2014). In the fifty-three years shown on the graph, one can see that the tons shipped increased in a nearly-continuous fashion until 2008, when the recent recession drove down demand.

The increase in scale is notable, but the other line on the graph – number of employees – tells a second story. From 1960 until roughly 1980, number of employees increased in a significant fashion, paralleling the increase in production. In 1980, a major shift occurs. Production continues to climb with only minor downturns, but number of employees drops from a little over six thousand to below five thousand over a five or six year period.

The great majority of mine employees in the Powder River Basin are either pit or maintenance personnel. Most people at the mines are actively employed in moving material or keeping equipment moving; whether that equipment is shovels, haul trucks, or conveyor belts. Therefore, when viewing a trend in mine employees, the line is likely to correspond closely with haul truck drivers and mechanics and is unlikely to represent an increase in office personnel.

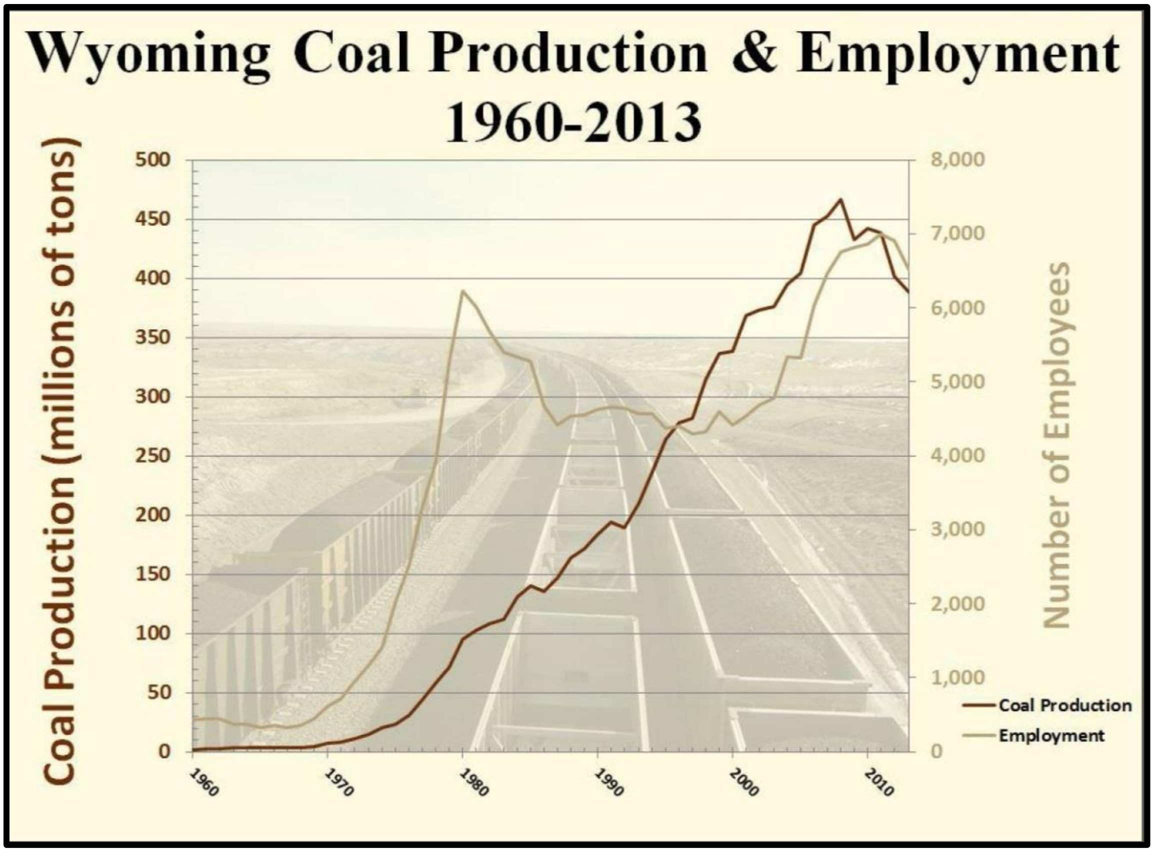


Figure 1.1: Wyoming Coal Production & Employment 1960-2013 (WYGS)

Over the time period represented in the graph, office personnel numbers are even less likely to have increased due to the improved efficiency brought about by technology such as personal computers, printer/copier machines, spreadsheet software, and digital drafting software.

An important fact about surface coal mining is that mining always starts at the lowest strip ratio available – meaning that to maximize profits, companies will start mining where the cost per ton is lowest, which coincides with areas where less dirt is above the coal. The net present value of deposits will push mining companies to mine from low strip ratio to higher strip ratio coal. An internet based spreadsheet maintained by the Wyoming Geological Survey shows coal production statistics for the Powder River Basin over the past three years (Wyoming Geological Survey, 2014), and the author used data from this spreadsheet to create Table 1.1. Average strip ratios today for the southern Powder River Basin range from 2.5 to 4.8 tons per cubic yard, and the application of mining principles and geologic maps indicates that strip ratios were lower than today's values when mining started in the Powder River Basin.

As a general rule for surface coal mining, strip ratio always increases as shallower coal deposits are mined out. When we combine this underlying principle with the production and employee curves shown in Figure 1.1, we see an interesting relationship.

Figure 1.1 shows coal tons produced, not total material (overburden cubic yards plus coal tons) moved. Therefore, it is reasonable to estimate that the overall units of material moved climbed on a steeper curve due to increasing volumes of overburden for the same coal production. These increasing quantities make the period from about 1980 to 2002 or 2003 remarkable. This area of the graph is a time where scale of equipment is growing. Prior to 1980, equipment size was relatively constant, as increases in production required more and more employees to operate more and more equipment of similar sizes to move more and more material. The period from 1980 to roughly 2002 shows a plateau in the quantity of employees, while material moved over that time period continues to increase.

Table 1.1: Strip Ratio Statistics for Wyoming's Powder River Basin

Strip Ratio Statistics for Wyoming's Powder River Basin (WYGS)					
Mining Area	Mine Name	Reported Strip Ratio [Bank CYD/Ton]	Average Strip Ratio	2013 Tons	Percentage of 2013 Tons by Mining Area
North POD Mining District	Buckskin	2.4 to 2.8	2.6	15,023,906	25.5%
	Dry Fork	1.8	1.8	5,433,936	9.2%
	Eagle Butte	2.9	2.9	19,904,433	33.8%
	Rawhide	1.6	1.6	14,246,329	24.2%
	Wyodak	1:1 to 2:1	1.5	4,285,445	7.3%
	Total	*2013 Wtd. Avg:*	*2.31*	**58,894,049**	**100.00%**
Middle Pod Mining District PRB	Belle Ayr	4.2	4.2	18,258,922	25.2%
	Caballo	4.2	4.2	8,979,111	12.4%
	Coal Creek	None reported, used average of other Mid PRB mines	4.0	8,522,265	11.8%
	Cordero Rojo	3.7	3.7	36,670,450	50.6%
	Total	*2013 Wtd. Avg:*	*3.93*	**72,430,748**	**100.00%**
South POD Mining District	Antelope	4.6:1 , 5:1	4.8	31,354,248	12.9%
	Black Thunder	4.2	4.2	100,687,876	41.4%
	NARM	3:1 to 2:1	2.5	111,005,549	45.7%
	Total	*2013 Wtd. Avg:*	*3.50*	**243,047,673**	**100.00%**
Grand Totals		*2013 Wtd. Avg:*	*3.40*	374,372,470	

Shovels, haul trucks, and support equipment are getting larger, and production continues to increase with a relatively constant pool of employees. Beginning around the year 2000, another change begins – equipment size is no longer growing, and employee counts are increasing. By the middle of the first decade in the 21st century, employee numbers met and passed the previous peak in employees experienced nearly thirty years before. The period from about 2000 to 2008 shows increase in production with a much smaller increase in equipment size. It is also likely that this period also indicates increased use of technology by mine operators, leading to more efficient operations with equipment of similar size, but this possibility could be difficult to prove, and lies outside the scope of this research. 2008 shows the turning point for production – as an intern in the PRB at the time the author noted a general feeling of discomfort when viewing the future. The bright times of the past were disappearing, and employees were not sure that the situation would improve.

As a truck/shovel engineer starting in the PRB in May of 2011, the author witnessed firsthand the part of the curve where employees outpaced production. This time period was characterized with employee layoffs and attempts to keep employees busy by cutting back on overtime hours and working on projects not directly related to coal production.

The Wyoming Geological Survey chart captures Powder River Basin mine operations at a glance, and illustrates the changes that have created the area of this research. Changes in equipment scale and quantity of production since 1980 have left D&B groups with a drastically different work environment than was found when Ash and Konya did the bulk of their research, and recent regulatory developments regarding emissions from coal-fired power plants (United States Environmental Protection Agency, 2014) – the primary customer of LSCM operations – makes the operating efficiency of LSCM operations all the more critical.

1.4. CURRENT BLAST DESIGN PRACTICES

Bench blasting is fairly straightforward – large rectangular volumes of material have holes drilled and filled with explosives which are then detonated, breaking the material for digging. Every blast has a few recognizable features and dimensions, as shown in Figure 1.2, regardless of where the blast takes place. The challenge of creating successful blast designs is not which dimensions are used, but how the designer determines the magnitude of those dimensions.

Usually, bench blasting at a specific site is done with some variation on a standard pattern. Standard patterns are exactly what they appear to be – a set of dimensions used everywhere for the same purpose. In the southern PRB, an example of a standard pattern would use a 30’ burden and 32’ spacing. Drillers are given a pattern and a target elevation, and will drill whatever depth is required to reach the target elevation for the next lower bench.

Standard patterns work well where conditions meet the original design criteria. However, in truck/shovel operations, the actual floor grade is often five to fifteen feet

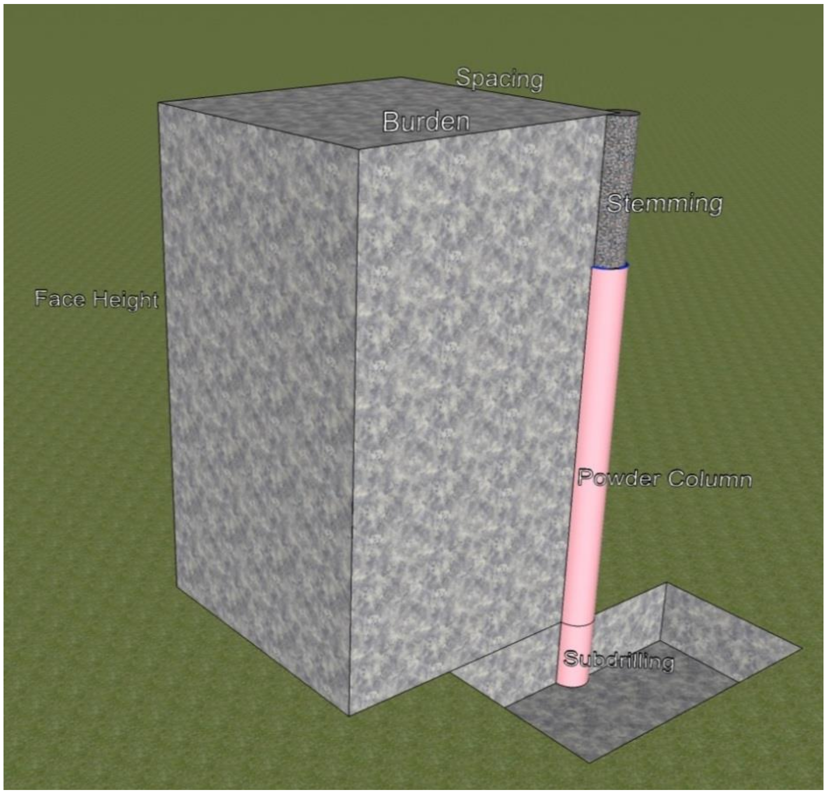


Figure 1.2: Standard Dimensions of Blast Design

above or below the design floor grade due to strata of varying hardness or inattentive shovel operators. This variation in elevation combined with an average planned bench height of fifty to sixty-five feet leads to large swings in overall drilling depth and proportionally large changes in powder factor. These changes are not immediately a problem for pit operations if shot results do not hinder overall production, but problems arise when variations in powder factor make cost control difficult. A bright engineer could design individual patterns using existing major methods of blast design to maintain a fixed powder factor across shots of variable depth by repeated use of existing traditional design processes. However, such complex designs are unlikely to be completed in good times due to the quantity of time required for each pattern design, and will almost certainly not be completed during market contractions. Since cost control is essential during market contractions, it is vitally important that shots be designed to maintain powder factor within acceptable ranges. If the engineering staff is already over-utilized someone else must monitor bench blasts to maintain budgeted powder factors, and it is reasonable that those people should be drillers and/or blasters in the field. These employees will be most familiar with the challenges and applications of blasting at any specific site and would be most suited to control their own work.

In the southern PRB, it is common for mine operators to use average powder factors to project budgets for future years. If the D&B team has averaged a 0.5 lb/cyd powder factor for all prestrip shots this year, and the budget calls for six million yards of prestrip next year, the budget will include three million pounds of explosives for prestrip shots. However, despite the use of powder factor to project costs and quantities for future mining practices; powder factor is not a part of the design process for bench blasting.

This dichotomy adds an additional complication: maintaining an average powder factor that matches budgetary requirements while powder factor is not an integral part of the design of blasts.

For LSCM bench blasting where face height is the dimension with the largest variability, powder factor and the efficiency of borehole use (which will be called the Efficiency Index for this research - defined as the percentage of the borehole filled with explosive) are proportional when stemming is held constant. The efficiency index is a useful indicator – how much of the borehole is being used for productive work? Figure 1.3 shows the effects of increasing face height for a common LSCM bench blast scenario. As face height increases, so does powder factor and the efficiency index.

A five to fifteen foot swing in face height can create large changes in powder factor and efficiency index for individual shots; and over time similar incremental changes can have large impacts on budgets. It should be noted that in graphical form, the Efficiency Index will often be represented as %/100 – the decimal value being easier to show on a graph. In the case of Figure 1.3, the efficiency index ranges from about 43% to roughly 73.5%.

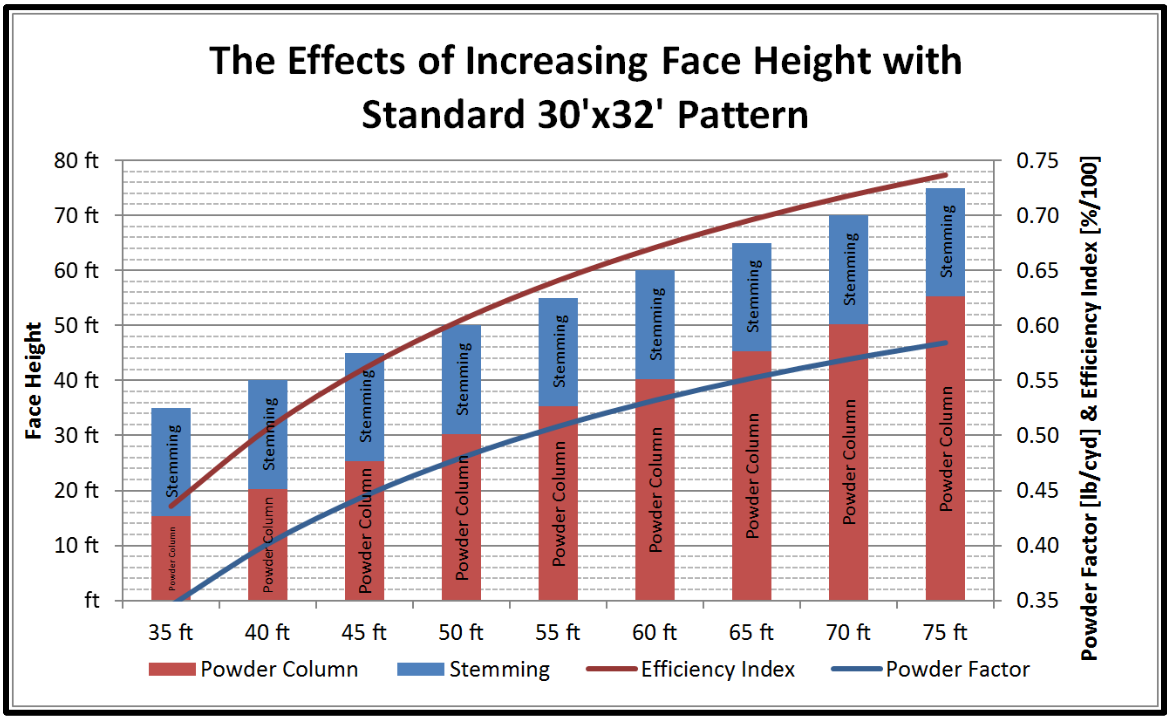


Figure 1.3: The Effects of Increasing Face Height

The decimal value was used in order to display the values in an easily readable format, and the mental arithmetic required to convert a decimal value to a percentage is trivial.

These factors gave this author a unique opportunity to add to the field of blasting knowledge by examining bench blasting at LSCM operations and to codify a design philosophy for their specific needs. Basing the new method of blast design on powder factor will help bridge the gap between design and budgeting. Integration of field capabilities and requirements in the design process will help create a broadly usable method, and careful testing and examination of the new method will enable tool development and suggestions towards field implementation.

1.5. PROBLEM STATEMENT

This research addresses a fundamental question: should the industry change the way it looks at bench blasting for Large Surface Coal Mines? Large scale mining in Wyoming consumed 870,000 metric tons of blasting agents in 2012, more than twice as much explosive quantity as any other state – West Virginia was second with 324,000 metric tons of blasting agents (Apodaca, 2014). This colossal scale of explosive consumption indicates many millions of cubic yards of material are moved per annum in the process of mining coal. Increasing strip ratios dictate that the use of bench blasting will only increase over time as the greater depth to coal deposits limits the ability of dragline methods, requiring continual and increasing prestrip volumes to be moved in benches. An efficient and effective blast design method tailored for LSCM bench blasting applications will prove more useful in the future than it does today.

The industry should change the way that bench blasting at LSCM operations is approached, and the following dissertation illustrates a novel improved method of blast design specifically for LSCM bench blasting operations.

2. LITERATURE REVIEW

2.1. BENCH BLASTING RESEARCH

Bench blasting is one of the most common ways to use explosives to break rock (Gustafsson, 1973). As such, many researchers have created their own preferred sets of equations to calculate the linear parameters of blast design such as burden, spacing, stemming, and subdrilling. Research into published methods of blast design has displayed a large number of equations for burden, where remaining dimensions are typically based on relationships with burden. Also, a few key blast design methods were repeatedly mentioned and occasionally directly quoted in many publications. These key blast design methods were work done by Langefors and Kihlstrom (Langefors & Kihlstrom, 1963), Ash (Ash, 1968), and Konya (Konya C. J., 1995) (Konya & Walter, 1991). These three published methods have been shown to be existing major methods (EMM) of traditional blast design.

2.1.1. Existing Major Methods of Traditional Blast Design. Existing major methods all begin with some known quantities and assumed relationships, then work toward the basic parameters of blast design. The early methods were created as a way to quantify how to successfully use explosives in their most common applications at the time (Worsey, 2012).

2.1.1.1. Langefors and Kihlstrom. Langefors and Kihlstrom (Langefors & Kihlstrom, 1963) advocated using a higher density explosive as a toe load in the bottom of the borehole; switching to a lighter density product for the remainder of the explosive column. This practice grew out of the knowledge that the toe of the hole is the most difficult portion to break effectively. Langefors and Kihlstrom were also proponents of angled boreholes, which improve the efficiency index by increasing borehole length within the bench while maintaining constant stemming length – lowering the total number of boreholes required for the shot. Fewer total boreholes becomes an important consideration when the majority of rock is granite or other difficult to drill material similar to the geology of Langefors and Kihlstrom's Scandinavian homeland. Unfortunately, the practice of toe loading is time consuming and requires greater attention to detail. This level of care may be worthwhile on construction projects or in urban quarries, but it is highly unlikely that differing product densities would intentionally be used within the same borehole in today's LSCM operations due to the risk of greatly exceeding scaled distance requirements through loader inattention. Likewise, while angled drilling would increase borehole efficiency of use, due to the geologic strata common in the Powder River Basin angled drilling would often result in losing boreholes or more difficult loading conditions for a typical bench blast. When dealing with comparatively short truck shovel benches, the added complexity of angled holes is not welcome. While working in the Powder River Basin, this author tried on multiple occasions to get the D&B group to use angled holes in an attempt to improve breakage, and on every occasion, the D&B group declined. As a final note, in some cases the site may only have one or two drills capable of drilling angled holes with those drills dedicated to full time drilling for cast blasts in dragline pits.

2.1.1.2. Richard Ash. Ash's work (Ash, 1968) led to an ingenious equation that weights explosive density against the rock density to arrive at what Ash called a "Burden Factor" which is then scaled by the diameter of explosives in the borehole to calculate burden.

$$K_B = \left(30 * \left(\frac{SG_E}{1.4}\right)^{1/3} * \left(\frac{160}{WT_{RK}}\right)^{1/3}\right) \quad \text{Eqn 2.1}$$

In the above equation, SG_E signifies the specific gravity of the explosive, WT_{RK} is the unit weight of rock in lb/cubic foot, , and K_B is the burden factor which is later multiplied by the explosive diameter in inches and divided by twelve to calculate burden. Ash's burden factor equation ensures that the overall burden is the result of a good match between explosive product and rock. His work is still taught today, and is an excellent method of design. However, Ash was not fond of powder factor as a component of design (Ash, 1968) and his work is derived from small quarries in the northern portion of the Midwest. Ash's method delivers great control of burden at the cost of some additional work in determining the unit weight of rock in its native state. It is unlikely that an effort to measure the unit weight of rock would be continued at a large surface coal mine, and the added control delivered by Ash's method would be of questionable utility at a site where nearest neighbors are measured in miles. Ash recommends stemming lengths from 0.7-1.0 times burden, spacing from 1.2-1.4 times burden, and subdrilling of 0.3 times burden. Ash recommended face heights that were a factor of equipment cutting height, swell factor, and a modifier for the type of cut, whether a well-confined box cut or more open corner cut. This recommendation seems to be more in line with surface mining best practices than blast design recommendations, and do not tie face height to the design process in any way. Ash's method can be considered a "greenfield" development. Just as a greenfield operation is new development on a previously undeveloped property Ash's method is intended to be used on a wide range of sites for initial blasting practices, rather than adapted to existing practices. The work created a broadly useful blast design method, one that can be used for a wide variety of explosive types, rock types, and borehole diameters as evidenced by the variables in Ash's burden factor equation.

2.1.1.3. Calvin Konya. Konya (Konya & Walter, 1991) is focused largely on quarrying and fragmentation work as evidenced by his focus on flexural rupture and his blasting seminars that are still being taught through the Academy for Explosives and Blasting Technology (Konya C. , 2015). His design method appears to be an extension of Ash's work with energy distribution, using a ratio of explosive and rock specific gravities. Konya recommends 0.7 x Burden for stemming if using crushed rock, 1.0 x Burden if using drill cuttings, and 0.3 x Burden for subdrill; all of which conform closely to Ash's recommendations for the same parameters.

$$B = \left(\frac{2SG_E}{SG_R} + 1.5\right) * D_E \qquad \text{Eqn 2.2}$$

Konya is much more specific than Ash with respect to face height by making recommendations based on a relationship known as stiffness ratio. The stiffness ratio is the face height divided by the burden, and Konya discusses recommended ratios, with the optimal stiffness ratio being around 4. Konya's spacing guidelines go a step further than Ash by providing multiple spacing equations that are dependent on the face height of the shot. Konya's work extends into volumetric concepts much further than Ash's work, and it is expected that this extension is at least partially due to increased availability of inexpensive processing power to solve more complex equations. Konya is also focused on delivering a "greenfield" style method, suitable for initial use at a wide range of sites.

2.1.2. Table of Researched Methods. Others have written about blast design methods, but many refer directly to one of the above authors, and as such, Langefors and Kihlstrom, Ash, and Konya constitute the Existing Major Methods (EMM) of blast design that best represent the industry standard design philosophy for bench blasting. Often when researching a topic one does not look for what is present; rather, what is absent tells the researcher much about the body of knowledge on that particular topic. In this light, the body of literature surrounding bench blast design was reviewed with a few key filters:

- Was the bench blasting design method targeted at LSCM operations?
- Were rows used in the design method, or was the design based on individual boreholes?
- Was the bench blasting design method a powder factor based method?
- What was the author's opinion of powder factor as design criteria?
- What (if any) existing major method of blast design did the author prefer or present as part of the research?

These key filters were chosen based on the scope of the research presented in this dissertation to ensure that the research is novel and unique in its field. While companies may have unpublished in-house methods of powder factor based design, to date, no major method of powder factor based blast design for large scale surface coal mines has been circulated within the industry. A survey of readily-obtainable blast design literature from a variety of print and electronic sources has delivered the information used in Tables 2.1 and 2.2 on the following pages.

The authors in Tables 2.1 and 2.2 represent many different approaches to blast design, with a broad range of geographic backgrounds and different types of mining.

2.2. DATA ANALYSIS

For the comparison testing conducted in this research, it was necessary to develop a tool to gauge the how well one set of data matches another. There is a staggering array of statistical methods designed to analyze complex data sets. This author prefers simple solutions where possible, and has developed a percentage graph and utilized some linear regression techniques based on personal experience and a discussion with Dr. V. A. Samaranayake of the Department of Mathematics and Statistics at the Missouri University of Science and Technology (Samaranayake, 2015).

Linear regression is the process determining whether data fits a certain trend expressed by an equation. Data are plotted on a two dimensional graph, and a trendline is drawn through the data to approximate the plotted data. How well the equation described by the trendline matches the plotted data can be determined by a number of methods, with one of the earliest techniques being the method of least squares (Abdi, 2006).
The method of least squares is a technique for measuring the accuracy of a equation describing a data set. This method introduces a value known as R^2– a term that essentially describes the quality of an equation's fit to plotted data. R^2 is often defined as as 1-SSE/SST. SSE is calculated by subtracting predicted data from measured data, squaring this value, and summing the squares. SST is calculated by subtracting the mean

Table 2.1: Blast Design References

Author	Bench Blasting Design Method Targeted at LSCM Operations	Row Design Method	Powder Factor Method	Opinion of Powder Factor Design	Preferred Existing Major Method	Notes
(Singh & Pal Roy, 1993)	No	No	No	Used as output – personal opinion not apparent	Ash, Langefors & Kihlstrom	• Much discussion of ground vibration with a lot of references to Langefors and Kihlstrom • Use a computerized blasting program • Does not emphasize powder factor for budgets
(Sinclair, 1969)	No	No	Yes	Just a ratio	None listed	• Discusses stripping shovels – quite different mining era from today's mining environment • Discusses equipment size – big trucks at the time are smaller trucks today • Uses a very simplistic design method • Does not mention stemming as part of design.
Explosives & Rock Blasting (Morhard, 1987)	No	No	No	Prefers Energy Factor	Ash, some Langefors & Kihlstrom	• Emphasize the value of toe loading with different explosive product except in a few types of operations
(Gustafsson, 1973)	No	No	No	Likes "Specific Charge" for design, uses as criteria, not input	Langefors & Kihlstrom	• States that bench blasting is most usual style of blasting • Uses toe loading practices as well
(Jimeno, Jimeno, & Carcedo, 1995)	No	No	No	Not better for design unless qualified by powder distrbution	Konya, with some Ash	• Presents lots of methods for calculating burden • Believes burden to be most critical dimension • Authors view classic equations as starting point for site adaptation • List what they call "most complete formulas" and state that a global study is not workable on Pgs. 199-200
ISEE Blaster's Handbook (Engineers, 1998) (Stiehr, 2011)	No	No	No	Not mentioned – Powder factor is barely mentioned in 17th ed.	None given in 17th Ed. Konya referenced in 18th Ed.	• P. 337: "Explosives distribution is generally the most important factor, other than preexisting joints, in determining fragmentation." - For LSCM operations, "diggability" can replace "fragementation". • P. 341: "Blasting methods and patterns in surface coal mining are essentially like those used for quarrying and open pit mining."
(Pavetto, 1990)	No	No	Yes	PF based design method totally ignores stemming	Ash	• Uses a version of Ash's equations for conventional blast design • Uses straight powder factor to find a volume then calculates the required explosive – does not talk about the challenges of stemming with powder factor based design.
(Pugliese, 1972)	No	No	No	Not apparent	Ash	• Appears to be field studies based entirely on Ash's design philosophy
(Dick, Fletcher, & D'Andrea, 1983)	No	No	No	States "not the best tool for designing blasts"	Ash	• "Blast design is not a precise science […]it is impossible to set down a series of equations which will enable the blaster to design the ideal blast without some field testing"
(Neale, 2010)	Not definitively – Used for LSCM in this application	No	Yes	Not apparent	None – uses method taught at U. of Pretoria in 2008	• Paper focuses on blast optimization, using a powder factor based design method referenced to an E. M. Thompson • Determines burden with set of ratios similar to Ash and others, using powder factor to determine overall volume per hole.

Table 2.1: Blast Design References, Continued

Author	Bench Blasting Design Method Targeted at LSCM Operations	Row Design Method	Powder Factor Method	Opinion of Powder Factor Design	Preferred Existing Major Method	Notes
(Ludwiczak, 2002)	No	No	Yes	Uses Powder Factor for a "Quarry Method" of design	Density Ratio method influenced by Ash and Konya	• States most common method of production blasting is bench blasting (p. 72) • Quarry method is a powder factor design method that ties stemming to borehole diameter with one foot of stemming per inch of borehole diameter. • There is no apparent check to determine whether the actual powder factor meets the targeted goals – no discussion of iteration.
(Gokhale, 2011)	Not solely, uses standard design methods	No	No	"First […] is to choose […] explosive […] powder factor" (p. 603)	Includes Langefors & Kihlstrom Konya and Walters and Ash.	• Book is aimed at large surface mines, but design methods are not specifically developed solely for large scale surface mines • Believes "The most important parameter in blast design in the burden" (p. 621) • Has a number of small nomographs for burden and spacing, and some ingenious cast blasting nomographs by D'Appolonia Consulting Engineers
(Hustrulid, 1999)	Not specifically for LSCM	No	Extends Ash's method: PF as design criteria	Not clearly stated, uses PF as a criteria in design	Mentions Langefors & Kihlstrom Uses Ash	• Contains many detailed derivational steps for Ash's formulas; uses Ash's methodology, works through several examples • Ties relationship factors to the burden •
(Pits and Quarries, TM 5-332, 1967)	No	No	No	Not mentioned	Ash	• Burden equations attributed directly to Ash • Includes basic nomographs to begin calculation processes • Army Technical Manual – presents a good method in simple terms for use in the field.
(Konya C. J., 1995) (Konya & Walter, 1991)	No	No	No	Does not appear to favor PF as design criteria	Burden equation appears to be an extension of Ash	• Defines burden as shortest distance to relief when hole detonates • States that of all design dimensions, burden is most critical • In talking about fragmentation, shows examples of different face configurations and states that powder factor is not constant throughout a shot.
(Ash, 1968)	No	No	No	Does not think PF is "normally a sound index for design" (P. 395)	N/A	• Talks about increasing borehole utilization also increasing powder factor – instead of adjusting pattern states that deck loading is used for deep holes • "The only practical value of the PF is for costing, since explosives are sold by weight" (P. 396)
(Kihlstrom & Langefors, 1978)]	No	No, some tables of parameters for multi-row design, but no apparent complete method presented.	No	Not clearly stated	N/A	• Lots of more detailed mathematical derivations than is common for blasting books • Mentions subdrill as proportional to square root of surface area of borehole influence at top of P.82 – not much discussion of why that particular relationship is used for that particular application • Also ties subdrill to burden on P.71 when discussing single row bench blasting • Contains a large table for variables used throughout book – despite having more than 60 variables, not one is labeled "stemming"

of the observed data from the individual observed data, squaring that entity, and summing the squares. This process is shown as Equation 2.1.

$$R^2 = \left(\frac{\sum_1^n (measured\ data - predicted\ data)^2}{\sum_1^n (measured\ data - mean\ of\ measured\ data)^2}\right) \quad \text{Eqn 2.3}$$

If the plotted (measured) data match the predicted (trendline) data perfectly, the R^2 value will equal 1. R^2 values can be thought of as percentages – a perfect match is 100% (equal to 1), and varying errors lower the R^2 value.

This research will use Microsoft Excel for data analysis and generating graphs to gauge the accuracy of the data match. Excel includes tools for adding trendlines to plotted data and will display the trendline equations and R^2 values directly on the graph of data (Microsoft, 2014).

2.3. NOMOGRAPHY

2.3.1. Overarching Goals of Nomography. Nomography was developed near the end of the 19th century by Philbert d'Ocagne (Doerfler, 2009) as a way to graphically represent complex problems in a two-dimensional plane. Nomographs were popular in many engineering disciplines until personal calculators and computers replaced nomographs in many applications. The creation and use of slide rules can be considered a subset of nomography. Some of the additional benefits of nomography are as follows.

2.3.1.1. Complex mathematical problems represented simply. A primary benefit of nomographs is the simple representation of complex mathematical problems or design processes. A prime example of nomographs can be seen in the CAT Performance Handbook as Rimpull Speed Gradeability charts and charts describing dozer ripping conditions (Caterpillar Inc., 2012). Brilliant examples of nomographs can be discovered by viewing old literature on steam power (Ellenwood, 1917), textbooks on underground mine ventilation, and some modern fan company literature (Greenheck, 2015) (Hartzell, 2015) (Illinois Blower, Inc., 2011) (The New York Blower Company, 2014) – wet and dry bulb temperature charts are also available as nomographs (Troxel, 1937). In each of the above cases, nomographs allow the reader to solve complex problems by tracing lines across the page.

2.3.1.2. Enables broader use of knowledge. Another benefit of nomographs is that they can be used with limited to no understanding of the equations the nomographs represent. Individuals with minimal training in mathematics can trace out the correct answer on a nomograph regardless of the complexity of the formulas the nomograph represents. This fact is one of the reasons of the original popularity of nomographs, as engineers could create nomographs and allow non-technical staff members to use them for calculations. (Marasco, 2010)

2.3.1.3. Saves time in repeated calculations. In cases where iterative calculations are required, nomographs can speed up the process of accurately solving equations (Peddle, 1910). This is especially beneficial in locations where the use of computers and spreadsheet software is inadvisable. Examples of potential uses would include determining ramp length for varying grades over a given elevation change, or determining loading densities for various product densities with a given borehole diameter, as shown in Figure 2.1.

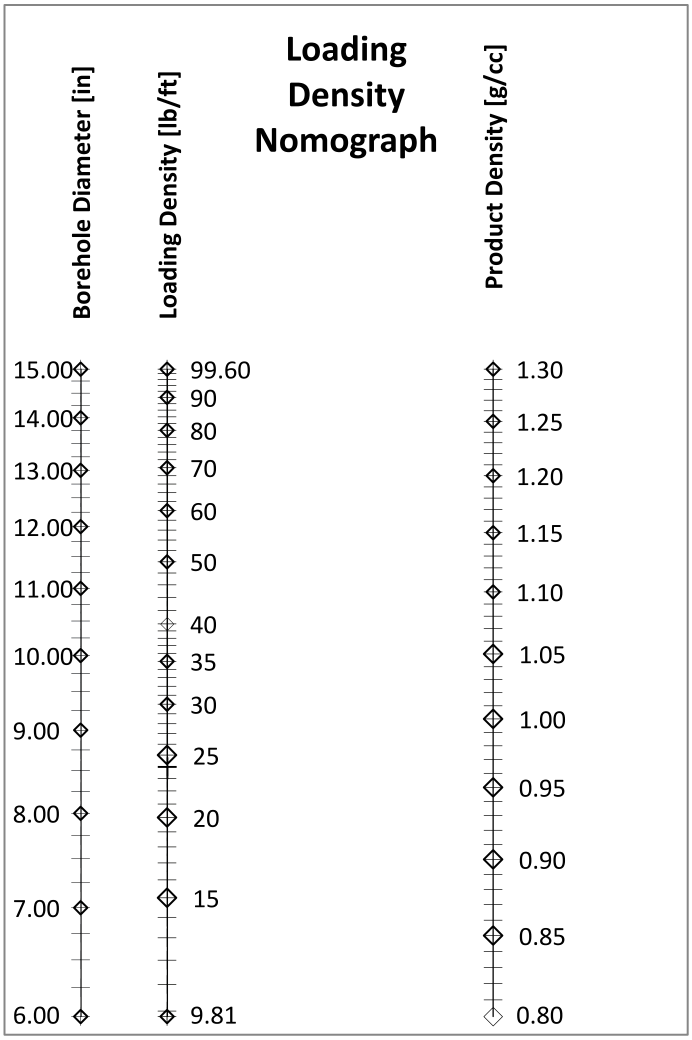


Figure 2.1: Loading Density Nomograph

2.3.1.4. Inexpensive replication. Scientific calculators or devices to run calculator applications and computers are typically expensive tools. These tools have varying levels of resistance (generally proportional to their purchase price) against drops from varying heights and resistance to dust and moisture. The typical size of a scientific calculator or handheld device makes them easy to lose or drop down a borehole on a blast pattern. These challenges: cost, susceptibility to environmental conditions, and ease of total loss make it difficult to justify increasing the use of handheld electronics on a wide basis for something as simple as a blast design. If a device is lost, replacement cost is often hundreds of dollars. In comparison, a well-designed nomograph can be printed on a standard sheet of paper and laminated to resist moisture for a few cents apiece. Inexpensive replication is a valuable benefit that can help make nomographs viable in today's technology rich world.

2.3.2. Table of Useful Authors. When studying nomography, several useful authors rise from the once-vibrant field of nomographic research. These authors are introduced in Table 2.3. Many more authors wrote papers and books concerning this field, and Google Books and Archive.Org contain several public domain examples.

Table 2.2: Useful Nomograph Authors

Author	Notes
Doerfler	• "Art of Nomography" (Doerfler, 2009) essay techniques used to create Figure 2.1 • Presents both matrix-based and non-matrix-based methods of nomography • See: Dead Reckonings blog: http://myreckonings.com/wordpress/ (Doerfler, 2015)
Doerfler,Marasco, and Roschier	• Written papers concerning the use of nomographs in medicine today • See: "Doc, What Are My Chances?" (Marasco, Doerfler, & Roschier, 2011)
Roschier	• Created the PyNomo software package in the Python programming language (Roschier, 2012) • PyNomo used for the non-Excel nomographs in this work • See: http://pynomo.org/wiki/index.php?title=Main_Page
Chung	• Maintains a web site with a subsection on nomography, aimed toward wargames (Chung Jr., 2008) • Presents several methods of nomograph creation • Reading list on website points toward several great authors • See: http://www.projectrho.com/nomogram/index.html
Mavis	• Covers matrix-based nomographs • See: The Construction of Nomographic Charts (Mavis, 1939)
Douglass and Adams	• Include a worksheet for consistent generation of nomographs • Work through many examples of nomography • See: Elements of Nomography (Douglass & Adams, 1947)
Ford	• Monograph on nomographs and alignment charts also covers custom slide rules • Excellent explanation of slide rule theory and use of logarithms • Explains concept that standard "slide rule" was devised as general purpose calculator rather than a problem-specific device • See: Alignment Charts (Ford, 1944)
Mowery	• Created a circular slide rule for averaging up to 20 grades that contain up to 100 points • No logarithms involved – just ratios of circumference • Best low-cost method the author has seen to date for averaging face heights • See: A Slide Rule for Averaging Grades or Experimental Data (Mowery Jr., 1951)

3. RESEARCH METHODS

3.1. DEFINITION OF SCOPE

This research is aimed at large surface coal mines like those found in Wyoming's Powder River Basin. Large scale high volume bench blasting is largely similar around the world, but in the interests of manageable research, this dissertation is limited to LSCM operations in the PRB. This geographical boundary brings about several other key limitations:

3.1.1. Geology. Geology in the PRB is largely similar – it is mostly highly weathered shales or limestones, with occasional compacted sand beds, with little cohesive strength and reasonable consistency across a mine site. The consistency of material across a mine site removes the need to include a geologic correction factor such as those included in Ash and Konya's methods if a design method is specifically created for LSCM surface mining.

3.1.2. Explosive Types and Strengths. Explosive use in the PRB is driven around safety, low cost, and reliability. These emphases dictate that bulk-loaded ANFO or emulsion-based products, initiated by cast boosters using non-electric or electronic blasting caps are the standard by which all others are judged. Typically, blasting will take place using either straight ANFO (industry shorthand for "ammonium nitrate and fuel oil"), an emulsion, or a blend of the two. Densities of these explosives typically range from 0.8-1.3 g/cc.

One item of interest that may not be widely understood is that the density of ammonium nitrate prill (the small pale spheres of ammonium nitrate – nearly identical to commercial fertilizer) is quite different from the published density of ANFO.

Ammonium nitrate prill is much denser than ANFO, due to the air space present between hemispherical prills in ANFO. This fact becomes important when calculating emulsion blend densities since blends replace the air voids with emulsions.

Different types of explosives may have varying strengths within certain density ranges. Many factors contribute to the output of explosives, including detonation pressure and detonation velocity (Cooper & Kurowski, 1996). These relationships are complex, and in some cases, influenced within the borehole based on water content and length of time waiting in the borehole. For the purposes of this research, explosive density will be considered the primary driver of explosive strength, as higher densities equate to more explosive product in a given length of borehole, and in fact explosive density is a factor in both detonation pressure and detonation velocity (Cooper, 1996). Based on the production methods of PRB mines, given densities of explosive will have extremely similar strengths due to marketplace competition and price points, and any strength differences within a density value are assumed to be negligible.

In summation, for the purposes of this research, explosive types will be confined to bulk loading ANFO, emulsions, and blends of the two, with densities consistent with common uses.

3.1.3. Borehole Diameters. Borehole diameters in the Powder River Basin are an interesting topic; diameters from around nine to twelve inches are common. Borehole diameter controls how much explosive is placed in any location, directly affecting the geometry of the pattern. From an economic point of view, larger boreholes are better. Larger boreholes mean fewer boreholes for given quantities of explosives which leads to lower labor and maintenance cost for the drill; fewer boreholes to load, and lower initiation costs. However, geometry is a key factor in blast design and performance, and as such, certain borehole diameters are widely used. For deep boreholes such as those employed for cast blasting, diameters around twelve inches are common. For deep boreholes, large explosive quantities are a goal, increased burden and spacing due to geometry does not present a problem, and the larger diameter adds stiffness to the drill string for more accuracy at greater depth. Shallower boreholes tend to use diameters closer to nine inches due to the geometry influencing mechanisms of breakage and a decreased need for drill string stiffness. PRB blasting often uses standard diameters employed in petroleum production, as the petroleum market ensures a supply of drilling consumables.

3.1.4. Cut Widths. Cut widths are based on design criteria and company philosophy. The single largest driver of minimum cut width is equipment size; too narrow a cut will not allow safe and productive operations. 190-200 feet is about the smallest cut likely to be used by large shovels and 240-340 ton haul trucks, while widths down to about 150 feet can be safely used where necessary. However, maximum cut widths are driven largely by production scheduling and strip ratio. In standard strip mining, operators will use the same cut width for overburden benches and coal benches. The wider the bench, the more material must be moved before coal is available to mine. Strip ratio affects this process during pit development. Initial pit development has a primary goal of mining coal and usually comes with a challenge of disposing of the material dug during pit development, since dump room in strip mining is inside the existing pit. These factors suggest the initial use of narrow cut widths; however, once a pit has reached steady state with existing benches and dumps on opposing sides of exposed coal, cut width is not influenced by strip ratio as long as consistent widths are taken from all benches and the coal. At this stage in mining, cut width is driven by production scheduling and company philosophy. Large volumes of material take longer to mine than small volumes, which means that for every cut progression, wider cut widths will mean greater times between uncovered coal. Larger widths mean uncovering larger quantities of coal, but the uncovered coal must last until the next cut is complete, or the pit will be empty. Dump room must also last until the coal is mined, creating a complicated cycle that can cause changes in cut width over time. Generally speaking, the wider the cut width, the more efficient the truck and shovel interaction can be in a cut, when considering power cable routing, lanes of traffic, and support equipment. This author has seen great success with cut widths of approximately 300 feet, and expects that the ideal cut width would be 300 feet or greater, while considering haul distance to the dumps and existing dump capacity. It is this author's expectation that much beyond 450 feet cut width would be too wide for steady state operations, with greatly increased haul distances from the shovel to the dump, greater risk of running out of dump room, and marginal operational benefit.

3.1.5. Bench Heights. Bench heights are varied by safety considerations, applicable regulations, pit design, and occasionally by nature. Bench heights of less than 35 feet are wasteful – on a P&H 4100 shovel, 35 feet is roughly the height of the saddle block (the pivot on which the dipper sticks traverse). Saddle block height is effectively the ideal height to have a full bucket, as this is approximately the bucket elevation a shovel operator would reach before being able to swing over the bed of a haul truck for loading purposes. On the opposite end of the scale, maximum planned bench heights did not exceed 65 feet at the author’s site, due to company policy of not digging above the point sheave (highest pulley on the shovel, at the tip of the boom) height of the shovel. In practice when a 65’ bench is shot, the material usually heaves anywhere from ten to twenty feet vertically, increasing the height of the bench past a safe digging height. Typically, benches were designed with a height of 55 feet to allow for some height increase while still maintaining a safe digging height. However, occasionally the designed bench height will not be practical due to material conditions – soft material may need to be dug out, or a hard layer near the bottom of the bench may not be broken well enough to be easily dug. These geological factors do nothing for existing blasting, but the varied floor elevations create problems for blasting lower benches.

3.1.6. Scope Summary. In short, for the purposes of this research, LSCM “bench blasting” indicates blasting using vertical boreholes of diameters between nine and thirteen inches, using explosive products of from 0.8-1.3 g/cc density in cuts from 150-500 feet wide and face heights of 35-65 feet.

3.2. RE-IMAGINING BLAST DESIGN

To reach the best solution for a problem, one must first closely examine the problem. Methods are the windows used to view underlying relationships. A basic knowledge of calculus makes much more sense of physics when someone explains the relationship between position, velocity, and acceleration, or in many cases, volume and surface area. This leads to the conclusion that the relationships that guide successful designs should be apparent in the design process; and to understand the relationships, one must re-examine the importance of various parts of blast design.

One oddity of major blast design methods is the grouping of terms related to explosive energy. When beginning to work through blast geometry it is important to know the specific gravity of explosives, and it is fairly common to calculate the weight of explosive per foot of borehole and overall quantity of explosive per borehole early in the process. However, after determining these initial explosive energy details, powder factor is not calculated until the end of the design process as a final check. Essentially, half the energy information is up front, and the other half is at the end. Why are these components separated? What if these quantities describing explosive energy were combined; using explosive density, loading density, and powder factor to create a single unit to describe the energy available to do work in blasting?

If one attempts to combine all the energy information up front, additional challenges develop. Traditional blast design uses explosive density, rock density, and borehole diameter to determine burden. If there is one thing that traditional blast design methods agree upon, it is the conception that "burden is the most critical dimension" of blasting (Konya & Walter, 1991) (Gokhale, 2011) (Jimeno, Jimeno, & Carcedo, 1995). In this author's opinion, burden is often over-rated, an opinion that will be explained in the following section. Focusing on burden (one dimension of volume) is shortsighted from an energy distribution viewpoint, as it ignores the other two-thirds of the problem.

3.3. BURDEN FIXATION AND SURFACE AREA BLANKET

Traditional blast design is focused on burden – the closest free face parallel to the borehole – because of standard quarry geometry and institutionalized beliefs. Today, this overall focus on burden seems shortsighted, as energy distribution and efficiency of energy utilization are what create successful blasts. Many of the blast design methods that focus on burden typically have a single complex calculation in the design method: the burden calculation itself. It is likely that the burden focus is partially a byproduct of technological expense. At the time when most of these blast design methods were being codified, slide rules were the standard and computers had much less power (and much more bulk) than they currently possess. Limitations in available computing power forced early researchers to use engineering judgment to assess the most critical dimensions of design and fix their work on those particular items. The result of the research programs of Ash and Konya are design methods that depend heavily on burden. Konya’s work that was carried out during the early days of personal computers does introduce varied spacing equations as some of the first steps toward creating more multi-dimensional design methods.

In any case, today’s technological landscape is vastly different than the one in place for Ash’s research in the 1960s and 1970s, and Konya’s from the 1970s to the mid 1990’s. Today computing power is inexpensive, and software has progressed in both capability and usability.

Field observations in the Powder River Basin have led to conclusions that further delineate LSCM bench blasting as a unique area of research. Traditional quarry-oriented blast design focuses on the burden dimension and recommends sufficient detonator delay timing to enable all rock from each row to move out of the way of subsequent rows prior to their detonation. As an example, for a theoretical small quarry blast, Figure 3.1 shows sample delay times designed to comply with federal regulations and utilize standard nonelectric initiation components.

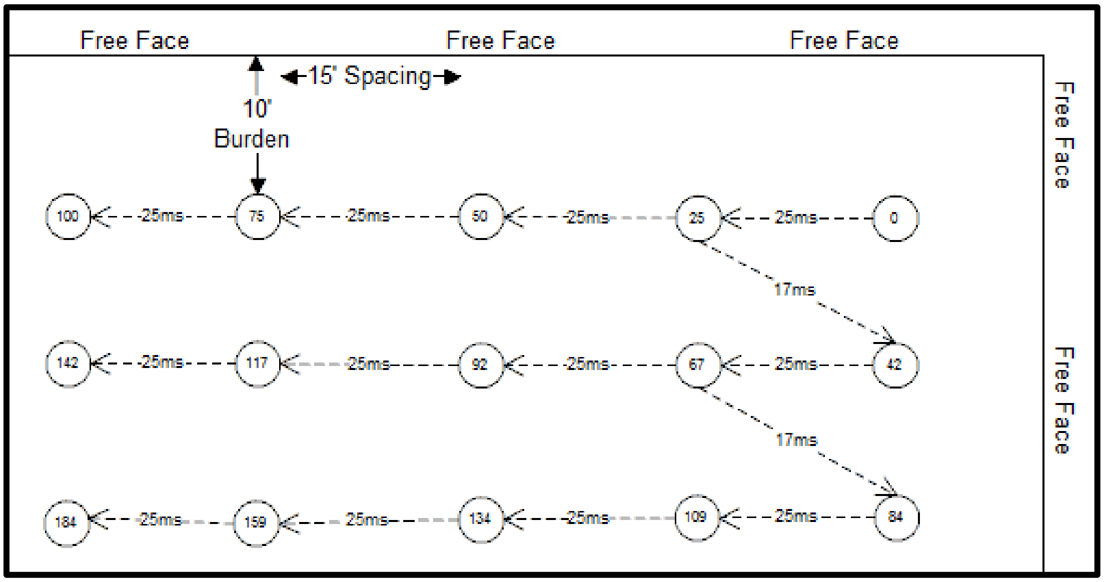


Figure 3.1: Sample Quarry Timing Design

The sample timing design illustrates a pattern of few rows with lots of room to move, called "relief", with timing designs that move the material toward the page number at the top right corner of the page. Typically, quarry blasts have relatively few rows, and plenty of room for material to move during the blasting process. Burden is a critical dimension for quarry blasting and must be consistent for the height and length of the shot because explosive energy takes the path of least resistance. Short burdens in one area of the face will cause that portion of the face to break slightly earlier than longer burdens in other areas. This uneven timing results in uneven breakage of rock since the gas pressure generated by the detonation of explosives will vent through the newly created holes, in much the same way that soda sprays from a punctured can or a balloon fragments when poked with a needle. Some satellite images of quarry blasting patterns can be seen as Figures 3.2 and 3.3. Note the large free face near the boreholes and the long rows parallel to the long dig face. These images are from Google Earth, and the built-in measuring tool (yellow ruler line) has been used to show known lengths for scale.

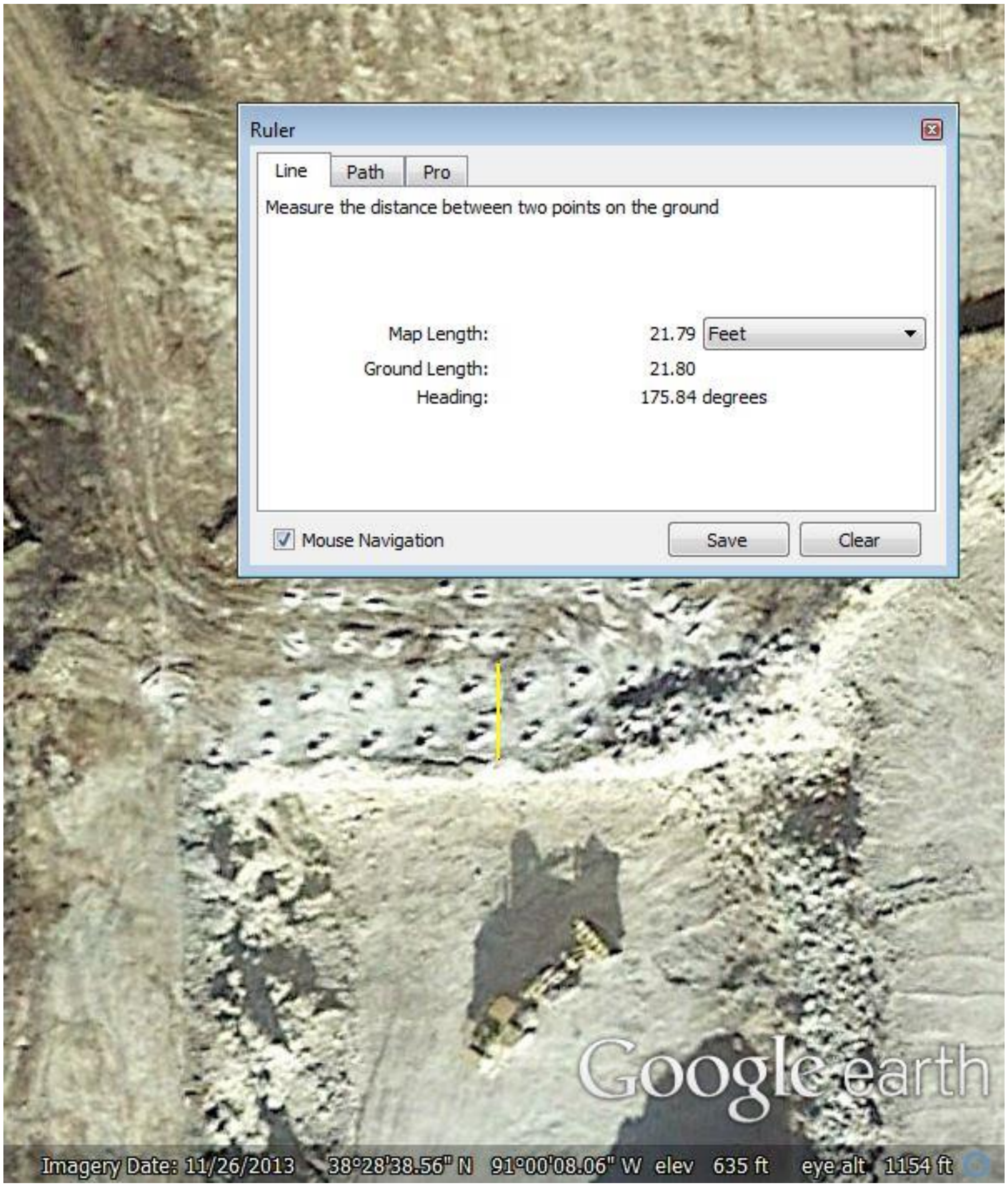


Figure 3.2: Quarry Between Washington and Union, MO

The small quarry in Figure 3.2 shows a pattern with two fully drilled rows and perhaps two more rows behind. Burden appears to be eight to ten feet long, and spacing is about ten to twelve feet long. This shot has the long side of the pattern toward relief, and when fired, material will move toward the wheel loader's location.

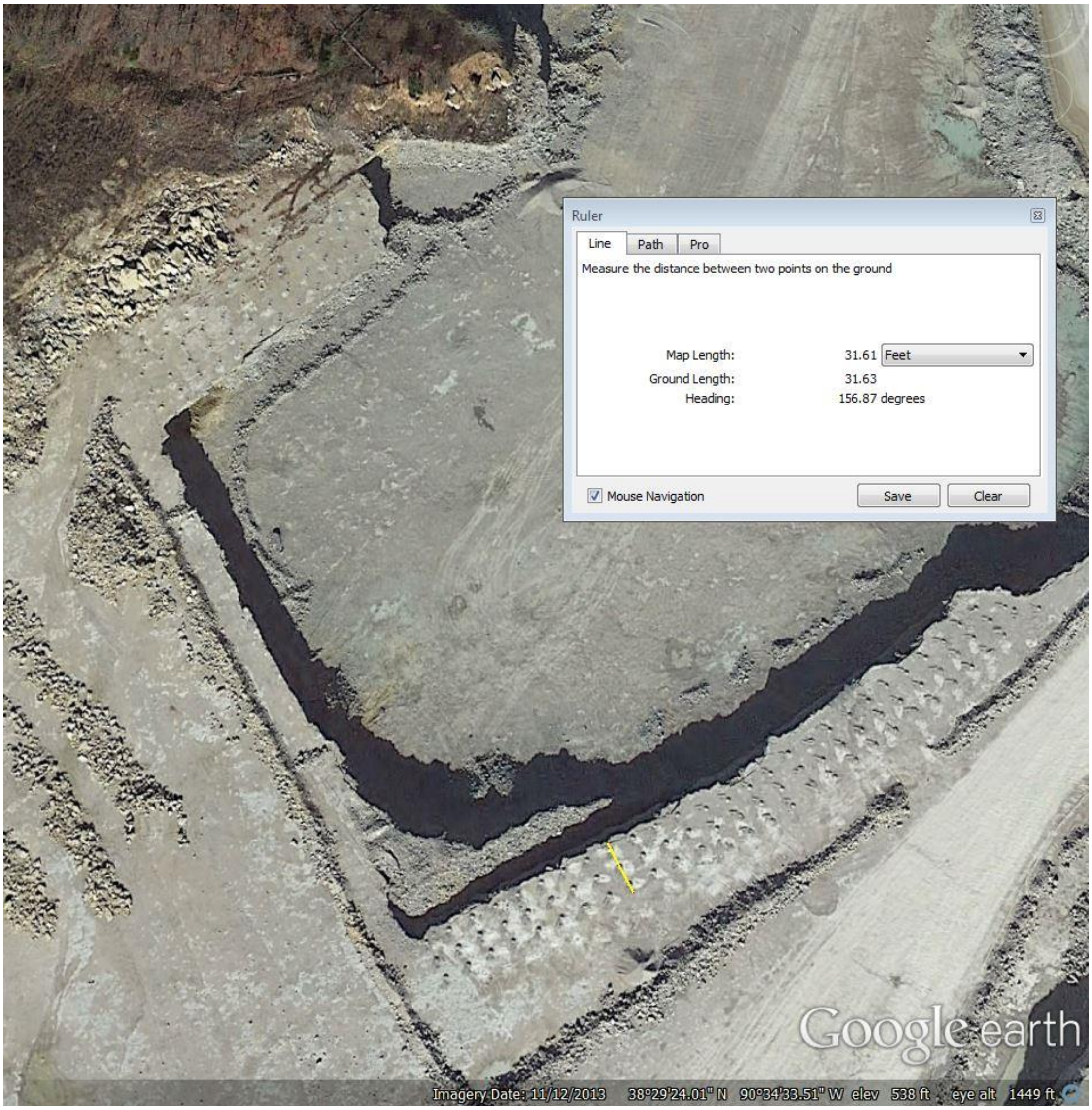


Figure 3.3: Eureka, MO Quarry

Figure 3.3 shows a quarry in Eureka, MO. Again, the long side of the blast is parallel with the direction of movement, and the shot contains three long rows with approximately ten feet of burden. This pattern appears to be square, with about ten feet of spacing as well. This shot has plenty of relief with a large area to move into at the time of the blast. The two quarry pictures in these two figures are representative of most quarry blasting with respect to relief and orientation. Pattern dimensions vary based on the scale of the quarry and its targeted throughput, but the overall philosophy is largely similar.

Bench blasting at LSCM operations is another matter. Due to production bottlenecks it is common to drill as much of a bench as possible at one time to minimize drill moves across the site. This practice results in large numbers of rows with occasionally hundreds of holes per shot and very little relief for material movement when the shot is fired. As a result of the geometric relationships of bench blasting in LSCM operations the mechanism of breakage is similar to cratering as presented by Cooper (Cooper, 1996), except that the individual craters do not break the surface; instead they appear to work together to lift a virtual mat of earth and create surface striations indicative of differential movement. Some work has recently been done concerning cratering affects in blasting (Zhu, 2009). Although Zhu’s theoretical models use vastly different materials and explosives, some of the simulation cross sections provide some support for a modified cratering hypothesis. The same basic cratering process at much larger scales can be seen in the mines of World War I (Leonard, 2011) and recent attacks in the Syrian civil war (Sherlock & McElroy, 2014). Field observations of the author support this claim, and satellite imagery of LSCM operations in the PRB further validates this hypothesis.

While the precise theoretical mechanism governing material breakage in LSCM bench blasting is beyond the scope of this research, certain practical aspects of the breakage of the material influence this work. When viewing typical post-blast benches in the PRB, the great majority of the material does not move laterally away from the bench; rather it moves vertically, humping up and increasing height significantly. Traditional quarry blasting moves primarily in the direction of burden and quarrying design methods focus on burden. LSCM bench blasting moves primarily upward, therefore the focus of LSCM bench blasting should be the surface area of the blast – the area defined by burden and spacing. From a purely theoretical approach, the dimensions of burden and spacing for a single hole in the middle of the blast should be perfectly interchangeable – it is the area defined by those two dimensions that matters for LSCM bench blasting. Additionally, stemming is also critical to success in LSCM bench blasting, as the depth of the stemming defines the LSCM dimension most analogous to the burden of quarry blasting. Consistent and quality stemming practices are critical to continual success in any form of blasting, and must not be ignored for LSCM bench blasting.

Figures 3.4 and 3.5 show two examples of LSCM bench blasting. Figure 3.4 shows an unusually large pattern at Cloud Peak Energy's Antelope Mine, and illustrates the practice of drilling all available material whenever possible. The pattern is quite large, nearly 500 feet square when originally shot, and there are a few interesting items about the surface of the shot.

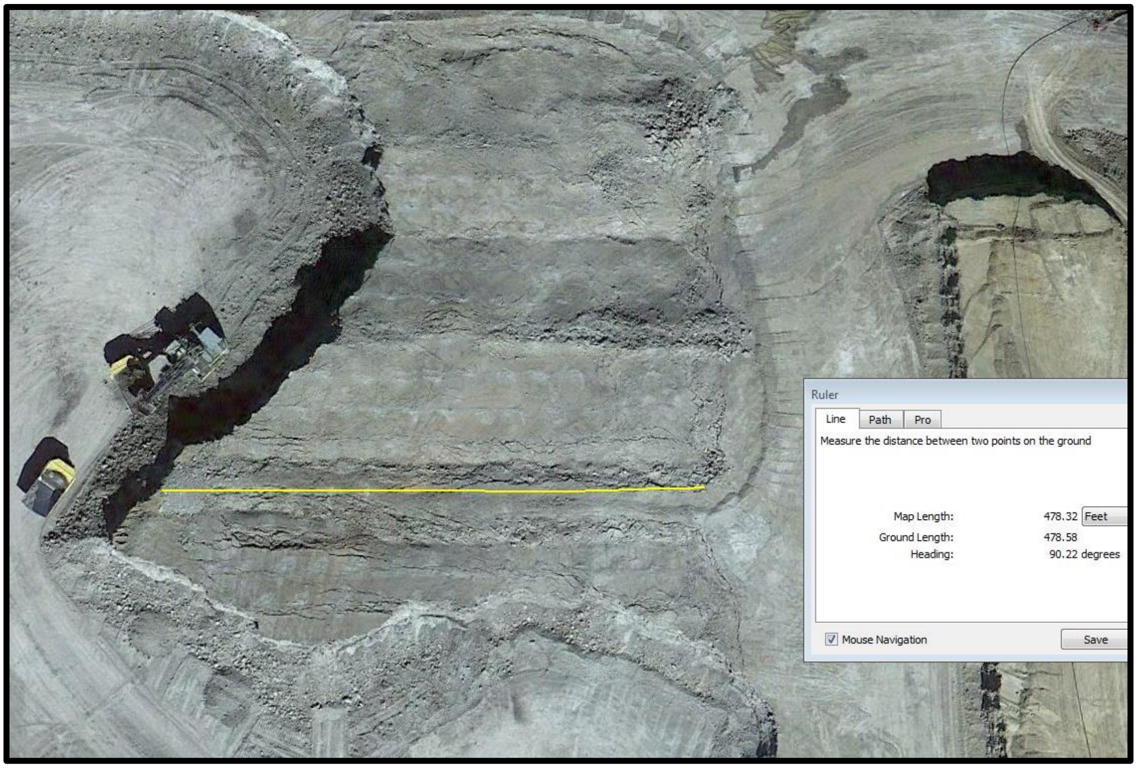


Figure 3.4: Cloud Peak Energy Antelope Mine Bench Blast

The dots of light color illustrate the location of boreholes, and the long cracks along the surface of the shot indicate that the material cracked along the surface when broken during the blasting process. Cracking of this nature is similar to cracks in concrete slabs where one side of the slab lifted higher than the other – the cracking is a marker of differential movement. The clearly visible locations of the boreholes indicate that blasting did not create much horizontal movement with respect to the bench – the differential movement was primarily vertical. To give a sense of scale for the shot, the electric rope shovel at the left of the image is a P&H 4100, either an XPB or XPC, and the haul trucks are either Komatsu 830E or 930E 240 or 340 ton haul trucks, respectively.

Figure 3.5 shows a shot at Peabody's North Antelope Rochelle operation (NARM) on the lowest bench in the pit, uncovering coal. A drill is visible at the left of the pattern and is drilling the next higher bench. This photo illustrates a typical scenario in PRB strip mining – the shovel is progressing down the cut from one end to the other. Again, the location of the boreholes is clearly marked by the slight color difference of the drill cuttings, and the longitudinal cracks are visible for the length of the shot. As an additional piece of information, the direction of the cracks is a likely indicator of the way the delay pattern was designed. It appears that the space to the right of the pattern was empty, and the blast pushed some material into the open space. This observation is confirmed by the presence of substantially larger longitudinal cracks on the left side of the bench. These deeper cracks represent a void at the back of the pattern, a phenomenon often called a "power trough" when discussing cast blasting. While on the topic of delay designs, coal shots, which are often even more confined than the standard bench pattern due to typical mining practices, tend to shoot the center row first in a deliberate attempt to get the material to lift vertically and create a void under the now-airborne first row. The temporary void would be filled by subsequent rows of blasted material shot toward the center of the cut, creating the longitudinal cracks on both sides of the cut rather than the single side shown in Figure 3.5.

Both LSCM figures also show a comparatively large number of rows with less overall relief than the quarry blasts. From photoanalysis alone, it is obvious that the geometries of the two types of blasting do not match. Therefore, blast design methods should also differ from quarries to LSCM bench blasting.

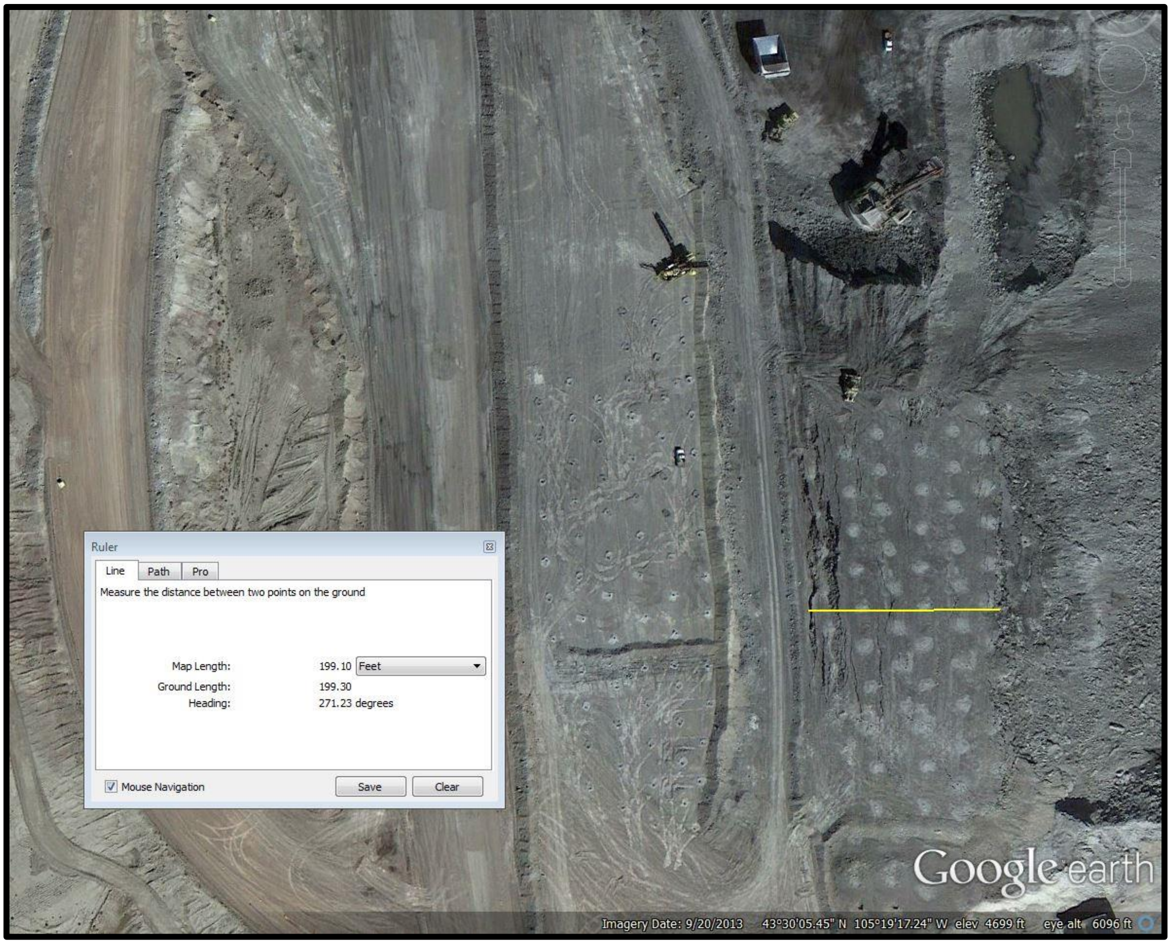


Figure 3.5: NARM Overburden shot

3.4. DESIGN DIMENSIONS

All blast design methods share terms that describe similar dimensions, and the following sections describe these dimensions.

3.4.1. Burden. Burden is defined as the shortest direction to relief and is generally perpendicular to the dig face. Burden has always been considered critical for a number of reasons that largely focus around the area of typical blasting research. Most blast design research has been done for bench blasting of relatively small scale, such as typical quarry blasts. Ash and Konya were quarry-focused, and the basic geometry present for quarry blasting is easy to replicate in other conditions, such as construction blasting for foundations and road cuts. Generally speaking, burden is a normal criteria for measuring fragmentation in quarry blasting. The focus on burden arises from a demand for consistent breakage across a range of conditions with a range of explosives used, and has been discussed extensively elsewhere.

3.4.2. Spacing. Interestingly, while detailed formulas for burden are advised, other dimensions such as spacing have much less stringent design requirements. Spacing is measured parallel to the dig face, and is often represented as a function of burden, using a simple multiplier to arrive at a range of values. This situation is partially a nod toward containing costs. The implied message is that while burden is critical to getting good fragmentation, try to stretch the spacing so not as many boreholes are required. Drilling is expensive, and the fewer boreholes drilled the lower the overall cost. Breakage and movement of material when blasted is also a factor that drives pattern geometry choices (Lusk, 2015).

3.4.3. Stemming. Stemming is another dimension generally represented as a function of burden, and this instance makes much more logical sense than the relationship between burden and spacing. Typically, burden is represented by the shortest distance to a free face. Explosive energy (in the form of gas pressure) will always take the path of least resistance, and blast design methods attempt to make this path of least resistance match the burden. However, because placing explosives in rock requires boreholes, these boreholes automatically become the path of least resistance because of the empty void between explosives and the surface. Stemming fills the void between the explosives and the surface and provides resistance to explosive energy once the explosives are detonated.

However, stemming is a variable quantity – some types (highly angular crushed rock) are more efficient than others (rounded and crushed powders such as drill cuttings). Stemming is typically represented as a function of burden because stemming is in direct competition with burden to harness the work made available by the detonation of explosives. The range of possible stemming values exists to most effectively balance the strengths of burden and stemming, while accounting for the quality of different stemming materials. The final word about stemming is that every foot of stemming replaces a foot of explosive, meaning because drilling is comparatively expensive blasters try to minimize the amount of stemming in order to maximize the efficiency of borehole use.

3.4.4. Subdrill. Subdrill is a simpler calculation, typically fixed at 1/3 the burden. This relationship also ties to the shortest distance to the free face, as subdrill is typically designed to break material in ways similar to a crater, and 1/3 the burden is traditionally the most reasonable value for this goal. Subdrill allows the blaster to place more energy in the borehole near the toe of the shot which is the most difficult location to break. Subdrill is typically minimized to keep from causing extra damage to the floor of the shot, as the floor of the current shot is usually the top of the next bench. Breakage created by subdrilling can make for difficult drilling later on, and challenges like these keep subdrill from growing longer.

3.4.5. Face Height. Face height is an interesting non-variable “variable”. Some blast design methods treat face height as a variable, and explain that it should be four times the burden (Konya & Walter, 1991). However, this relationship assumes that the drill and blast group will be the ones in charge of determining face height. Perhaps this was true fifty years ago, but today, face height is determined almost exclusively by equipment operating parameters and overall pit characteristics. Differences of opinion exist, but for LSCM truck shovel operations higher benches mean less road maintenance and fewer shovel moves, along with less work to create and maintain access. Typically, these factors alone are large enough to drive bench heights near the maximum safe working height of loading equipment.

3.5. DIFFERENCES FROM EXISTING METHODS

The proposed blast design method should use powder factor as a design input, and work cut width into the design. The goal of this research is to build an adaptive design method for large surface coal mines that uses powder factor as a design input for cuts of fixed width and variable height. This design method is to be tailored specifically for use in large surface coal mine operations, with potential future applications outside that scope.

3.6. DEVELOPMENT OF NEW ENERGY DISTRIBUTION TERM

Safe and efficient explosives use in blasting hinges around energy distribution and effective energy utilization. Therefore, the first focus should be energy distribution, as defined by the geometry of the blast pattern.

3.6.1. Loading Density, Powder Factor, and Available Energy. Energy distribution in blasting is defined by two numbers: loading density, and powder factor. Loading density shows the quantity of explosive per linear foot of borehole, and powder factor is a ratio that represents the quantity of explosives to the quantity of material blasted. Loading density is usually represented by variations on Equation 3.1:

$$Loading\ Density = 0.3402 * \rho * D^2 \qquad \text{Eqn. 3.1}$$

The derivation of the loading density equation is simple – explosive densities are generally described in units of grams per cubic centimeter [g/cc], terms that relate well to specific gravity. In order to calculate loading density, some terms related to borehole volume must work with terms related to specific gravity of explosives. Equations 3.2, 3.3, and 3.4 walk through this progression.

$$Loading\ Density = \left(\pi * \left(\frac{D[ft]}{24}\right)^2 * 62.4\left[\frac{lb}{cft}\right] * \rho\left[\frac{g}{cc}\right] * 1[ft]\right) \qquad \text{Eqn 3.2}$$

$$Loading\ Density = \left(\pi * D^2 * \rho * \frac{62.4}{576}\right) \qquad \text{Eqn 3.3}$$

$$Loading\ Density = (\pi * 0.1083 * \rho * D^2) \qquad \text{Eqn 3.4}$$

The final result is Equation 3.1, which is a widely distributed equation in blast design, although the conversion factor is often represented as 0.34 or other minor variations.

Powder factor, on the other hand, is a simple ratio of explosives used to material blasted. Powder factor is calculated on either a per-borehole or per-shot basis.

These two values define energy distribution, as the loading density states how much energy is available within a unit length of borehole, and powder factor describes how much material that energy will break. Combining loading density and powder factor gives a single number that outlines the amount of work that can be done with a single foot of borehole filled with explosive, providing a universal scale for design comparison – an extension of the original intent of powder factor. There are essentially three practical ways to combine the two numbers, multiplication (with one resulting value) or division (with two possible resulting values). Adding or subtracting the values provides no benefit, while multiplication or division allows the use of dimensional analysis to complete the design process. Multiplication does not provide a useful value, whereas division will generate a ratio; and ratios are useful in blasting as evidenced by powder factor itself. The remaining issue is which value becomes the numerator or denominator. Examining the units of both values – loading density in [lb/ft] and powder factor in [lb/cyd] – indicates at first glance that loading density divided by powder factor results in units of [cyd/ft], which in context represents a volume per foot of borehole. The reverse (powder factor divided by loading density) gives units of [ft/cyd], which may be useful, but is not as intuitively clear as [cyd/ft]. Additionally, loading density divided by powder factor gives a wide range of whole numbers as possible values; whereas powder factor divided by loading density results in a range of percentages where several decimal places must be used to differentiate between levels of energy. Therefore, the new ratio that describes energy distribution for blasting should be loading density divided by powder factor. This ratio describes the amount of material that can be moved by a linear foot of borehole and will be called Available Energy.

3.6.2. Importance of Available Energy. The Available Energy (AE) concept is a natural extension of the original intent of powder factor, and as such, can be considered an improvement on powder factor as currently defined by the industry. AE provides a quick comparative reference to use when evaluating blast designs, and defines a universal scale giving at-a-glance identification of power levels for each shot. AE can also simplify shot design by placing powder factor at the beginning of the design process, and intensifies focus on a critical issue: How much work can be done with what is available?

AE liberates lateral thinking: by combining the three variables of borehole diameter, explosive density, and powder factor into one number, the relationship between those variables is illuminated in a new way. For any given AE value, three different variables can be changed.

3.7. AVAILABLE ENERGY BLAST DESIGN METHOD

To complete the design process, the AE value must translate into burden, spacing, stemming, and subdrill values. Figure 3.6 illustrates the AE design process.

AE design uses seven total inputs for the design process. Three of these inputs calculate Available Energy itself, meaning that the bulk of the design process takes five inputs: Available Energy (AE), Stemming Factor (St_f), Subdrill Factor(Su_f), Face Height (FH), and Cut Width (CW).

After calculating AE, stemming is the next calculation, as shown in Equation 3.5:

$$Stemming = \left(\sqrt{AE * 27}\right) * St_F \qquad \text{Eqn 3.5}$$

Subdrilling is based on stemming, as represented in Equation 3.6:

$$Subdrill = Stemming * Su_F \qquad \text{Eqn 3.6}$$

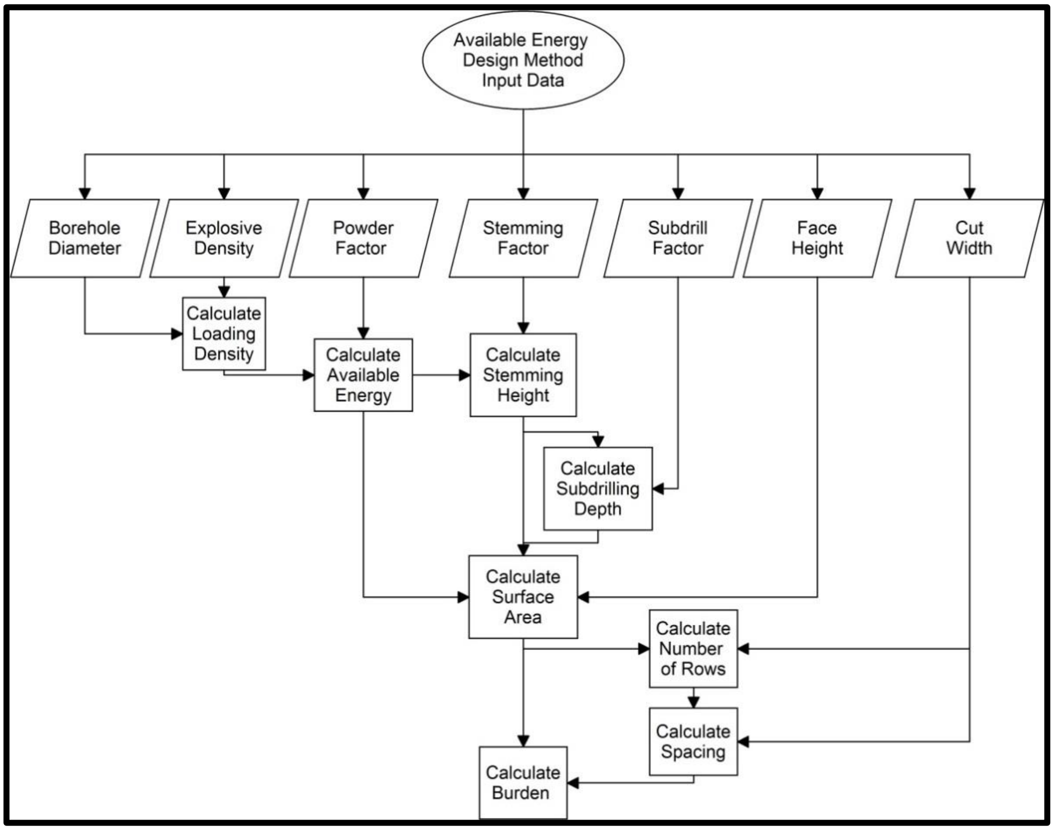


Figure 3.6: Available Energy Blast Design Flowchart

The next calculation is for Surface Area, the actual area of influence that a fixed level of AE can break. Surface Area and AE are similar numbers, but not equal. AE is equivalent to the surface area of a single linear foot of borehole entirely filled with explosives, which would represent an efficiency index of 100%. An efficiency index of 100% is unworkable in practice, as a total lack of stemming would vent all the gas pressure of the explosive detonation to the open air, at which point the microfractures created by the shockwave would remain unpressurized and the rock relatively unfractured, with next to no fragmentation or breakage. The surface area calculation, illustrated by Equation 3.7, takes stemming and subdrill into account to arrive at an actual surface area of influence for each borehole.

$$Surface\ Area = AE * \left(\frac{1-(Stemming-Subdrilling)}{Face\ Height}\right) * 27 \qquad \text{Eqn. 3.7}$$

Now the dimensions of burden and spacing can be calculated. This calculation can be as simple as the square root of the surface area if a square pattern is desired, and other geometric patterns are also easily calculated at this point in the process. However, for LSCM operations, cut width is fixed and spacing values should be evenly divisible within the cut. Equation 3.8 shows how to calculate the number of rows required to cross the cut.

$$Number\ of\ Rows = \frac{Cut\ Width}{\sqrt{Surface\ Area}} \qquad \text{Eqn. 3.8}$$

Once the number of rows is calculated, spacing can be determined using Equation 3.9.

$$Spacing = \frac{Cut\ Width}{ROUND(Number\ of\ Rows)} \qquad \text{Eqn. 3.9}$$

The spacing calculation contains an Excel formula called ROUND. This formula can take a number and round it to the desired number of significant digits. In practice, if the design process was being completed by hand, the number should be rounded by the user. In practice, an integer is the desired number so that the cut width is equally divisible by the spacing.

Surface area is defined as burden times spacing, so once spacing is determined, burden is one step away, as shown in Equation 3.10:

$$Burden = \frac{Surface\ Area}{Spacing} \qquad \text{Eqn. 3.10}$$

All the formulas so far have been rather simple, with Surface Area (Equation 3.7) being the most complex. However, this simplicity is somewhat deceptive. Equation 3.11 shows the burden calculation for AE as a single step:

$$AE\ Burden = \left(\frac{\dfrac{\left(\frac{0.3402*\rho*D^2}{PF}\right)*\left(\dfrac{1-\left(\left(\sqrt{\left(\frac{0.3402*\rho*D^2}{PF}\right)}*27\right)*St_F-\left(\left(\sqrt{\left(\frac{0.3402*\rho*D^2}{PF}\right)}*27\right)*St_F\right)*Su_F\right)}{Face\ Height}\right)*27}{Cut\ Width}}{ROUND\left(\dfrac{Cut\ Width}{\sqrt{AE*\left(\dfrac{1-\left(\left(\sqrt{\left(\frac{0.3402*\rho*D^2}{PF}\right)}*27\right)*St_F-\left(\left(\sqrt{\left(\frac{0.3402*\rho*D^2}{PF}\right)}*27\right)*St_F\right)*Su_F\right)}{Face\ Height}\right)*27}}\right)} \right) \qquad \text{Eqn. 3.11}$$

Contrast this with burden equations for Ash (Equation 3.12) and Konya (Equation 3.13)

$$B = \left(30 * \left(\frac{SG_E}{1.4}\right)^{1/3} * \left(\frac{160}{WT_{RK}}\right)^{1/3}\right) * D_E \qquad \text{Eqn. 3.12}$$

Where SG_E = Specific Gravity of Explosive, WT_{RK} = Unit Weight of Rock, D_E = Diameter of Explosive, and B = Burden

$$B = \left(\frac{2SG_E}{SG_R} + 1.5\right) * D_E \qquad \text{Eqn 3.13}$$

Where B = Burden, SG_E = Specific Gravity of Explosive, SG_R = Specific Gravity of Rock, and D_E = Diameter of Explosive

AE has a much larger burden formula than either Ash or Konya, and from a practical perspective, this fact is largely due to inexpensive processing power and spreadsheet software. The ability to test multiple design options and many iterations of the AE method has distilled the design process to the above formulas. Recent improvements in technology allow modern researchers to look at old problems in new ways, which illustrates the importance of priorities and engineering judgement in previous work – in the cases of Ash, Konya, and earlier researchers, more costly processing limited the complexity of models that could be quickly tested. The necessary limitations on complexity forced early researchers to prioritize their focus on dimensions of design they judged critical, which moved the industry toward burden-based blast design and its accompanying formulas. A more detailed discussion of the derivation of Available Energy formulas is given in Appendix C, and preliminary testing of a quarry-oriented geometry AE method is shown in Appendix F.

4. TESTING NEW METHOD

4.1. INITIAL COMPARISON OVERVIEW

Traditional blast design says the following items are important:

1. Explosive Density
2. Unit Weight of Rock
3. Borehole Diameter
4. Burden
5. Spacing
6. Stemming
7. Subdrilling
8. Face Height
9. Explosive Weight
10. Volume per Borehole
11. Powder Factor

For a method like Ash's, the above list is also roughly the order of use. Figure 4.1 details the Ash design process, which uses seven input variables to create the blast design. There is no difference in importance or meaning of dashed versus solid lines in Figure 4.1; the difference was included solely to help trace connections.

The end user must know explosive density, unit weight of rock, and borehole diameter to calculate burden; then spacing, stemming, and subdrilling are all based on burden. Also, explosive weight, volume, and powder factor depend on the burden for accurate calculation. Available Energy takes a different approach:

1. Powder Factor
2. Borehole Diameter
3. Explosive Density
4. Face Height
5. Cut Width

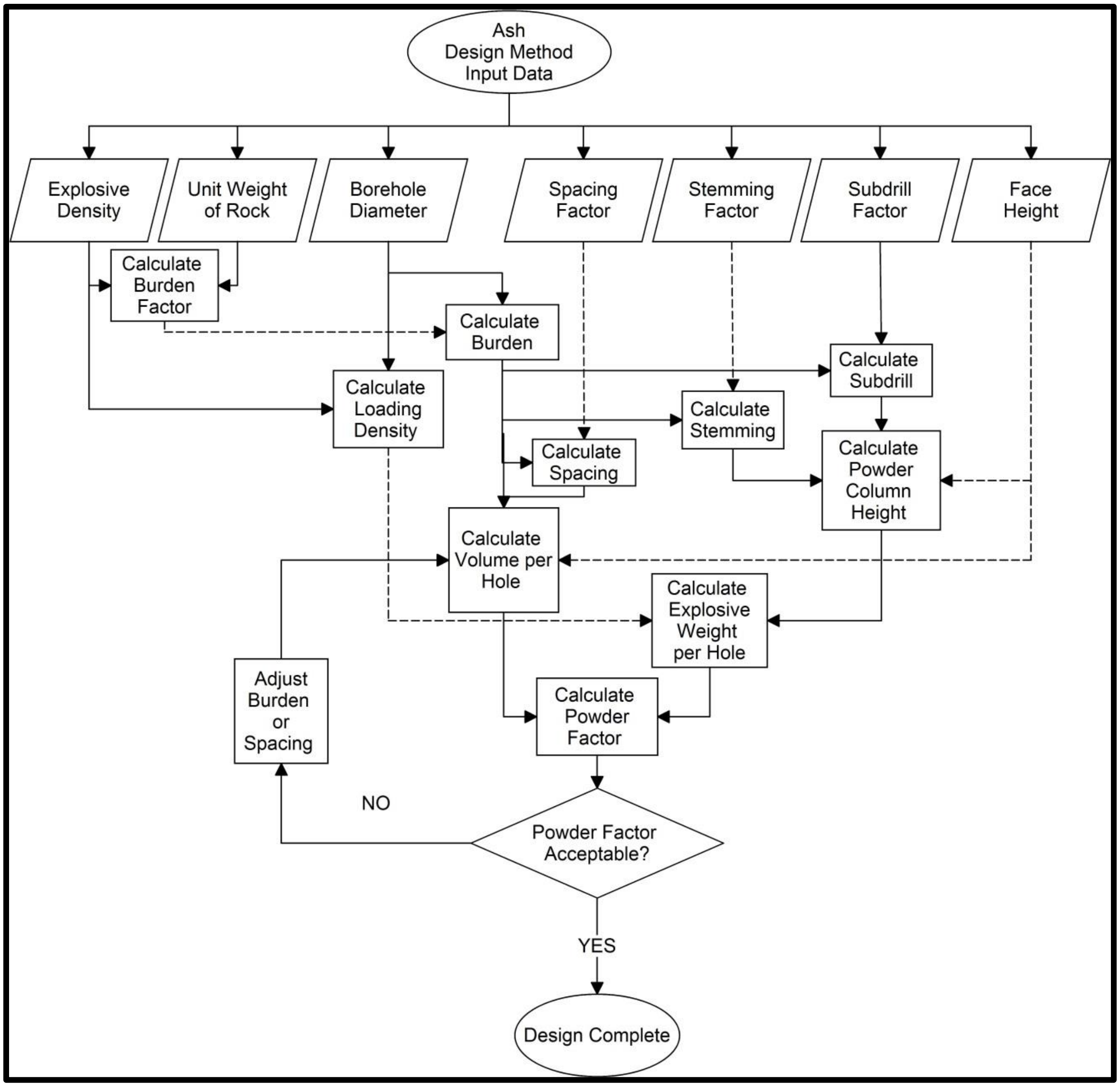


Figure 4.1: Ash Design Method Flowchart

6. Stemming
7. Subdrill
8. Surface Area
9. Number of Rows
10. Spacing
11. Burden

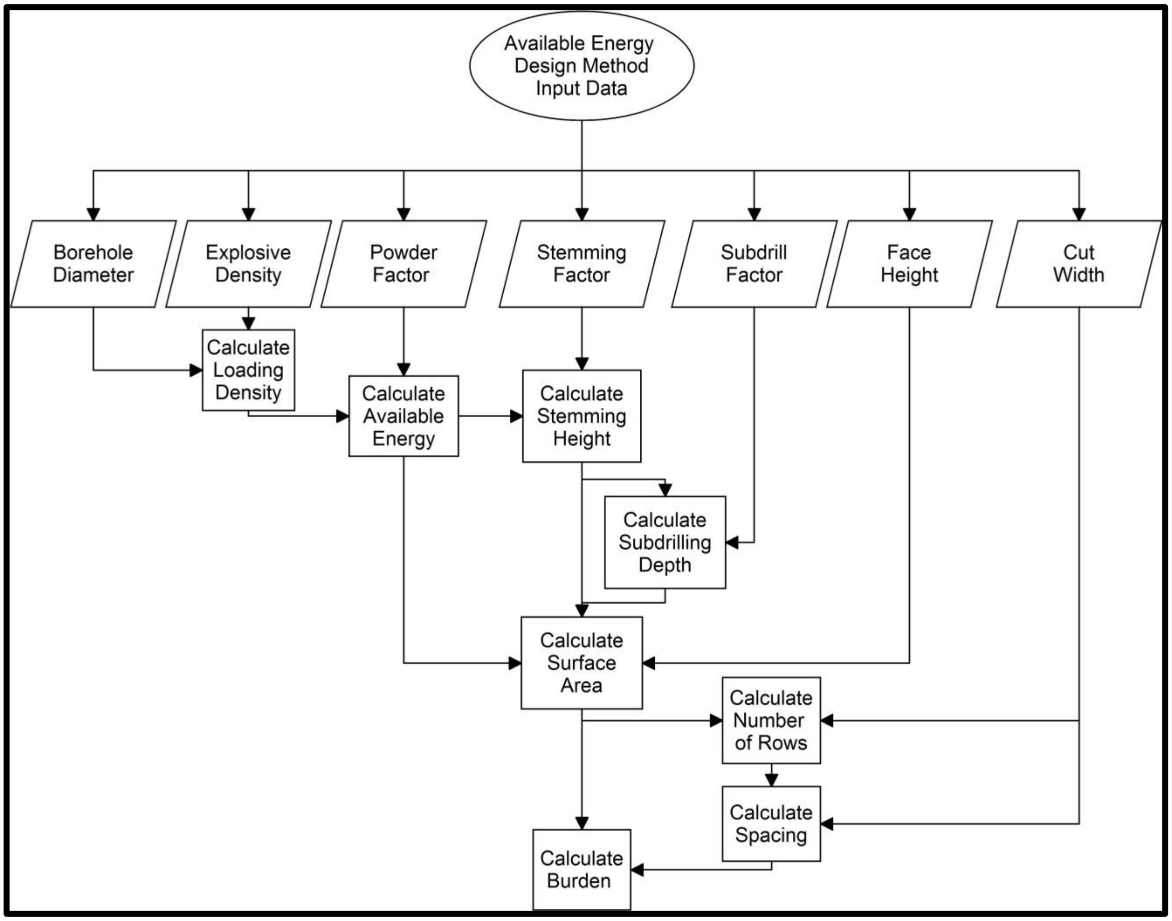


Figure 4.2: Available Energy Design Method Flowchart

Again, the numbers roughly follow the order of use. AE has an entirely different priority of calculation, moving burden to the last place, as shown in Figure 4.2.

By nature of its method of calculation, AE can adapt to match scenarios from a wide range of design methods. If a design method has a specified powder factor that should be matched with face height, borehole diameter, and explosive density fixed, by adjusting stemming and subdrill values appropriately, AE will replicate the design surface area. Variations in exact comparisons between burden and spacing values may be brought about by cut width changes, but the surface area of AE and the method being compared will match if the stemming and subdrill can be brought to magnitudes equal to the original design method.

Direct comparison between Ash and AE is difficult, because to start the AE calculation process, one must first know the final result of the Ash design method. Also, directly comparing burdens and spacings will not paint the full picture, as Ash is geometrically geared toward a rectangular pattern design, whereas AE generates essentially square patterns based on current practices in the PRB. Finally, AE generates stemming and subdrill values in a fundamentally different manner than Ash. The AE method directly ties stemming to AE, and subdrilling to stemming. Ash ties both variables to the burden. In both cases, the design method bases the calculation on the design criteria deemed most important by the method developer.

Based on these differences, a direct comparison of Ash and AE would practically be comparing apples to oranges, with both items roughly spherical, yet entirely different. In this case, the best method of comparison is to use AE to replicate an Ash design scenario, since the powder factor output of Ash can serve as the powder factor input of AE. The geometric burden and spacing difficulties remain, and can be met by focusing the comparison on surface area – the product of burden and spacing. When comparing Ash and AE, the order of importance for matching values should be as follows:

1. Surface Area
2. Explosive Weight
3. Stemming
4. Subdrill
5. Burden or Spacing
6. Spacing or Burden

If the surface areas and explosive weights match, then the two patterns are essentially identical, with one caveat – if stemming and subdrill are both much larger in one method than another, the same explosive weight can be generated but with bad geometry – in some cases the explosive column may be halfway into a lower bench instead of the design bench. In situations with excessive stemming and subdrilling, the numbers match, but a design based on those numbers would not work correctly in the field. Therefore, it is also important that both stemming and subdrilling values match closely in magnitude between the two methods. Burden and spacing are listed interchangeably, because if one matches the other should.

Konya calculations and subsequent comparisons are largely similar to Ash, with some differences in burden and spacing equations. Konya's design criteria tie spacing to what Konya calls a stiffness ratio, indicating different spacing equations for different stiffness ratios and timing designs. The additional spacing equations make for a more complicated design process, as shown in Figure 4.3**.**

The order of importance for matching values for Konya is the same as for Ash, due to the similarities of the methods. Surface area and explosive weight are the primary concern, with stemming and subdrill coming in second, leaving burden and spacing last.

4.2. SCALE OF DESIGNS FOR COMPARISON

The new Available Energy based blast design method relies heavily on dimensional analysis and a few correction factors to dial in a precise blast design for given requirements. This flexible nature with relatively few correction factors allows close replication of design criteria from other blast design methods. Ash and Konya originally worked with borehole diameters smaller than those currently employed in the

Powder River Basin, and their research was aimed primarily at quarrying. For the best comparison to Ash and Konya, it would be best to compare design scenarios similar to those at a quarry, using borehole diameters of two to six inches instead of nine to thirteen inches.

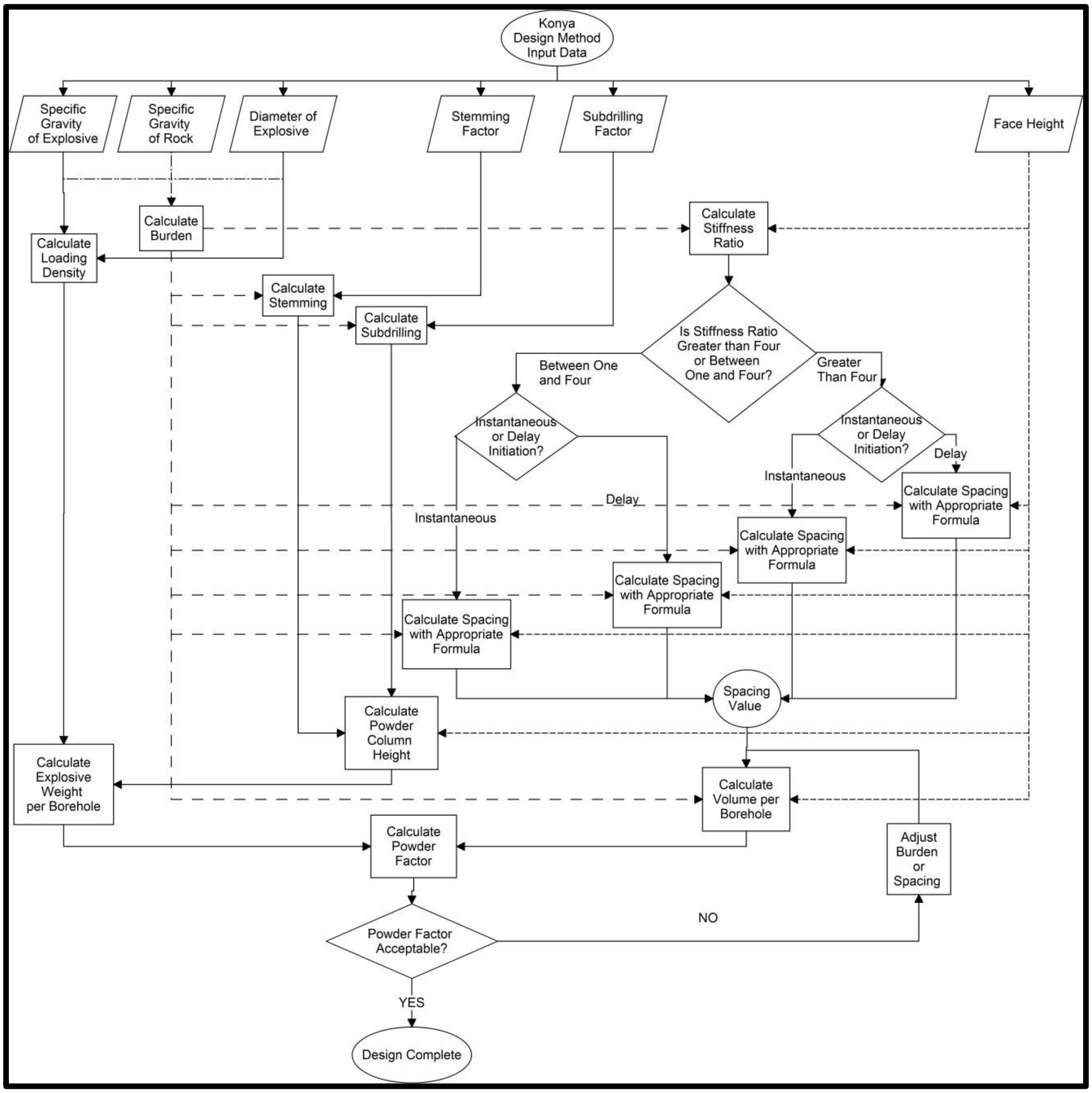


Figure 4.3: Konya Design Method Flowchart

A small scale comparison would help ensure that any Ash and Konya designs are interpolations within the target domains for their methods, rather than extrapolations into diameters and scales that may not have been considered in Ash and Konya's original research. Once the comparison method is developed for small-scale blasting, it will be a simple change to verify small-scale results at large-scale borehole diameters.

4.3. COMPARISON SPREADSHEET SETUP

Setting up the testing method is straightforward after addressing the above issues. An Excel spreadsheet was constructed with three major areas: inputs, calculations, and analysis. Inputs are shown in Figure 4.4, which shows the first thirty design scenarios for Ash Test 8. Spreadsheet design for a Konya comparison is essentially similar.

As both Ash and Konya designs requires a rock density, a value of 162 lb/cft was chosen as a reasonable approximation for limestone, a common quarry rock. The rest of the inputs varied depending on the individual spreadsheet and position within the spreadsheet – more information is contained in the next subsection: "Sampling Intervals".

The spreadsheet calculates a blast design using either Ash or Konya guidelines, and once the EMM design is complete, the powder factor of the EMM method is fed into the AE method along with the other input variables necessary to create an AE design.

The calculations portion of the spreadsheet is represented by Figure 4.5, showing the design problems for the inputs of Figure 4.4.

Design Inputs									
Trial	Hole Diameter [in]	Product Density [g/cc]	Face Height [ft]	Cut Width [ft]	AE Stemming Factor	Ash Stemming Factor	AE Subdrill Factor	Ash Subdrill Factor	Ash Rock Density
1	9	0.8	67.5	150	0.607	0.7	0.428	0.3	162
2	9	0.9	67.5	150	0.607	0.7	0.428	0.3	162
3	9	1	67.5	150	0.607	0.7	0.428	0.3	162
4	9	1.1	67.5	150	0.607	0.7	0.428	0.3	162
5	9	1.2	67.5	150	0.607	0.7	0.428	0.3	162
6	9	1.3	67.5	150	0.607	0.7	0.428	0.3	162
7	10	0.8	75	150	0.607	0.7	0.428	0.3	162
8	10	0.9	75	150	0.607	0.7	0.428	0.3	162
9	10	1	75	150	0.607	0.7	0.428	0.3	162
10	10	1.1	75	150	0.607	0.7	0.428	0.3	162
11	10	1.2	75	150	0.607	0.7	0.428	0.3	162
12	10	1.3	75	150	0.607	0.7	0.428	0.3	162
13	11	0.8	82.5	150	0.607	0.7	0.428	0.3	162
14	11	0.9	82.5	150	0.607	0.7	0.428	0.3	162
15	11	1	82.5	150	0.607	0.7	0.428	0.3	162
16	11	1.1	82.5	150	0.607	0.7	0.428	0.3	162
17	11	1.2	82.5	150	0.607	0.7	0.428	0.3	162
18	11	1.3	82.5	150	0.607	0.7	0.428	0.3	162
19	12	0.8	90	150	0.607	0.7	0.428	0.3	162
20	12	0.9	90	150	0.607	0.7	0.428	0.3	162
21	12	1	90	150	0.607	0.7	0.428	0.3	162
22	12	1.1	90	150	0.607	0.7	0.428	0.3	162
23	12	1.2	90	150	0.607	0.7	0.428	0.3	162
24	12	1.3	90	150	0.607	0.7	0.428	0.3	162
25	13	0.8	97.5	150	0.607	0.7	0.428	0.3	162
26	13	0.9	97.5	150	0.607	0.7	0.428	0.3	162
27	13	1	97.5	150	0.607	0.7	0.428	0.3	162
28	13	1.1	97.5	150	0.607	0.7	0.428	0.3	162
29	13	1.2	97.5	150	0.607	0.7	0.428	0.3	162
30	13	1.3	97.5	150	0.607	0.7	0.428	0.3	162

Figure 4.4: Comparison Spreadsheet Inputs

The evaluation portion of the spreadsheets consisted of measuring differences between outputs of the design scenarios to generate data used in the analytical methods described in the rest of this section. Direct comparisons of values such as burden, spacing, stemming, subdrill, surface area, and explosive weight generated percentage match data, and information used for linear regression.

Figure 4.6 shows the comparison portion of the spreadsheet where both the EMM and the AE method solutions are shown. The EMM values are used as the X axis of the regression charts, and the AE values provide Y axis data. Dr. Samaranayanke was consulted on the construction of the data analysis portions of this research (Samaranayake, 2015), and his advice helped shape the style of percentage match test that is included in this research. The third column for each item shows the AE value divided by the Ash value to show a percentage match between AE and Ash. This data is graphed on the Y axis with the number of trials on the X axis to show where the best fits are across the design domain. If the Ash and AE values match, the percentage match shows a value of 100%. If Ash is larger than AE the percentage is less than 100%, and if AE is larger than Ash, the percentage is greater than 100%. These techniques are illustrated with a smaller data set in Section 4.4.

Ash's Method								AE from Ash Low PF										
Loading Density	Ash's Burden	Ash Spacing Low	Ash Low Surface Area	Ash Stemming	Ash Subdrill	Ash Exp Wt	Ash Low Area PF	Ash Low PF	AE	AE Stem	AE Subdrill	AE Surface Area	AE # Rows	AE Spacing	AE Burden	AE Exp Wt	AE Calc PF	PF Mismatch
22.06	18.59	22.31	414.88	13.02	5.58	1325.24	1.28	1.28	17.27	13.11	5.61	414.47	7.37	21.43	19.34	1323.926	1.28	0.000%
24.82	19.34	23.21	448.77	13.54	5.80	1483.50	1.32	1.32	18.77	13.67	5.85	448.16	7.09	21.43	20.91	1481.484	1.32	0.000%
27.58	20.03	24.04	481.43	14.02	6.01	1640.71	1.36	1.36	20.23	14.19	6.07	480.59	6.84	21.43	22.43	1637.869	1.36	0.000%
30.34	20.68	24.81	513.01	14.47	6.20	1796.94	1.40	1.40	21.65	14.68	6.28	511.93	6.63	21.43	23.89	1793.154	1.40	0.000%
33.10	21.28	25.54	543.65	14.90	6.39	1952.24	1.44	1.44	23.04	15.14	6.48	542.30	6.44	25.00	21.69	1947.402	1.44	0.000%
35.85	21.86	26.23	573.45	15.30	6.56	2106.67	1.47	1.47	24.40	15.58	6.67	571.81	6.27	25.00	22.87	2100.665	1.47	0.000%
27.24	20.66	24.79	512.20	14.46	6.20	1817.89	1.28	1.28	21.32	14.56	6.23	511.69	6.63	21.43	23.88	1816.086	1.28	0.000%
30.65	21.49	25.78	554.04	15.04	6.45	2034.98	1.32	1.32	23.18	15.18	6.50	553.29	6.38	25.00	22.13	2032.214	1.32	0.000%
34.05	22.26	26.71	594.35	15.58	6.68	2250.63	1.36	1.36	24.98	15.76	6.75	593.33	6.16	25.00	23.73	2246.734	1.36	0.000%
37.46	22.97	27.57	633.35	16.08	6.89	2464.93	1.40	1.40	26.73	16.31	6.98	632.01	5.97	25.00	25.28	2459.745	1.40	0.000%
40.86	23.65	28.38	671.17	16.55	7.09	2677.97	1.44	1.44	28.45	16.82	7.20	669.51	5.80	25.00	26.78	2671.333	1.44	0.000%
44.27	24.29	29.15	707.96	17.00	7.29	2889.81	1.47	1.47	30.12	17.31	7.41	705.94	5.65	25.00	28.24	2881.571	1.47	0.000%
32.96	22.73	27.27	619.76	15.91	6.82	2419.61	1.28	1.28	25.80	16.02	6.86	619.15	6.03	25.00	24.77	2417.21	1.28	0.000%
37.08	23.64	28.36	670.39	16.55	7.09	2708.56	1.32	1.32	28.04	16.70	7.15	669.48	5.80	25.00	26.78	2704.877	1.32	0.000%
41.20	24.48	29.38	719.17	17.14	7.34	2995.59	1.36	1.36	30.22	17.34	7.42	717.92	5.60	25.00	28.72	2990.402	1.36	0.000%
45.32	25.27	30.33	766.35	17.69	7.58	3280.83	1.40	1.40	32.35	17.94	7.68	764.74	5.42	30.00	25.49	3273.921	1.40	0.000%
49.44	26.01	31.22	812.12	18.21	7.80	3564.38	1.44	1.44	34.42	18.50	7.92	810.10	5.27	30.00	27.00	3555.545	1.44	0.000%
53.56	26.72	32.06	856.63	18.70	8.02	3846.34	1.47	1.47	36.45	19.04	8.15	854.19	5.13	30.00	28.47	3835.371	1.47	0.000%
39.23	24.79	29.75	737.57	17.35	7.44	3141.31	1.28	1.28	30.70	17.48	7.48	736.84	5.53	25.00	29.47	3138.196	1.28	0.000%
44.13	25.78	30.94	797.82	18.05	7.74	3516.45	1.32	1.32	33.37	18.22	7.80	796.73	5.31	30.00	26.56	3511.666	1.32	0.000%
49.03	26.71	32.05	855.87	18.69	8.01	3889.09	1.36	1.36	35.97	18.92	8.10	854.39	5.13	30.00	28.48	3882.356	1.36	0.000%
53.94	27.57	33.08	912.02	19.30	8.27	4259.41	1.40	1.40	38.50	19.57	8.38	910.10	4.97	30.00	30.34	4250.44	1.40	0.000%
58.84	28.38	34.06	966.49	19.87	8.51	4627.53	1.44	1.44	40.96	20.19	8.64	964.09	4.83	30.00	32.14	4616.064	1.44	0.000%
63.74	29.15	34.98	1019.46	20.40	8.74	4993.59	1.47	1.47	43.38	20.77	8.89	1016.55	4.70	30.00	33.89	4979.355	1.47	0.000%
46.04	26.86	32.23	865.62	18.80	8.06	3993.90	1.28	1.28	36.03	18.93	8.10	864.76	5.10	30.00	28.83	3989.94	1.28	0.000%
51.79	27.93	33.52	936.33	19.55	8.38	4470.86	1.32	1.32	39.17	19.74	8.45	935.05	4.91	30.00	31.17	4464.774	1.32	0.000%
57.54	28.93	34.72	1004.46	20.25	8.68	4944.64	1.36	1.36	42.21	20.49	8.77	1002.72	4.74	30.00	33.42	4936.074	1.36	0.000%
63.30	29.87	35.84	1070.35	20.91	8.96	5415.46	1.40	1.40	45.18	21.20	9.07	1068.10	4.59	30.00	35.60	5404.06	1.40	0.000%
69.05	30.74	36.89	1134.28	21.52	9.22	5883.50	1.44	1.44	48.07	21.87	9.36	1131.47	4.46	37.50	30.17	5868.919	1.44	0.000%
74.81	31.58	37.89	1196.45	22.10	9.47	6348.91	1.47	1.47	50.91	22.50	9.63	1193.04	4.34	37.50	31.81	6330.811	1.47	0.000%

Figure 4.5: Comparison Spreadsheet Designs

Figure 4.6: Comparison Spreadsheet Data Comparisons

Trial	Spacing w/Normalized Burden: Ash Low Spacing	AE Spacing with Normalized Burden	Spacing w/Normalized Burden AE/Ash	Burden: Ash Low Burden	AE Burden	Burden AE/Low Ash	Spacing: Ash Low Spacing	AE Spacing	Spacing AE/Low Ash	Burden w/Normalized Spacing: Ash Low Burden	AE Burden with Normalized Spacing	Burden w/Normalized Spacing AE/Ash
1	22.31	22.29	99.90%	18.59	19.34	104.02%	22.31	21.43	96.04%	18.59	18.58	99.90%
2	23.21	23.17	99.86%	19.34	20.91	108.15%	23.21	21.43	92.34%	19.34	19.31	99.86%
3	24.04	23.99	99.83%	20.03	22.43	111.97%	24.04	21.43	89.15%	20.03	20.00	99.83%
4	24.81	24.76	99.79%	20.68	23.89	115.54%	24.81	21.43	86.37%	20.68	20.63	99.79%
5	25.54	25.48	99.75%	21.28	21.69	101.91%	25.54	25.00	97.88%	21.28	21.23	99.75%
6	26.23	26.16	99.71%	21.86	22.87	104.63%	26.23	25.00	95.30%	21.86	21.80	99.71%
7	24.79	24.77	99.90%	20.66	23.88	115.58%	24.79	21.43	86.43%	20.66	20.64	99.90%
8	25.78	25.75	99.86%	21.49	22.13	103.00%	25.78	25.00	96.96%	21.49	21.46	99.86%
9	26.71	26.66	99.83%	22.26	23.73	106.64%	26.71	25.00	93.61%	22.26	22.22	99.83%
10	27.57	27.51	99.79%	22.97	25.28	110.04%	27.57	25.00	90.68%	22.97	22.93	99.79%
11	28.38	28.31	99.75%	23.65	26.78	113.24%	28.38	25.00	88.09%	23.65	23.59	99.75%
12	29.15	29.06	99.71%	24.29	28.24	116.26%	29.15	25.00	85.77%	24.29	24.22	99.71%
13	27.27	27.24	99.90%	22.73	24.77	108.98%	27.27	25.00	91.67%	22.73	22.70	99.90%
14	28.36	28.32	99.86%	23.64	26.78	113.30%	28.36	25.00	88.14%	23.64	23.60	99.86%
15	29.38	29.33	99.83%	24.48	28.72	117.30%	29.38	25.00	85.10%	24.48	24.44	99.83%
16	30.33	30.26	99.79%	25.27	25.49	100.87%	30.33	30.00	98.93%	25.27	25.22	99.79%
17	31.22	31.14	99.75%	26.01	27.00	103.80%	31.22	30.00	96.10%	26.01	25.95	99.75%
18	32.06	31.97	99.71%	26.72	28.47	106.57%	32.06	30.00	93.57%	26.72	26.64	99.71%
19	29.75	29.72	99.90%	24.79	29.47	118.88%	29.75	25.00	84.03%	24.79	24.77	99.90%
20	30.94	30.90	99.86%	25.78	26.56	103.00%	30.94	30.00	96.96%	25.78	25.75	99.86%
21	32.05	31.99	99.83%	26.71	28.48	106.64%	32.05	30.00	93.61%	26.71	26.66	99.83%
22	33.08	33.01	99.79%	27.57	30.34	110.04%	33.08	30.00	90.68%	27.57	27.51	99.79%
23	34.06	33.97	99.75%	28.38	32.14	113.24%	34.06	30.00	88.09%	28.38	28.31	99.75%
24	34.98	34.88	99.71%	29.15	33.89	116.26%	34.98	30.00	85.77%	29.15	29.06	99.71%
25	32.23	32.20	99.90%	26.86	28.83	107.33%	32.23	30.00	93.08%	26.86	26.83	99.90%
26	33.52	33.47	99.86%	27.93	31.17	111.58%	33.52	30.00	89.50%	27.93	27.90	99.86%
27	34.72	34.66	99.83%	28.93	33.42	115.53%	34.72	30.00	86.41%	28.93	28.88	99.83%
28	35.84	35.76	99.79%	29.87	35.60	119.21%	35.84	30.00	83.71%	29.87	29.80	99.79%
29	36.89	36.80	99.75%	30.74	30.17	98.14%	36.89	37.50	101.64%	30.74	30.67	99.75%
30	37.89	37.78	99.71%	31.58	31.81	100.76%	37.89	37.50	98.97%	31.58	31.49	99.71%

Trial	Area: Ash Low Area	AE Area	Area AE/Low Ash	Stemming: Ash Stemming	AE Stemming	Stemming AE/Ash	Subdrill: Ash Subdrill	AE Subdrill	Subdrill AE/Ash	Explosive Weight: Ash Weight	AE Weight	Explosive Weight AE/Ash
1	414.88	414.47	99.90%	13.02	13.11	100.70%	5.58	5.61	100.57%	1325.24	1323.93	99.90%
2	448.77	448.16	99.86%	13.54	13.67	100.95%	5.80	5.85	100.82%	1483.50	1481.48	99.86%
3	481.43	480.59	99.83%	14.02	14.19	101.19%	6.01	6.07	101.05%	1640.71	1637.87	99.83%
4	513.01	511.93	99.79%	14.47	14.68	101.41%	6.20	6.28	101.27%	1796.94	1793.15	99.79%
5	543.65	542.30	99.75%	14.90	15.14	101.62%	6.39	6.48	101.48%	1952.24	1947.40	99.75%
6	573.45	571.81	99.71%	15.30	15.58	101.81%	6.56	6.67	101.68%	2106.67	2100.67	99.71%
7	512.20	511.69	99.90%	14.46	14.56	100.70%	6.20	6.23	100.57%	1817.89	1816.09	99.90%
8	554.04	553.29	99.86%	15.04	15.18	100.95%	6.45	6.50	100.82%	2034.98	2032.21	99.86%
9	594.35	593.33	99.83%	15.58	15.76	101.19%	6.68	6.75	101.05%	2250.63	2246.73	99.83%
10	633.35	632.01	99.79%	16.08	16.31	101.41%	6.89	6.98	101.27%	2464.93	2459.75	99.79%
11	671.17	669.51	99.75%	16.55	16.82	101.62%	7.09	7.20	101.48%	2677.97	2671.33	99.75%
12	707.96	705.94	99.71%	17.00	17.31	101.81%	7.29	7.41	101.68%	2889.81	2881.57	99.71%
13	619.76	619.15	99.90%	15.91	16.02	100.70%	6.82	6.86	100.57%	2419.61	2417.21	99.90%
14	670.39	669.48	99.86%	16.55	16.70	100.95%	7.09	7.15	100.82%	2708.56	2704.88	99.86%
15	719.17	717.92	99.83%	17.14	17.34	101.19%	7.34	7.42	101.05%	2995.59	2990.40	99.83%
16	766.35	764.74	99.79%	17.69	17.94	101.41%	7.58	7.68	101.27%	3280.83	3273.92	99.79%
17	812.12	810.10	99.75%	18.21	18.50	101.62%	7.80	7.92	101.48%	3564.38	3555.54	99.75%
18	856.63	854.19	99.71%	18.70	19.04	101.81%	8.02	8.15	101.68%	3846.34	3835.37	99.71%
19	737.57	736.84	99.90%	17.35	17.48	100.70%	7.44	7.48	100.57%	3141.31	3138.20	99.90%
20	797.82	796.73	99.86%	18.05	18.22	100.95%	7.74	7.80	100.82%	3516.45	3511.67	99.86%
21	855.87	854.39	99.83%	18.69	18.92	101.19%	8.01	8.10	101.05%	3889.09	3882.36	99.83%
22	912.02	910.10	99.79%	19.30	19.57	101.41%	8.27	8.38	101.27%	4259.41	4250.44	99.79%
23	966.49	964.09	99.75%	19.87	20.19	101.62%	8.51	8.64	101.48%	4627.53	4616.06	99.75%
24	1019.46	1016.55	99.71%	20.40	20.77	101.81%	8.74	8.89	101.68%	4993.59	4979.35	99.71%
25	865.62	864.76	99.90%	18.80	18.93	100.70%	8.06	8.10	100.57%	3993.90	3989.94	99.90%
26	936.33	935.05	99.86%	19.55	19.74	100.95%	8.38	8.45	100.82%	4470.86	4464.77	99.86%
27	1004.46	1002.72	99.83%	20.25	20.49	101.19%	8.68	8.77	101.05%	4944.64	4936.07	99.83%
28	1070.35	1068.10	99.79%	20.91	21.20	101.41%	8.96	9.07	101.27%	5415.46	5404.06	99.79%
29	1134.28	1131.47	99.75%	21.52	21.87	101.62%	9.22	9.36	101.48%	5883.50	5868.92	99.75%
30	1196.45	1193.04	99.71%	22.10	22.50	101.81%	9.47	9.63	101.68%	6348.91	6330.81	99.71%

4.3.1. Sampling Intervals. The accuracy of any comparison is related to sample size. Too few data points may show promising data, but no researcher can be certain that the comparison fully maps the design space. Too many data points, and the researcher is wasting time in unnecessary testing. For the purposes of these comparisons, convenient data points are already defined by varying borehole diameter, product density, face height, cut width, and the stemming and subdrilling correction factors. By testing across a variety of these design inputs, the entire design domain can be mapped with reasonable accuracy while maintaining a manageable quantity of data by avoiding tests of fractional values.

In the case of Ash-AE comparisons, additional work needed to be done concerning appropriate face heights and spacing values. One of the largest challenges of the Ash comparison test was to determine what face heights were appropriate for use with the method. Ash's single face height recommendation based on surface mine design (Ash, 1968) does nothing to relate to burden or spacing, which creates a situation where face heights may be quite low relative to the borehole diameter. Low face heights bring low efficiencies of borehole use and at some point, the blast design will require more stemming than borehole unless guidelines are modified. To determine what face heights worked best, a number of tests were conducted with a wide range of face heights, narrowing the range until the best results were obtained. A general guideline of ten feet of face height per inch of borehole diameter was used as a starting point for the testing; this rule of thumb is currently taught at S&T as a good starting place for design (Worsey, 2012). From this starting point, the face height was both shortened and extended to determine what face height ranges were reasonable for design purposes.

Each Ash comparison test consisted of 5040 individual design scenarios. This number of design scenarios tested five borehole diameters, six product densities, seven face height factors (multiples of the 10*borehole diameter guideline), six cut widths, and four stemming factors. The hierarchy of variables is as follows:

- Entire test: 5,040 trials
  - Stem Factor: 1,260 trials at four separate values *(4*1,260=5,040)*
    - Cut Width: 210 trials at six separate values *(6*210=1,260)*
      - Face Height: thirty trials at seven values *(30*7=210)*
        - Borehole Diameter: six trials at five values *(6*5=30)*
          - Product Density: one trial at six values *(1*6=6)*

This test construction allowed a single spreadsheet to test the entire design domain for the five cut widths. Several tests were run to try different face height multiplier, spacing relationships, and the effects of subdrill. To keep the amount of data per test at a reasonable level, only five cut widths were tested. The great majority of testing used ten foot intervals from 150-200 feet, with two final tests using seventy foot intervals to reach from 150-500 feet. The actual testing parameters used for the Ash - AE comparison are discussed in Section 5 and displayed in Appendix A.

Konya comparisons to the Available Energy method were slightly less complicated than Ash comparisons. Konya varies spacing based on stiffness ratio (defined as burden divided by face height), removing the spacing challenges. Face height still required some initial variation to test the best fit, and the same ten feet of face height per inch of borehole diameter was used as a starting point. Konya also specifies rock density in terms of specific gravity rather than unit weight, meaning that the 162 lb/cft value used for Ash was converted to a specific gravity for Konya's comparisons.

The only notable addition to the comparison spreadsheet was a column to track the stiffness ratio of each design. Konya ties the selection of spacing equation to stiffness ratio, and the equation selection process (and the equations themselves) was programmed into the comparison spreadsheet.

4.3.2. Truing Up the Models. Available Energy based design methods deviate from traditional design methods in several ways, making direct comparisons between methods difficult. Since the main quantities of explosive weight and volume are defined by powder factor, modifying the stemming and subdrilling compensation factors is the primary challenge of truing up or matching linear dimensions of blast design between traditional methods like Ash and Konya and the AE based method.

4.4. COMPARISON TESTING TOOLS

The testing setups described in this section generated thousands of individual design scenarios that needed to monitored during testing and ultimately be examined to determine how well the blast design methods compare. Scrolling through thousands of design scenarios is not practical and can easily become confusing. Two methods of data tracking have been devised that enabled monitoring of the comparison process and the tracked the accuracy of the final comparison.

4.4.1. Graphical Divergence Monitoring. Monitoring the comparisons graphically presents the best solution to tracking the accuracy of a wide range of solutions across a large test size. By creating graphs that track comparison results, the entire domain of the test can be monitored throughout the testing process.

4.4.1.1. Linear regression. A type of linear regression graph has been created to show how well the AE values match the Ash or Konya values while testing. Two sets of values are plotted on a chart, with the X axis representing data set A and the Y axis representing data set B, and a trendline is drawn through the data points. How closely the data sets match can be monitored through the slope of the trendline and how well the trendline fits the data points. If the two data sets match, the slope of a trendline drawn through the data points will equal one, and the R^2 value will also equal one. Variations in either trendline slope or R^2 value indicate that the data sets do not match well, and further modifications are required to true up the methods. One of the benefits of this particular type of graph is that by using logarithmic scales for both the X and Y axes, multiple data sets with widely ranging values can be viewed on the same graph.

4.4.1.2. Percentage match guidance. While the linear regression graph tracks the overall fit of the data, it does little to tell the user where problems may be found in the process of matching the data sets. To find problem areas in the data, such as design scenarios where the face height is too low, additional charts are needed. The Percentage Match chart tracks the difference between individual entities within the two data sets. For instance, if data set A had a value of 10.8 and data set B had a value of 11.2 for the same design scenario, the Percentage Match chart would use Equation 4.1 to calculate how well the values match – in this case, the value is slightly over 96%.

$$Percentage\ Match = \frac{A}{B} = \frac{10.8}{11.2} = 0.9643\ or\ 96.43\% \qquad \text{Eqn. 4.1}$$

The error between these two values is relatively small and logically, the closer the values the closer the calculated percentage will be to 100% - no error. A chart of data representing trial number on the X axis and percentage match on the Y axis indicates to the user where the data sets match well, where the values diverge, and the magnitude of the divergence. Tracking the percentage match of data sets for several variables on the same chart is easily done, and adjusting the scale of the Y axis helps increase the viewable range of good and bad matches.

4.4.2. Sample Data Sets and Comparisons. Sample data sets and graphs have been created to help illustrate the points already discussed with a manageable quantity of data. The following data sets illustrate two stages in a truing up process: First, the raw data prior to compensation factor adjustment, and second, the refined data similar to what would exist after thorough adjustment of compensation factors to result in the final product. These sample data sets and graphs are arbitrary creations for the sole purpose of illustrating the comparison process. Analysis of testing results in the following section will consist of graphs from the actual data comparisons. The construction of the Ash and Konya comparison spreadsheets and the specifications of data used are contained in Appendix A.

4.4.2.1. Sample comparison 1. Sample comparison 1 shows ten trials for eight data types. These data types could represent Burden, Spacing, Available Energy, Explosive Weight, or any of the critical comparison values. Table 4.1 shows the data sets with the percentage matches already calculated in accordance with Equations 4.1. The data contained in Table 4.1 represents the raw data with no modification of values to represent the adjustment of compensation factors for a better match between the design methods.

Figure 4.7 shows linear regression on the data in Table 4.1. The trendline equations are shown on the graph, and the varying slopes (represented by the exponents of the power equations) and R^2 values indicate that the two data sets do not match very well. The X and Y columns in Table 4.1 are represented by the X and Y axes, respectively, of the linear regression chart. Figure 4.7 also shows the percentage error graph for the same Sample 1 data set. The graph shows that the majority of the eighty data points representing ten trials for eight types of data compare within 20% of each other. The highest error is 50% for Trial 1 of Alpha, and the lowest error is less than one percent for Gamma on Trial 5. Visual analysis of this graph reveals that the best single solution across all variables was Trial 9, where Alpha was approximately 15% error, and that Trial 1 has the largest single error. By monitoring a graph such as this, the user can immediately identify problem areas in the data sets and mark them for further review.

4.4.2.2. Sample comparison 2. Table 4.2 shows the results of modifying the data set. The X columns have all been arranged in increasing order, and the Y columns have been modified similar to the results of changing compensation factors for the actual comparison tests. Table 4.2 shows the new data set.

The linear regression for sample comparison 2 is represented in Figure 4.8. The data represents a much better fit, as evidenced by the improved R^2 values and trendline slopes much closer to one. Similarly, the percentage match graph shown in Figure 4.8 represents much better data comparisons across the ten trials. The highest error is now around 10%, and the best solution appears to be Trial 9. These techniques can be expanded to monitor many thousands of trials and indicate areas of interest where data sets do not match well.

Table 4.1: Sample 1 Data

Sample 1 Data

Trial	X Alpha	Y Alpha2	X/Y	Trial	X Delta	Y Delta2	X/Y
1	1	2	50.00%	1	40	44	90.91%
2	2	3	66.67%	2	41	45	91.11%
3	3	4	75.00%	3	40	42	95.24%
4	4	5	80.00%	4	44	41	107.32%
5	5	6	83.33%	5	48	50	96.00%
6	6	7	85.71%	6	43	46	93.48%
7	7	8	87.50%	7	42	48	87.50%
8	8	9	88.89%	8	44	41	107.32%
9	9	10	90.00%	9	48	46	104.35%
10	10	11	90.91%	10	50	42	119.05%

Trial	X Beta	Y Beta2	X/Y	Trial	X Tau	Y Tau2	X/Y
1	10	10.2	98.04%	1	50	53	94.34%
2	10.2	11	92.73%	2	55	54	101.85%
3	10.1	10.5	96.19%	3	56	58	96.55%
4	10.4	10.7	97.20%	4	58	52	111.54%
5	10.6	10.3	102.91%	5	52	56	92.86%
6	10.1	10.5	96.19%	6	54	57	94.74%
7	11	11	100.00%	7	59	51	115.69%
8	10.8	10	108.00%	8	50	53	94.34%
9	10	10.2	98.04%	9	56	55	101.82%
10	10.4	10.8	96.30%	10	57	50	114.00%

Trial	X Epsilon	Y Epsilon2	X/Y	Trial	X Gamma	Y Gamma2	X/Y
1	22	23	95.65%	1	100	95	105.26%
2	24	18	133.33%	2	110	115	95.65%
3	28	20	140.00%	3	105	110	95.45%
4	24	25	96.00%	4	120	113	106.19%
5	28	22	127.27%	5	112	113	99.12%
6	26	29	89.66%	6	108	106	101.89%
7	22	30	73.33%	7	97	115	84.35%
8	30	26	115.38%	8	104	114	91.23%
9	21	21	100.00%	9	102	100	102.00%
10	24	29	82.76%	10	110	108	101.85%

Trial	X Sigma	Y Sigma2	X/Y	Trial	X Omega	Y Omega2	X/Y
1	31	33	93.94%	1	120	130	92.31%
2	35	34	102.94%	2	125	133	93.98%
3	36	39	92.31%	3	140	133	105.26%
4	33	35	94.29%	4	160	132	121.21%
5	31	31	100.00%	5	158	175	90.29%
6	34	37	91.89%	6	132	151	87.42%
7	39	32	121.88%	7	156	148	105.41%
8	37	36	102.78%	8	164	169	97.04%
9	36	35	102.86%	9	182	176	103.41%
10	30	33	90.91%	10	128	145	88.28%

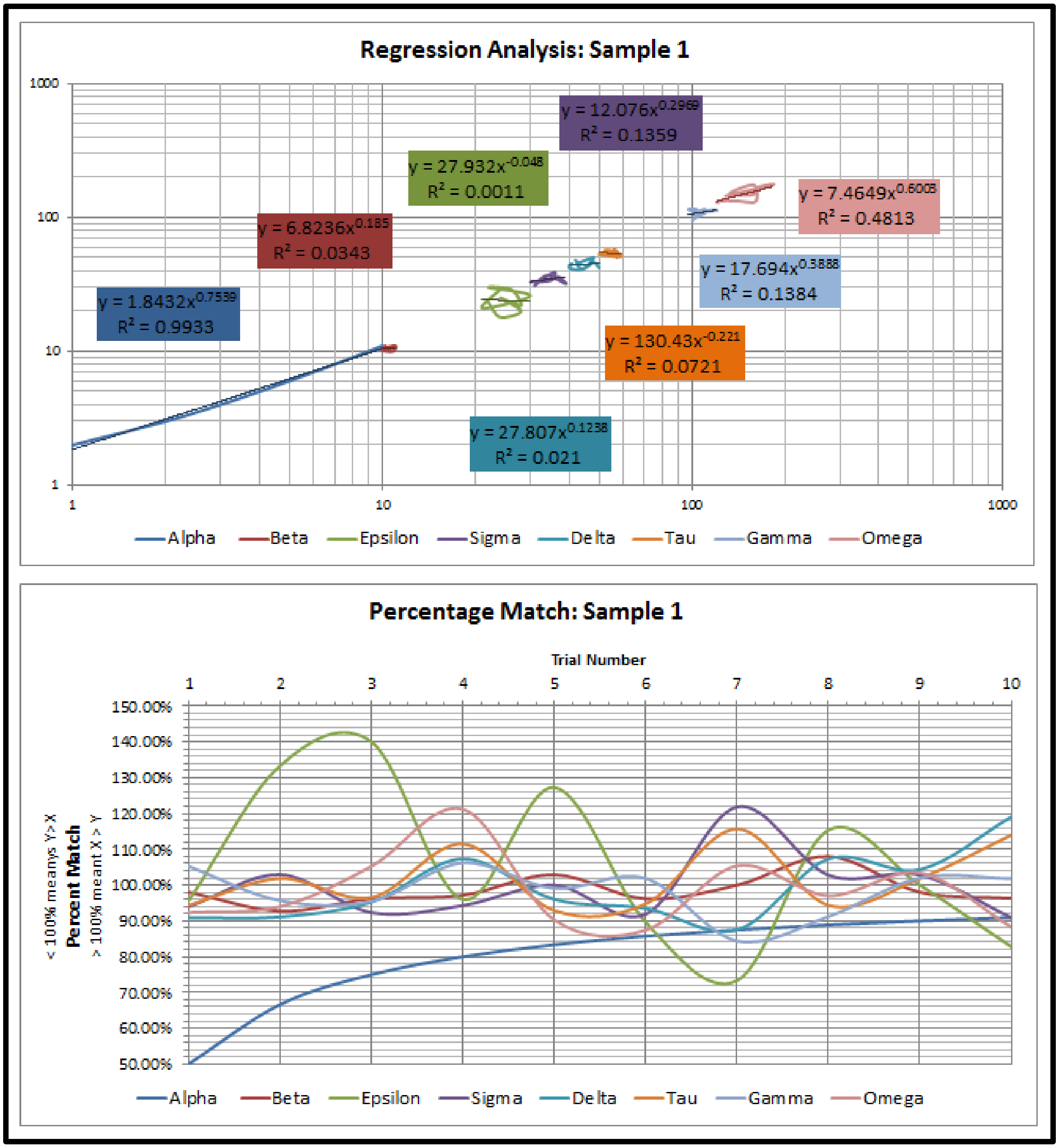


Figure 4.7: Sample 1 Graphs

In cases with many thousands of trials using similar patterns of design scenarios, the percentage match chart is particularly useful in determining which trials are the best and worst matches – information that helps determine which design inputs cause problems. This capability will be particularly useful in determination of appropriate stemming and face height relationships

4.5. FINALIZED TESTING METHOD

The comparison testing between the AE method, Ash and Konya, consisted of Excel spreadsheets that generated Ash or Konya pattern designs based on a range of input values. AE designs were created based on the same input values and the powder factor of Ash or Konya as applicable, and the two pattern designs were compared to determine whether the AE method is intrinsically comparable to the widely accepted Ash and Konya methods. The comparison tests generated large quantities of data, and the accuracy of the matches was monitored using the methods outlined in this section.

Table 4.2: Sample 2 Data

Sample 2 Data

Trial	X Alpha	Y Alpha2	X/Y	Trial	X Delta	Y Delta2	X/Y
1	1	1.1	90.91%	1	40	41	97.56%
2	2	1.9	105.26%	2	41	41.2	99.51%
3	3	2.8	107.14%	3	40	40.4	99.01%
4	4	4.2	95.24%	4	44	44.5	98.88%
5	5	4.8	104.17%	5	48	47.8	100.42%
6	6	5.9	101.69%	6	43	43.6	98.62%
7	7	6.9	101.45%	7	42	41.7	100.72%
8	8	8.1	98.77%	8	44	43.9	100.23%
9	9	9	100.00%	9	48	47	102.13%
10	10	9.9	101.01%	10	50	49	102.04%

Trial	X Beta	Y Beta2	X/Y	Trial	X Tau	Y Tau2	X/Y
1	10	10.1	99.01%	1	50	50.5	99.01%
2	10.2	10.9	93.58%	2	55	55.4	99.28%
3	10.1	10	101.00%	3	56	55.8	100.36%
4	10.4	10.2	101.96%	4	58	57.9	100.17%
5	10.6	10.8	98.15%	5	52	53	98.11%
6	10.1	9.9	102.02%	6	54	53.6	100.75%
7	11	11	100.00%	7	59	60	98.33%
8	10.8	10.7	100.93%	8	50	51	98.04%
9	10	10.1	99.01%	9	56	56.3	99.47%
10	10.4	10.6	98.11%	10	57	57	100.00%

Trial	X Epsilon	Y Epsilon2	X/Y	Trial	X Gamma	Y Gamma2	X/Y
1	22	22.2	99.10%	1	100	99	101.01%
2	24	23.9	100.42%	2	110	111	99.10%
3	28	28.1	99.64%	3	105	107	98.13%
4	24	23.7	101.27%	4	120	118	101.69%
5	28	27.5	101.82%	5	112	111	100.90%
6	26	28	92.86%	6	108	107	100.93%
7	22	22.4	98.21%	7	97	99	97.98%
8	30	31	96.77%	8	104	105	99.05%
9	21	20.7	101.45%	9	102	101	100.99%
10	24	24.6	97.56%	10	110	109	100.92%

Trial	X Sigma	Y Sigma2	X/Y	Trial	X Omega	Y Omega2	X/Y
1	31	31	100.00%	1	120	125	96.00%
2	35	35.3	99.15%	2	125	127	98.43%
3	36	35.8	100.56%	3	140	138	101.45%
4	33	32.4	101.85%	4	160	155	103.23%
5	31	31.3	99.04%	5	158	163	96.93%
6	34	35.1	96.87%	6	132	135	97.78%
7	39	39.6	98.48%	7	156	152	102.63%
8	37	37.4	98.93%	8	164	162	101.23%
9	36	35.9	100.28%	9	182	177	102.82%
10	30	30	100.00%	10	128	135	94.81%

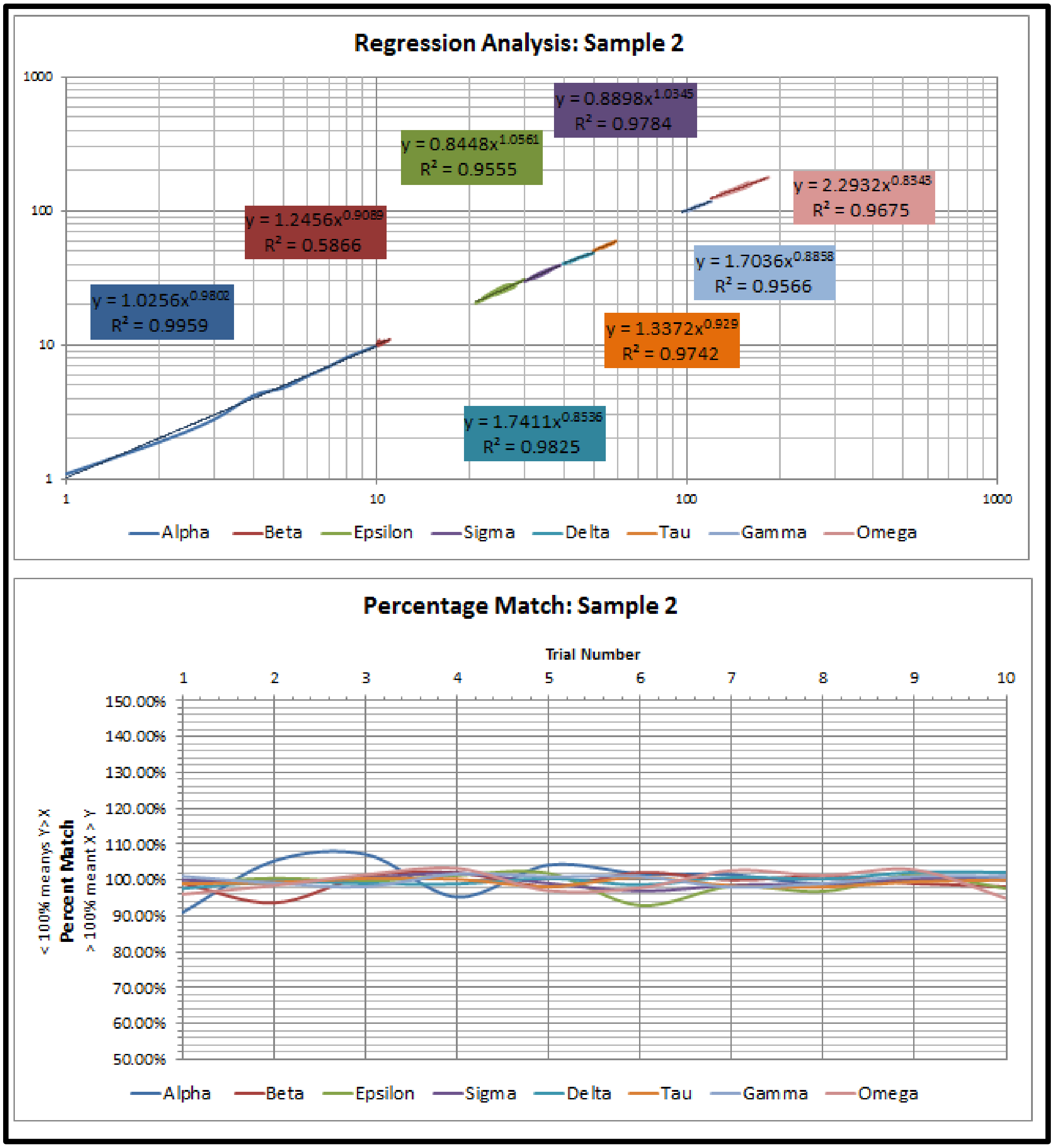


Figure 4.8: Sample 2 Graphs

5. DATA ANALYSIS

5.1. RESULTS OF TESTING

Comparison testing was conducted separately, first against Ash, then against Konya. Small diameter testing took place first to ensure that the tests were largely conducted within the original design domains envisioned by Ash and Konya, then the tests were expanded to large diameter boreholes. Testing also differentiated between designs with subdrilling and designs with no subdrilling. Additional partitioning was done with respect to face height. Face heights were generated as multipliers based on the general guideline of ten feet of face height per inch of borehole diameter. A relationship using borehole diameter was important to allow face heights to grow proportional to the size of the hole. Established practices for blast design often use a multiple of burden for calculating various parameters such as stemming, spacing, and subdrilling. These factors depend on borehole diameter since burden is always calculated based on borehole diameter; therefore, using a face height guideline that integrates borehole diameter continues the logic and gives a starting point for comparisons. Spacing was varied for Ash's method using values from the recommended ranges, whereas Konya's method had separate spacing formulas for use with varying face heights as appropriate. Excellent results were obtained in all cases.

The testing generated large quantities of data in formats not conducive to printing on a standard 8.5" x 11" sheet. Excerpts from the spreadsheets may be found in Appendix A. For the purposes of data analysis, the percentage match and linear regression charts will illustrate the quality of the fit between data methods and will be shown in the following sections.

A key point to remember is that not all dimensions are equally important. Explosive weight is important, as it represents half the powder factor ratio. In this case, due to geometric differences, burden and spacing are not nearly as critical as surface area – if the surface area matches, geometric differences will account for the differences in burden and spacing. One item of critical importance is relative stemming values. In preliminary testing, an interesting phenomenon was observed. Since AE calculates subdrill as a percentage of stemming, it was occasionally possible to arrive at reasonable surface areas and explosive weights yet have far too much stemming. The high stemming value corresponded to a high subdrilling value, maintaining explosive quantity while virtually pushing the explosive column down into a lower bench. This sort of situation is not practical and brought a potential problem with the design method to light. In order, the most important variables are explosive weight and surface area, followed by stemming and subdrill (if present), with spacing and burden in last place.

5.1.1. Ash Comparison. The Ash tests used two subsets of borehole diameters: two to six inches for the small subset, and nine to thirteen inches for the large subset. Explosive densities from 0.8-1.3 grams per cubic centimeter were used, and spacing factors of either 1.2 or 1.4. Face heights consisted of two ranges based on the ten feet of face height per inch of borehole diameter guideline – with a wide range from 25% to 175% and a narrow range from 75% to 125% of the recommended height. Table 5.1 identifies the parameters of the comparison tests, and also shows the R^2 values and slopes for each of the items in each of the tests. A sampling of the test graphs will be discussed following the tables; the entire range of test graphs is available in Appendix A.

Table 5.1: Ash Comparison Results

Ash - Available Energy Comparison Results

Test	Spacing Factor	Borehole Diameter	Subdrill?	Face Height Range	AE Stem Factor for Given Ash Factor				AE Sub Factor for Given Ash Factor			
					0.7	0.8	0.9	1	0.7 St, 0.3 Sub	0.8 St, 0.3 Sub	0.9 St, 0.3 Sub	1.0 St, 0.3 Sub
Ash Test 1	1.2	Small	No	Wide	0.581	0.653	0.723	0.790	NA	NA	NA	NA
Ash Test 2	1.2	Small	No	Narrow	0.581	0.653	0.723	0.790	NA	NA	NA	NA
Ash Test 3	1.2	Small	Yes	Narrow	0.607	0.684	0.758	0.830	0.428	0.375	0.334	0.300
Ash Test 4	1.2	Small	Yes	Wide	0.607	0.684	0.758	0.830	0.428	0.375	0.330	0.300
Ash Test 5	1.4	Small	No	Narrow	0.537	0.605	0.670	0.736	NA	NA	NA	NA
Ash Test 6	1.4	Small	Yes	Narrow	0.562	0.633	0.702	0.769	0.428	0.375	0.334	0.300
Ash Test 7	1.2	Large	No	Narrow	0.581	0.653	0.723	0.790	NA	NA	NA	NA
Ash Test 8	1.2	Large	Yes	Narrow	0.607	0.684	0.758	0.830	0.428	0.375	0.334	0.300
Ash Test 9	1.4	Large	No	Narrow	0.538	0.605	0.669	0.731	NA	NA	NA	NA
Ash Test 10	1.4	Large	Yes	Narrow	0.562	0.633	0.702	0.769	0.428	0.375	0.334	0.300

Test	Explosive Weight		Area		Stemming		Subdrill		Spacing		Burden	
	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope
Ash Test 1	NA	NA	NA	NA	0.7079	1.0358	NA	NA	NA	NA	NA	NA
Ash Test 2	1	1.0006	0.9999	0.9997	0.9969	1.0006	NA	NA	0.998	1.0003	0.998	0.9991
Ash Test 3	1	1.0002	1	0.9999	0.9989	1.0002	0.9988	1.0015	0.9981	1.0001	0.9981	0.9996
Ash Test 4	NA	NA	NA	NA	0.9351	1.0119	0.9268	1.0029	NA	NA	NA	NA
Ash Test 5	1	1.0007	0.9999	0.9997	0.997	1.0024	NA	NA	0.9975	0.9999	0.9976	0.9995
Ash Test 6	1	1.0002	1	0.9999	0.9989	1.0005	0.9988	1.0015	0.9976	0.9999	0.9976	0.9999
Ash Test 7	0.9998	1.0041	0.9995	0.9975	0.9862	1.0029	NA	NA	0.9025	1.0014	0.9018	0.9937
Ash Test 8	1	1.0014	0.9999	0.9991	0.9949	1.001	0.9908	1.0113	0.9043	1.0091	0.901	0.9892
Ash Test 9	0.9998	1.0041	0.9995	0.9975	0.9861	1.0016	NA	NA	0.8905	1.0036	0.8877	0.9915
Ash Test 10	1	1.0014	0.9999	0.9991	0.995	1.0021	0.9909	1.0113	0.8906	1.002	0.8895	0.9962

Based on the methods explained in the previous section, all R^2 and slope values would equal one in the case of a perfect fit. Reviewing Table 5.1, it becomes apparent that while the fit was not consistently perfect, the fit is often quite close to perfect. “NA” blanks in the table represent tests where the data was so scattered that reasonable trendlines could not be drawn, or the item in question was not used in the tests. Figure 5.1 shows Ash Test 1 to explain how some tests had extremely poor fit.

Referring to Table 5.1, Ash Test 1 had the widest range of face heights to determine whether the original “face height in feet equal to ten times the borehole diameter in inches” guideline was accurate. The percentage match graph for Ash Test 1 indicates that approximately every 210 trials, a solution would have extremely high error.

These errors coincide with low face heights, where the required stemming height fills a large proportion of the borehole.

Ash's design method is based on borehole diameter, explosive density, and rock density, which generate a burden independent of face or stemming height. With Ash's method, powder factor is allowed to fluctuate and is only calculated after the design is complete.

Ash's powder factor for a design where a large proportion of the borehole is filled with stemming would be quite small, forcing the AE method to try to generate a pattern for that small powder factor. In some cases, these tests would actually generate unsolvable problems where the required height of stemming based on Ash's design methods would entirely fill the borehole. If the borehole is full of stemming, no explosive can be used and there is no solution. Because of these problems that occur on the fringes of the design domain, the author has begun emphasizing the efficiency index and wider practical variation in stemming heights, to allow blasters to safely monitor and adjust patterns to find reasonable and economical solutions. The efficiency index will indicate whether the method has found a solution, or if the desired stemming factor and AE level is creating an unsolvable problem. Further discussion of potential design challenges is contained in Appendix E.

The linear regression on Figure 5.1 indicates that certain designs are varying widely from the planned values. Wide variations are noticeable in Area, Explosive Weight, and Stemming. Note that the "Burden" and "Spacing" values on the regression charts are the straight burden and spacing, with no normalizing calculations completed.

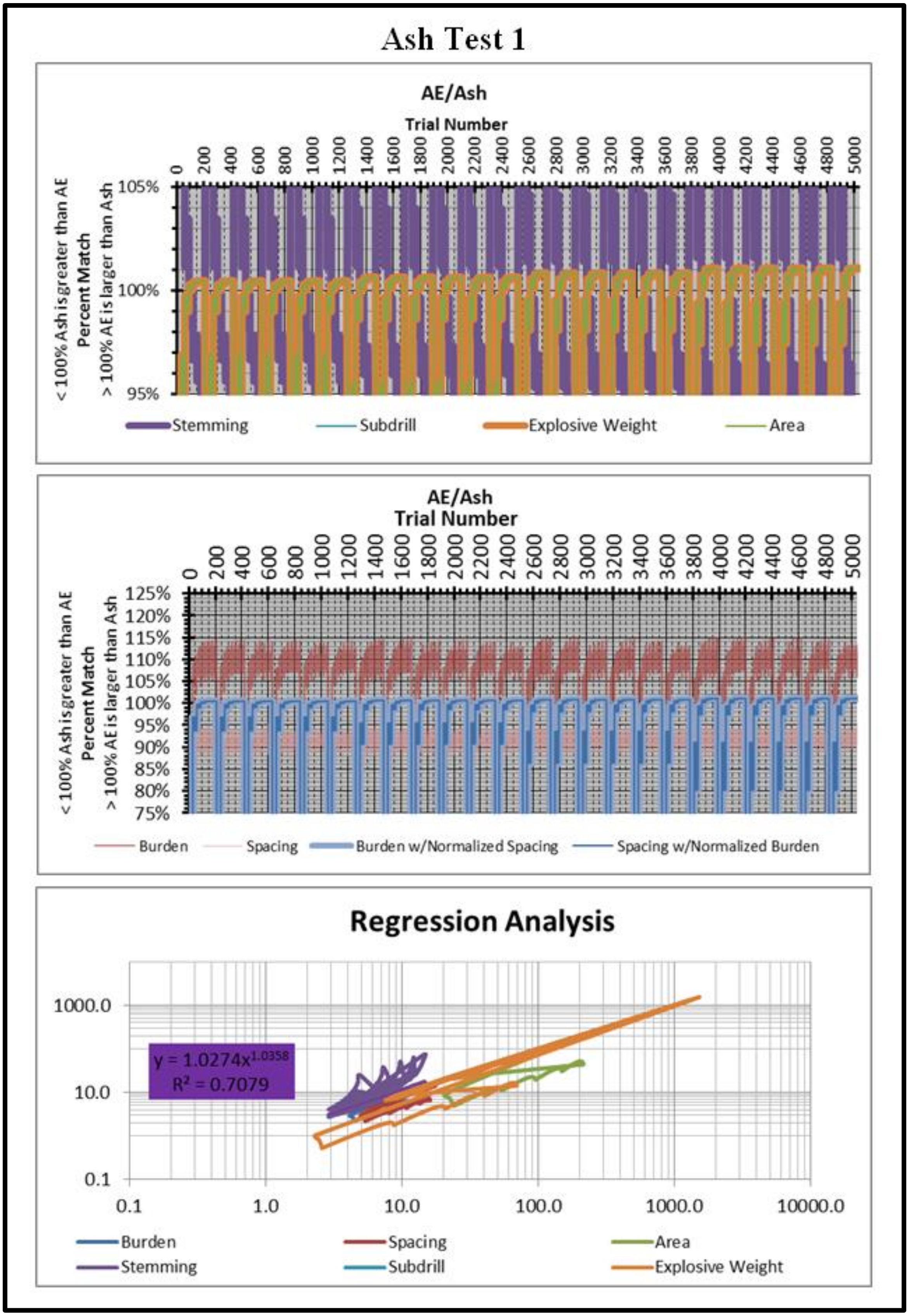


Figure 5.1: Ash Test 1 Graphs

These variations are triggered by the wide range in face height differences shown by Ash Test 1. The wide range of face height values prevents one set of spacing and subdrilling values from working for all problems within that particular design range. Figure 5.2 shows the results of a narrow range of face heights and illustrates how well the patterns can match.

Ash Test 2 shows a significantly more accurate solution than Ash Test 1. The difference between the tests is the width of face height values that were tested – with Test 1 using the wide range, and Test 2 using the narrow range. All other factors are held constant between the tests. The same peaks and valleys are observed at approximately 210 trial intervals, illustrating the effects of low and high face heights, respectively, relative to borehole diameter. Note the stability of the two most critical factors – area and explosive weight. The maximum error observed from either of those factors is at most 3%. Stemming varies up to approximately 5%.

The second graph in Figure 5.2 tells an important story that is now much more visible than the version in Figure 5.1. The second graph illustrates how well burden and spacing match between methods. The comparison of Ash and Available Energy burden and spacing values is similar to comparing apples and oranges. Ash's patterns are rectangular in nature, evidenced by spacing factors from 1.2-1.4 times the burden. Available Energy patterns are closer to square to better distribute energy under the blanket of material represented by the surface area of individual borehole influence. Rectangles and squares do not have matching side lengths, but they can have matching areas.

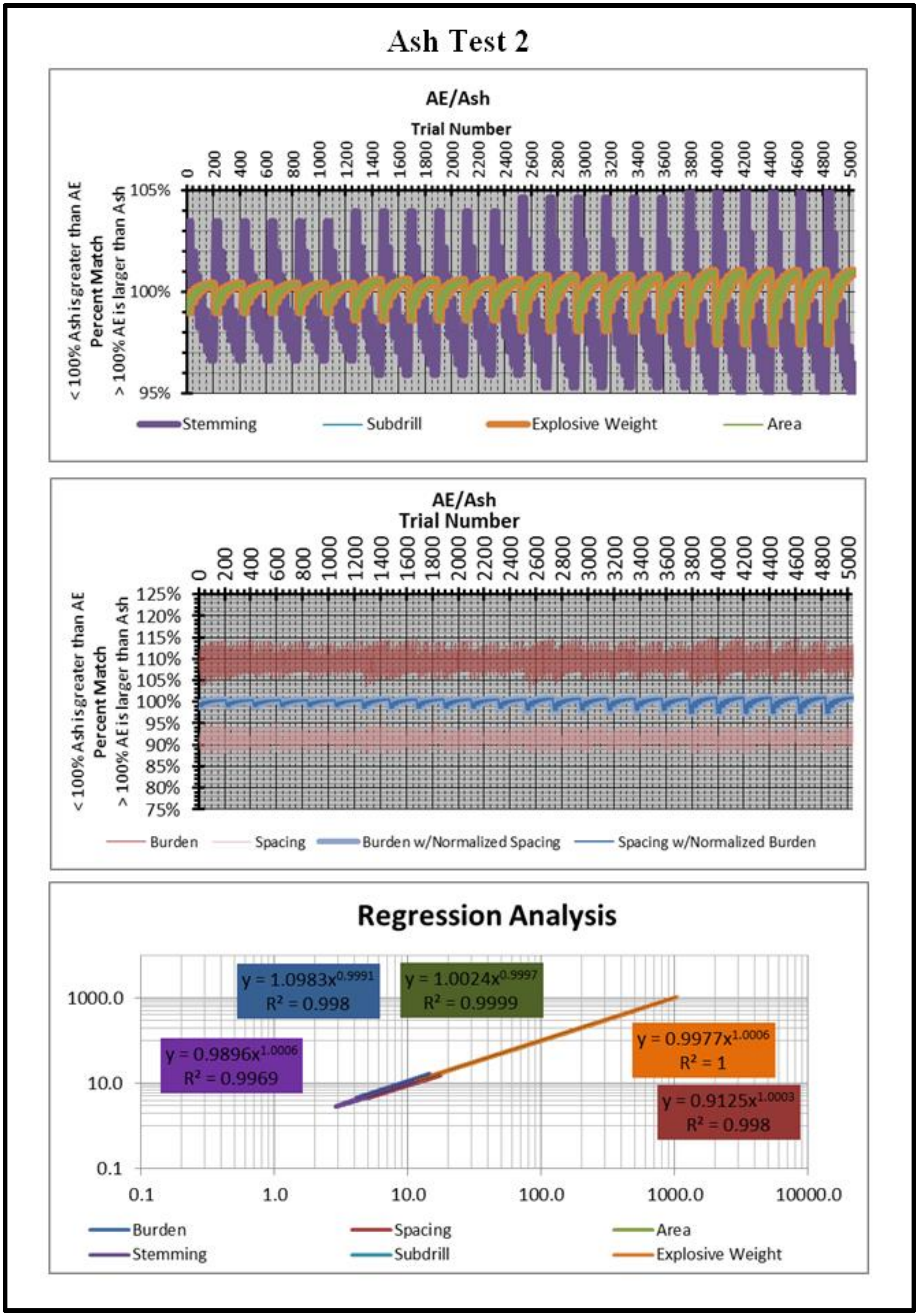


Figure 5.2: Ash Test 2 Graphs

Attempting to match burdens and spacings with no corrections to either length between Ash and Available Energy will be misleading, as the areas may well be similar but the edges of the areas remain different. Therefore, the second graph shows two burden values and two spacing values. Normal burden and spacing matches are shown in different shades of red and vary from 5-15% error, which is not unreasonable considering the two values are so conceptually different. The blue lines on the second graph represent normalized burden and spacing – calculated by using the AE area divided by Ash spacing and burden to generate a normalized burden and spacing, respectively. This process illustrates how closely the areas of the two methods match, since the normalized values of burden and spacing consistently have much lower error than the straight values with no modifications. Normalization is not strictly necessary, as comparing surface area (often just called area during the testing) will immediately verify the accuracy of the method comparison. However, normalization has been included for visual reference, to remind the reader that while direct comparisons of burden and spacing are informative, they are not the best measure of the accuracy of method comparison.

Ash Test 3 is similar to Ash Test 2 but also includes subdrilling. Face height range is still narrow, and borehole diameters are still small. Figure 5.3 illustrates Ash Test 3. Test 3 looks much like Test 2 with the addition of a subdrilling trace directly on top of the stemming trace. Maximum error is in the neighborhood of 3.5%, and the R^2 values and slopes in the linear regression are all quite close to 1.

These small diameter tests illustrate the process of matching the Available Energy method to Ash's work. Large scale testing is unremarkably similar to small scale testing – a logical condition since all Ash's work hinges off borehole diameter as an input of the burden equations – the starting point for all of Ash's design work. Figure 5.4 illustrates Ash Test 10, the culmination of the testing process. Test 10 uses the large spacing value, narrow face height range, and subdrilling. Very little difference is observed between the graphs of Test 3 and Test 10, except in the regression values for burden and spacing. The regression values for burden and spacing are the straight values with no normalization, therefore since the spacing value has increased from 1.2 to 1.4 times burden, Ash's rectangular apple measures less like Available Energy's square orange.

However, both surface area and explosive weight match very nicely, indicating that the patterns on the whole are similar, and both stemming and subdrill match well, indicating that the explosive column is indeed within the target bench.

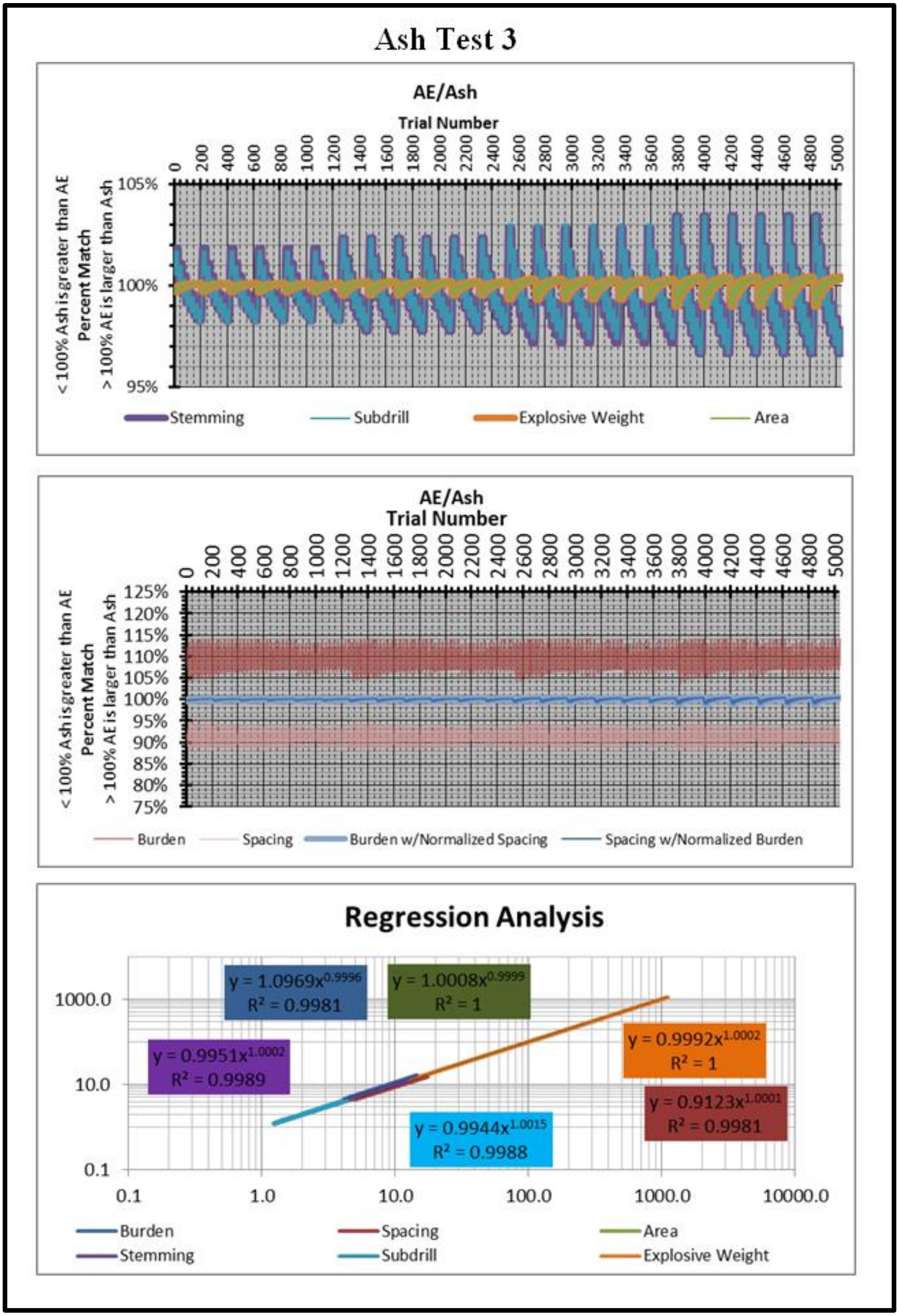


Figure 5.3: Ash Test 3 Graphs

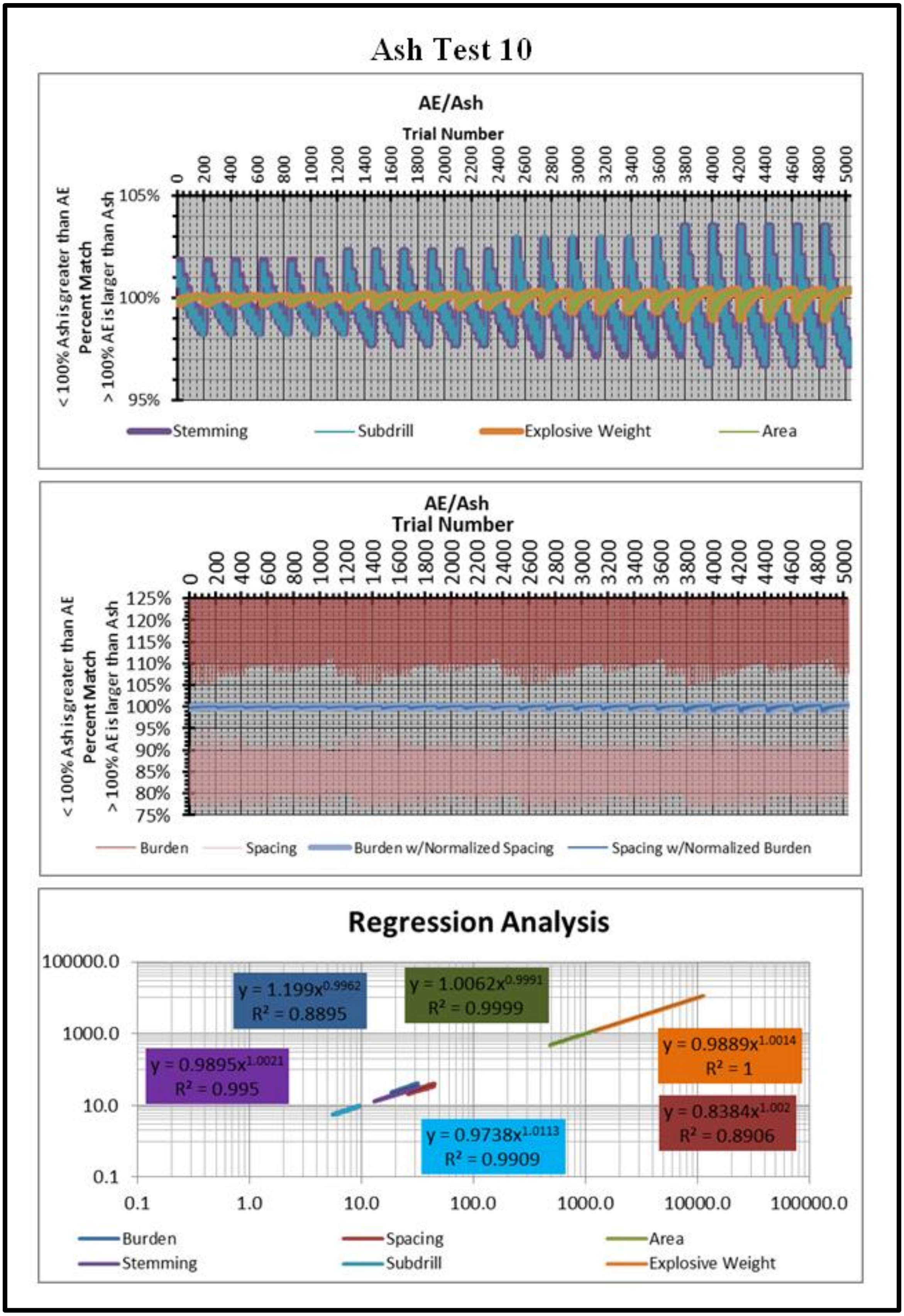


Figure 5.4: Ash Test 4 Graphs

5.1.2. Konya Comparison. The Konya comparison spreadsheet is constructed similar to the Ash comparison spreadsheet with a few alterations to enable the use of Konya blast design equations. The Konya comparison spreadsheet included an extra column to track stiffness ratio, which Konya defines as face height divided by burden. Konya provides four spacing equations (Konya & Walter, 1991) that the user must choose from depending on site conditions. Two Konya spacing equations are used for faces with stiffness ratios between one and four, and two are used for faces with stiffness ratios above four. Of the two equations per stiffness ratio, one is for an initiation system with delays for each borehole, and the other is for instantaneous initiation where all boreholes fire at the same time. The Konya tests were conducted using the two spacing equations for delayed initiation systems according to industry best practice. The spacing column of the Konya comparison spreadsheet was programmed to calculate the appropriate spacing based on the stiffness ratio of the individual design scenario.

Konya's additional spacing formulas and two stemming heights simplifies the comparison process, requiring only six tests of 2,520 trials. The same explosive densities, face height ranges, and borehole diameters were used for the Konya comparison, and all graphs and pertinent inputs can be found in Appendix A. Table 5.2 shows the results of the Konya comparison.

The Konya comparisons generated useful data showing excellent fits for the narrow range of face heights. As with the Ash comparisons, wide face height ranges resulted in poor data fits as reflected by a lack of linear regression trendline and slope values. Graphs for Konya Test 1 are shown in Figure 5.5.

Table 5.2: Konya Comparison Results

Konya - Available Energy Comparison Results

Test	Borehole Diameter	Subdrill?	Face Height	AE Stem Factor for Given Konya Factor 0.7	AE Stem Factor for Given Konya Factor 1	AE Sub Factor for Given Konya Factor 0.7 St, 0.3 Sub	AE Sub Factor for Given Konya Factor 1.0 St, 0.3 Sub
Konya Test 1	Small	No	Wide	0.545	0.745	NA	NA
Konya Test 2	Small	No	Narrow	0.545	0.745	NA	NA
Konya Test 3	Small	Yes	Narrow	0.572	0.780	0.429	0.300
Konya Test 4	Small	Yes	Wide	0.572	0.780	0.429	0.300
Konya Test 5	Large	No	Narrow	0.547	0.750	NA	NA
Konya Test 6	Large	Yes	Narrow	0.572	0.780	0.429	0.300

Test	Explosive Weight		Area		Stemming		Subdrill		Spacing		Burden	
	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope
Konya Test 1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Konya Test 2	1.0000	1.0003	1.0000	0.9999	0.9993	1.0015	NA	NA	0.9958	0.9979	0.9954	0.9980
Konya Test 3	1.0000	1.0000	1.0000	1.0000	0.9996	0.9975	0.9995	1.0000	0.9956	0.9981	0.9958	0.9980
Konya Test 4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Konya Test 5	0.9999	1.0021	0.9998	0.9995	0.9976	1.0104	NA	NA	0.8765	0.9891	0.8709	0.9798
Konya Test 6	1.0000	0.9999	1.0000	0.9997	0.9986	0.9910	0.9961	1.0001	0.8742	0.9875	0.8728	0.9816

Konya Test 1 is a small borehole test with a wide face height variation and no subdrill. The wide face height variations kept Konya Test 1 from finding good fits, although the data shows reasonable values approximately halfway through the 210 trial rotation generated by face height changes.

Konya Test 3 is another small borehole test with subdrill and a narrow range of face heights. This test showed a remarkable quality of data fit, as evidenced in Figure 5.6. Both explosive weight and surface area show a R^2 value of 1 and a slope of 1, indicating a perfect fit of data between the two methods. The rest of the tracked values also show high R^2 values and slopes nearly equal to 1.

Konya Test 6 is a large borehole test with subdrill and a narrow range of face heights. Konya Test 6 is shown as Figure 5.7.

The rest of the Konya comparison tests can be seen in Appendix A.

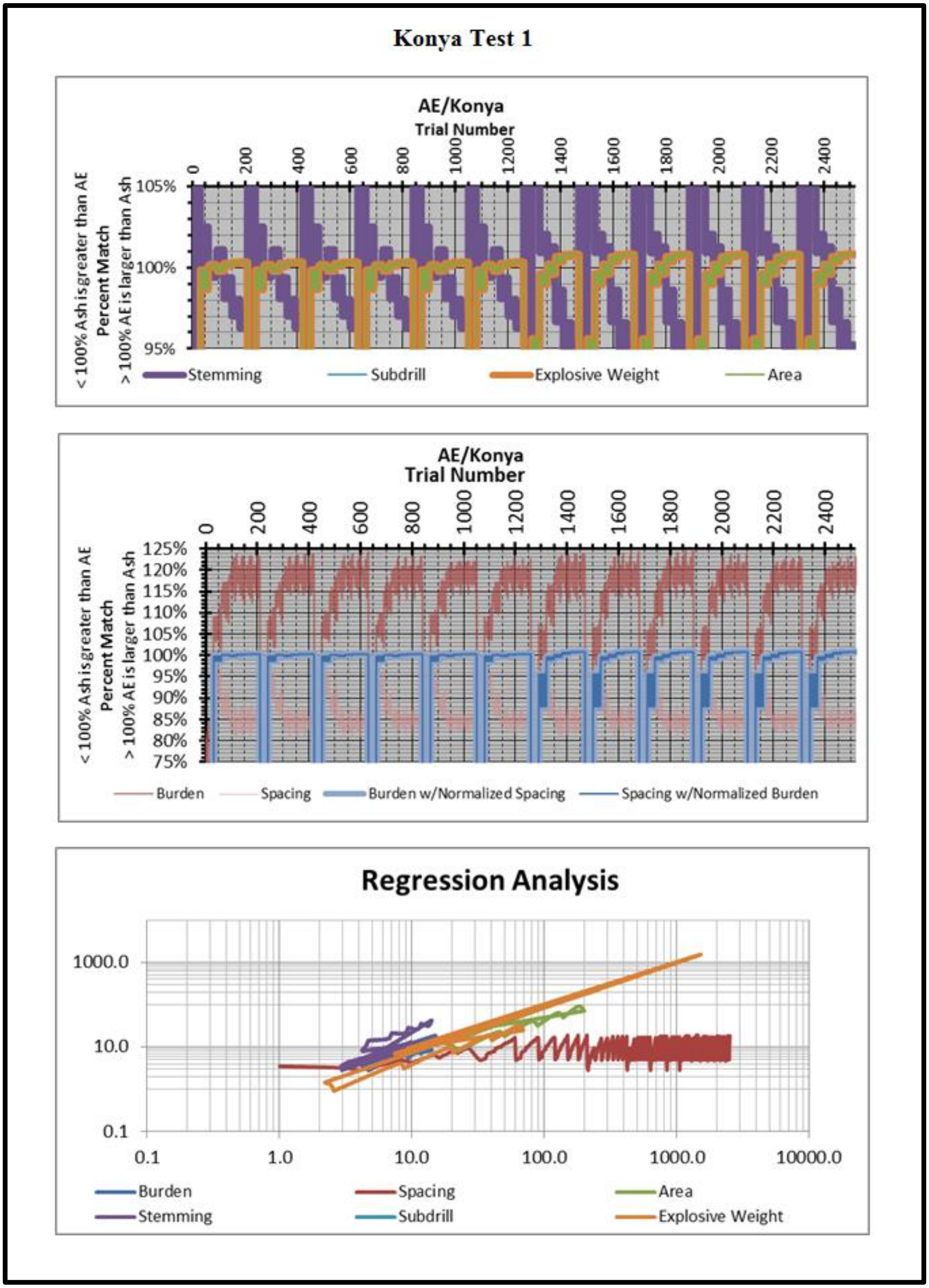


Figure 5.5: Konya Test 1 Graphs

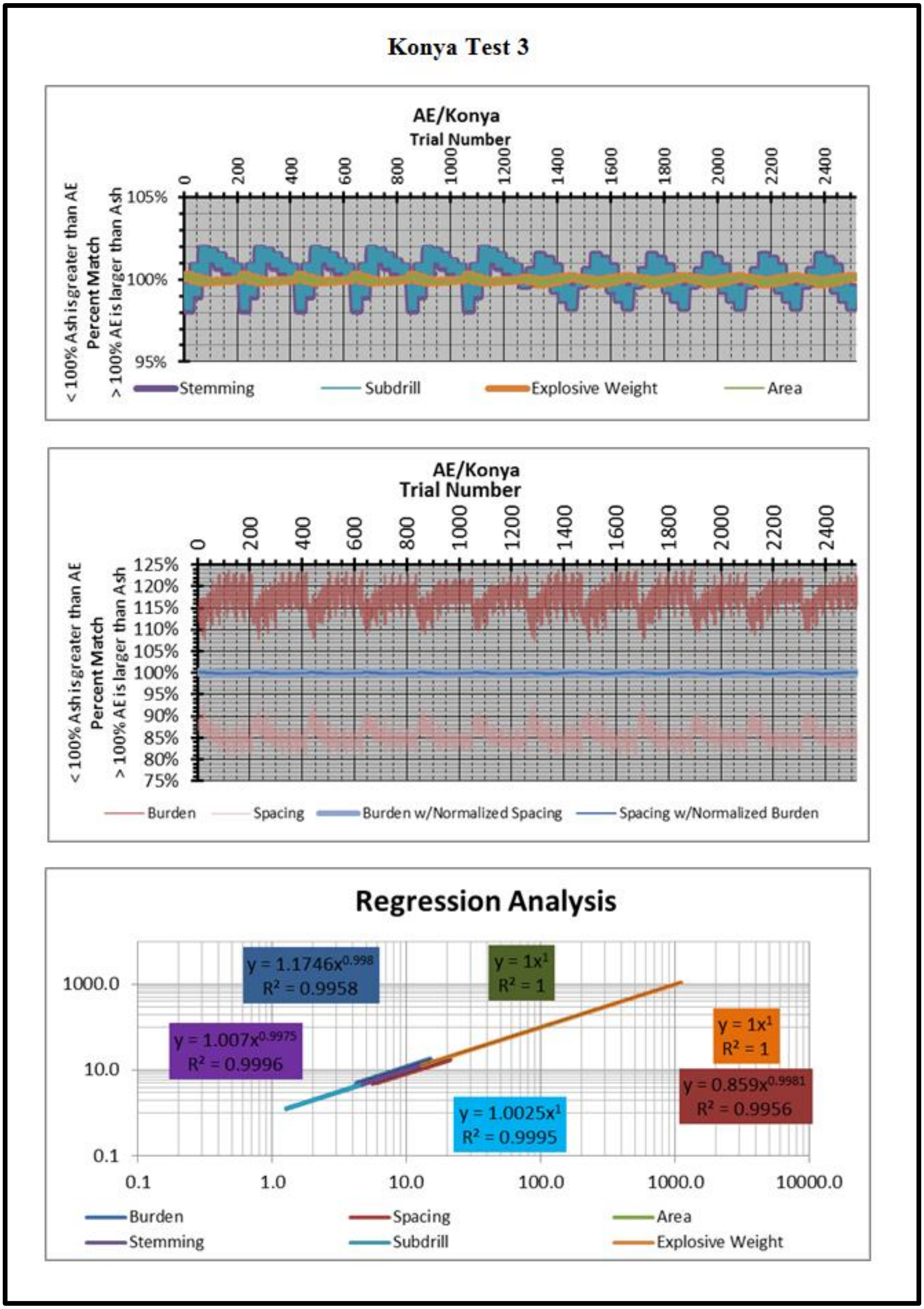


Figure 5.6: Konya Test 3 Graphs

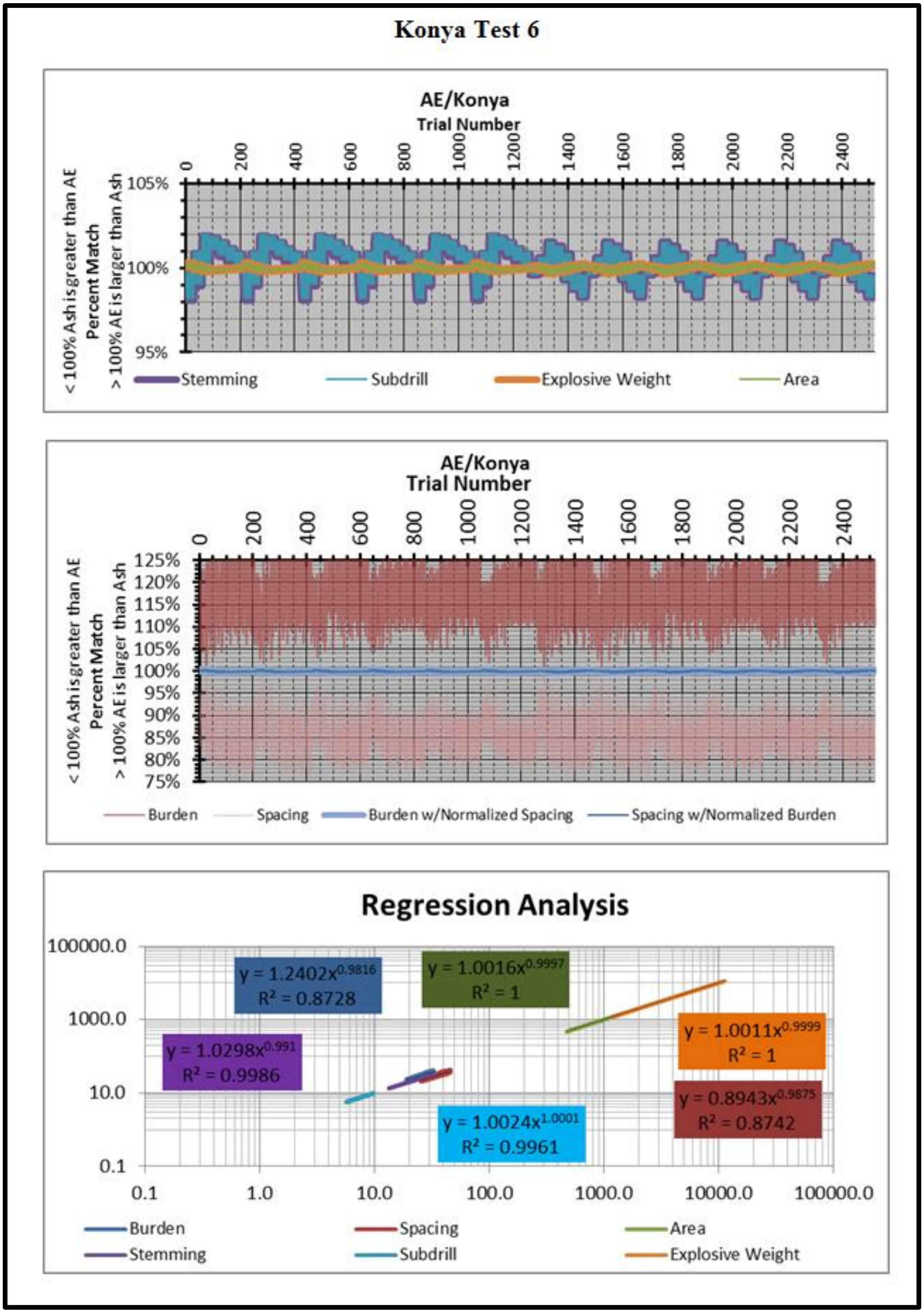


Figure 5.7: Konya Test 6 Graphs

5.1.3. Ash and Konya Cut Width Tests. In the interest of maintaining reasonable quantities of data in each test, only a few cut widths were used for the majority of testing, and while evaluating the comparison tests for Ash and Konya, the author questioned whether the cut width used in the tests would affect the results. Theoretically, the width used for design should have limited influence on the outcome of the design, provided that the width is great enough that several rows would be necessary to complete a design. Essentially, if the cut is only 50' wide, then a large diameter borehole may force the AE method to create only one row and generate an abnormally small burden to compensate for the large spacing. The cut widths used for the majority of the testing were 150', 160', 170', 180', 190', and 200'. The author felt that this interval of cut widths should contain values large enough to ensure that no abnormally shaped patterns were being generated, the rest of the cut widths likely to be used in the design domain would share factors with the tested cut widths, and if any large errors were noticed in the testing, further research could be conducted at that time. No large errors were noticed in the testing, and the Ash – Konya – AE comparisons went well. However, to be certain that cut width was not a significant factor in the design, a Cut Width Test was conducted. The Cut Width Test ran Ash Test 10 and Konya Test 6 data at six new cut widths: 150', 220', 290', 360', 430', and 500'. These new widths span the entire research scope and should illustrate any affects due to cut width in the design process.

Specifications for the Cut Width Tests are shown as Figure 5.8. The tests used narrow face height ranges and generally followed the patterns of Ash Test 10 and Konya Test 6 except for the cut widths.

Cut Width Test

Ash - Available Energy Comparison Test

Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.562	0.3	0.428
0.80	0.633	0.3	0.375
0.90	0.702	0.3	0.334
1.00	0.769	0.3	0.300
Cut Widths [ft]	**Borehole Diameters [in]**	**Face Height Multipliers [% of 10*D]**	**Spacing Factor [B*#]**
150	9	75%	
220	10	83%	
290	11	92%	
360	12	100%	1.40
430	13	108%	
500		117%	
		125%	

Konya - Available Energy Comparison Test

Konya Stem Factor	AE Stem Factor	Konya Subdrill Factor	AE Subdrill Factor
0.70	0.572	0.3	0.429
1.00	0.780	0.3	0.300
Cut Widths [ft]	**Borehole Diameters [in]**	**Face Height Multipliers [% of 10*D]**	
150	9	75%	
220	10	83%	
290	11	92%	
360	12	100%	
430	13	108%	
500		117%	
		125%	

Figure 5.8: Cut Width Tests Specifications

The following pages show the Ash and Konya graphs of the Cut Width Test as Figure 5.9 and Figure 5.10, respectively. Stemming and subdrill percentage match graphs look quite similar to the narrow range of cut widths, and the normalized burden and spacing traces also appear to have very little error.

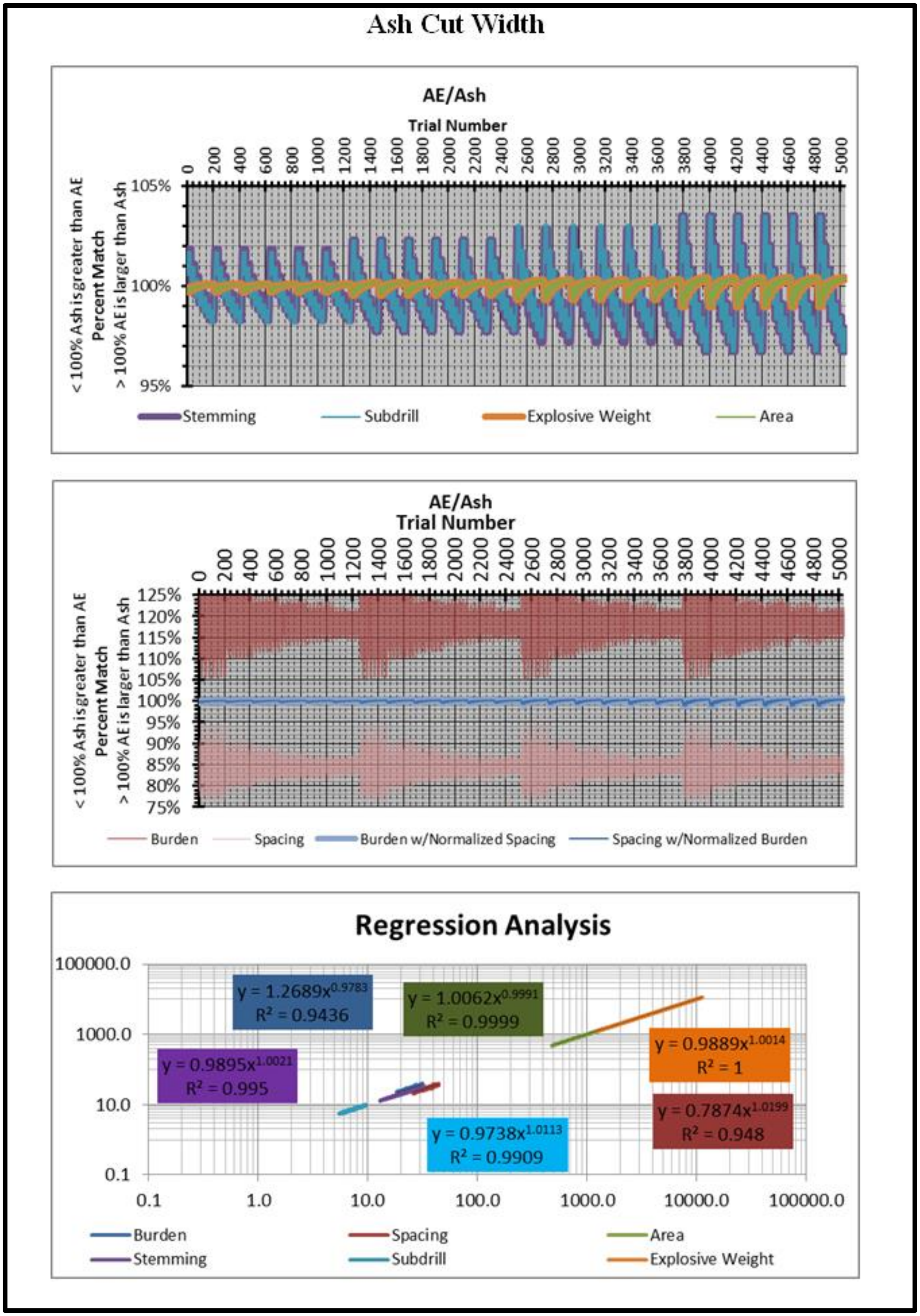


Figure 5.9: Ash Cut Width Test

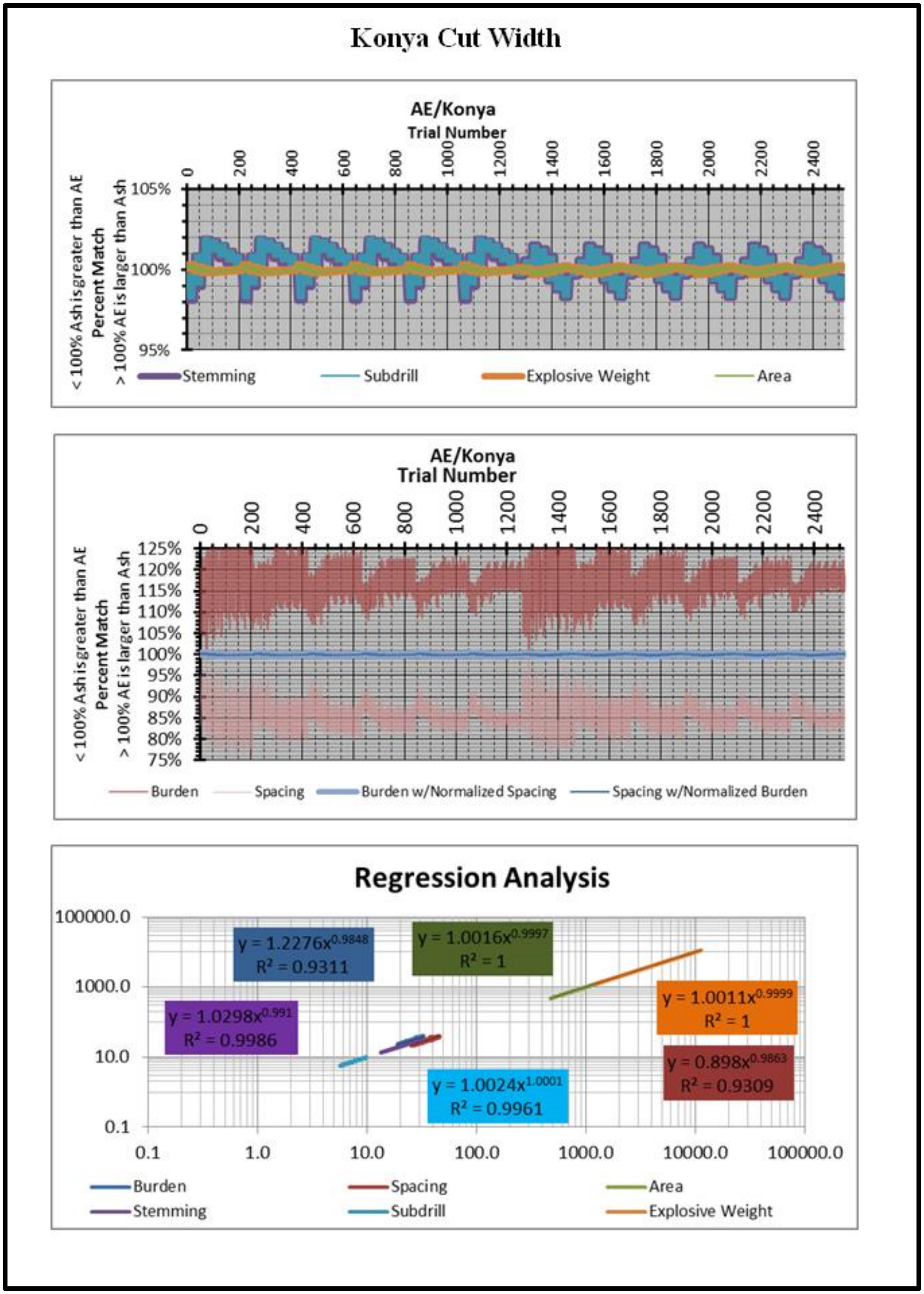


Figure 5.10: Konya Cut Width Test

The only notable difference is shown in the straight burden and spacing traces on the Ash graphs – at wider cut widths, the variability in the burden and spacing stabilizes around 115%-120% for burden and 85% for spacing. When the length of the linear burden and spacing dimensions change as patterns are changed from rectangular Ash and Konya to equal-area AE square, the magnitude of the change is some percentage of the original dimension.

Narrow cut widths have few rows, and adjustments made to spacing in order to have a whole number of rows in the cut must be distributed across a small number. When cut widths are wider, the magnitude of the required change in spacing is spread out over more rows, resulting in a more stable percentage of change. As an example, if the cut is 150 feet wide, and spacing for the design is initially 20 feet, a ten foot difference must be distributed across seven rows (150-(20*7)=10), for a percentage change of 7% ((10/7)/20). However, if the cut width is 330 feet, the same ten foot difference can be spread over 16 rows (330-(20*16)=10) for a percentage change of 3% ((10/16)/20).

Several things can cause burden and spacing to change – an adjustment in AE level or face height, stemming height or subdrilling depth. With a fixed or nearly fixed cut width, changes to things like AE have a much greater impact on the final design. If an Ash design were to change from a 9.875” borehole to a 12.25” borehole, the burden and spacing would change significantly – much more so than a cut width change from 150’ to 160’ would affect an AE pattern. Comparatively speaking, the effects of the cut width change are minimal. However, when combining the effects of cut width and AE changes and face heights and stemming or subdrill changes, a much greater variability is present. The author believes the burden and spacing trace stabilization seen in the Ash Cut Width graph illustrates a case where narrow cut widths are a limiting force in pattern adjustment – and at larger cut widths, the effect is lessened, allowing the traces to stabilize.

In any case, the cut width change shows little to no effect on surface area or explosive weight, and both stemming and subdrill are also unaffected by the change in cut width. From a practical perspective, the testing conducted at narrow cut widths is representative of the AE method's ability to match both Ash and Konya, and any other observed phenomena may be the focus of future work.

5.2. RESULTS AND REALITY CHECKS

5.2.1. Accuracy of Data Analysis. When researching Excel's techniques of generating trendlines, a host of problems with Excel's statistical tools were discovered (McCullough, 2008) (McCullough & Heiser, 2008), including disputes over the accuracy of R^2 values for trendlines. Some users claim that Excel values of R^2 displayed on charts do not match values found using the best methods of calculating R^2 (Hargreaves & McWilliams, 2010). Microsoft claims (Microsoft, 2014) that its R^2 value equals 1-SSE/SST, although Microsoft does clarify that for logarithmic, power, and exponential trendlines Excel uses an unnamed transformed regression model (power trendlines were used in this research). These differences cause this author to question the accuracy of the R^2 values reported as part of the linear regression analysis. It is beyond the knowledge and expertise of this author to verify whether Excel works according to the best statistical techniques available. However, provided that the calculation method is consistent in its implementation, the comparative value of the regression analysis tests are still useful;

while the absolute number may be inaccurate, the displayed values can be compared to each other to gauge improvement or decline. Ultimately, the value of the regression analysis in this research is to show that the changes made over the testing process did improve the quality of the data fit between the Available Energy method and EMM methods.

As far as data accuracy for the rest of the testing is concerned, no additional statistical methods were used in Excel, and the most complex formulas used were nested "IF" statements. The percentage match graphs were simple XY scatter plots of separate data columns and contained no complex graphs or other items of concern.

5.2.2. Maximum Errors in Light of Field Practices. The percentage match graphs tracked how well the AE method compared to Ash or Konya (hereafter described as EMM in this section) by dividing the AE value by EMM for individual testing. This division resulted in a percentage and a perfect match between AE and EMM would result in a value of 100%. If AE is greater than EMM, the percentage will be greater than 100% and if AE is less than EMM, the percentage will be less than 100%. The key to this comparison is the magnitude of the error (which is defined as the reported number minus 100%) between AE and EMM, and how this error relates to actual practice. In the best EMM tests, the maximum errors of useful data were observed in stemming and subdrill, which have the smallest magnitudes of the comparisons (Straight burden and spacing generated larger errors than stemming and subdrill due to the geometric dissimilarities between the two methods. Straight burden and spacing were only included for illustrative purposes, not as useful data). These errors varied due to the peaks caused by less than ideal face heights, and when viewing the best EMM comparisons, the maximum observable error in stemming and subdrill was equal to ~3.5% for Ash and ~2% for Konya.

In practice, stemming height is dependent on attentive shot loaders who use weighted tapes to gauge the depth from the top of the bench to the top of the explosive powder column as the borehole is loaded. These shot loaders stand upright and bob the tip of the weighted tape on the top of the explosives while watching to see when the appropriate length of borehole remains empty for stemming. Many factors come into play to determine actual stemming length in the field, including the reflex time of the shot loader, parallax issues from the loader's eyes to the marked tape, the skill with which the shot loader can feel the contact of the weighted tape with the explosives, and the rate of the explosives being loaded into the borehole. When all these issues combine, it is reasonable to assume that stemming height in the field may vary up to a foot plus or minus – meaning that for a targeted stemming height, actual heights in the field for large boreholes could easily be a foot higher or lower. For a target height of 20' of stemming, this foot of variation represents 5% error, and for a target height of 10', the error is 10%. In other words, the maximum observable error from the AE-EMM comparison tests is less than likely field variations. It is noteworthy that the maximum observable error occurs at the fringes of appropriate design methods where face heights are not well matched to borehole diameters and associated AE values.

To the author, the observed results indicate that the AE method adequately matches EMM methods. In the case of the critical measurements of explosive weight and surface area, the great majority of the observable error was below 1%. Further testing and classification of face height ranges could further reduce the observable error, but such testing is unnecessary to prove the premise of this research.

5.2.3. General Conclusions on the Available Energy Method. A critical item for consideration is face height. Variations in face height are what drive the curves of the graphs. The original geometric guideline of ten feet of face height per inch of borehole appears to be validated for Ash testing, since the most accurate comparisons generally happened midway through the 210 trial face height cycle that created the graph peaks and valleys in Ash comparisons. Konya, on the other hand, appears to prefer a slightly higher initial assumption, closer to 11 or 12 feet based on the location of the best match of data within the same 210 trial cycle.

It is apparent that burden or AE based stemming guidelines that do not take face height into account are likely to cause problems with shorter face heights. A large borehole with heavy explosives and a low powder factor creates a high AE value, indicating that wide spacings and burdens are required. However, using high AE values with short face heights introduces the conundrum of excessive stemming and inadequate explosives, which contracts the burden and spacing dimensions. From an economic perspective, this difficulty is expensive. Blindly designing patterns without considering the overarching relationships that govern designs could result in a situation where increasing borehole diameter (which proportionally increases AE value) would actually increase the number of boreholes required due to lower efficiency of borehole use. This illustrates a paradoxical situation brought about by the low total weight of explosive contained in the bottom of the large diameter boreholes almost entirely filled with stemming. In contrast, choosing a smaller borehole diameter, which uses much less stemming due to its lower AE value, may actually be able to contain more explosive and blast more material at a given powder factor than the less efficient larger diameters. Avoiding these potential pitfalls requires understanding of design relationships on the part of the blast designer, and intelligent guidelines from the method creators (see Appendix D for a sample pattern design, and Appendix E for general use guidelines).

The author expects that with additional work, reasonable AE levels for individual face heights could be tallied and tabulated to give a useful guideline for new blasters. However, the author knows that quite often, patterns that are not theoretically advised work well in the field, and the theoretical problem of low borehole efficiency due to excessive stemming is already solved from a practical perspective in the field. The field solution involves using less stemming than theory recommends. Some methods give alternate recommendations for stemming – rather than being burden (therefore energy level) dependent, these recommendations are borehole diameter dependent. One such recommendation is two feet of stemming per inch of borehole diameter (Worsey, 2012). This guideline gives eighteen feet of stemming for a nine inch diameter borehole, yielding a borehole efficiency index of 49% for a 35' face, a workable if not necessarily optimal value. The actual mechanics of stemming in a borehole are not within the scope of this research. However, knowledge of theoretical issues and field solutions indicates that avoiding hard and fast recommendations on stemming practices is advised in this case. The ultimate goal of blasting at LSCM operations is safe and economic production of materials for commerce, and provided that field blasters are currently capable of safe production, it is expected that the use of the AE method will not present problems with respect to safety, and may present benefits with respect to economics.

The final recommendation for stemming and the AE method is to start with an AE design that closely matches existing patterns and over time, modify the AE pattern to optimize its use at the individual site. Such optimization practice will not be new to any D&B personnel involved, because all blasting is continual optimization.

5.2.4. Ash Results. Several conclusions can be drawn from viewing the test graphs. The squarer Ash patterns match AE patterns better than the rectangular ones, and borehole diameter has little influence on the ability of the methods to match.

In fact, it is reasonable to expect that borehole diameter, product density, and rock density will have little to no effect on the comparison results. The construction of the testing method causes AE design to follow in the footsteps of Ash's method – meaning that the factors that go into calculating Ash's design are largely replicated in the AE testing. Powder factor is the most significant area where the two design methods part, and the present testing uses Ash's calculated powder factor as part of AE's initial inputs. The immediately important factor at play is that there is no need to track down accurate rock densities for varying geologic conditions or little reason to be concerned over practical explosive densities for comparison purposes. Ash's burden factor uses rock density, explosive density, and borehole diameter to begin the calculation process that ultimately ends in a volume of material to blast and a weight of explosives that can be represented as a powder factor.

5.2.5. Konya Results. Konya's testing differs from Ash in a few key regards. First, the design philosophy of Konya's design method is substantially different than Ash. The additional spacing equations help the method adapt to variable face heights in a different manner than Ash's burden-centric spacing calculations, as evidenced by the different shape of the data traces in the percent match graphs. The work of Konya shows a more advanced capability to geometrically scale patterns and adapt as part of the process. Also, the automated Konya spacing geometry tended to lower the R^2 value of the burden and spacing linear regression with the larger borehole diameters, which follows the general trend shown by Ash.

Second, Konya does not display same the stemming and subdrilling error creep that is apparent in Ash's work. If the percent match traces are viewed for narrow face heights, each successive stemming factor for Ash Tests 3 and 10 show increased error from a perfect match: 0.7 = 2%, 0.8 = 2.5%, 0.9 = 3%, 1.0 = 3.5%, approximately. Konya's Tests 3 and 6do not display this error creep; in fact, Konya's error decreases with the larger stemming value. For Konya's work: 0.7 = 2% and 1.0 = ~1.8%. This change in error creep is interesting in that it shows Ash's method decays at a higher rate – meaning that Ash's method is less geometrically stable across a range of inputs. This difference is not dependent on differences in spacing calculation or borehole diameter, as Ash Test 3 uses small spacing and borehole diameter while Ash Test 10 uses large spacing and borehole diameter.

These differences help explain the endurance of Konya's design method, and why some (Hemphill, 1981) consider Konya's work the best design method to date. Konya's general approval is even reflected by being an author published in the Blaster's Handbook (Stiehr, 2011) of the International Society of Explosives Engineers – the largest global association of blasters and explosives technicians (ISEE, 2015).

5.2.6. Reality Checks. It is important to note that the overall goal of the comparison testing was to verify that the AE method returns similar values for similar inputs when compared to Ash and Konya. The goal of the comparison testing was **NEVER** to affirm that any particular design is safe for use under all circumstances. Regardless of the blast design method used, mistakes in the process or lapses in judgment on the part of the driller, designer, or loader can create conditions for serious accidents. No amount of data generation or analysis can make an unsafe condition safe, and it is imperative that persons using energetic materials including blasting agents and other explosives realize that they are the ultimate guardian of their own safety. Attempts to "idiot-proof" processes generally discover more talented idiots.

Nothing in this work is intended to replace the intelligence and experienced judgment of the blaster in the field. Ultimately, responsibility for each shot is in the hands of the blaster, and the intent of this research is solely to develop new approaches and new tools for an existing problem.

6. NOMOGRAPH DEVELOPMENT

6.1. CONCEPTUAL DESIGN

The goals of well-constructed nomographs line up with the benefits listed in previous discussion: they should be easy to use and increase accessibility of information by enabling a broader range of users to benefit from the formulas represented on the page. Therefore, the proposed tool should represent the blast design method across the scope of the research and enable the user to quickly find a solution for the design problem at hand. Creating a nomograph for the AE method is challenging, and the efforts presented in this research could be improved upon with further research. First and foremost, the use of the AE method requires a tool that can be used to rapidly determine the linear parameters of design by someone in the field – conceptually a driller – and can adapt to changing conditions on the fly.

6.1.1. Divergence of Theory and Practice. Blasting practices in the PRB often appear nonsensical when first examined. When shooting coal, often detonating cord will be used as the primary means of initiation, including down the hole. Using detonating cord down a blast hole is not generally a recommended best practice (Worsey, 2012); however, many mines in the PRB do not contain preparation plants to clean the coal. Often, the coal is blasted, loaded, and hauled to silos where the coal is loaded into unit trains for immediate shipment to customers. In circumstances such as these there is no point in the process for recovering plastic tubes used in shock tube initiation, and electric cap legwires are often made of copper which limits the usefulness of electromagnets usually installed over conveyor belts to catch shovel teeth and other scrap metal. In light of the limited coal cleaning capabilities of some mines, using an initiation system that is consumed when fired makes financial and practical sense. The elimination of blasting waste in the form of bits of plastic or wire is the driving force for using detonating cord as a primary initiation system rather than a limited component in the initiation system. Similarly, the use of drill cuttings for stemming is traditionally discouraged because the rounded and pulverized characteristics of drill cuttings do not lock up and seal boreholes as well as more angular crushed rock. When loading several hundred 9.875" diameter boreholes a day with more than ten feet of stemming considerable material volume is consumed; and the additional time and cost required to use crushed rock (even the local baked clay known as scoria) does not provide sufficient benefit to outweigh the theoretical and practical limitations of drill cuttings when used for stemming. Finally, mines often use comparatively large borehole diameters on quite short benches. The author has seen 9.875" diameter boreholes been drilled fourteen to sixteen feet deep and shot successfully to break the waste material between coal seams. For such low face heights, boreholes of 2"-4" make much more sense. However, the economies of scale have driven mines to standardize on larger borehole diameters, and some blasts are outside of generally recommended practices. In short, it is expected that while the AE method testing shown here has delivered excellent results when compared to Ash and Konya, PRB blasters will already have ingrained preferences for blasting in the field that may not match theoretical best practices. Safe site-specific practices have been developed over years of use and as a general rule, site-specific knowledge should be employed rather than discarded.

6.1.2. Order of Operations. The order of operations is critical for successful design. Which variables must be represented on the nomograph across a range of solutions, and which variables can be fixed for the purposes of simplicity? It is reasonable to imply that a blaster will know the desired loading density, borehole diameter, and powder factor for any shot, so creating a nomograph with a fixed AE value is a reasonable starting point, with the recommendation that a separate nomograph to calculate AE is also provided. Also, cuts generally have a targeted width to maintain strip ratios over the course of mining, implying that cut widths can be fixed for the new nomograph. One of the reasons the new method of design is necessary is due to fluctuation in face height as a regular part of truck shovel operations; so face height should be a variable. Stemming height is a point where theoretical recommendations should yield to practical considerations; the nomograph should employ a stemming height of the blaster's choosing. Powder column height is a useful measurement for blasters, and if possible should also be displayed on the nomograph.

The author has never seen traditional subdrill used in the PRB, and while the use of subdrill has been explored during the method testing, there is little practical need for subdrill in the sample nomographs to follow. Subdrill is either present or absent, and separate nomographs are recommended for either case as combining both cases on a single nomograph would invite confusion and mistakes.

Burden and spacing should be present as variables on the nomograph. Since face height is generally fixed by design and site conditions, burden and spacing are ultimately the primary dimensions of interest for the driller in the field.

One other item not strictly necessary as a design component, but useful nonetheless, is the efficiency index. If possible, the efficiency index of the different design scenarios should be present on the nomograph to reinforce the importance of efficient utilization of what can be a costly borehole.

The final list of nomograph requirements shows AE and cut width as fixed, with face height, stemming, powder column height, subdrill (when present), burden, spacing, and efficiency index presented as variables. Two fixed measures, and six to seven variables.

6.1.3. Python Programming in PyNomo. PyNomo is an open source software package for creating nomographs using the Python programming language. The software, written by Leif Roschier (Roschier, 2012) supports many types of nomographs, and with some personal ingenuity, the potential for nomograph creation is virtually limitless. However, there are some significant drawbacks to making nomographs in PyNomo.

- Programming Required: PyNomo is software lacking a graphical user interface – in order to create a nomograph, the user must understand and use Python to code the formulas and formats. Additionally, the PyNomo software requires bits and pieces from several other open source software platforms, meaning that to use one program the user must install several programs.
- Black Box Operation: When using the software, a patch of code runs through the software outside the control of the user. If an error is encountered, the warning messages frequently refer to bits of software not currently being edited by the user. During the author's experiments with the program, it was occasionally easier

to throw away the offending file and start again. Tracking down errors in the code can be difficult and requires a keen eye for detail.

- Complicated Control of Final Outputs: While PyNomo is a versatile and powerful software tool, the formatting options and techniques can create challenges. It can be difficult to adjust the nomograph for ease of use – occasionally the automatic scaling done by the software will make certain axes enormous and other axes small enough to be practically unreadable.

It should be noted that the above complaints are common with all sorts of software. In the case of this research, the major limiting factor is the author's lack of experience with both the Python programming language, and PyNomo. With additional practice, excellent nomographs can be produced with the PyNomo software, as evidenced by the works of Marasco, Doerfler, and Roschier (Marasco, Doerfler, & Roschier, 2011)

Some limited work with the software resulted in the creation of some useful nomographs for everyday blasters. Figure 6.1 is an example loading density nomograph – compare Figure 6.1 (created entirely in PyNomo) with Figure 2.1 (created entirely in Excel) for a good overview of the improvements that are possible with the purpose-built PyNomo software.

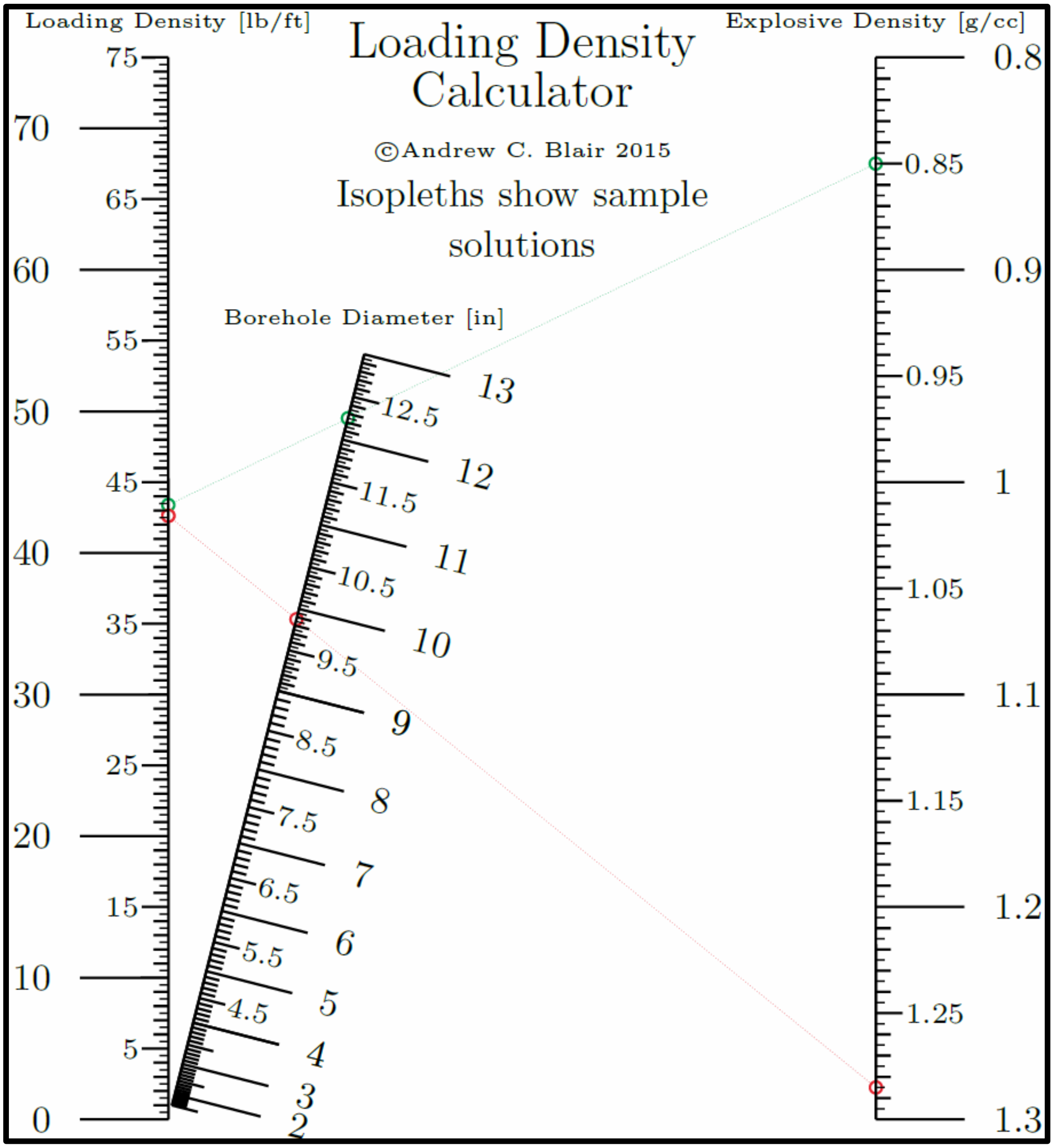


Figure 6.1: Loading Density Nomograph from PyNomo

The largest problem with Figure 6.1 is the crowded lines in the lower left corner, but on the whole, the nomograph is clear and easy to follow. Any person knowing two of the variables for the loading density can easily find the third variable. Figure 6.2 shows a nomograph for calculating scaled distance explosive weights within five thousand feet of a shot.

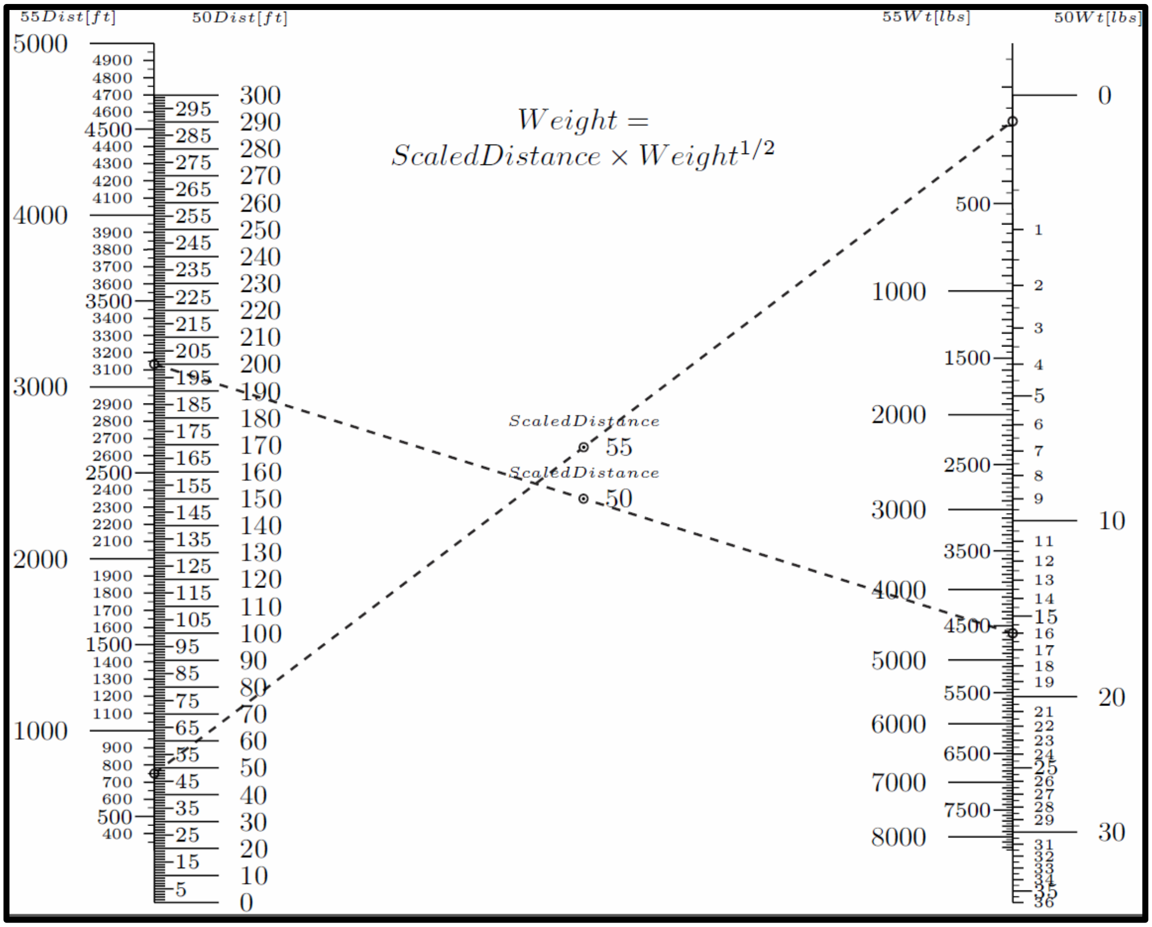


Figure 6.2: Scaled Distance Nomograph

The left side of the scales is used for a scaled distance of 55 (301-5000 ft), and the right side of the scales is used for a scaled distance of 50 (0-300 ft). This nomograph also introduces an isopleth – the dotted line showing the user how to trace across the nomograph. The final PyNomo nomograph, Figure 6.3, shows how to calculate Available Energy. Figure 6.3 is the final version of several attempts to create an AE nomograph with the PyNomo software. After creating the AE nomograph, attempts to add steps and work through the AE design method were unsuccessful due to the author's lack of experience with the Python programming language and PyNomo program.

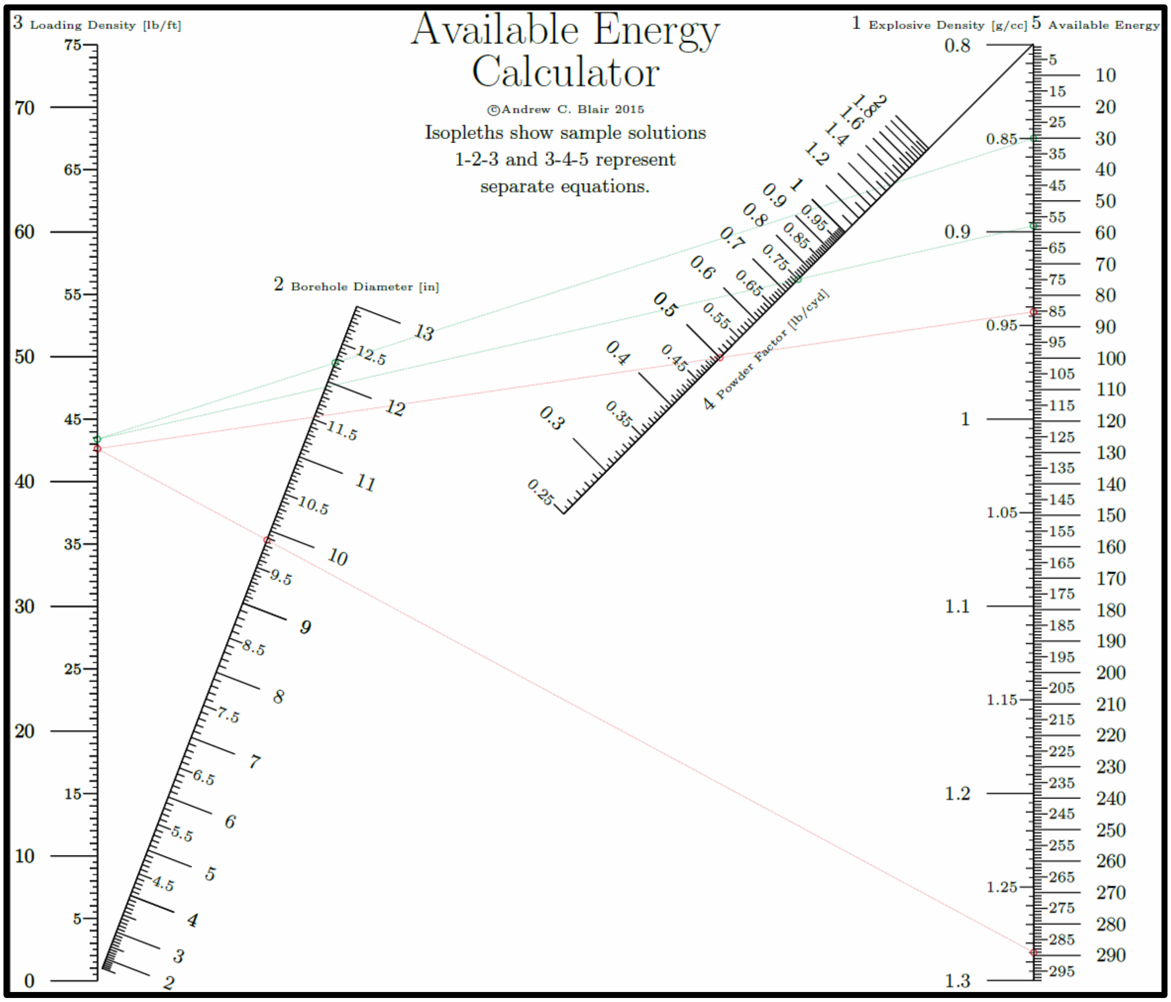


Figure 6.3: Available Energy Nomograph

The Available Energy Nomograph is an expansion of the earlier loading density nomograph. Isopleths show the user how to use the compound nomograph.

When properly constructed, PyNomo nomographs represent some of the best modern nomographical work the author has seen. However, limited practice with the software and the computational complexity of the AE method presented significant challenges to the creation of a broadly usable tool for the present research effort. It is anticipated that in future, a traditional nomograph such as Figures 6.1, 6.2, and 6.3 may be created for the AE method. However, for the goals of this research, Excel provides a more intuitive and useful tool.

6.1.4. Using Excel for Graphical Representation of Complex Problems. A traditional nomograph for the AE method such as those created by PyNomo would be quite challenging to create and properly scale. However, by using chart tools built into Excel, a serviceable nomograph can be created with relative ease. Excel has a number of handy tools that make it ideal for the creation of nomographs.

The most difficult part of creating a successful nomograph in Excel is visualizing the final result. Two fixed values and six variables are quite challenging to present on a two-dimensional chart that contains at most four axes displaying four separate scales. What is the best way to break up the fixed and variable measures to present all the data on a single page? The question is answered by units and scale.

6.1.4.1. Units. Ordinarily, units are part of the conversation – numbers everywhere are defined by their units. When examining the AE method, we find variables with wide ranges of values using various units. Burden, spacing, stemming, subdrilling, and powder column are all expressed in units of feet and will range between zero and sixty-five depending on the design scenario chosen. The efficiency index is a percentage that can be represented as a number between zero and one, and AE ranges from around eleven up to several hundred. The primary difficulty becomes how to show all these variables in a usable manner with so few scales. If the efficiency index and AE are plotted on the same axis, the efficiency index is unreadable due to its limited range. Burden and spacing are largely similar due to the geometric construction of the AE method, but plotting burden, spacing, and face height on the same axis seriously limits the visible resolution due to the wider range between values The same is true if attempting to plot stemming and powder column with burden and spacing – wider ranges of values decreases readability when printed on a standard sheet of letter paper.

Therefore, one of the primary challenges of creating an AE nomograph lies in the distribution of value ranges and selection of units. What combinations will work best to provide usable data? In a perfect world, burden and spacing would have their own axis, as these two values are closely related and should be clearly legible. Continuing the process, face height must be a variable, but AE and cut width may be fixed, as each shot should have a target AE, and individual nomographs for different cut widths seems reasonable. This grouping covers most of the major variables with two axes, leaving stemming, powder column, and the efficiency index. These three variables can be combined on a single axis, using decimal values.

Decimal values open up a new range of possibilities. Essentially, decimal values are the original number divided by ten or one hundred to minimize the overall range covered by the variable. If stemming and powder column height are shown in decimal ranges by dividing the actual values by one hundred, the variables can use the same axis as the efficiency index and only cover a range between zero and one. The decimal values will give readings accurate to the nearest foot, which is reasonably accurate for the variables in question. An example of decimal scales can be seen in Figure 6.4 (a nomograph created entirely in Excel) as part of the stemming value calculations. Instructions for the use of Figure 6.4 are as follows:

This nomograph is based on a slightly modified form of Worsey's Rules of Thumb (Worsey, 2012) and is designed for borehole diameters from 2-15 inches and product densities from 0.8-1.3 g/cc. You can solve for varying densities, borehole diameters, etc. by interpolating between the lines.

To use the nomograph:

1. Start at the X-axis and find your borehole diameter in inches. The solid lines are whole numbers, with the dashed lines representing tenths of the unit you're measuring
2. Trace the proper diameter upwards until you intersect the product density you're using, then trace horizontally to the left and to the right.
   a. Read burden (green numbers) and spacing (red numbers) from the intersection of your horizontal line with the Y-Axis at right.
   b. Where your horizontal line crosses the MaxSubdrill line, trace down to the X-Axis and read off the number – this is your maximum subdrill in feet
   c. Your horizontal line will cross the orange area for stemming – the orange area represents stemming ranging from 0.7 (left side) to 1.4 (right side) times the burden. StemAvg is stemming equal to burden for your reference. When you decide whether you want a lot or a little of stemming (based on ground conditions and type of stemming), trace down to the X-Axis, and multiply the number you read by ten to arrive at feet of stemming required.

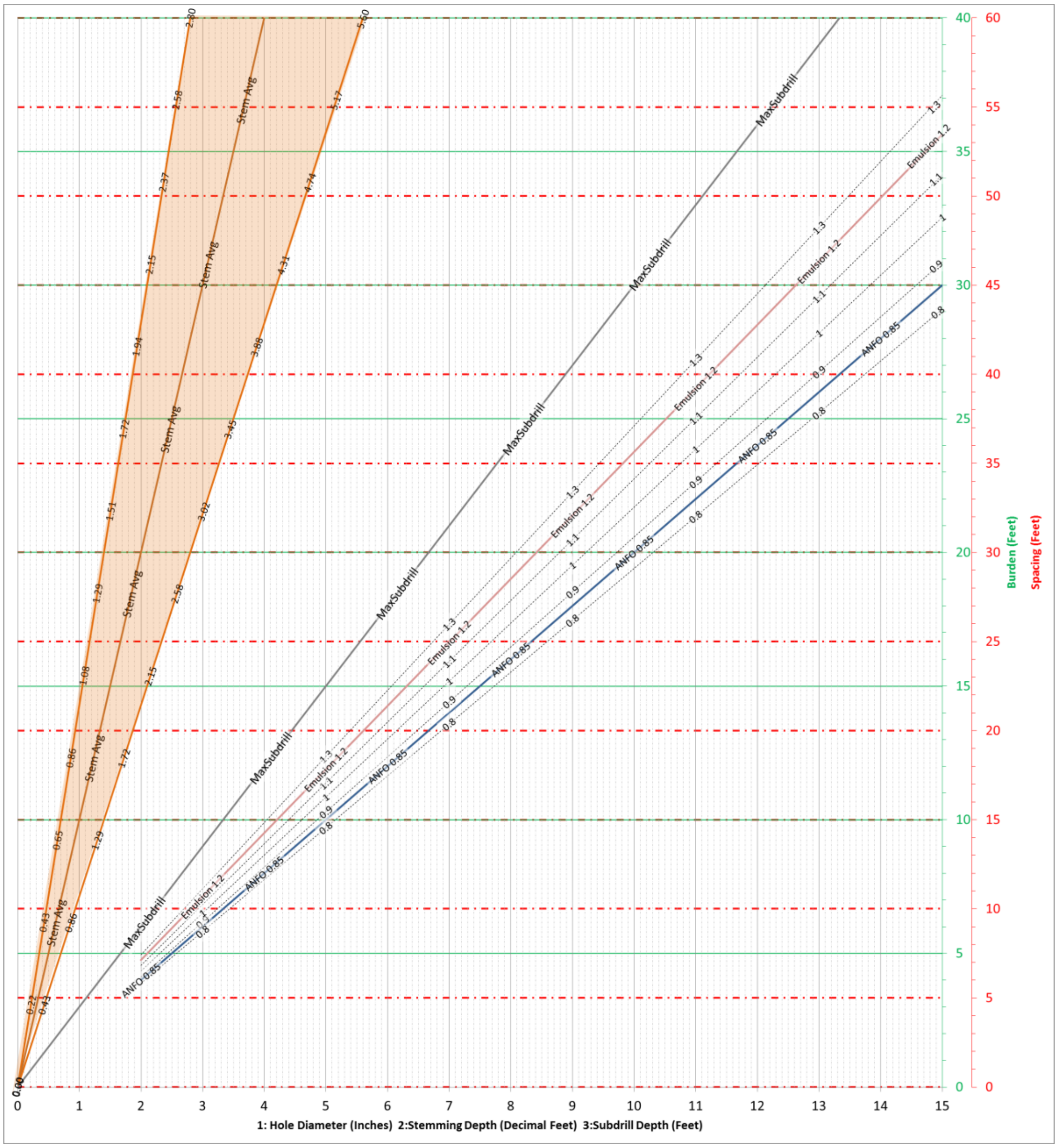


Figure 6.4: Rules of Thumb Blast Design Nomograph

6.1.4.2. Scales. When creating nomographs, scales become vitally important. Graphs in Excel can be used to show a number of different scales, but what scales are most appropriate? At least three axes are necessary, one for burden and spacing, one for face height, and one for the efficiency index, stemming, and powder column height. These three axes will need different scales – feet for burden, spacing, and face height; decimals for the efficiency index, stemming, and powder column height.

6.1.4.3. Colors. Colors may seem like a minor issue, but when viewing nomographs with a multitude of lines, color coding certain subsets of the data can be a powerful aid to rapid use of the nomograph, or can unnecessarily confuse the user. Additional challenges arise from a cost perspective – fewer colors are cheaper to reproduce. In practice, using the minimum number of colors necessary is advisable to minimize confusion while improving ease of use. Specific color choices are also important: if a nomograph originally designed in color is printed in black and white, will it still be usable? While grayscale coloration is unadvisable due to the limited color options and the difficulty of differentiating between shades, any color choices should be made with grayscale printing in mind: Will this tool still be useful if printed in black and white? With these thoughts in mind, it is best to limit use of colors to a few vibrant colors that visually catch the eye and take additional steps to ensure that the nomograph is still useful when printed in black and white.

6.2. AVAILABLE ENERGY BLAST DESIGN NOMOGRAPH

Taking everything outlined in the previous section, the final AE nomograph should allow the user to rapidly determine several parameters of design based on a few known values. The use of color should enhance and not detract from the nomograph, and units should be distributed and scales intelligently constructed so as to provide the maximum amount of valuable information from a single page. Instead of a singular nomograph, a range of nomographs are recommended to separate out variables such as subdrill.

Two sample AE nomographs (Figure 6.5 and Figure 6.6) have been created in Excel for this research, as examples of potential tools for drillers or blasters in the field. These nomographs are part of an automated workbook that allows the user to instantly update the design scenarios to reflect the user's needs. For the sample nomographs presented as a part of this research, the following design scenario has been used:

- Borehole diameter of 9.875"
- Explosive product density of 1.285, representing a 70/30 AN/emulsion blend.
- Powder factor of 0.5 lb/cyd.
- Face heights from 35'-65', with a target face height of 55'
- Cut width of 150'
- Target stemming height of 20'

These variables give us an AE value of 85.26, and a Stem Factor of 0.23. Some methods (Worsey, 2012) give an alternate calculation of 24 times the borehole diameter in inches; two feet of stemming per inch of borehole diameter. Using that approximation, twenty feet of stemming should be reasonable for a 9.875" diameter borehole. In any event, the above scenario is a reasonable design one might easily find in the southern PRB.

The automated workbook that created these nomographs was constructed so that specific nomographs could be rapidly created and tailored to the needs of the individual user. The nomographs are sized to fit on standard 8.5"x11" paper, and include a number of useful details. The input sheet for the workbook is shown in Figure 6.5.

Input Data	
Emulsion Specific Gravity [g/cc]	1.25
AN Specific Gravity [g/cc]	1.3
AN Percentage:	70%
Borehole Dia [in]	9.875
Powder Factor [lb/cyd]	0.5
Starting Face Height [ft]	35
Target Face Height [ft]	55
Cut Width [ft]	150
Target Stem Height [ft]	20
Stem Factor [Stem Ht/AE]	0.23
Blend Density [g/cc]	1.285
AE	85.26

Figure 6.5: AE Nomograph Calculator Workbook

Blue cells are inputs, and the green cell is a dropdown list. The Target Face Height cell is used to generate the red lines around specific design scenarios on the following figures.

Figure 6.6 shows an AE nomograph for a range of cut widths. The intent of Figure 6.5 is to illustrate some of the potential of Excel for the creation of AE nomographs. The figure gives an excellent overview of the changes that take place in the design scenarios based on cut width.

Figure 6.7 is a nomograph for a single cut width. It should be noted that in either Excel AE nomograph, all the pertinent information for the AE design method is available on a single line. The user need only trace along that line to determine the magnitude of the linear parameters of design. The nomograph also allows limited interpolation if necessary.

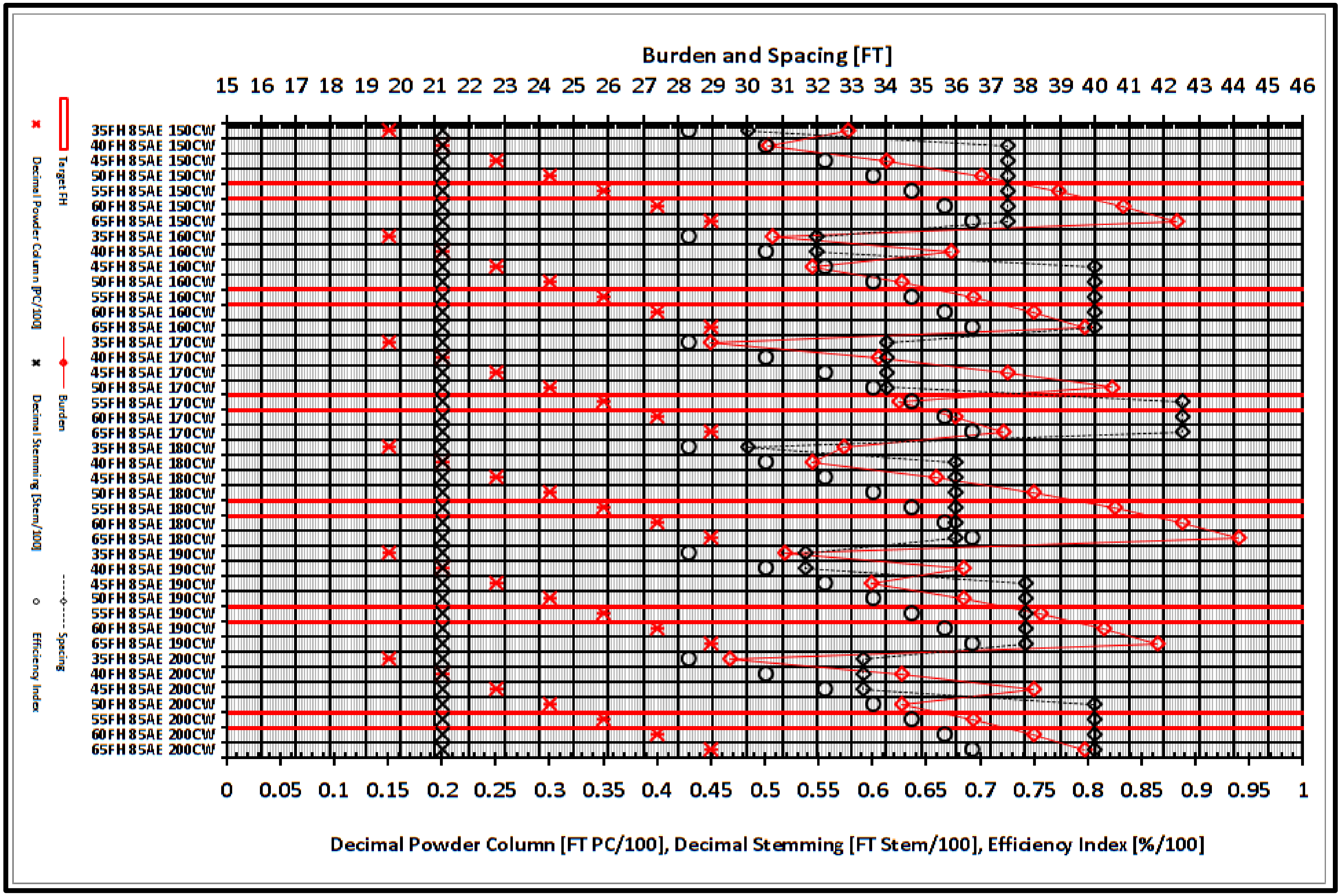


Figure 6.6: Cut Width Range Nomograph

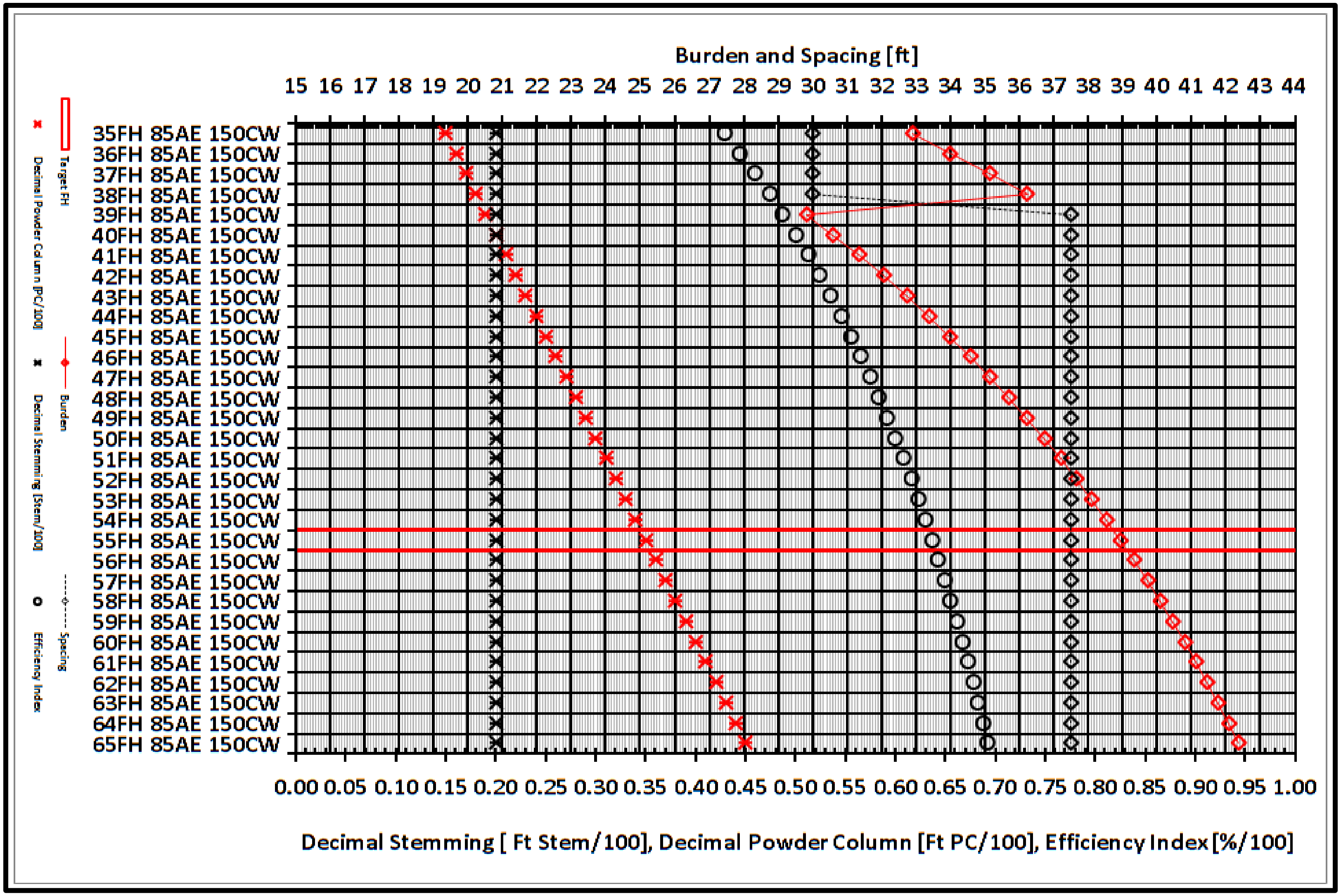


Figure 6.7: Available Energy Design Nomograph

The final AE design nomograph should be read in landscape mode. The nomograph shows all the required information with useful demarcations of units and scale – major gridlines for the Burden and Spacing axis show feet; minor gridlines show inches. The face height, AE value, and cut width are displayed on the left of the nomograph, and the stemming, powder column, and efficiency index axis show decimal values between zero and one; presenting stemming and powder column values accurate to the nearest foot. Gridlines are not drawn for the decimal axis, as the abundance and range of gridlines for burden and spacing make close approximations possible with existing lines. The target face height design scenario is shown outlined in red, and variation in face height from that mark can be found by selecting neighboring rows. A legend shows the different types of markers and lines used for individual items, and use of color is limited to avoid confusion if printed in grayscale.

The sample AE design nomograph presents a useful tool for visualizing the design options available for a given scenario in LSCM bench blasting. Additional blasting-related nomographs are shown in Appendix B.

7. CONCLUSIONS

The completed Available Energy blast design method provides a new alternative for large surface coal mines. The method encompasses several key characteristics specific to Powder River Basin bench blasting, and does so using basic principles like dimensional analysis. Perhaps the single most important contribution of the method is Available Energy itself: a new paradigm for understanding the use of explosive energy in blasting. The Available Energy paradigm establishes a novel framework for approaching blast design, and creates several avenues for immediate research and expansion.

More work remains to be done in fully quantifying appropriate AE levels for varying face heights and material types. Rather than make sweeping statements that may not fully address the design domain, a few suggestions have been made concerning stemming practices for the AE method, and it is expected that by adapting design values to match field-proven techniques, appropriate practices will be easily determined on a site-by-site basis.

Releasing the theoretical grip of burden as the most important variable of design and considering a more three-dimensional model opens new avenues of exploration and potential areas of further research. Practical evidence of the breakage mechanism present in PRB operations indicates that a surface area approach is a logical basis for design. The integration of cut width and powder factor in the design process are novel steps toward matching practical tools with practiced methods.

The graphical data analysis methods employed deliver a useful comparison process for other research projects as well. Using one graph to track the location of errors and another to gauge the overall fit of the data gave instant feedback on the effects of minor changes in adjustment factors and enabled rapid testing of wide ranges of data once the spreadsheet was completed.

The AE nomograph samples presented as part of this research offer a tool for rapid implementation of the AE design process, and a template for further development of AE nomographs. Explorations into the art and science of nomography leave this author convinced that there are many more areas in mining where well-constructed nomographs could provide a practical benefit for day-to-day operations. Almost every research project is an expansion or integration of prior work, and while a single nomograph covering the entire AE design domain would have been a welcome contribution for the present research effort, general guidelines for nomograph creation have been outlined and areas for future work are clear to see.

8. RECOMMENDATIONS AND FUTURE WORK

Completing the current research effort has illuminated several avenues of future research. The following recommendations outline potential future research areas.

8.1. DEVELOPMENT OF AVAILABLE ENERGY GUIDELINES

The current research has largely avoided making hard and fast recommendations for field implementations of the AE method due to the unique requirements of LSCM operators. It is expected that additional work could better define key guidelines for the AE method, such as optimal ranges of AE with respect to various face heights.

8.2. FIELD TESTING

It is anticipated that the AE design method would deliver incremental improvements that may be difficult to measure over short periods of time. Improvements to LSCM costs or performance would need to be monitored over time to determine the impact of the research process.

Field testing of the AE process could provide data for an excellent Masters' project. The development of a field training process, guidelines toward field implementation, and improvement over time could deliver a multidisciplinary research project for interested parties.

8.3. EXPAND AVAILABLE ENERGY CONCEPT TO BROADER TOPICS

In the interest of maintaining a reasonable scope this research focused on LSCM bench blasting, but the work on Available Energy blast design methods that has been completed for this dissertation shows promise for expansion into other blasting areas. The small-scale comparison testing shows that the AE theoretical approach meshes well with Ash and Konya's practical experience. Road cuts, which have target widths, would be an ideal area to test the current Available Energy based blast design method at smaller scales. With minor adaptations (addition of a burden to spacing geometric factor for rectangular patterns), the AE method may well be useful for small diameter blasting in quarries (preliminary work on an AE quarry method may be seen in Appendix F).

Additional work in other blasting areas could determine appropriate ranges of Available Energy factors for various rock types. It is expected that a large quantity of data could be obtained via mine operator surveys since only a few factors are necessary for calculating AE and understanding its appropriate uses: loading density, powder factor, rock type, and results.

The goal of this research was to codify a new blast design method for a very specific subset of the blasting world. The Available Energy concept as defined in this research serves as an extension of powder factor; and as the explosives industry becomes acquainted with the technique and additional research is completed, Available Energy could be used as an updated Powder Factor – a universal scale of the application of explosive energy.

8.4. EDUCATIONAL RESEARCH

Educational research would primarily seek to discover whether AE provides a better, more intuitive foundation for understanding blast design. One of the author's original motivations to pursue volumetric blasting methods was to find a simpler method of blast design to teach – a method that would be easier to grasp and more intuitive for the typical student of mining or explosives engineering. The author believes that the AE method holds great promise for educational uses, and strongly suggests that this avenue be explored and documented for the benefit of the mining engineering community.

8.5. NOMOGRAPHICAL RESEARCH

Philosophically, nomography is a different approach to sharing information than today's popular methods. Developments in personal computing and the exponential availability of "smartphones" have created a profligate dependency on electronic instruments to solve everyday problems. The capabilities of today's technologies are unsurpassed in the history of civilization; but, it is possible that in the rush for the "latest and greatest" techniques, useful tools are occasionally forgotten by society. Nomographs offer great benefits from cost, use, and approximation perspectives, and are easy to distribute in today's environment. The mining industry should ask whether the nomograph or the computer application better meets needs on a case-by-case basis. Further research into nomography for mining will likely uncover a wide range of applications where this tool of the late 19^{th} and early 20^{th} centuries may still prove useful in the 21^{st} century.

APPENDIX A
SPREADSHEET DATA AND COMPARISON GRAPHS

Both design comparisons used similar spreadsheets. The next few pages will illustrate the workings of the spreadsheets. Each spreadsheet contains a separate input table that governs some portions of the design scope and then the individual designs are composed on rows. The pictures show the first twenty design scenarios (designated Trials), with Trial 2 having its formulas shown. Each photo displays a letter across the top, and a number near the end to allow the user to identify the appropriate row and column for the references. Each page shows a different portion of the spreadsheet, and in some cases two pictures have been combined to illustrate the rows and columns efficiently.

Ash Comparison Spreadsheet

Input Table

A	B	C	D	E	F	G
6	AE Stem Factor	AE Subdrill Factor		Ash Stem Factor	Ash Subdrill Factor	Ash Rock Density
7	0.562	0.428		0.7	0.3	162
8	0.633	0.375		0.8	0.3	162
9	0.702	0.334		0.9	0.3	162
10	0.769	0.3		1	0.3	162
11						
12			Cut Width			
13	150	220	290	360	430	500
14						
15						
16		Select Spacing	High		Dropdown Data	
17		Select Diameter	Large		Spacing	
18					High	1.4
19	Face Height Multipliers				Low	1.2
20	1	7.5	75%		Diameter	
21	2	8.33	83%		Small	Large
22	3	9.17	92%		2	9
23	4	10	100%		3	10
24	5	10.83	108%		4	11
25	6	11.67	117%		5	12
26	7	12.5	125%		6	13

A	B	C	D	E	F	G	H	I	J	K
53	**Design Inputs**									
54–56	Trial	Hole Diameter [in]	Product Density [g/cc]	Face Height [ft]	Cut Width [ft]	AE Stemming Factor	Ash Stemming Factor	AE Subdrill Factor	Ash Subdrill Factor	Ash Rock Density
57	1	9	0.8	67.5	150	0.562	0.7	0.428	0.3	162
58	2	9	0.9	67.5	150	0.562	0.7	0.428	0.3	162
59	3	9	1	67.5	150	0.562	0.7	0.428	0.3	162
60	4	9	1.1	67.5	150	0.562	0.7	0.428	0.3	162
61	5	9	1.2	67.5	150	0.562	0.7	0.428	0.3	162
62	6	9	1.3	67.5	150	0.562	0.7	0.428	0.3	162
63	7	10	0.8	75	150	0.562	0.7	0.428	0.3	162
64	8	10	0.9	75	150	0.562	0.7	0.428	0.3	162
65	9	10	1	75	150	0.562	0.7	0.428	0.3	162
66	10	10	1.1	75	150	0.562	0.7	0.428	0.3	162
67	11	10	1.2	75	150	0.562	0.7	0.428	0.3	162
68	12	10	1.3	75	150	0.562	0.7	0.428	0.3	162
69	13	11	0.8	82.5	150	0.562	0.7	0.428	0.3	162
70	14	11	0.9	82.5	150	0.562	0.7	0.428	0.3	162
71	15	11	1	82.5	150	0.562	0.7	0.428	0.3	162
72	16	11	1.1	82.5	150	0.562	0.7	0.428	0.3	162
73	17	11	1.2	82.5	150	0.562	0.7	0.428	0.3	162
74	18	11	1.3	82.5	150	0.562	0.7	0.428	0.3	162
75	19	12	0.8	90	150	0.562	0.7	0.428	0.3	162
76	20	12	0.9	90	150	0.562	0.7	0.428	0.3	162

A	L	M	N	O	P	Q	R	S	T	U
53		**Ash's Method**								
54–56		Loading Density	Ash's Burden	Ash Spacing High	Ash High Surface Area	Ash Stemming	Ash Subdrill	Ash Exp Wt	Ash High Area PF	
57		22.06	18.59	26.03	484.03	13.02	5.58	1325.24	1.10	
58		24.82	19.34	27.07	523.57	13.54	5.80	1483.50	1.13	
59		=0.3405*D59*C59^2	=(30*((D59/1.4)^(1/3))*((160/K59)^(1/3)))*(C59/12)	=N59*IF($D$16=$F$18,$G$18,IF($D$16=$F$19,$G$19,"CHECK"))	=N59*O59	=N59*H59	=N59*J59	=M59*(E59+R59-Q59)	=S59/((P59*E59)/27)	
60		30.34	20.68	28.95	598.51	14.47	6.20	1796.94	1.20	
61		33.10	21.28	29.80	634.26	14.90	6.39	1952.24	1.23	
62		35.85	21.86	30.60	669.02	15.30	6.56	2106.67	1.26	
63		27.24	20.66	28.92	597.57	14.46	6.20	1817.89	1.10	
64		30.65	21.49	30.08	646.38	15.04	6.45	2034.98	1.13	
65		34.05	22.26	31.16	693.41	15.58	6.68	2250.63	1.17	
66		37.46	22.97	32.16	738.90	16.08	6.89	2464.93	1.20	
67		40.86	23.65	33.11	783.03	16.55	7.09	2677.97	1.23	
68		44.27	24.29	34.00	825.95	17.00	7.29	2889.81	1.26	
69		32.96	22.73	31.82	723.06	15.91	6.82	2419.61	1.10	
70		37.08	23.64	33.09	782.12	16.55	7.09	2708.56	1.13	
71		41.20	24.48	34.27	839.03	17.14	7.34	2995.59	1.17	
72		45.32	25.27	35.38	894.07	17.69	7.58	3280.83	1.20	
73		49.44	26.01	36.42	947.47	18.21	7.80	3564.38	1.23	
74		53.56	26.72	37.41	999.40	18.70	8.02	3846.34	1.26	
75		39.23	24.79	34.71	860.50	17.35	7.44	3141.31	1.10	
76		44.13	25.78	36.10	930.79	18.05	7.74	3516.45	1.13	

A	B	C	D	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
53						AE from Ash High PF											
54 55 56	Trial	Hole Diameter [in]	Product Density [g/cc]	Ash High Area PF		Ash High PF	AE	AE Stem	AE Subdrill	AE Surface Area	AE # Rows	AE Spacing	AE Burden	AE Exp Wt	AE Calc PF	PF Mismatch	
57	1	9	0.8	1.10		1.10	20.15	13.11	5.61	483.55	6.82	21.43	22.57	1323.918	1.10	0.000%	
58	2	9	0.9	1.13		1.13	21.90	13.67	5.85	522.85	6.56	21.43	24.40	1481.475	1.13	0.000%	
59	3	9	1	=S59/((P59*E59)/27)		=T59	=M59/V59	=((W59*27)^(1/2))*G59	=X59*I59	=W59*(1-((X59-Y59)/E59))*27	=F59/(Z59^(1/2))	=F59/ROUND(AA59,0)	=Z59/AB59	=M59*(E59+Y59-X59)	=AD59/((Z59*E59)/27)	=(V59-AE59)/AE59	
60	4	9	1.1	1.20		1.20	25.26	14.68	6.28	597.25	6.14	25.00	23.89	1793.142	1.20	0.000%	
61	5	9	1.2	1.23		1.23	26.88	15.14	6.48	632.68	5.96	25.00	25.31	1947.388	1.23	0.000%	
62	6	9	1.3	1.26		1.26	28.47	15.58	6.67	667.11	5.81	25.00	26.68	2100.65	1.26	0.000%	
63	7	10	0.8	1.10		1.10	24.87	14.56	6.23	596.97	6.14	25.00	23.88	1816.075	1.10	0.000%	
64	8	10	0.9	1.13		1.13	27.04	15.18	6.50	645.50	5.90	25.00	25.82	2032.201	1.13	0.000%	
65	9	10	1	1.17		1.17	29.14	15.76	6.75	692.21	5.70	25.00	27.69	2246.719	1.17	0.000%	
66	10	10	1.1	1.20		1.20	31.19	16.31	6.98	737.34	5.52	25.00	29.49	2459.728	1.20	0.000%	
67	11	10	1.2	1.23		1.23	33.19	16.82	7.20	781.09	5.37	30.00	26.04	2671.314	1.23	0.000%	
68	12	10	1.3	1.26		1.26	35.14	17.31	7.41	823.59	5.23	30.00	27.45	2881.55	1.26	0.000%	
69	13	11	0.8	1.10		1.10	30.10	16.02	6.86	722.33	5.58	25.00	28.89	2417.195	1.10	0.000%	
70	14	11	0.9	1.13		1.13	32.72	16.70	7.15	781.05	5.37	30.00	26.03	2704.86	1.13	0.000%	
71	15	11	1	1.17		1.17	35.26	17.34	7.42	837.57	5.18	30.00	27.92	2990.383	1.17	0.000%	
72	16	11	1.1	1.20		1.20	37.74	17.94	7.68	892.19	5.02	30.00	29.74	3273.898	1.20	0.000%	
73	17	11	1.2	1.23		1.23	40.16	18.51	7.92	945.12	4.88	30.00	31.50	3555.519	1.23	0.000%	
74	18	11	1.3	1.26		1.26	42.52	19.04	8.15	996.55	4.75	30.00	33.22	3835.343	1.26	0.000%	
75	19	12	0.8	1.10		1.10	35.82	17.48	7.48	859.64	5.12	30.00	28.65	3138.177	1.10	0.000%	
76	20	12	0.9	1.13		1.13	38.94	18.22	7.80	929.51	4.92	30.00	30.98	3511.643	1.13	0.000%	

AG	AH	AI	AJ	AK	AL	AN	AO	AP	AR	AS	AT	AV	AW	AX	BO
			Spacing w/Normalized Burden			Burden			Spacing			Burden w/Normalized Spacing			53
		Trial	Ash High Spacing	AE Spacing with Normalized Burden	Spacing w/Normaliz ed Burden AE/Ash	Ash High Burden	AE Burden	Burden AE/High Ash	Ash High Spacing	AE Spacing	Spacing AE/High Ash	Ash High Burden	AE Burden with Normalized Spacing	Burden w/Normaliz ed Spacing AE/Ash	54 55 56
		1	26.03	26.01	99.90%	18.59	22.57	121.36%	26.03	21.43	82.32%	18.59	18.58	99.90%	57
		2	27.07	27.04	99.86%	19.34	24.40	126.17%	27.07	21.43	79.15%	19.34	19.31	99.86%	58
		3	=O59	=Z59/N59	=AK59/AJ 59	=N59	=AC59	=AO59/A N59	=O59	=AB59	=AS59/A R59	=N59	=Z59/O59	=AW59/A V59	59
		4	28.95	28.89	99.79%	20.68	23.89	115.54%	28.95	25.00	86.37%	20.68	20.63	99.79%	60
		5	29.80	29.72	99.75%	21.28	25.31	118.90%	29.80	25.00	83.90%	21.28	21.23	99.75%	61
		6	30.60	30.52	99.71%	21.86	26.68	122.07%	30.60	25.00	81.69%	21.86	21.80	99.71%	62
		7	28.92	28.90	99.90%	20.66	23.88	115.58%	28.92	25.00	86.43%	20.66	20.64	99.90%	63
		8	30.08	30.04	99.86%	21.49	25.82	120.16%	30.08	25.00	83.11%	21.49	21.46	99.86%	64
		9	31.16	31.10	99.83%	22.26	27.69	124.41%	31.16	25.00	80.24%	22.26	22.22	99.83%	65
		10	32.16	32.10	99.79%	22.97	29.49	128.38%	32.16	25.00	77.73%	22.97	22.93	99.79%	66
		11	33.11	33.03	99.75%	23.65	26.04	110.09%	33.11	30.00	90.61%	23.65	23.59	99.75%	67
		12	34.00	33.91	99.71%	24.29	27.45	113.03%	34.00	30.00	88.22%	24.29	24.22	99.71%	68
		13	31.82	31.78	99.90%	22.73	28.89	127.14%	31.82	25.00	78.58%	22.73	22.70	99.90%	69
		14	33.09	33.05	99.86%	23.64	26.03	110.15%	33.09	30.00	90.66%	23.64	23.60	99.86%	70
		15	34.27	34.21	99.83%	24.48	27.92	114.04%	34.27	30.00	87.53%	24.48	24.44	99.83%	71
		16	35.38	35.30	99.79%	25.27	29.74	117.68%	35.38	30.00	84.80%	25.27	25.22	99.79%	72
		17	36.42	36.33	99.75%	26.01	31.50	121.10%	36.42	30.00	82.37%	26.01	25.95	99.75%	73
		18	37.41	37.30	99.71%	26.72	33.22	124.33%	37.41	30.00	80.20%	26.72	26.64	99.71%	74
		19	34.71	34.67	99.90%	24.79	28.65	115.58%	34.71	30.00	86.43%	24.79	24.77	99.90%	75
		20	36.10	36.05	99.86%	25.78	30.98	120.16%	36.10	30.00	83.11%	25.78	25.75	99.86%	76

AX	AZ	BA	BB	BD	BE	BF	BH	BI	BJ	BL	BM	BN	BO
Spacing	Area			Stemming			Subdrill			Explosive Weight			53
Burden w/Normalized Spacing AE/Ash	Ash High Area	AE Area	Area AE/High Ash	Ash Stemming	AE Stemming	Stemming AE/Ash	Ash Subdrill	AE Subdrill	Subdrill AE/Ash	Ash Weight	AE Weight	Explosive Weight AE/Ash	54 55 56
99.90%	484.03	483.55	99.90%	13.02	13.11	100.71%	5.58	5.61	100.57%	1325.24	1323.92	99.90%	57
99.86%	523.57	522.85	99.86%	13.54	13.67	100.96%	5.80	5.85	100.82%	1483.50	1481.47	99.86%	58
=AW59/AV59	=P59	=Z59	=BA59/AZ59	=Q59	=X59	=BE59/BD59	=R59	=Y59	=BI59/BH59	=S59	=AD59	=BM59/BL59	59
99.79%	598.51	597.25	99.79%	14.47	14.68	101.41%	6.20	6.28	101.28%	1796.94	1793.14	99.79%	60
99.75%	634.26	632.68	99.75%	14.90	15.14	101.62%	6.39	6.48	101.48%	1952.24	1947.39	99.75%	61
99.71%	669.02	667.11	99.71%	15.30	15.58	101.82%	6.56	6.67	101.68%	2106.67	2100.65	99.71%	62
99.90%	597.57	596.97	99.90%	14.46	14.56	100.71%	6.20	6.23	100.57%	1817.89	1816.07	99.90%	63
99.86%	646.38	645.50	99.86%	15.04	15.18	100.96%	6.45	6.50	100.82%	2034.98	2032.20	99.86%	64
99.83%	693.41	692.21	99.83%	15.58	15.76	101.19%	6.68	6.75	101.06%	2250.63	2246.72	99.83%	65
99.79%	738.90	737.34	99.79%	16.08	16.31	101.41%	6.89	6.98	101.28%	2464.93	2459.73	99.79%	66
99.75%	783.03	781.09	99.75%	16.55	16.82	101.62%	7.09	7.20	101.48%	2677.97	2671.31	99.75%	67
99.71%	825.95	823.59	99.71%	17.00	17.31	101.82%	7.29	7.41	101.68%	2889.81	2881.55	99.71%	68
99.90%	723.06	722.33	99.90%	15.91	16.02	100.71%	6.82	6.86	100.57%	2419.61	2417.20	99.90%	69
99.86%	782.12	781.05	99.86%	16.55	16.70	100.96%	7.09	7.15	100.82%	2708.56	2704.86	99.86%	70
99.83%	839.03	837.57	99.83%	17.14	17.34	101.19%	7.34	7.42	101.06%	2995.59	2990.38	99.83%	71
99.79%	894.07	892.19	99.79%	17.69	17.94	101.41%	7.58	7.68	101.28%	3280.83	3273.90	99.79%	72
99.75%	947.47	945.12	99.75%	18.21	18.51	101.62%	7.80	7.92	101.48%	3564.38	3555.52	99.75%	73
99.71%	999.40	996.55	99.71%	18.70	19.04	101.82%	8.02	8.15	101.68%	3846.34	3835.34	99.71%	74
99.90%	860.50	859.64	99.90%	17.35	17.48	100.71%	7.44	7.48	100.57%	3141.31	3138.18	99.90%	75
99.86%	930.79	929.51	99.86%	18.05	18.22	100.96%	7.74	7.80	100.82%	3516.45	3511.64	99.86%	76

The Konya comparison spreadsheet is quite similar to the Ash spreadsheet, and is laid out in the same manner.

Konya Comparison Spreadsheet

Input Table

A	B	C	D	E	F	G
8–9	AE Stem Factor	AE Subdrill Factor		Konya Stem Factor	Konya Subdrill Factor	Konya Rock Density
10	**0.572**	**0.429**		0.7	0.3	162
11	**0.780**	**0.3**		1	0.3	162
12						
13				**Cut Width**		
14	**150**	**220**	**290**	**360**	**430**	**500**
15						
16						
17		Select Spacing	Standard		Dropdown Data	
18		Select Diameter	Large		Spacing	
19					Standard	
20	Face Height Multipliers					
21	1	7.5	75%		Diameter	
22	2	8.33	83%		Small	Large
23	3	9.17	92%		2	9
24	4	10	100%		3	10
25	5	10.83	108%		4	11
26	6	11.67	117%		5	12
27	7	12.5	125%		6	13

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
41	**Design Inputs**											**Konya's Method**									
42 43 44	Trial	Hole Diameter [in]	Product Density [g/cc]	Face Height [ft]	Cut Width [ft]	AE Stemming Factor	Konya Stemming Factor	AE Subdrill Factor	Konya Subdrill Factor	Konya Rock Density		Loading Density	Konya's Burden	Konya's Stiffness Ratio	Konya Spacing Standard	Konya Standard Surface Area	Konya Stemming	Konya Subdrill	Konya Exp Wt	Konya Standard Area PF	
45	1	9	0.8	67.5	150	0.572	0.7	0.429	0.3	2.60		22.06	19.05	3.54	25.10	478.13	13.33	5.71	1321.25	1.11	
46	2	9	0.9	67.5	150	0.572	0.7	0.429	0.3	2.60		=0.3405*D46*C46^2	=(((2*D46)/K46)+1.5)*C46	=E46/N46	=IF(AND(O46<4,O46>=1),((E46+7*N46)/8),IF(O46>=4,N46*1.4,"CHECK"))	=N46*P46	=N46*H46	=N46*J46	=M46*(E46+S46-R46)	=T46/((Q46*E46)/27)	
47	3	9	1	67.5	150	0.572	0.7	0.429	0.3	2.60		27.58	20.43	3.30	26.32	537.74	14.30	6.13	1636.26	1.22	
48	4	9	1.1	67.5	150	0.572	0.7	0.429	0.3	2.60		30.34	21.13	3.20	26.92	568.80	14.79	6.34	1791.47	1.26	
49	5	9	1.2	67.5	150	0.572	0.7	0.429	0.3	2.60		33.10	21.82	3.09	27.53	600.70	15.27	6.55	1945.15	1.30	
50	6	9	1.3	67.5	150	0.572	0.7	0.429	0.3	2.60		35.85	22.51	3.00	28.14	633.45	15.76	6.75	2097.31	1.32	
51	7	10	0.8	75	150	0.572	0.7	0.429	0.3	2.60		27.24	21.16	3.54	27.89	590.29	14.81	6.35	1812.41	1.11	
52	8	10	0.9	75	150	0.572	0.7	0.429	0.3	2.60		30.65	21.93	3.42	28.57	626.56	15.35	6.58	2029.52	1.17	
53	9	10	1	75	150	0.572	0.7	0.429	0.3	2.60		34.05	22.70	3.30	29.24	663.87	15.89	6.81	2244.53	1.22	
54	10	10	1.1	75	150	0.572	0.7	0.429	0.3	2.60		37.46	23.47	3.20	29.91	702.22	16.43	7.04	2457.44	1.26	
55	11	10	1.2	75	150	0.572	0.7	0.429	0.3	2.60		40.86	24.24	3.09	30.59	741.61	16.97	7.27	2668.25	1.30	
56	12	10	1.3	75	150	0.572	0.7	0.429	0.3	2.60		44.27	25.01	3.00	31.26	782.04	17.51	7.50	2876.96	1.32	
57	13	11	0.8	82.5	150	0.572	0.7	0.429	0.3	2.60		32.96	23.28	3.54	30.68	714.25	16.30	6.98	2412.32	1.11	
58	14	11	0.9	82.5	150	0.572	0.7	0.429	0.3	2.60		37.08	24.13	3.42	31.42	758.14	16.89	7.24	2701.29	1.17	
59	15	11	1	82.5	150	0.572	0.7	0.429	0.3	2.60		41.20	24.97	3.30	32.16	803.29	17.48	7.49	2987.46	1.22	
60	16	11	1.1	82.5	150	0.572	0.7	0.429	0.3	2.60		45.32	25.82	3.20	32.91	849.69	18.08	7.75	3270.85	1.26	
61	17	11	1.2	82.5	150	0.572	0.7	0.429	0.3	2.60		49.44	26.67	3.09	33.65	897.35	18.67	8.00	3551.44	1.30	
62	18	11	1.3	82.5	150	0.572	0.7	0.429	0.3	2.60		53.56	27.52	3.00	34.39	946.27	19.26	8.25	3829.24	1.32	
63	19	12	0.8	90	150	0.572	0.7	0.429	0.3	2.60		39.23	25.40	3.54	33.47	850.02	17.78	7.62	3131.84	1.11	
64	20	12	0.9	90	150	0.572	0.7	0.429	0.3	2.60		44.13	26.32	3.42	34.28	902.25	18.42	7.90	3507.00	1.17	

A	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH
41			AE from Konya Standard PF											
42–44	Konya Standard Area PF		Konya Standard PF	AE	AE Stem	AE Subdrill	AE Surface Area	AE # Rows	AE Spacing	AE Burden	AE Exp Wt	AE Calc PF	PF Mismatch	
45	1.11		1.11	19.96	13.28	5.70	478.42	6.86	21.43	22.33	1322.043	1.11	0.000%	
46	=T46/((Q46*E46)/27)		=T46/((Q46*E46)/27)	=M46/W46	=((X46*27)^(1/2))*G46	=Y46*I46	=X46*(1-((Y46-Z46)/E46))*27	=F46/(AA46^(1/2))	=F46/ROUND(AB46,0)	=AA46/AC46	=M46*(E46+Z46-Y46)	=AE46/((AA46*E46)/27)	=(W46-AF46)/AF46	
47	1.22		1.22	22.66	14.15	6.07	538.59	6.46	25.00	21.54	1638.868	1.22	0.000%	
48	1.26		1.26	24.08	14.59	6.26	569.98	6.28	25.00	22.80	1795.184	1.26	0.000%	
49	1.30		1.30	25.55	15.02	6.45	602.23	6.11	25.00	24.09	1950.09	1.30	0.000%	
50	1.32		1.32	27.07	15.46	6.63	635.34	5.95	25.00	25.41	2103.577	1.32	0.000%	
51	1.11		1.11	24.64	14.75	6.33	590.65	6.17	25.00	23.63	1813.502	1.11	0.000%	
52	1.17		1.17	26.28	15.24	6.54	627.25	5.99	25.00	25.09	2031.758	1.17	0.000%	
53	1.22		1.22	27.98	15.72	6.74	664.93	5.82	25.00	26.60	2248.104	1.22	0.000%	
54	1.26		1.26	29.73	16.21	6.95	703.68	5.65	25.00	28.15	2462.529	1.26	0.000%	
55	1.30		1.30	31.55	16.69	7.16	743.49	5.50	25.00	29.74	2675.02	1.30	0.000%	
56	1.32		1.32	33.42	17.18	7.37	784.38	5.36	30.00	26.15	2885.565	1.32	0.000%	
57	1.11		1.11	29.82	16.23	6.96	714.68	5.61	25.00	28.59	2413.772	1.11	0.000%	
58	1.17		1.17	31.80	16.76	7.19	758.98	5.44	30.00	25.30	2704.27	1.17	0.000%	
59	1.22		1.22	33.85	17.29	7.42	804.57	5.29	30.00	26.82	2992.226	1.22	0.000%	
60	1.26		1.26	35.97	17.83	7.65	851.45	5.14	30.00	28.38	3277.626	1.26	0.000%	
61	1.30		1.30	38.17	18.36	7.88	899.63	5.00	30.00	29.99	3560.452	1.30	0.000%	
62	1.32		1.32	40.44	18.90	8.11	949.09	4.87	30.00	31.64	3840.687	1.32	0.000%	
63	1.11		1.11	35.49	17.71	7.60	850.53	5.14	30.00	28.35	3133.732	1.11	0.000%	
64	1.17		1.17	37.84	18.28	7.84	903.25	4.99	30.00	30.11	3510.878	1.17	0.000%	

AH	AI	AJ	AK	AL	AM	AN	AO	AP	AG	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BP
			Spacing w/Normalized Burden				Burden				Spacing				Burden w/Normalized Spacing				
		Trial	Konya Standard Spacing	AE Spacing with Normalized Burden	Spacing w/Normalized Burden AE/Konya		Konya Standard Burden	AE Burden	Burden AE/Standard Konya		Konya Standard Spacing	AE Spacing	Spacing AE/Standard Konya		Konya Standard Burden	AE Burden with Normalized Spacing	Burden w/Normalized Spacing AE/Konya		
		1	25.10	25.12	100.06%		19.05	22.33	117.22%		25.10	21.43	85.36%		19.05	19.06	100.06%		45
		2	=P46	=AA46/N46	=AL46/AK46		=N46	=AD46	=AP46/AO46		=P46	=AC46	=AT46/AS46		=N46	=AA46/P46	=AX46/AW46		46
		3	26.32	26.36	100.16%		20.43	21.54	105.43%		26.32	25.00	95.00%		20.43	20.47	100.16%		47
		4	26.92	26.98	100.21%		21.13	22.80	107.92%		26.92	25.00	92.86%		21.13	21.17	100.21%		48
		5	27.53	27.60	100.25%		21.82	24.09	110.40%		27.53	25.00	90.81%		21.82	21.88	100.25%		49
		6	28.14	28.22	100.30%		22.51	25.41	112.88%		28.14	25.00	88.85%		22.51	22.58	100.30%		50
		7	27.89	27.91	100.06%		21.16	23.63	111.64%		27.89	25.00	89.63%		21.16	21.18	100.06%		51
		8	28.57	28.60	100.11%		21.93	25.09	114.39%		28.57	25.00	87.51%		21.93	21.96	100.11%		52
		9	29.24	29.29	100.16%		22.70	26.60	117.15%		29.24	25.00	85.50%		22.70	22.74	100.16%		53
		10	29.91	29.98	100.21%		23.47	28.15	119.91%		29.91	25.00	83.57%		23.47	23.52	100.21%		54
		11	30.59	30.67	100.25%		24.24	29.74	122.67%		30.59	25.00	81.73%		24.24	24.31	100.25%		55
		12	31.26	31.36	100.30%		25.01	26.15	104.52%		31.26	30.00	95.96%		25.01	25.09	100.30%		56
		13	30.68	30.70	100.06%		23.28	28.59	122.80%		30.68	25.00	81.48%		23.28	23.29	100.06%		57
		14	31.42	31.46	100.11%		24.13	25.30	104.86%		31.42	30.00	95.47%		24.13	24.15	100.11%		58
		15	32.16	32.22	100.16%		24.97	26.82	107.39%		32.16	30.00	93.27%		24.97	25.01	100.16%		59
		16	32.91	32.97	100.21%		25.82	28.38	109.91%		32.91	30.00	91.17%		25.82	25.87	100.21%		60
		17	33.65	33.73	100.25%		26.67	29.99	112.44%		33.65	30.00	89.16%		26.67	26.74	100.25%		61
		18	34.39	34.49	100.30%		27.52	31.64	114.97%		34.39	30.00	87.24%		27.52	27.60	100.30%		62
		19	33.47	33.49	100.06%		25.40	28.35	111.64%		33.47	30.00	89.63%		25.40	25.41	100.06%		63
		20	34.28	34.32	100.11%		26.32	30.11	114.39%		34.28	30.00	87.51%		26.32	26.35	100.11%		64

A	BA	BB	BC	BE	BF	BG	BI	BJ	BK	BM	BN	BO	BP
	Area			Stemming			Subdrill			Explosive Weight			41
liz ng a	Konya Standard Area	AE Area	Area AE/Standard Konya	Konya Stemming	AE Stemming	Stemming AE/Konya	Konya Subdrill	AE Subdrill	Subdrill AE/Konya	Konya Weight	AE Weight	Explosive Weight AE/Konya	42 43 44
%	478.13	478.42	100.06%	13.33	13.28	99.60%	5.71	5.70	99.70%	1321.25	1322.04	100.06%	45
A	=Q46	=AA46	=BB46/BA46	=R46	=Y46	=BF46/BE46	=S46	=Z46	=BJ46/BI46	=T46	=AE46	=BN46/BM46	46
%	537.74	538.59	100.16%	14.30	14.15	98.92%	6.13	6.07	99.02%	1636.26	1638.87	100.16%	47
%	568.80	569.98	100.21%	14.79	14.59	98.63%	6.34	6.26	98.72%	1791.47	1795.18	100.21%	48
%	600.70	602.23	100.25%	15.27	15.02	98.36%	6.55	6.45	98.46%	1945.15	1950.09	100.25%	49
%	633.45	635.34	100.30%	15.76	15.46	98.13%	6.75	6.63	98.23%	2097.31	2103.58	100.30%	50
%	590.29	590.65	100.06%	14.81	14.75	99.60%	6.35	6.33	99.70%	1812.41	1813.50	100.06%	51
%	626.56	627.25	100.11%	15.35	15.24	99.24%	6.58	6.54	99.34%	2029.52	2031.76	100.11%	52
%	663.87	664.93	100.16%	15.89	15.72	98.92%	6.81	6.74	99.02%	2244.53	2248.10	100.16%	53
%	702.22	703.68	100.21%	16.43	16.21	98.63%	7.04	6.95	98.72%	2457.44	2462.53	100.21%	54
%	741.61	743.49	100.25%	16.97	16.69	98.36%	7.27	7.16	98.46%	2668.25	2675.02	100.25%	55
%	782.04	784.38	100.30%	17.51	17.18	98.13%	7.50	7.37	98.23%	2876.96	2885.56	100.30%	56
%	714.25	714.68	100.06%	16.30	16.23	99.60%	6.98	6.96	99.70%	2412.32	2413.77	100.06%	57
%	758.14	758.98	100.11%	16.89	16.76	99.24%	7.24	7.19	99.34%	2701.29	2704.27	100.11%	58
%	803.29	804.57	100.16%	17.48	17.29	98.92%	7.49	7.42	99.02%	2987.46	2992.23	100.16%	59
%	849.69	851.45	100.21%	18.08	17.83	98.63%	7.75	7.65	98.72%	3270.85	3277.63	100.21%	60
%	897.35	899.63	100.25%	18.67	18.36	98.36%	8.00	7.88	98.46%	3551.44	3560.45	100.25%	61
%	946.27	949.09	100.30%	19.26	18.90	98.13%	8.25	8.11	98.23%	3829.24	3840.69	100.30%	62
%	850.02	850.53	100.06%	17.78	17.71	99.60%	7.62	7.60	99.70%	3131.84	3133.73	100.06%	63
%	902.25	903.25	100.11%	18.42	18.28	99.24%	7.90	7.84	99.34%	3507.00	3510.88	100.11%	64

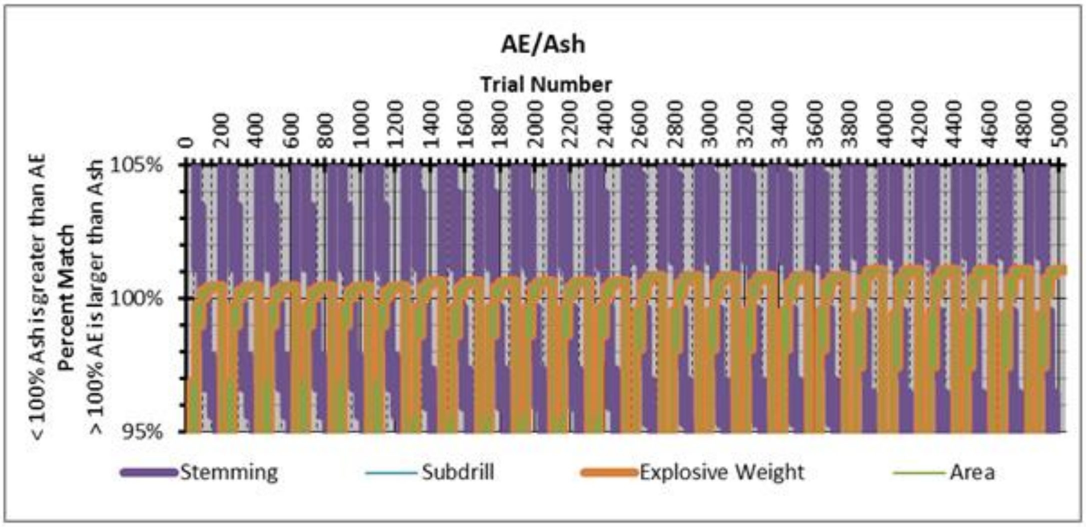
The AE-Ash and AE-Konya comparisons generated a large quantity of data that is best summarized by the following figures. The specifications for each test are followed by the resulting graphs of each test. Short descriptions will accompany the specifications.

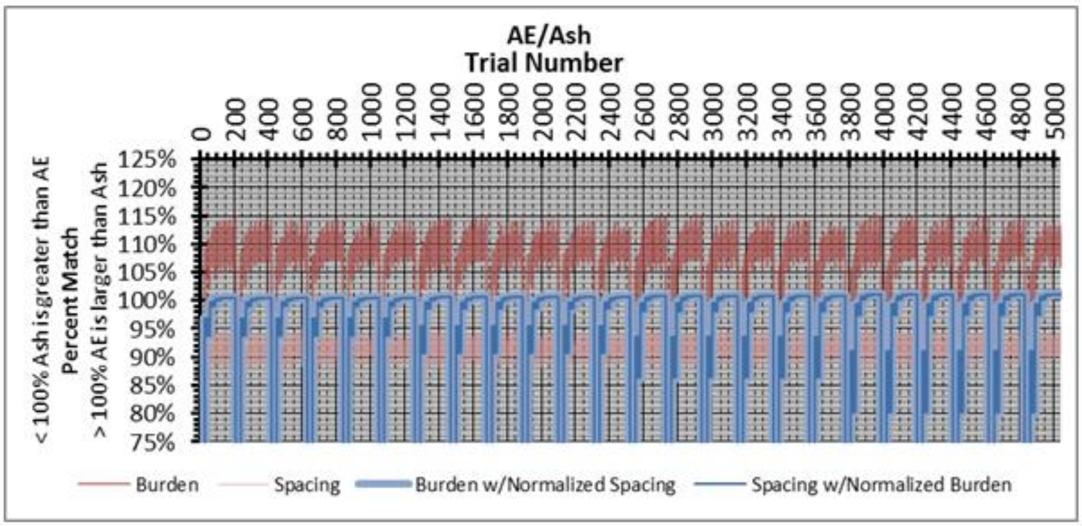
Ash Test 1

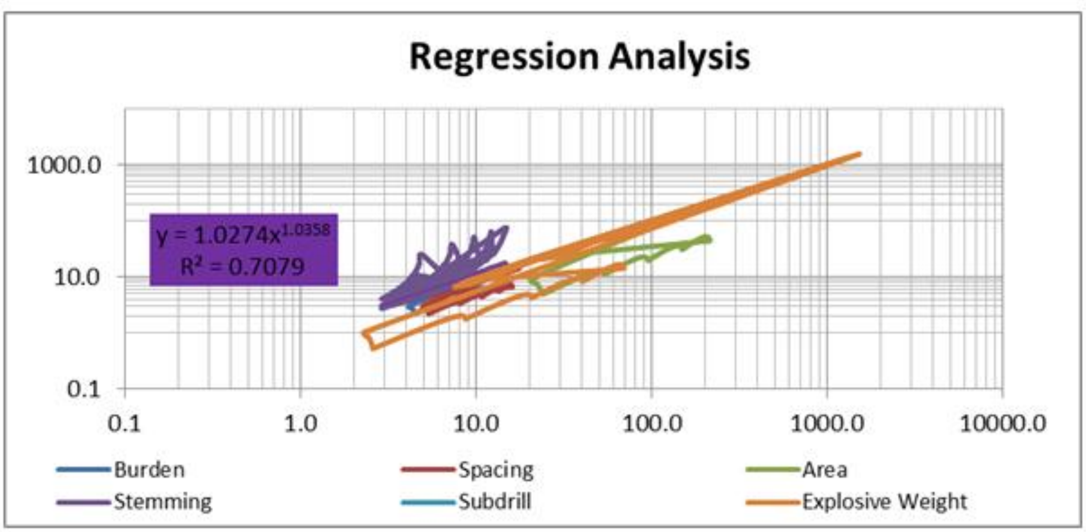
Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.581	0	0.000
0.80	0.653	0	0.000
0.90	0.723	0	0.000
1.00	0.790	0	0.000
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	Spacing Factor [B*#]
150	2	25%	1.20
160	3	50%	
170	4	75%	
180	5	100%	
190	6	125%	
200		150%	
		175%	

Ash Test 1 was a small diameter borehole test using wide face height ranges, the small spacing factor, and no subdrilling. The wide face height range delivers a wide range of results, and the regression graph does not successfully track all variables

Ash Test 1


AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
105%
100%
95%
Stemming
Subdrill
Explosive Weight
Area


AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
125%
120%
115%
110%
105%
100%
95%
90%
85%
80%
75%
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden

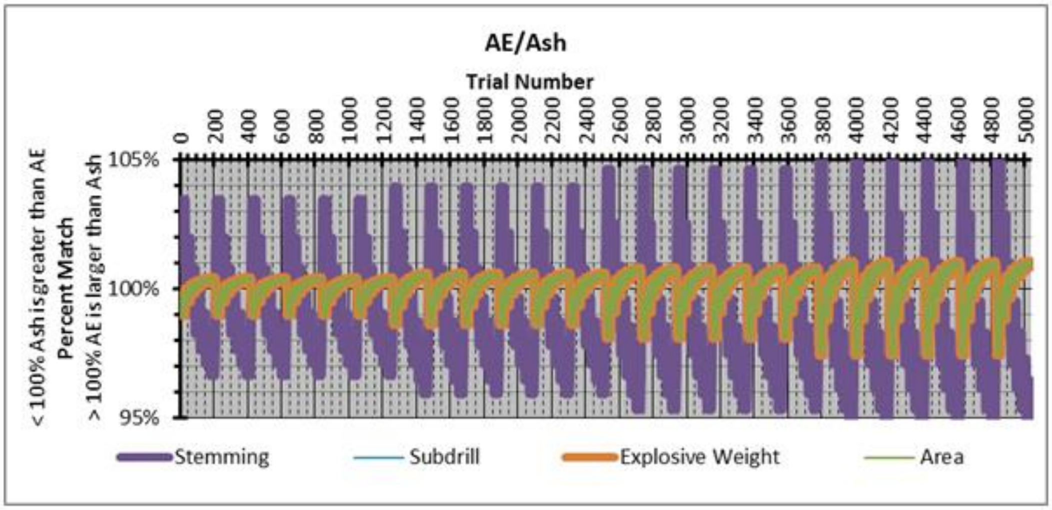

Regression Analysis
y = 1.0274x^1.0358
R² = 0.7079
1000.0
10.0
0.1
0.1
1.0
10.0
100.0
1000.0
10000.0
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

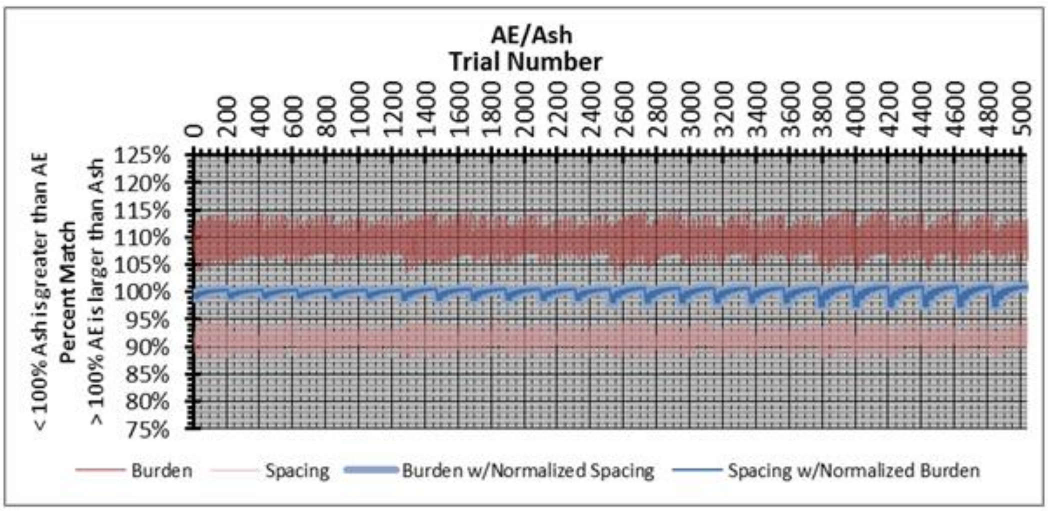
Ash Test 2

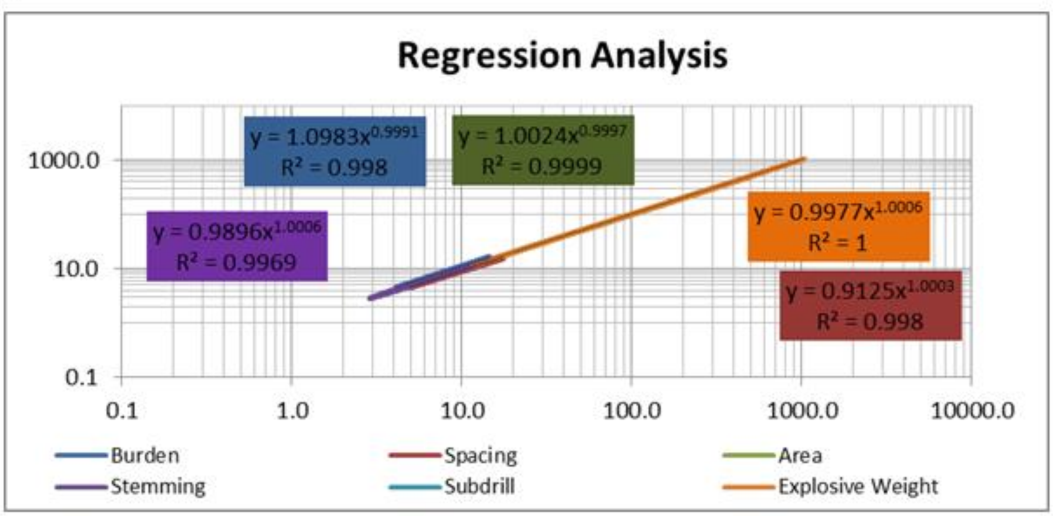
Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.581	0	0.000
0.80	0.653	0	0.000
0.90	0.723	0	0.000
1.00	0.790	0	0.000
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	Spacing Factor [B*#]
150	2	75%	1.20
160	3	83%	
170	4	92%	
180	5	100%	
190	6	108%	
200		117%	
		125%	

Ash Test 2 is another small diameter, low spacing test with no subdrilling. Ash Test 2 is the first introduction of the narrow face height spacing, and the effects are immediately visible in the linear regression. The narrower face height range results in a much better match of data. Also note that the stemming error is much lower and fully visible for the majority of the graph.

Ash Test 2


AE/Ash
Trial Number
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
105%
100%
95%
Stemming
Subdrill
Explosive Weight
Area


AE/Ash
Trial Number
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
125% 120% 115% 110% 105% 100% 95% 90% 85% 80% 75%
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden

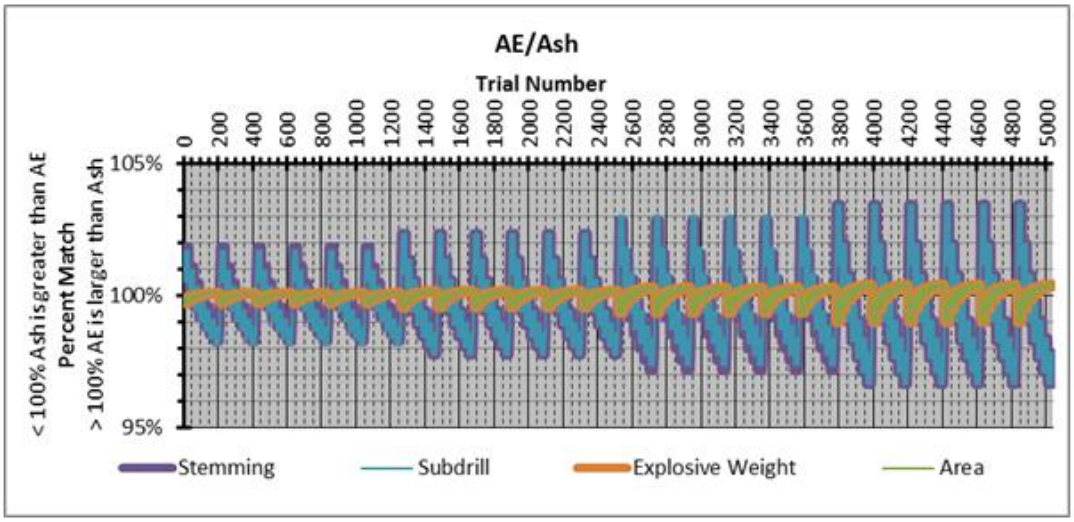

Regression Analysis
y = 1.0983x^0.9991
R² = 0.998
y = 1.0024x^0.9997
R² = 0.9999
y = 0.9896x^1.0006
R² = 0.9969
y = 0.9977x^1.0006
R² = 1
y = 0.9125x^1.0003
R² = 0.998
1000.0
10.0
0.1
0.1 1.0 10.0 100.0 1000.0 10000.0
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

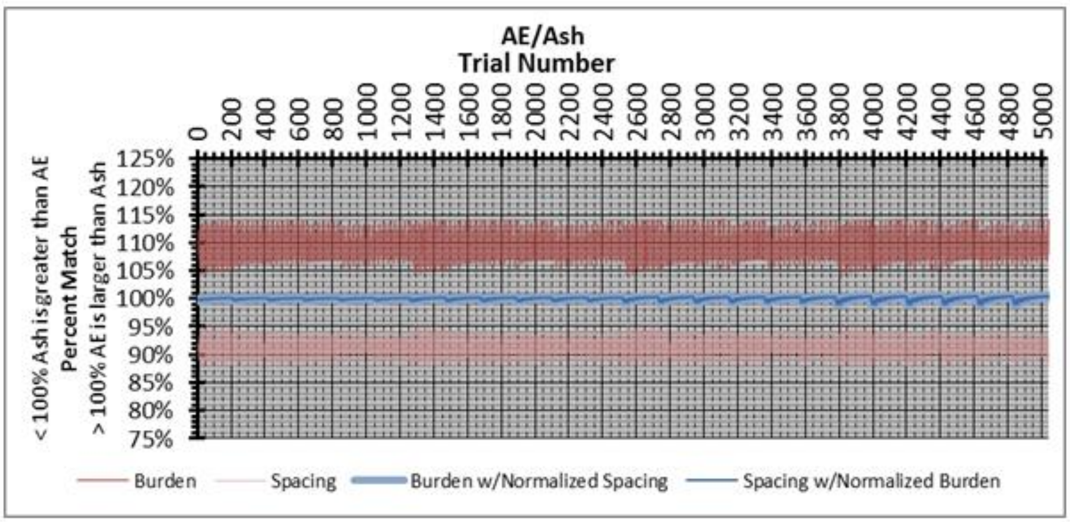
Ash Test 3

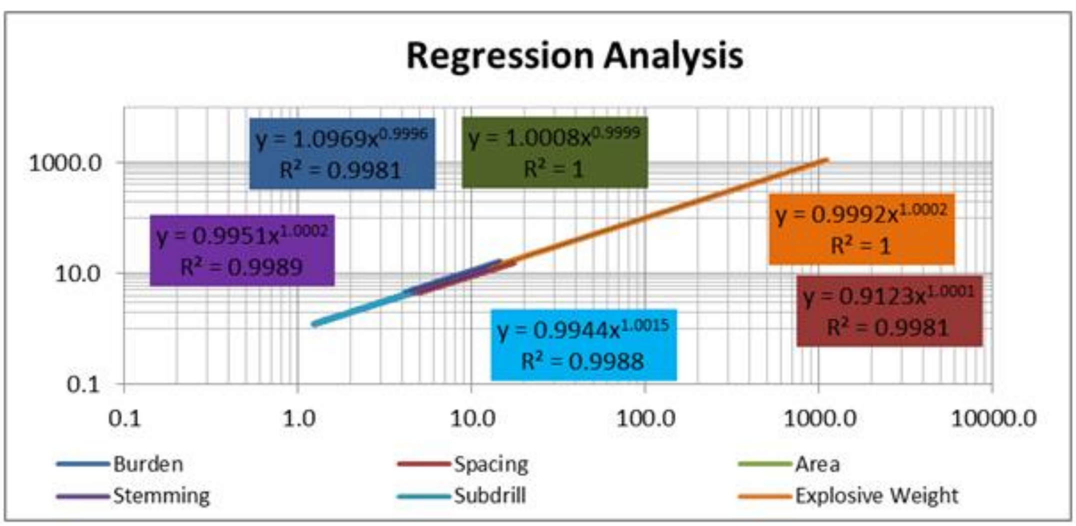
Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.607	0.3	0.428
0.80	0.684	0.3	0.375
0.90	0.758	0.3	0.334
1.00	0.830	0.3	0.300
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	Spacing Factor [B*#]
150	2	75%	1.20
160	3	83%	
170	4	92%	
180	5	100%	
190	6	108%	
200		117%	
		125%	

Ash Test 3 is another small borehole diameter, low spacing test. It is also narrow face height range, and includes subdrill. The linear regression shows good R^2 values and slopes, and the stemming and subdrill error is under 4%.

Ash Test 3


AE/Ash
Trial Number
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
4200
4400
4600
4800
5000
105%
100%
95%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area


AE/Ash
Trial Number
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
4200
4400
4600
4800
5000
125%
120%
115%
110%
105%
100%
95%
90%
85%
80%
75%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden

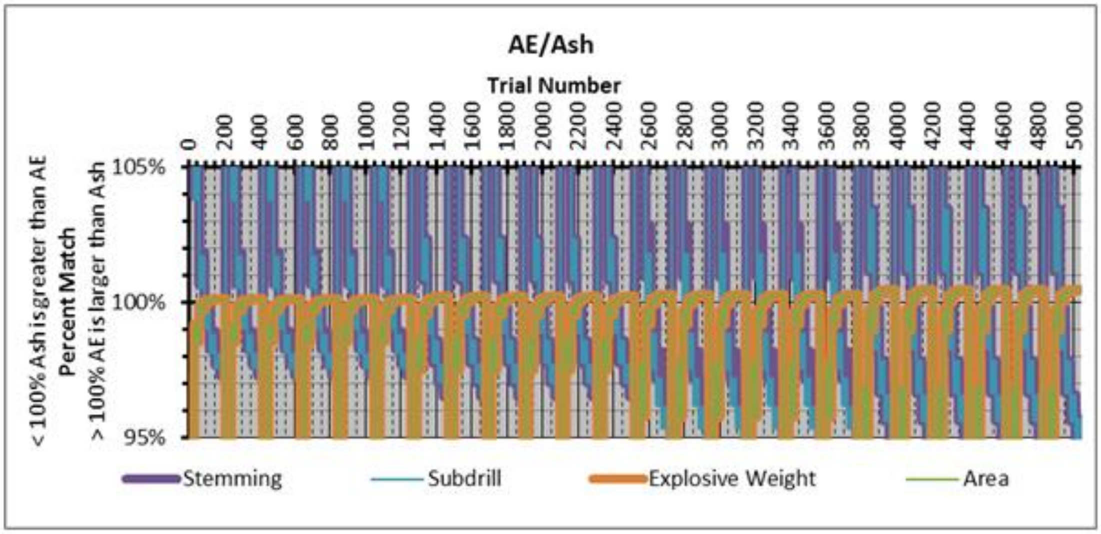

Regression Analysis
y = 1.0969x^0.9996
R² = 0.9981
y = 1.0008x^0.9999
R² = 1
y = 0.9951x^1.0002
R² = 0.9989
y = 0.9992x^1.0002
R² = 1
y = 0.9123x^1.0001
R² = 0.9981
y = 0.9944x^1.0015
R² = 0.9988
1000.0
10.0
0.1
0.1
1.0
10.0
100.0
1000.0
10000.0
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

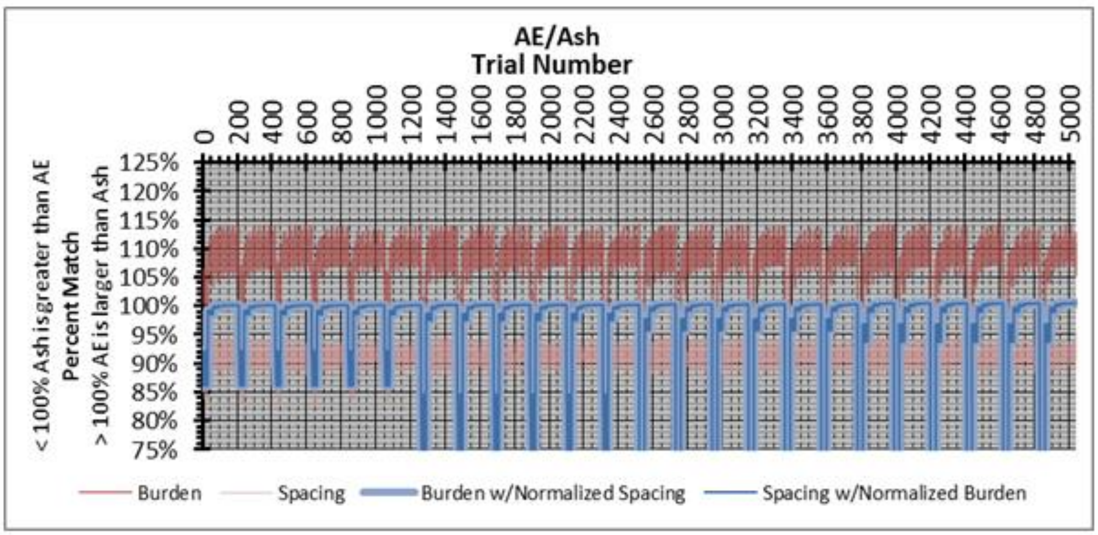
Ash Test 4

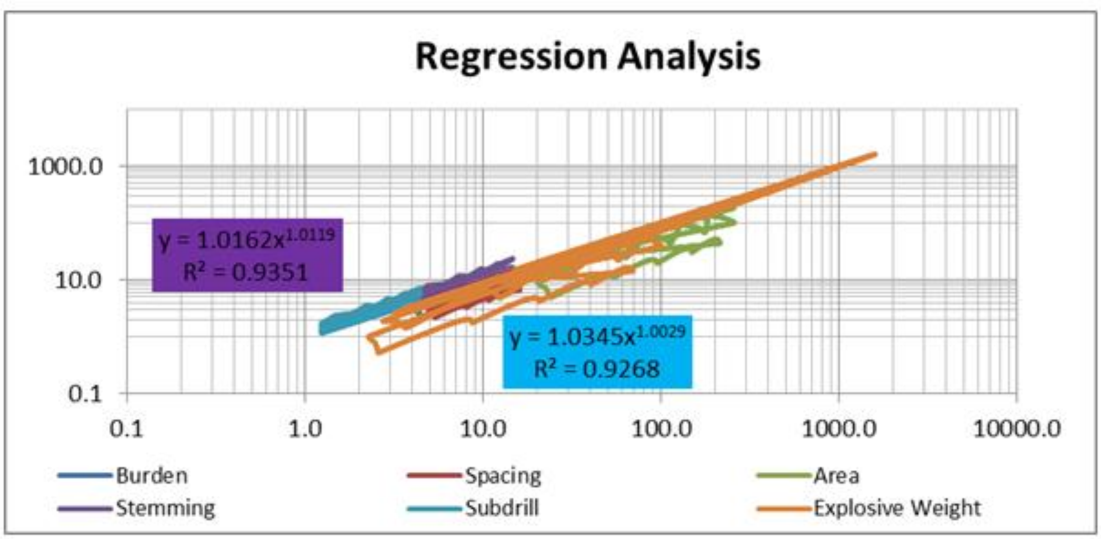
Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.607	0.3	0.428
0.80	0.684	0.3	0.375
0.90	0.758	0.3	0.330
1.00	0.830	0.3	0.300
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	Spacing Factor [B*#]
150	2	25%	1.20
160	3	50%	
170	4	75%	
180	5	100%	
190	6	125%	
200		150%	
		175%	

Ash Test 4 is similar to Ash Test 3 except it returns to the wide face height range. The linear regression shows that wider ranges make for worse data matches, as only two data sets – stemming and subdrilling – had measurable matches. Also, some of the area and explosive weight data toward the middle and end of the 210 trial iteration appear to fit rather well – the traces for stemming, subdrill, explosive weight, and area show that the low face heights approximately every 210 trials cause large errors.

Ash Test 4


AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
105%
100%
95%
Stemming
Subdrill
Explosive Weight
Area


AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden


Regression Analysis
y = 1.0162x^1.0119
R² = 0.9351
y = 1.0345x^1.0029
R² = 0.9268
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

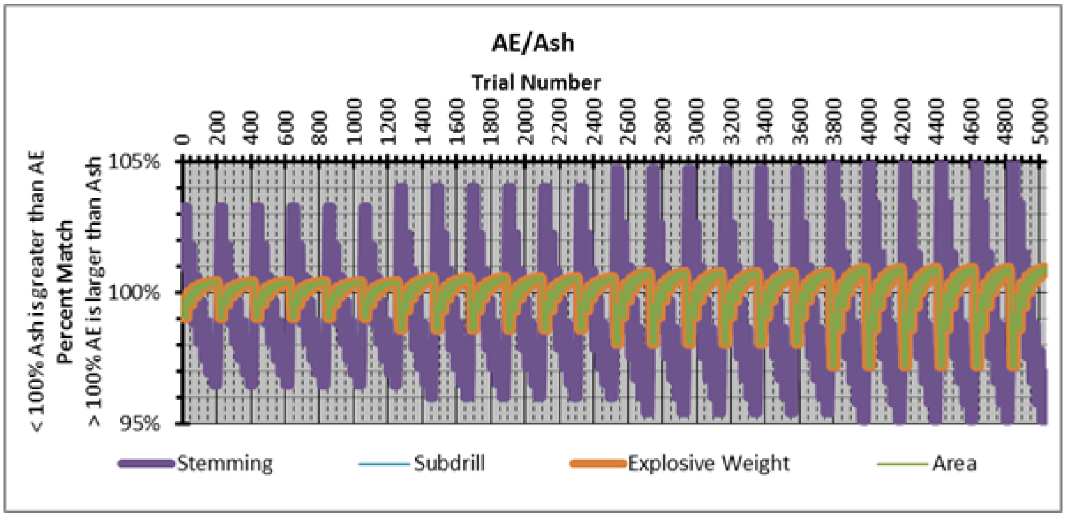
Ash Test 5

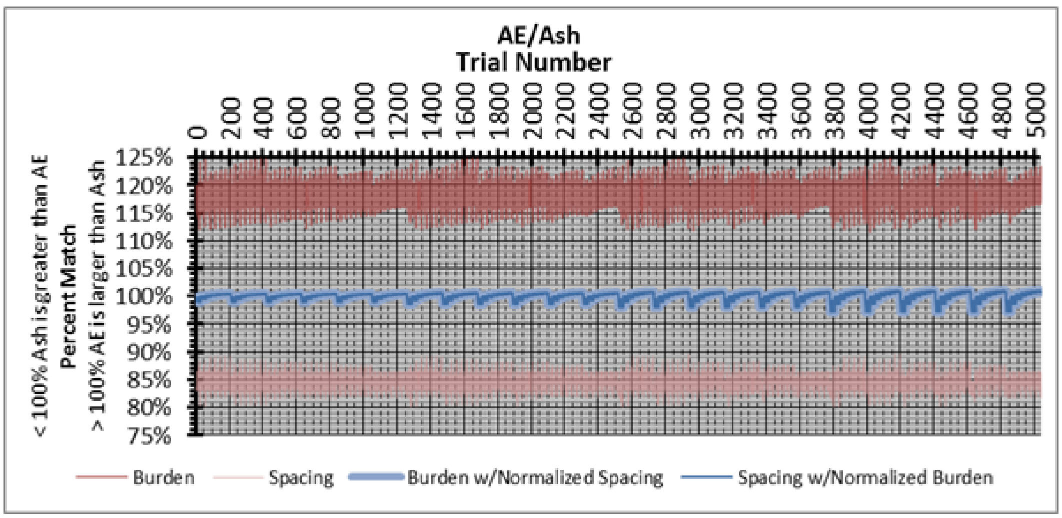
Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.537	0	0.000
0.80	0.605	0	0.000
0.90	0.670	0	0.000
1.00	0.735	0	0.000

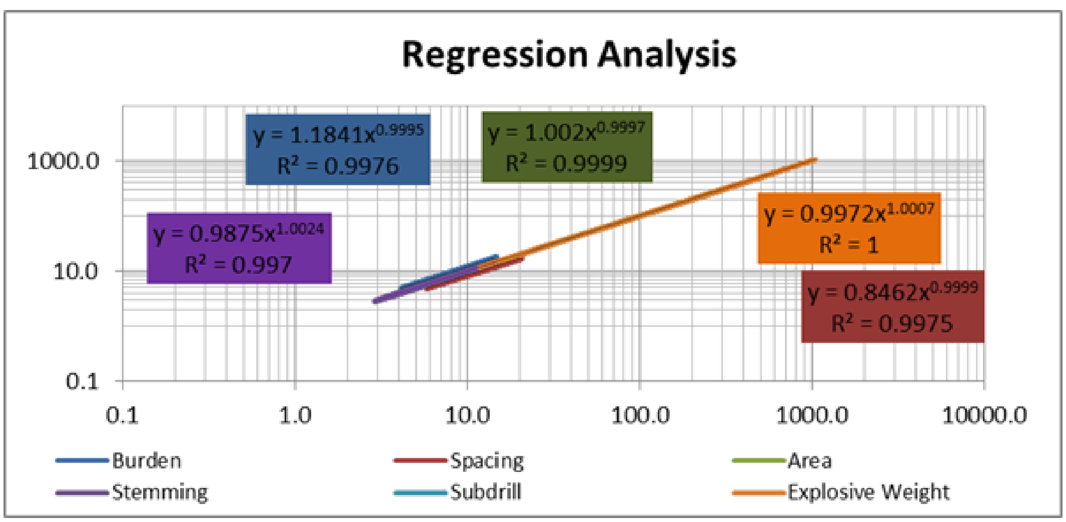
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	Spacing Factor [B*#]
150	2	75%	
160	3	83%	
170	4	92%	
180	5	100%	1.40
190	6	108%	
200		117%	
		125%	

Ash Test 5 introduces the large spacing value. The test is still small diameter, with the narrow face height range, and no subdrill. Linear regression looks good, and the errors are much smaller than Ash Test 4.

Ash Test 5


AE/Ash
Trial Number
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000
105%
100%
95%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area


AE/Ash
Trial Number
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000
125% 120% 115% 110% 105% 100% 95% 90% 85% 80% 75%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden

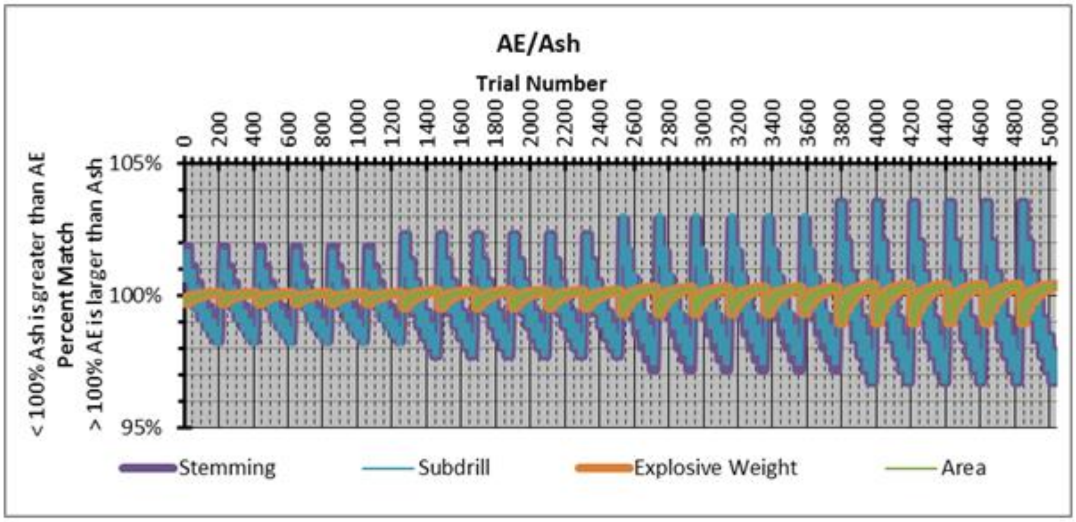

Regression Analysis
y = 1.1841x^0.9995
R² = 0.9976
y = 1.002x^0.9997
R² = 0.9999
y = 0.9875x^1.0024
R² = 0.997
y = 0.9972x^1.0007
R² = 1
y = 0.8462x^0.9999
R² = 0.9975
1000.0
10.0
0.1
0.1 1.0 10.0 100.0 1000.0 10000.0
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

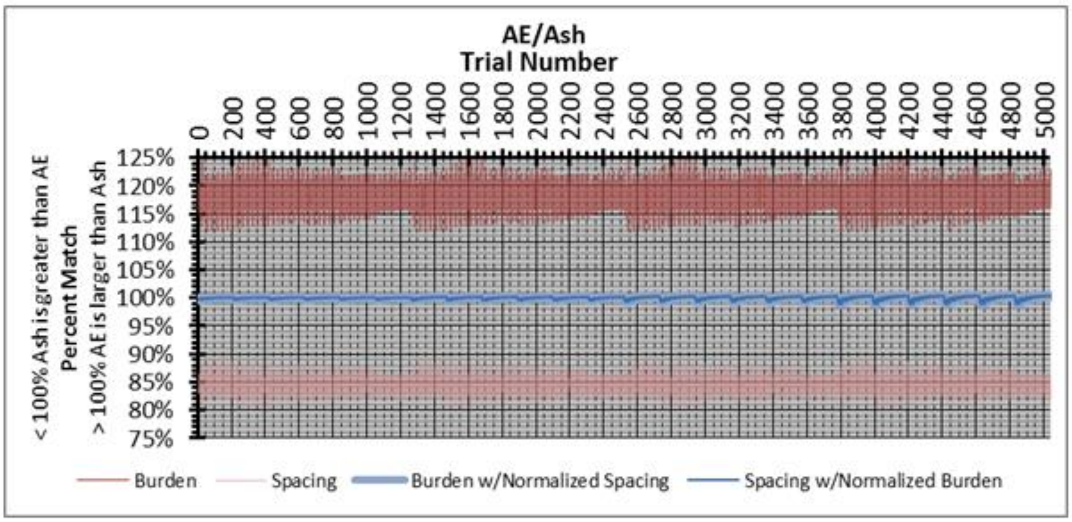
Ash Test 6

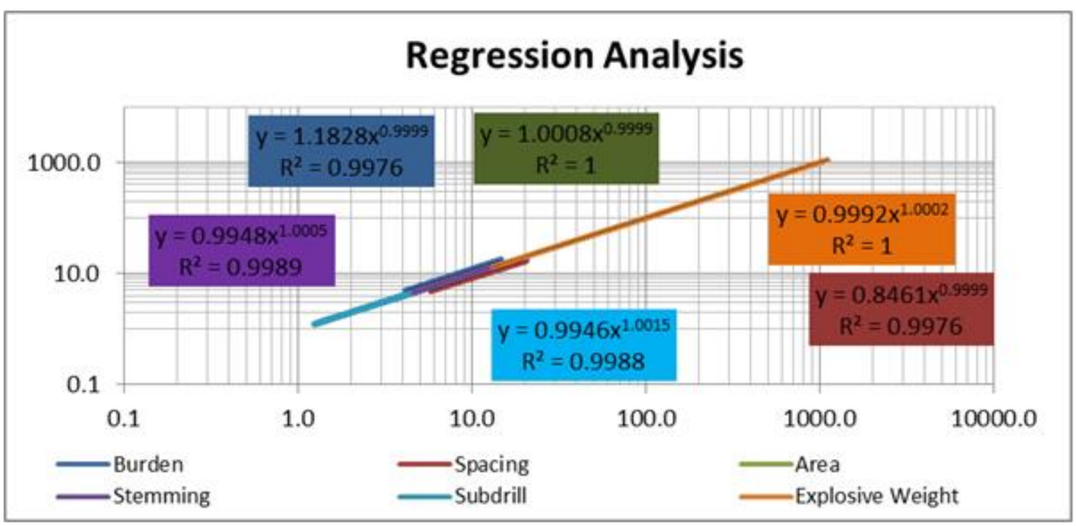
<table>
<tr><th colspan="4">Ash - Available Energy Comparison Test</th></tr>
<tr><th>Ash Stem Factor</th><th>AE Stem Factor</th><th>Ash Subdrill Factor</th><th>AE Subdrill Factor</th></tr>
<tr><td>0.70</td><td>0.562</td><td>0.3</td><td>0.428</td></tr>
<tr><td>0.80</td><td>0.633</td><td>0.3</td><td>0.375</td></tr>
<tr><td>0.90</td><td>0.702</td><td>0.3</td><td>0.334</td></tr>
<tr><td>1.00</td><td>0.769</td><td>0.3</td><td>0.300</td></tr>
<tr><th>Cut Widths [ft]</th><th>Borehole Diameters [in]</th><th>Face Height Multipliers [% of 10*D]</th><th>Spacing Factor [B*#]</th></tr>
<tr><td>150</td><td>2</td><td>75%</td><td rowspan="7">1.40</td></tr>
<tr><td>160</td><td>3</td><td>83%</td></tr>
<tr><td>170</td><td>4</td><td>92%</td></tr>
<tr><td>180</td><td>5</td><td>100%</td></tr>
<tr><td>190</td><td>6</td><td>108%</td></tr>
<tr><td>200</td><td></td><td>117%</td></tr>
<tr><td></td><td></td><td>125%</td></tr>
</table>

Ash Test 6 is similar to Ash Test 5 with the addition of subdrill. Excellent data is noticeable in the linear regression, and the maximum error for the stemming and subdrill is less than 4%.

Ash Test 6


AE/Ash
Trial Number
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
105%
100%
95%
Stemming
Subdrill
Explosive Weight
Area

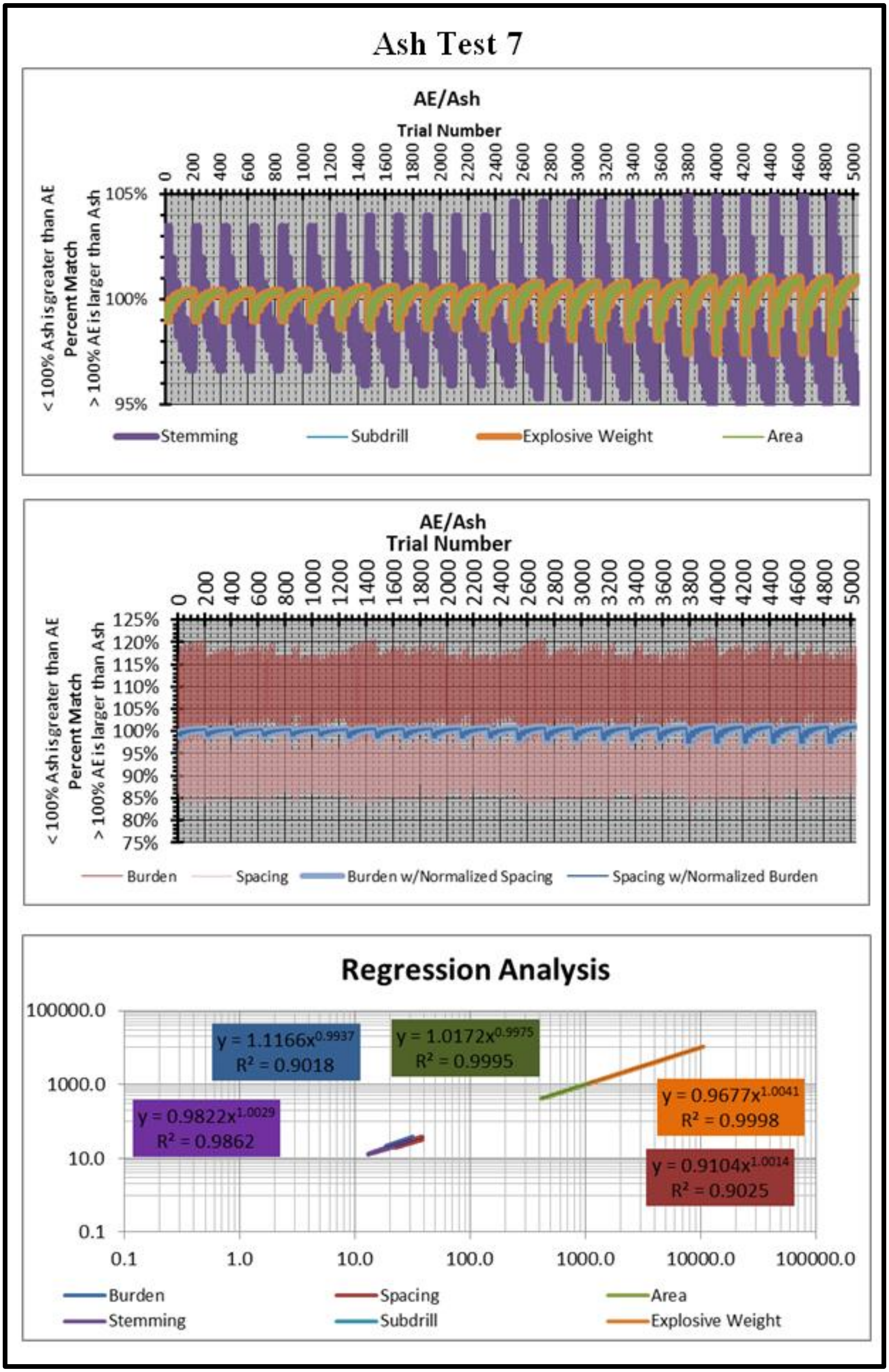

AE/Ash
Trial Number
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
125% 120% 115% 110% 105% 100% 95% 90% 85% 80% 75%
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden


Regression Analysis
y = 1.1828x^0.9999
R² = 0.9976
y = 1.0008x^0.9999
R² = 1
y = 0.9948x^1.0005
R² = 0.9989
y = 0.9992x^1.0002
R² = 1
y = 0.8461x^0.9999
R² = 0.9976
y = 0.9946x^1.0015
R² = 0.9988
1000.0
10.0
0.1
0.1 1.0 10.0 100.0 1000.0 10000.0
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

Ash Test 7

Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.581	0	0.000
0.80	0.653	0	0.000
0.90	0.723	0	0.000
1.00	0.790	0	0.000
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	Spacing Factor [B*#]
150	9	75%	1.20
160	10	83%	
170	11	92%	
180	12	100%	
190	13	108%	
200		117%	
		125%	

Ash Test 7 goes back to low spacing and no subdrill while introducing large borehold diameters. The linear regression shows a reasonable match, and the first three of four stemming factors show stemming and subdrill error less than 5%.

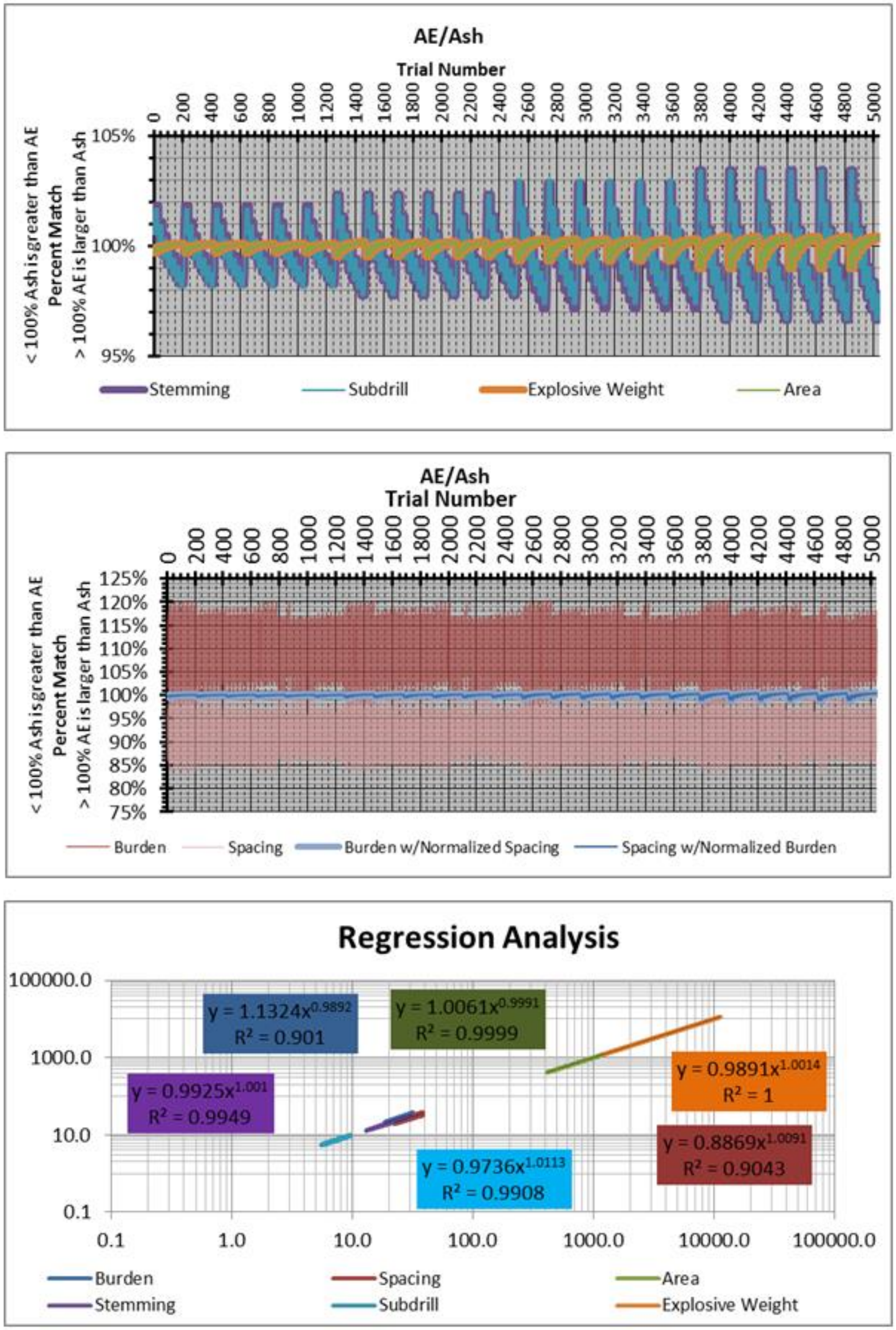

Ash Test 7
AE/Ash
Trial Number
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000
105%
100%
95%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area
AE/Ash
Trial Number
125% 120% 115% 110% 105% 100% 95% 90% 85% 80% 75%
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden
Regression Analysis
100000.0
1000.0
10.0
0.1
0.1 1.0 10.0 100.0 1000.0 10000.0 100000.0
y = 1.1166x^0.9937
R² = 0.9018
y = 1.0172x^0.9975
R² = 0.9995
y = 0.9822x^1.0029
R² = 0.9862
y = 0.9677x^1.0041
R² = 0.9998
y = 0.9104x^1.0014
R² = 0.9025
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

Ash Test 8

Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.607	0.3	0.428
0.80	0.684	0.3	0.375
0.90	0.758	0.3	0.334
1.00	0.830	0.3	0.300
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	Spacing Factor [B*#]
150	9	75%	1.20
160	10	83%	
170	11	92%	
180	12	100%	
190	13	108%	
200		117%	
		125%	

Ash Test 8 introduces subdrilling to Ash Test 7. Excellent data fits, and all stemming and subdrill error less than 4%.

Ash Test 8

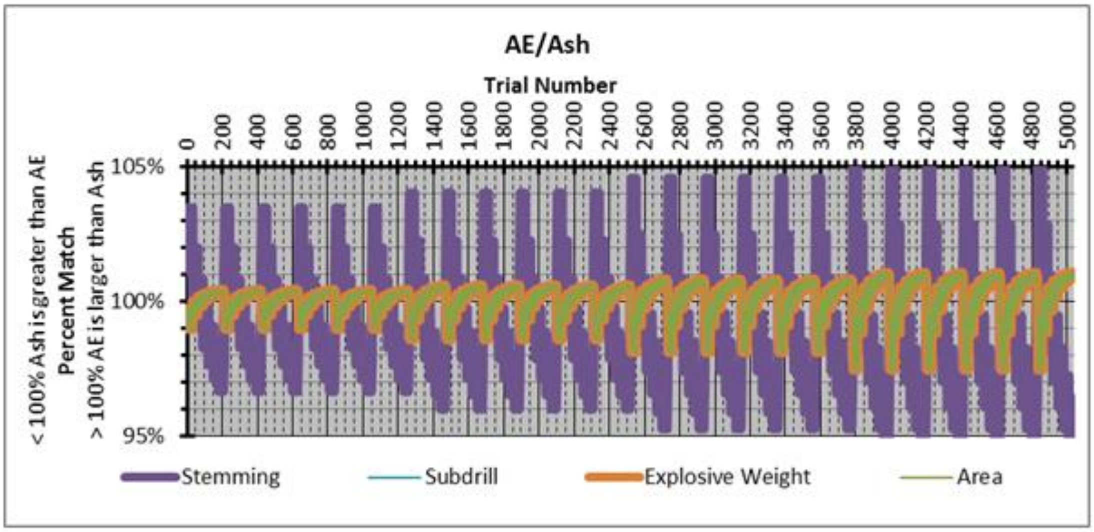

AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area
AE/Ash
Trial Number
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden
Regression Analysis
y = 1.1324x^0.9892
R² = 0.901
y = 1.0061x^0.9991
R² = 0.9999
y = 0.9925x^1.001
R² = 0.9949
y = 0.9891x^1.0014
R² = 1
y = 0.8869x^1.0091
R² = 0.9043
y = 0.9736x^1.0113
R² = 0.9908
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

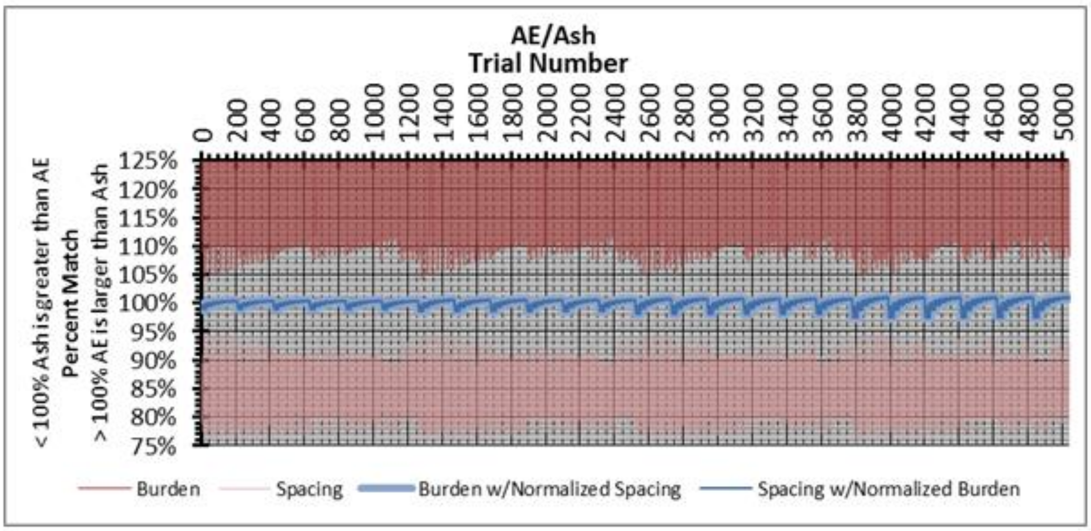
Ash Test 9

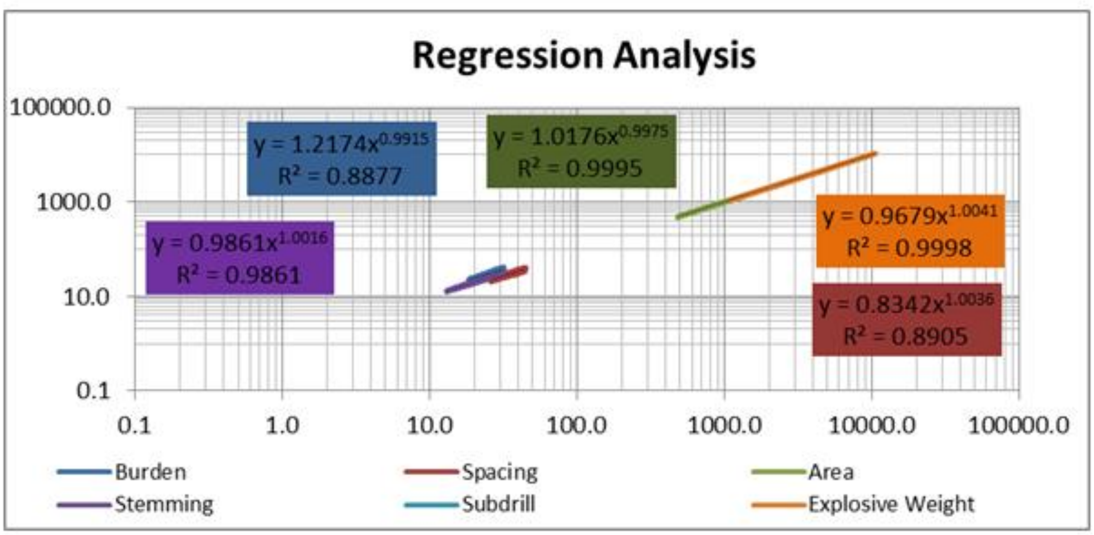
Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.538	0	0.000
0.80	0.605	0	0.000
0.90	0.669	0	0.000
1.00	0.731	0	0.000
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	Spacing Factor [B*#]
150	9	75%	1.40
160	10	83%	
170	11	92%	
180	12	100%	
190	13	108%	
200		117%	
		125%	

Ash Test 9 is Ash Test 7 with the large spacing value. Results are quite similar to Ash Test 7, with slightly different AE stemming factors.

Ash Test 9


AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
105%
100%
95%
Stemming
Subdrill
Explosive Weight
Area

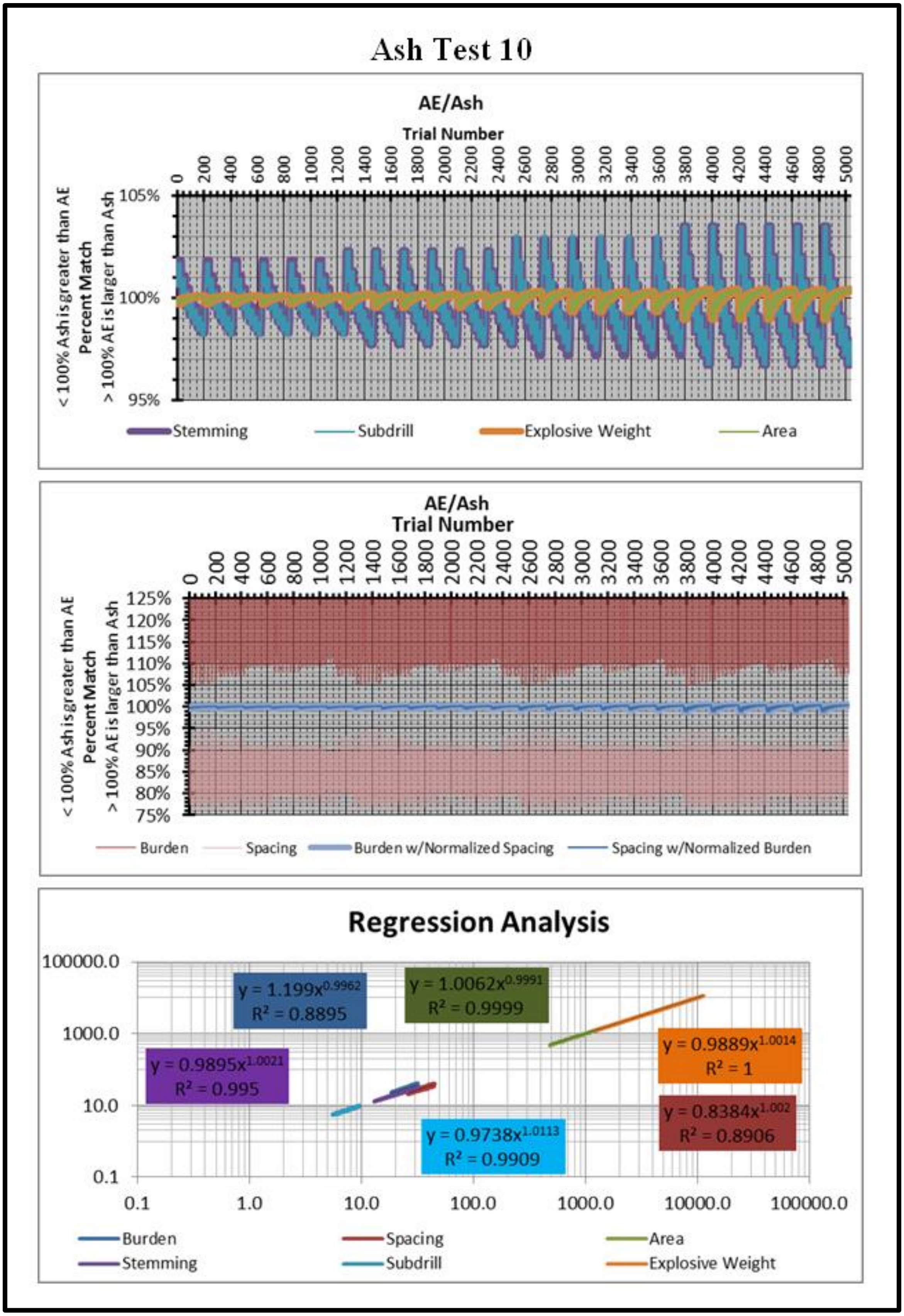

AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden


Regression Analysis
y = 1.2174x^0.9915
R² = 0.8877
y = 1.0176x^0.9975
R² = 0.9995
y = 0.9861x^1.0016
R² = 0.9861
y = 0.9679x^1.0041
R² = 0.9998
y = 0.8342x^1.0036
R² = 0.8905
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

Ash Test 10

Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.562	0.3	0.428
0.80	0.633	0.3	0.375
0.90	0.702	0.3	0.334
1.00	0.769	0.3	0.300
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	Spacing Factor [B*#]
150	9	75%	1.40
160	10	83%	
170	11	92%	
180	12	100%	
190	13	108%	
200		117%	
		125%	

Ash Test 10 is Ash Test 8 with the large spacing value, and slightly different AE stemming factors. Stemming and subdrill errors are below 4%, while area and explosive weight errors have crept up to slightly over 1%

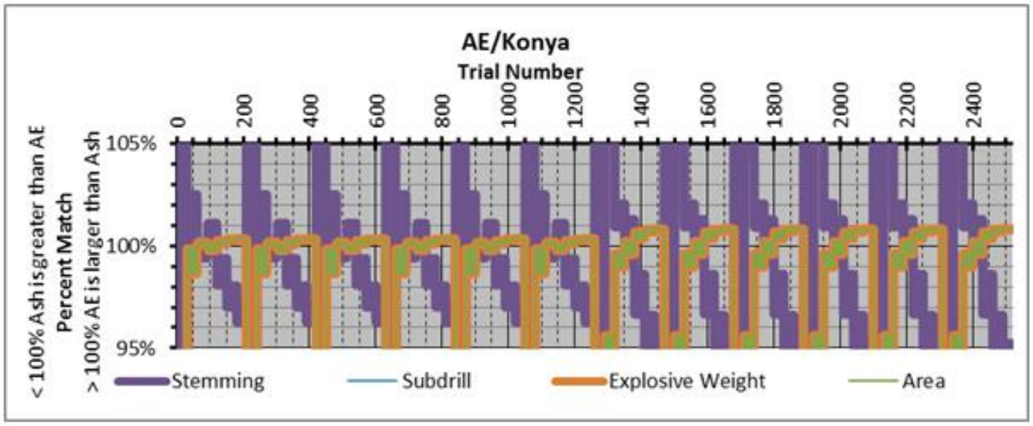

Ash Test 10
AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area
AE/Ash
Trial Number
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden
Regression Analysis
y = 1.199x^0.9962
R² = 0.8895
y = 1.0062x^0.9991
R² = 0.9999
y = 0.9895x^1.0021
R² = 0.995
y = 0.9889x^1.0014
R² = 1
y = 0.8384x^1.002
R² = 0.8906
y = 0.9738x^1.0113
R² = 0.9909
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

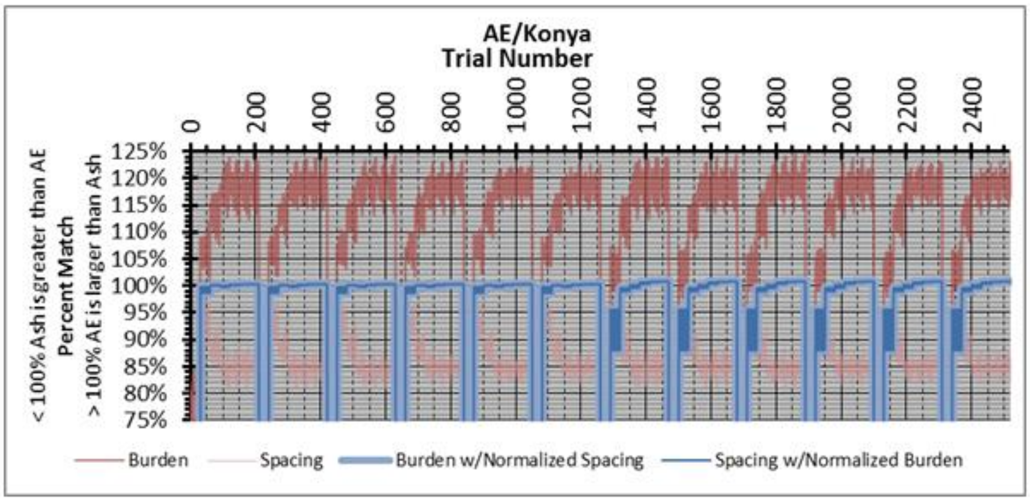
Konya Test 1

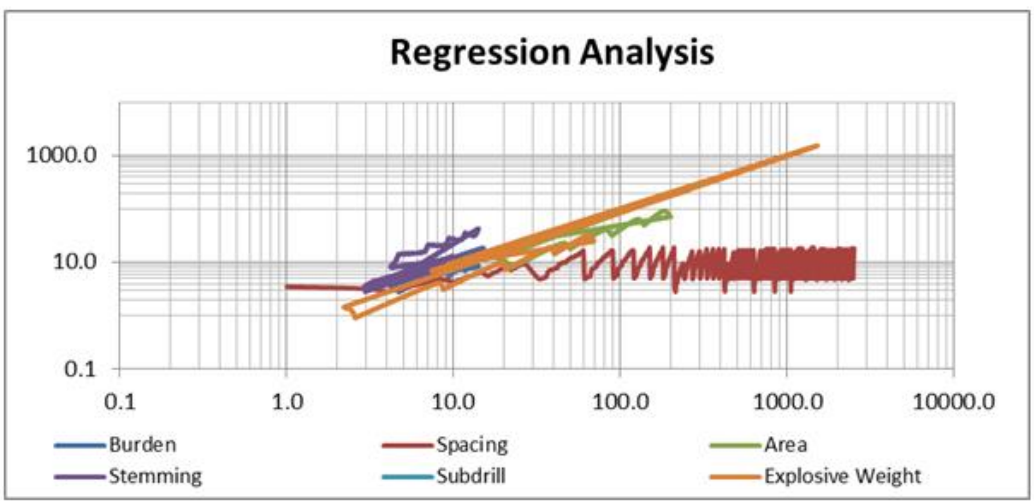
Konya - Available Energy Comparison Test			
Konya Stem Factor	AE Stem Factor	Konya Subdrill Factor	AE Subdrill Factor
0.70	0.545	0	0.000
1.00	0.745	0	0.000
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	
150	2	25%	
160	3	50%	
170	4	75%	
180	5	100%	
190	6	125%	
200		150%	
		175%	

Konya Test 1 shows some of the differences between Ash and Konya testing. Konya has half the stemming factors, resulting in half the number of trials. Additionally, Konya has more detailed spacing equations that are programmed into the comparison spreadsheet. Both of these changes reduce the number of tests necessary for the same degree of testing. Konya Test 1 is a small borehole diameter test with no subdrill and a wide range of face heights. As observed with Ash testing, wide ranges of face heights give poor data matches.

Konya Test 1


AE/Konya
Trial Number
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
105%
100%
95%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area


AE/Konya
Trial Number
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
125%
120%
115%
110%
105%
100%
95%
90%
85%
80%
75%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden

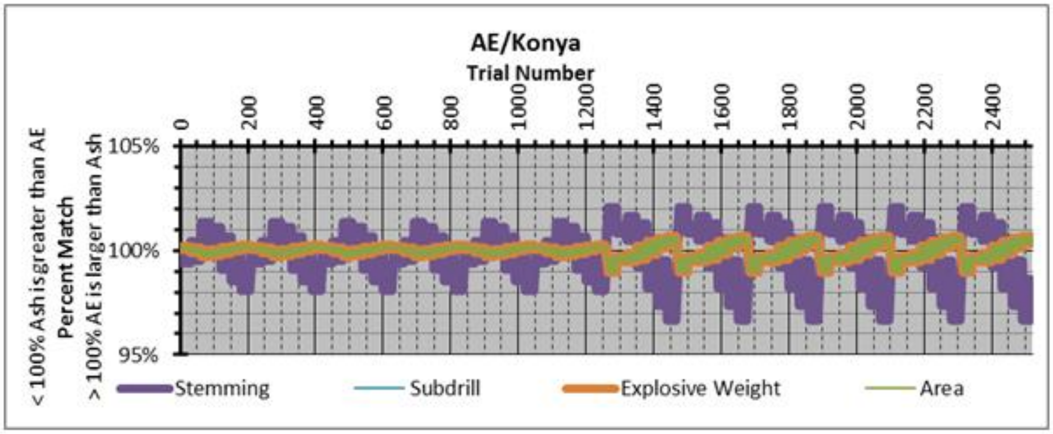

Regression Analysis
1000.0
10.0
0.1
0.1
1.0
10.0
100.0
1000.0
10000.0
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

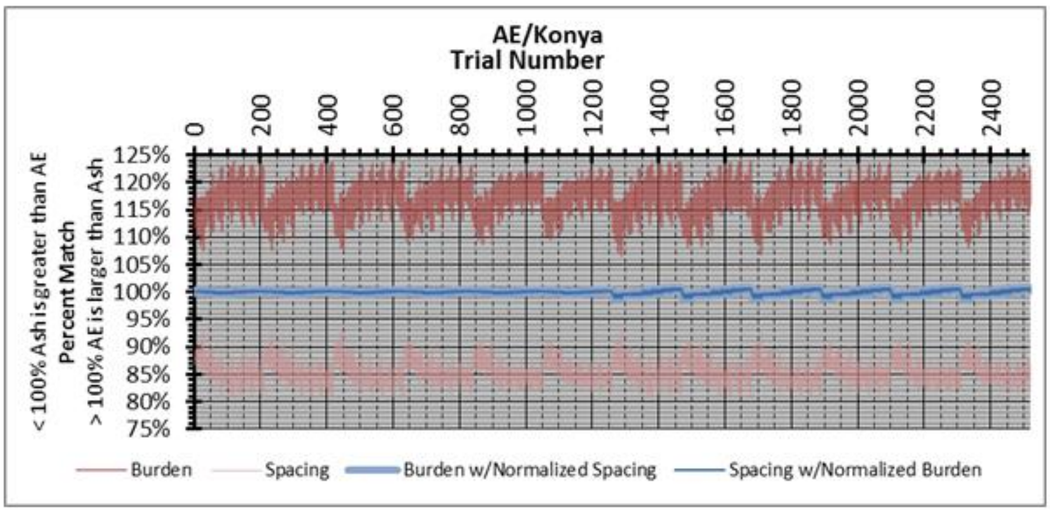
Konya Test 2

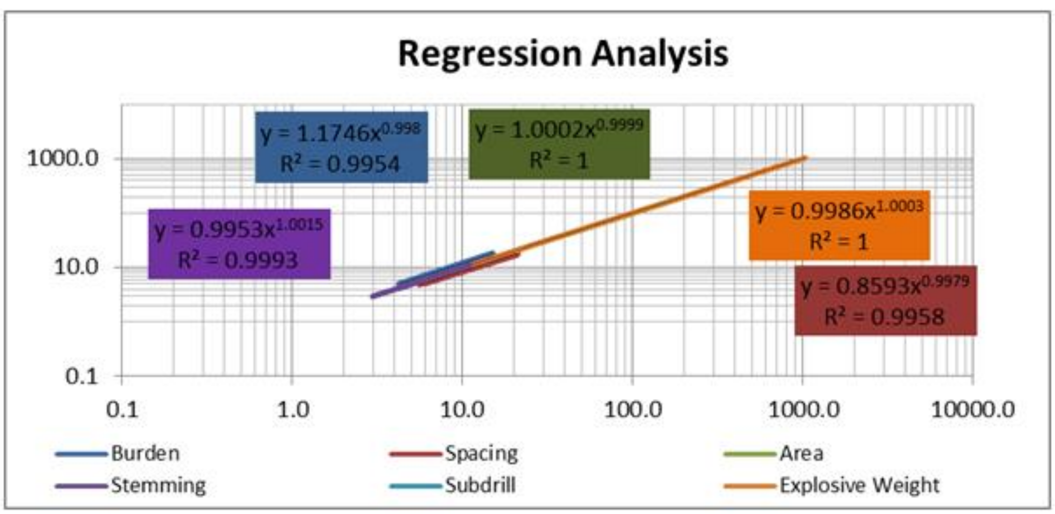
Konya - Available Energy Comparison Test			
Konya Stem Factor	AE Stem Factor	Konya Subdrill Factor	AE Subdrill Factor
0.70	0.545	0	0.000
1.00	0.745	0	0.000
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	
150	2	75%	
160	3	83%	
170	4	92%	
180	5	100%	
190	6	108%	
200		117%	
		125%	

Konya Test 2 is Konya Test 1 with a narrow face height range. The improvement in data match is noticeable, with stemming error below 4% in all cases.

Konya Test 2


AE/Konya
Trial Number
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
105%
100%
95%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area


AE/Konya
Trial Number
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
125%
120%
115%
110%
105%
100%
95%
90%
85%
80%
75%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden


Regression Analysis
y = 1.1746x^0.998
R² = 0.9954
y = 1.0002x^0.9999
R² = 1
y = 0.9953x^1.0015
R² = 0.9993
y = 0.9986x^1.0003
R² = 1
y = 0.8593x^0.9979
R² = 0.9958
1000.0
10.0
0.1
0.1
1.0
10.0
100.0
1000.0
10000.0
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

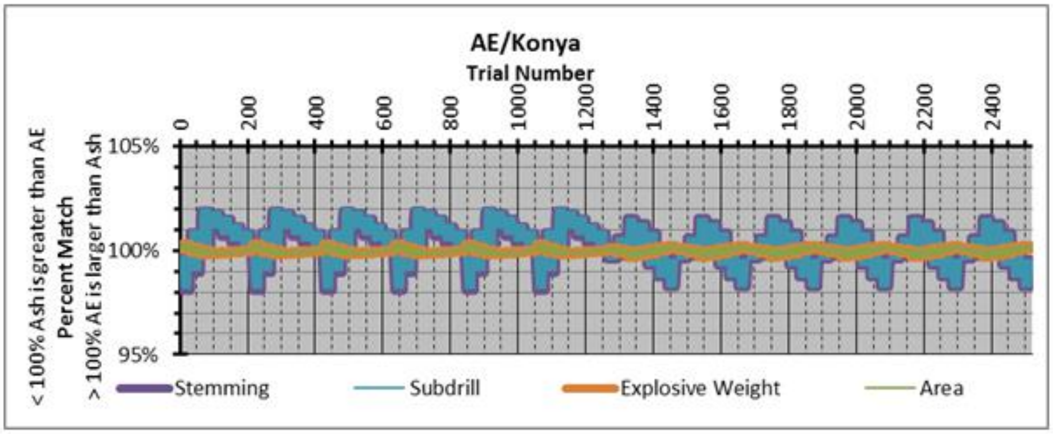
Konya Test 3

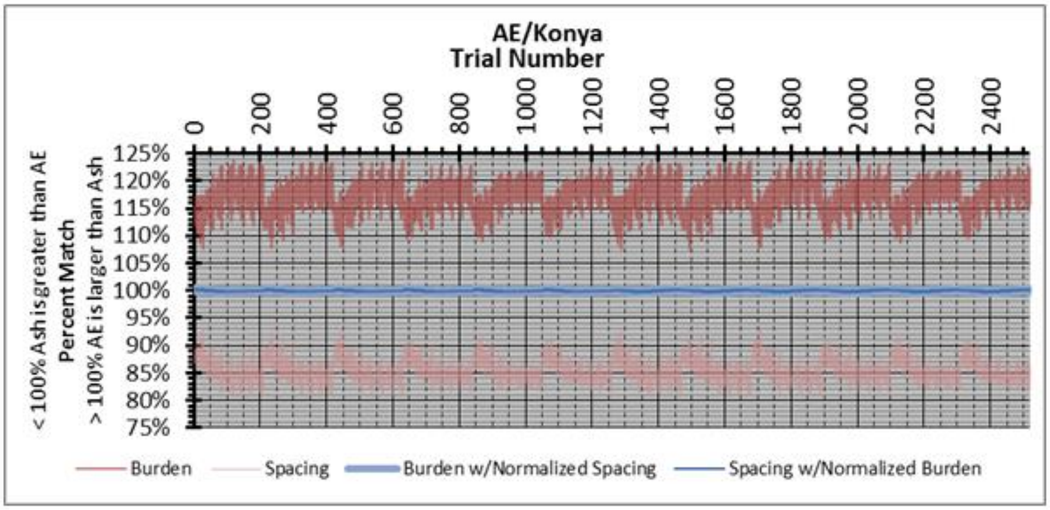
Konya - Available Energy Comparison Test			
Konya Stem Factor	AE Stem Factor	Konya Subdrill Factor	AE Subdrill Factor
0.70	0.572	0.3	0.429
1.00	0.780	0.3	0.300

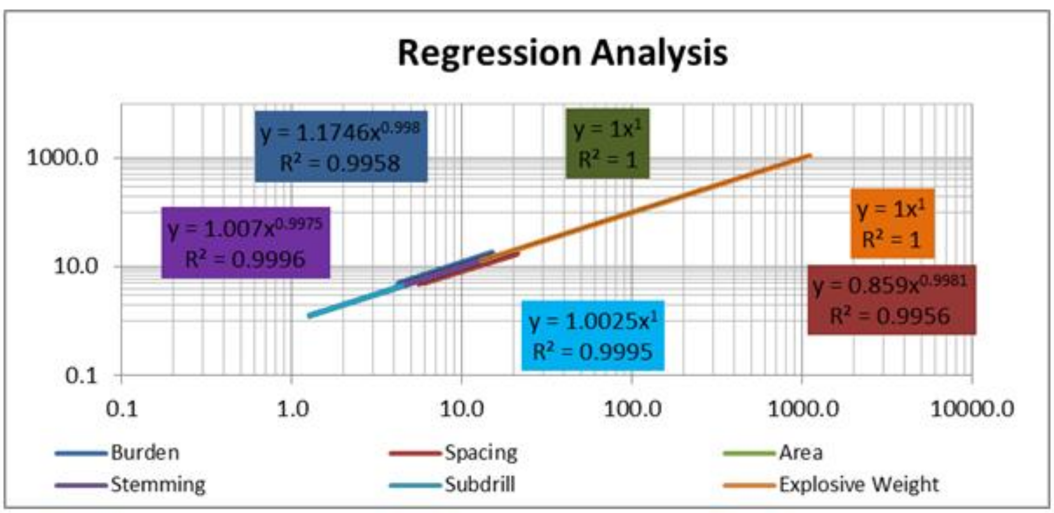
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]
150	2	75%
160	3	83%
170	4	92%
180	5	100%
190	6	108%
200		117%
		125%

Konya Test 3 adds subdrill to Konya Test 2. Konya Test 3 shows the best match of data observed throughout the comparison testing. Both surface area and explosive weight have R^2 values of 1, slopes of 1, and intercepts of 1, illustrating a perfect match between Konya data (X axis), and AE data (Y axis).

Konya Test 3


AE/Konya
Trial Number
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
105%
100%
95%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area


AE/Konya
Trial Number
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
125%
120%
115%
110%
105%
100%
95%
90%
85%
80%
75%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden

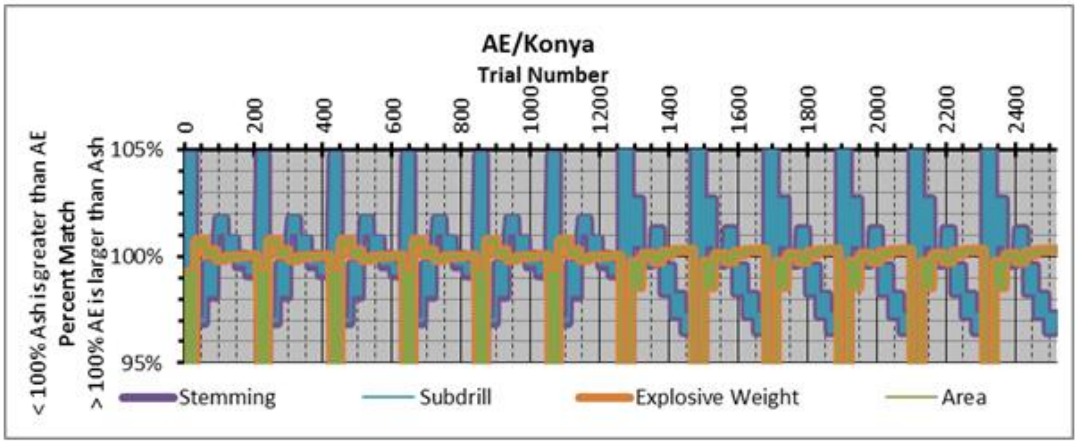

Regression Analysis
y = 1.1746x^0.998
R² = 0.9958
y = 1x^1
R² = 1
y = 1.007x^0.9975
R² = 0.9996
y = 1x^1
R² = 1
y = 0.859x^0.9981
R² = 0.9956
y = 1.0025x^1
R² = 0.9995
1000.0
10.0
0.1
0.1
1.0
10.0
100.0
1000.0
10000.0
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

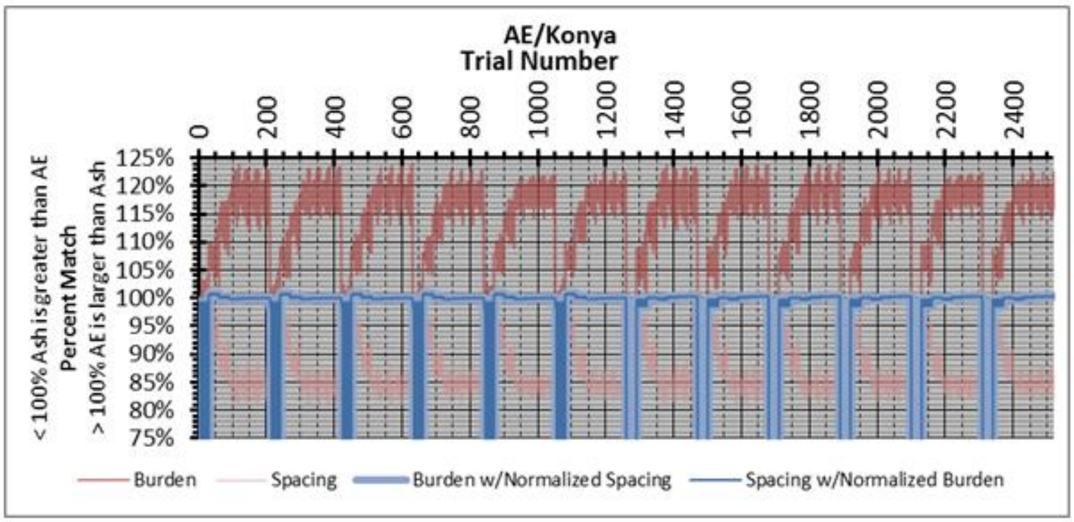
Konya Test 4

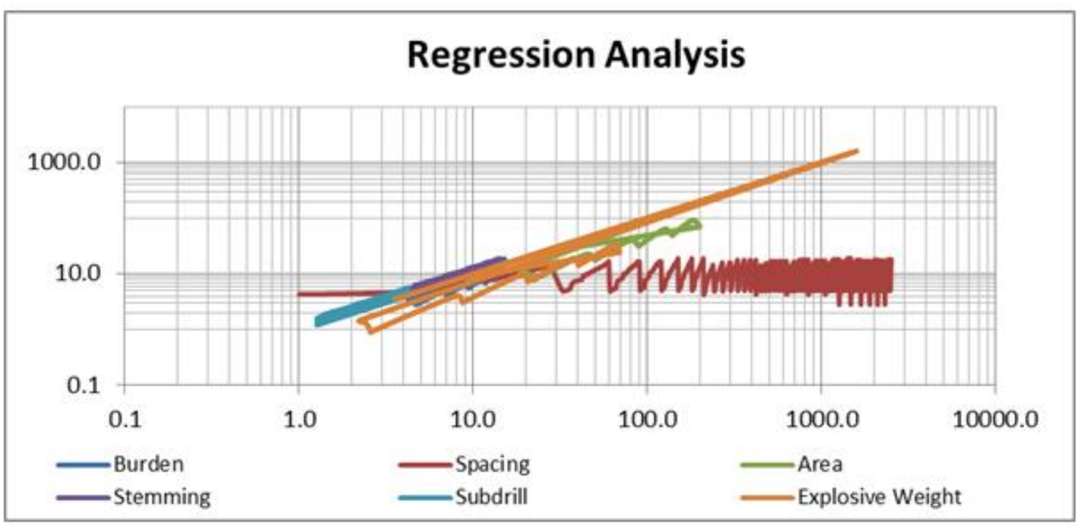
Konya - Available Energy Comparison Test			
Konya Stem Factor	AE Stem Factor	Konya Subdrill Factor	AE Subdrill Factor
0.70	0.572	0.3	0.429
1.00	0.780	0.3	0.300
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	
150	2	25%	
160	3	50%	
170	4	75%	
180	5	100%	
190	6	125%	
200		150%	
		175%	

Konya Test 4 is Konya Test 3 with a wide face height range, creating poor matches across the board.

Konya Test 4


AE/Konya
Trial Number
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
105%
100%
95%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area


AE/Konya
Trial Number
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
125%
120%
115%
110%
105%
100%
95%
90%
85%
80%
75%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden

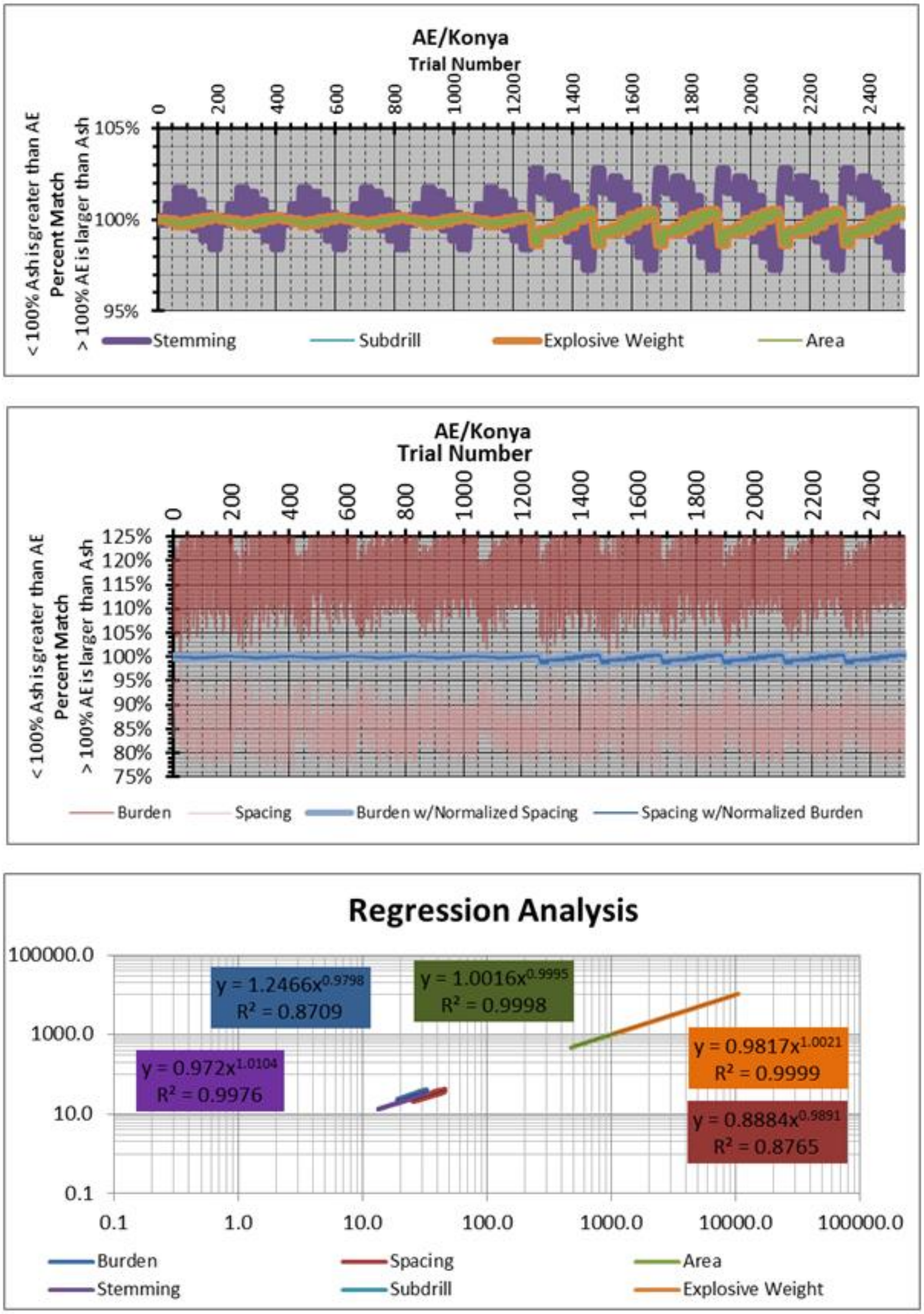

Regression Analysis
1000.0
10.0
0.1
0.1
1.0
10.0
100.0
1000.0
10000.0
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

Konya Test 5

Konya - Available Energy Comparison Test			
Konya Stem Factor	AE Stem Factor	Konya Subdrill Factor	AE Subdrill Factor
0.70	0.547	0	0.000
1.00	0.750	0	0.000
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	
150	9	75%	
160	10	83%	
170	11	92%	
180	12	100%	
190	13	108%	
200		117%	
		125%	

Konya Test 5 is a large diameter test with no subdrill and a narrow range of face heights. This test is most representative of likely blast designs in the PRB, and illustrates a great fit of the AE solutions to the Konya design, with all stemming error under 3%.

Konya Test 5

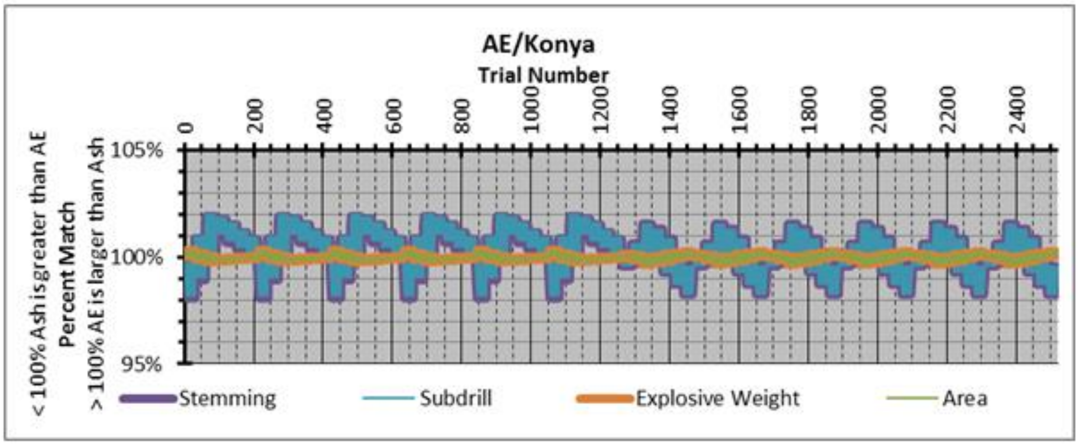

AE/Konya
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area
AE/Konya
Trial Number
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden
Regression Analysis
y = 1.2466x^0.9798
R² = 0.8709
y = 1.0016x^0.9995
R² = 0.9998
y = 0.972x^1.0104
R² = 0.9976
y = 0.9817x^1.0021
R² = 0.9999
y = 0.8884x^0.9891
R² = 0.8765
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

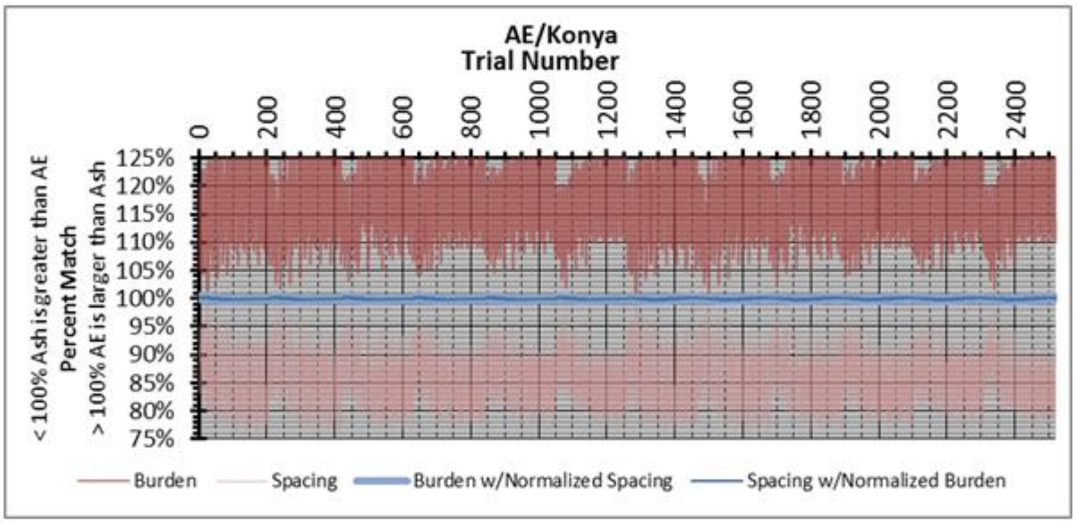
Konya Test 6

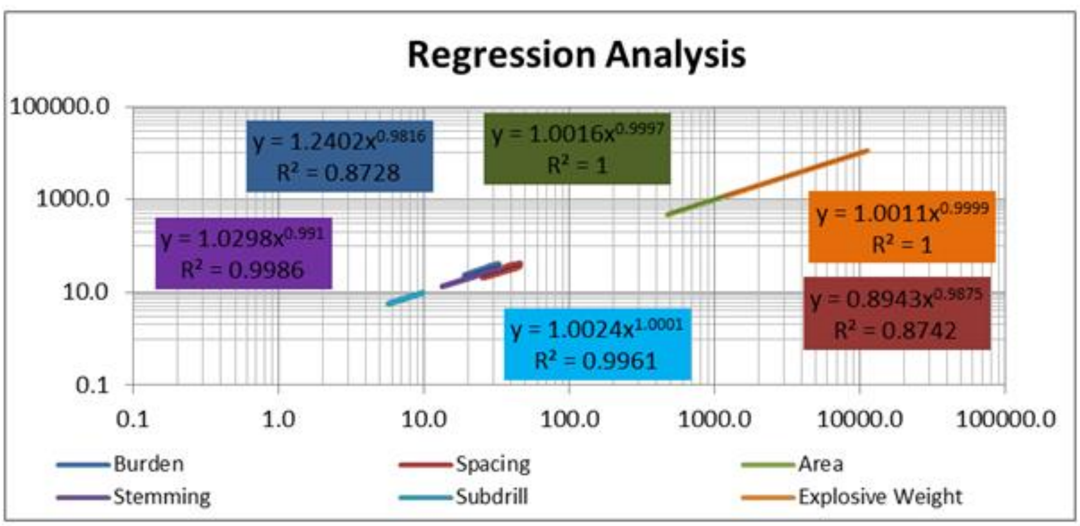
Konya - Available Energy Comparison Test			
Konya Stem Factor	AE Stem Factor	Konya Subdrill Factor	AE Subdrill Factor
0.70	0.572	0.3	0.429
1.00	0.780	0.3	0.300
Cut Widths [ft]	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	
150	9	75%	
160	10	83%	
170	11	92%	
180	12	100%	
190	13	108%	
200		117%	
		125%	

Konya Test 6 is Konya Test 5 with the addition of subdrill. Excellent fits of data, and stemming and subdrill errors under 2%.

Konya Test 6


AE/Konya
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
105%
100%
95%
Stemming
Subdrill
Explosive Weight
Area


AE/Konya
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Burden
Spacing
Burden w/Normalized Spacing
Spacing w/Normalized Burden

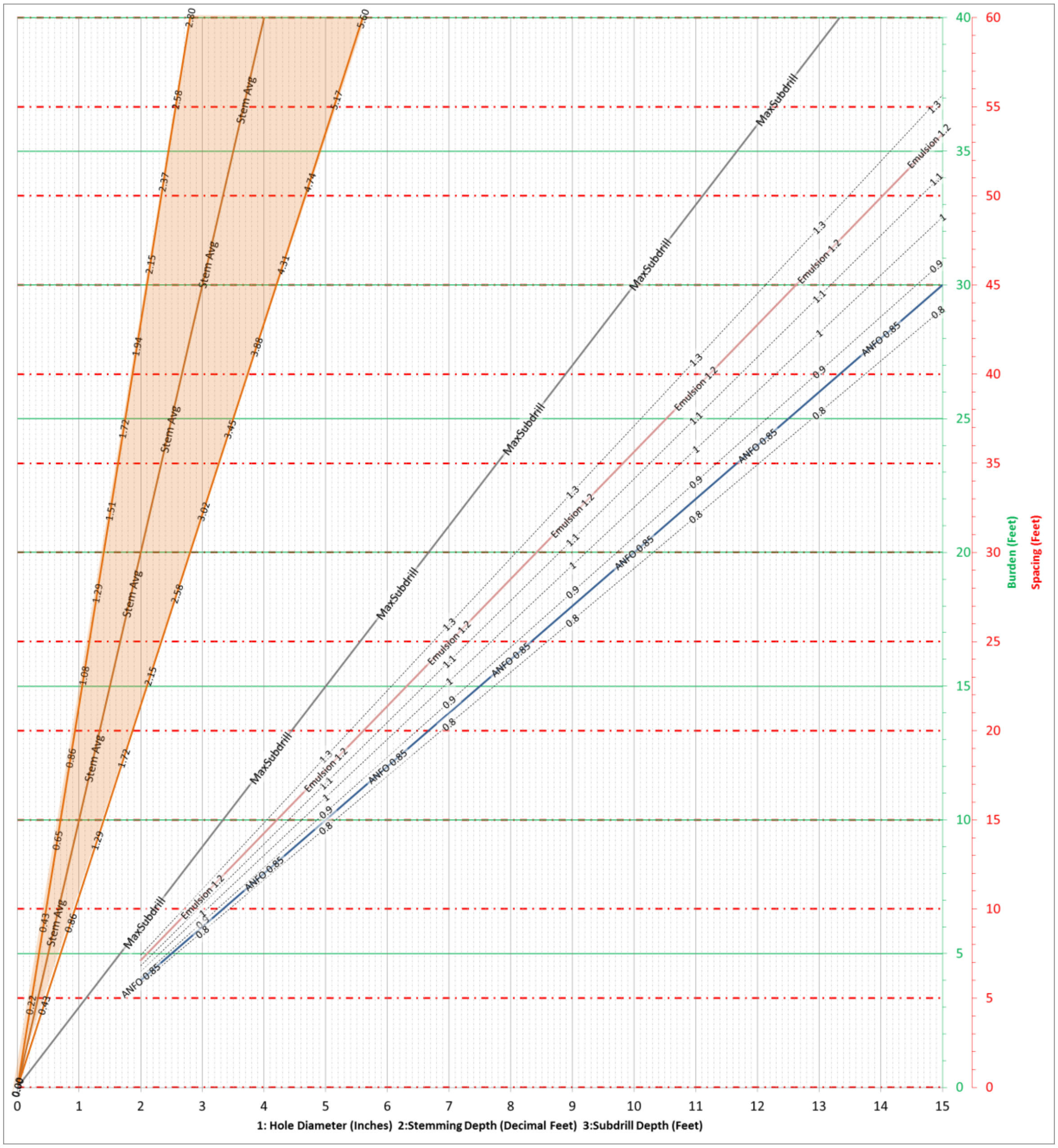

Regression Analysis
y = 1.2402x^0.9816
R² = 0.8728
y = 1.0016x^0.9997
R² = 1
y = 1.0298x^0.991
R² = 0.9986
y = 1.0011x^0.9999
R² = 1
y = 0.8943x^0.9875
R² = 0.8742
y = 1.0024x^1.0001
R² = 0.9961
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

APPENDIX B

SAMPLE NOMOGRAPHS

This appendix shows several blasting-related nomographs that the author has developed over the course of the research project. Short explanations generally accompany the nomographs. Some of these nomographs have been featured in the dissertation body, and some have not. In a few cases, the nomographs shown in this appendix are larger and easier to read than those shown in the dissertation.

In addition, there are two new narrow-range Loading Density and Available Energy nomographs for small-diameter boreholes ranging from 1.5” - 6” inches. These narrow range nomographs are designed to work in conjunction with the Available Energy Quarry Method that is briefly introduced in Appendix F.



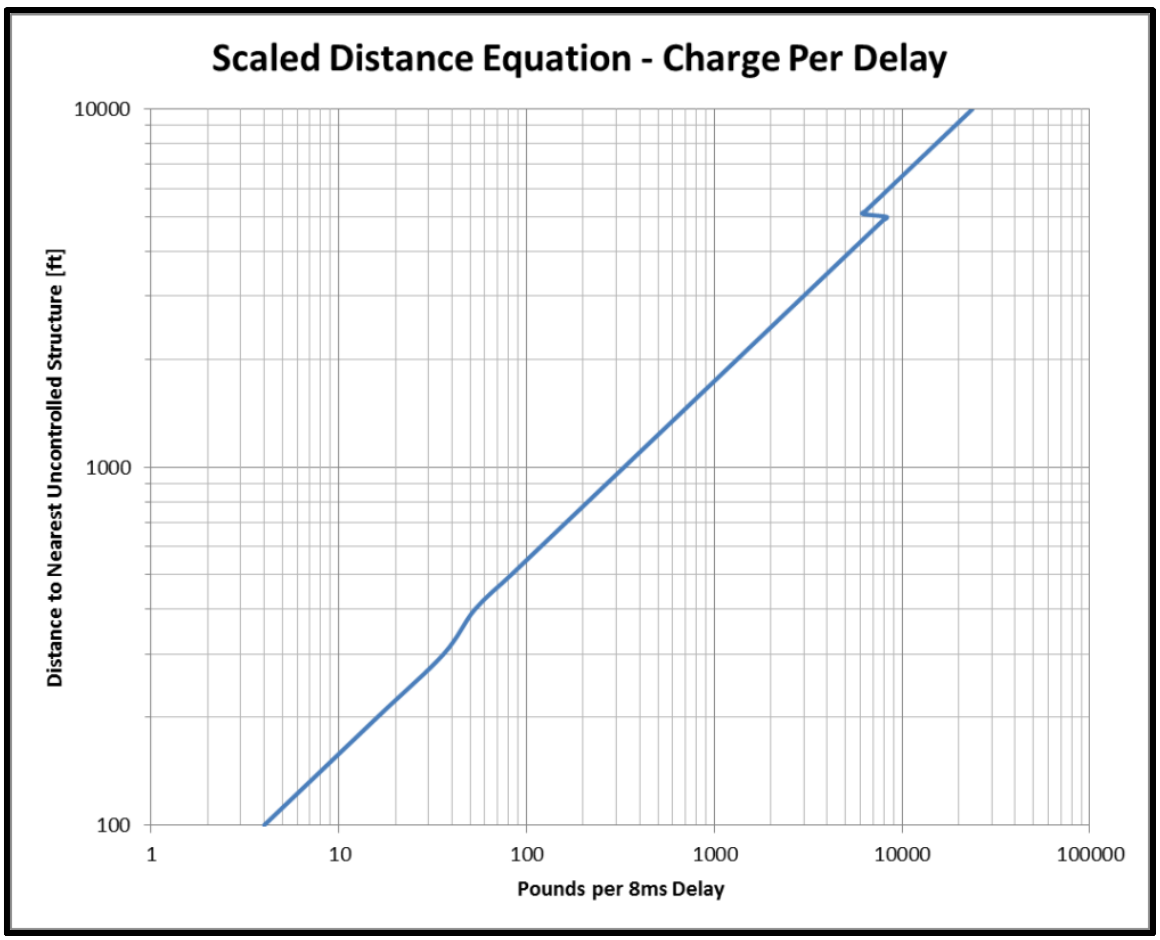
Rule Of Thumb Blast Design Nomograph

This nomograph is based on a slightly modified form of Worsey's Rules of Thumb and is designed for hole diameters from 2-15 inches and product densities from 0.8-1.3 g/cc. You can solve for varying densities, hole diameters, etc. by interpolating between the lines. **To use the nomograph:**

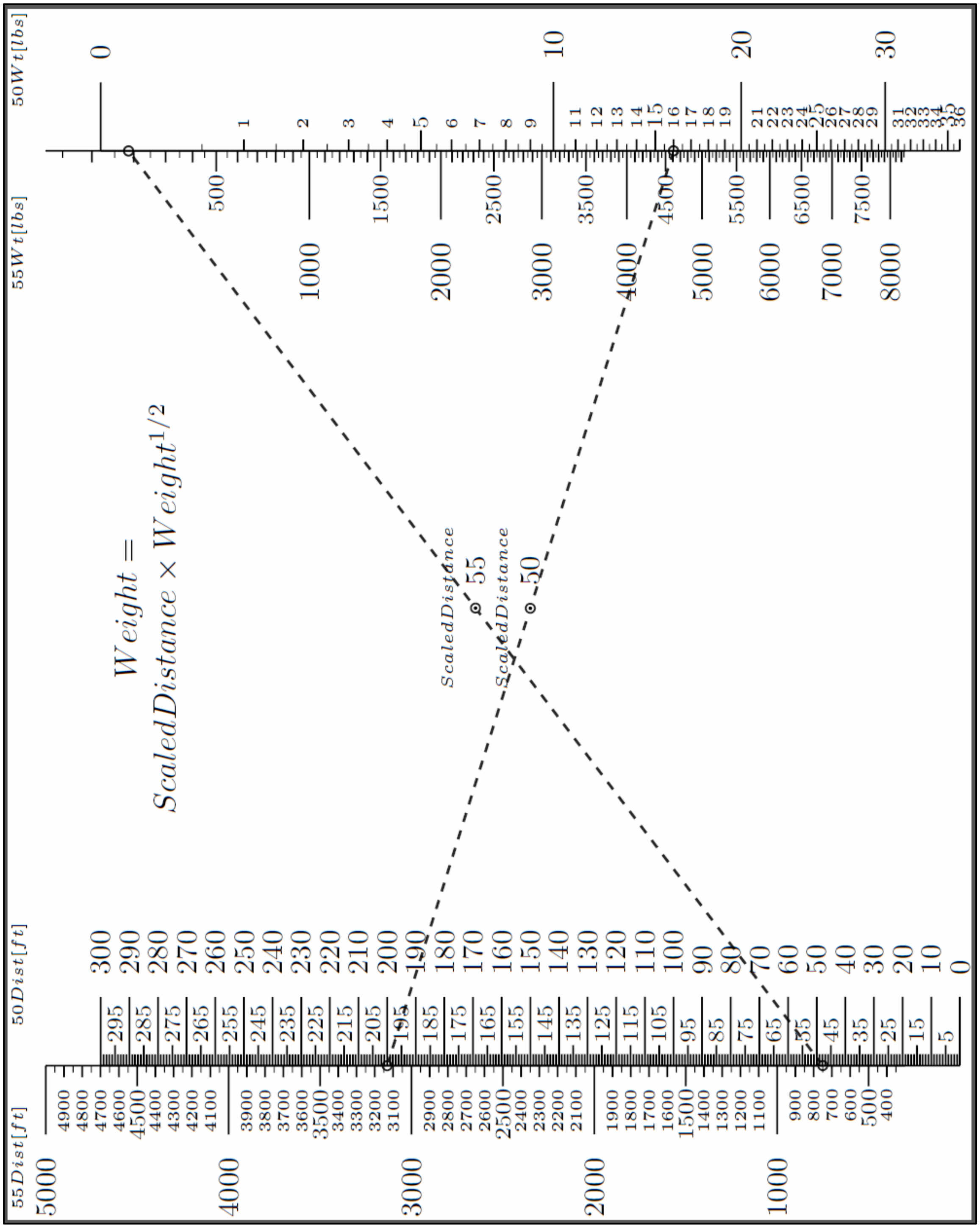
1. Start at the X-axis and find your hole diameter in inches. The solid lines are whole numbers, with the dashed lines representing tenths of the unit you're measuring
2. Trace the proper diameter upwards until you intersect the product density you're using, then trace horizontally to the left and to the right.
    a. Read burden (green numbers) and spacing (red numbers) from the intersection of your horizontal line with the Y-Axis at right.
    b. Where your horizontal line crosses the MaxSubdrill line, trace down to the X-Axis and read off the number – this is your maximum subdrill in feet
    c. Your horizontal line will cross the orange area for stemming – the orange area represents stemming ranging from 0.7 (left side) to 1.4 (right side) times the burden. StemAvg is stemming equal to burden for your reference. When you decide whether you want a lot or a little of stemming (based on ground conditions and type of stemming), trace down to the X-Axis, and multiply the number you read by ten to arrive at feet of stemming required.

The following two nomographs deal with Scaled Distance. This page contains an Excel Scaled Distance nomograph. Start on either axis and trace straight to the blue line, then trace to the other axis. An interesting item is the jog in the blue line – this represents the switch from a scaled distance of 55 to a scaled distance of 65 at 5,001 feet. The next page contains a second Scaled Distance nomograph, this one made with PyNomo. The isopleths illustrate its use – take note of the titles of the scales.

It has come to the author's attention that the scaled distance ranges as recommended by the International Society of Explosives Engineers have been modified for the second printing of the 18th Edition of the Blaster's Handbook, and the previously defined 5,001 value has been shortened to 1,001. Some controversy exists concerning

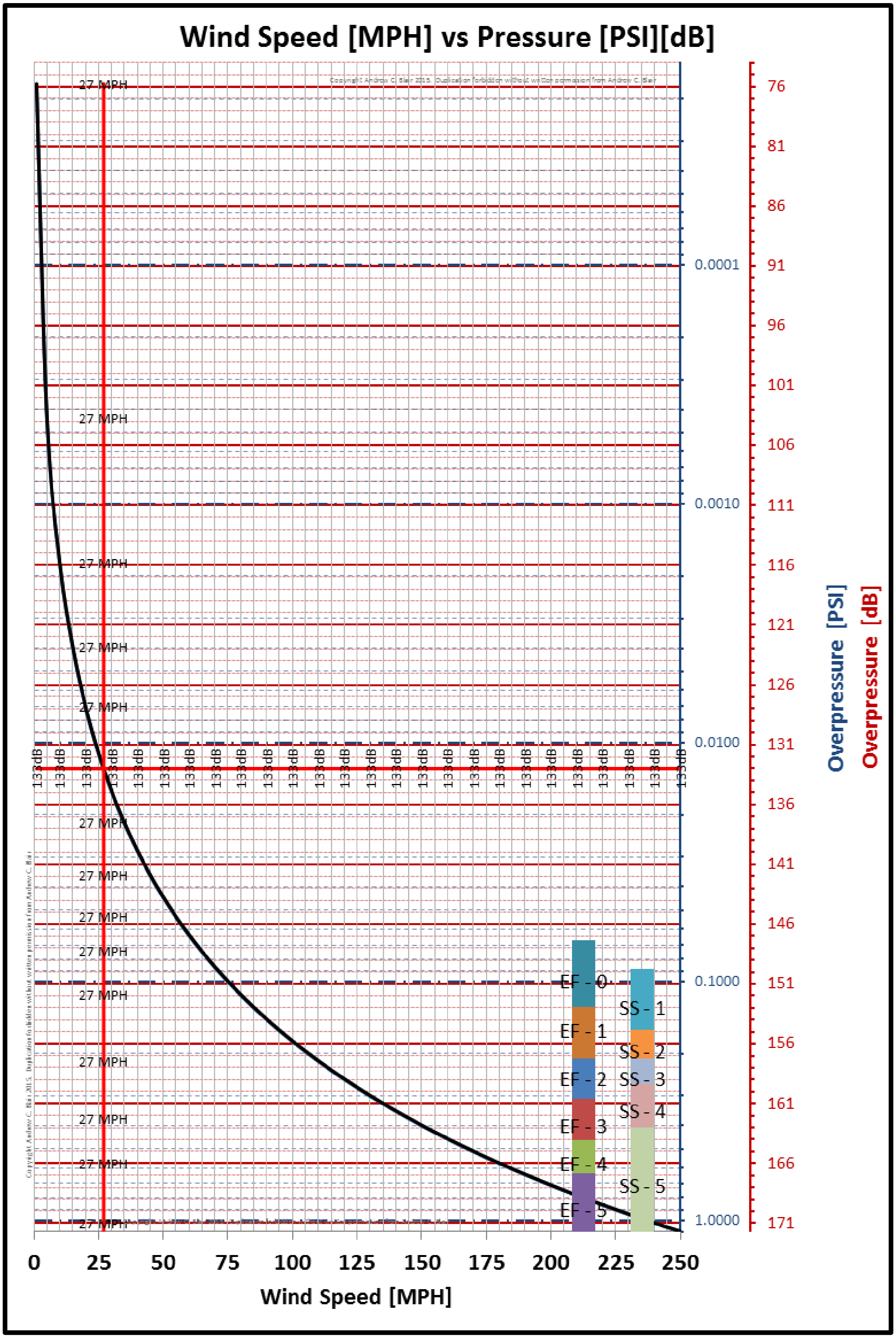


this change, and the eventual outcome is unclear at this time. The nomographs shown in this work reflect the old 5,001 value for the switch from a scaled distance of 55 to a scaled distance of 65.

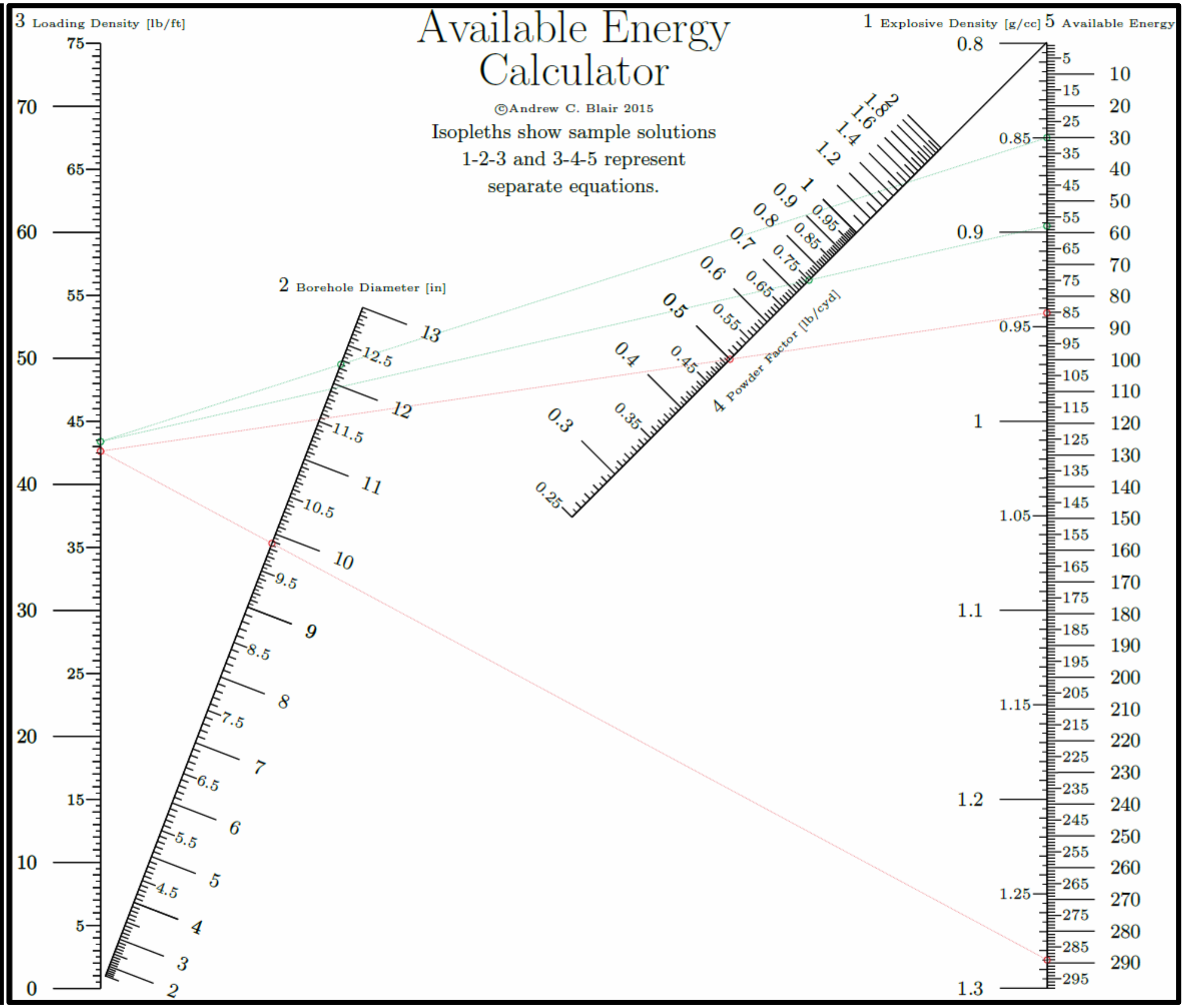


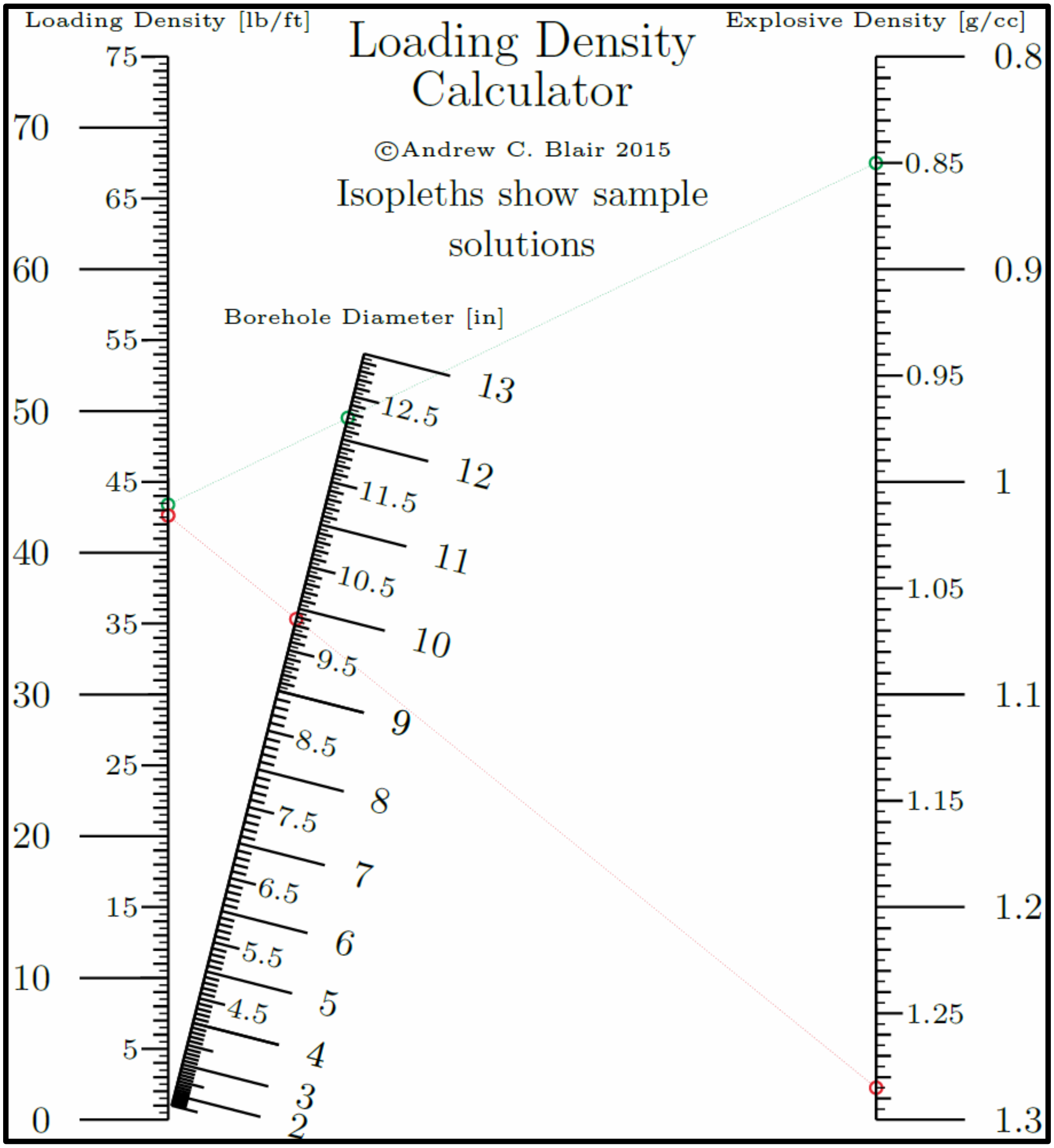
The next page contains a Wind Speed vs. Pressure nomograph; which assumes instantaneous wind speeds to convert to pressure at that specific moment in time. Also includes tornado (Enhanced Fujita) and hurricane (Saffir-Simpson) scales translated to instantaneous pounds per square inch [PSI] and decibels [dB].

This style of nomograph is useful to illustrate the difficulty of damaging structures with air overpressure from blasting. Typically, air overpressure from blasting is measured in dB, a logarithmic scale that is difficult to mentally relate to a linear scale. The challenge introduced by logarithmic scales in relating accurate information about blasting to the public was explored by Lusk (Lusk, 2006). This nomograph was developed to allow users to determine wind speeds equal to various air overpressures that may be encountered by blasting at variable distances. A common limit for air overpressure when blasting, 133 dB, is equal to winds of roughly 27 miles per hour. In practice, wind will cause more damage than air overpressure from blasting due to the relative duration of both loadings. Air overpressure from blasting is much shorter duration than typical wind loading, imparting much less energy into the structure in question.


Wind Speed [MPH] vs Pressure [PSI][dB]
Wind Speed [MPH]
Overpressure [PSI]
Overpressure [dB]
0
25
50
75
100
125
150
175
200
225
250
0.0001
0.0010
0.0100
0.1000
1.0000
76
81
86
91
96
101
106
111
116
121
126
131
136
141
146
151
156
161
166
171
27 MPH
133dB
EF - 0
EF - 1
EF - 2
EF - 3
EF - 4
EF - 5
SS - 1
SS - 2
SS - 3
SS - 4
SS - 5

This Available Energy Calculator allows the user to generate a loading density based on a range of explosive densities and borehole diameters, then calculate the AE value for various powder factors.

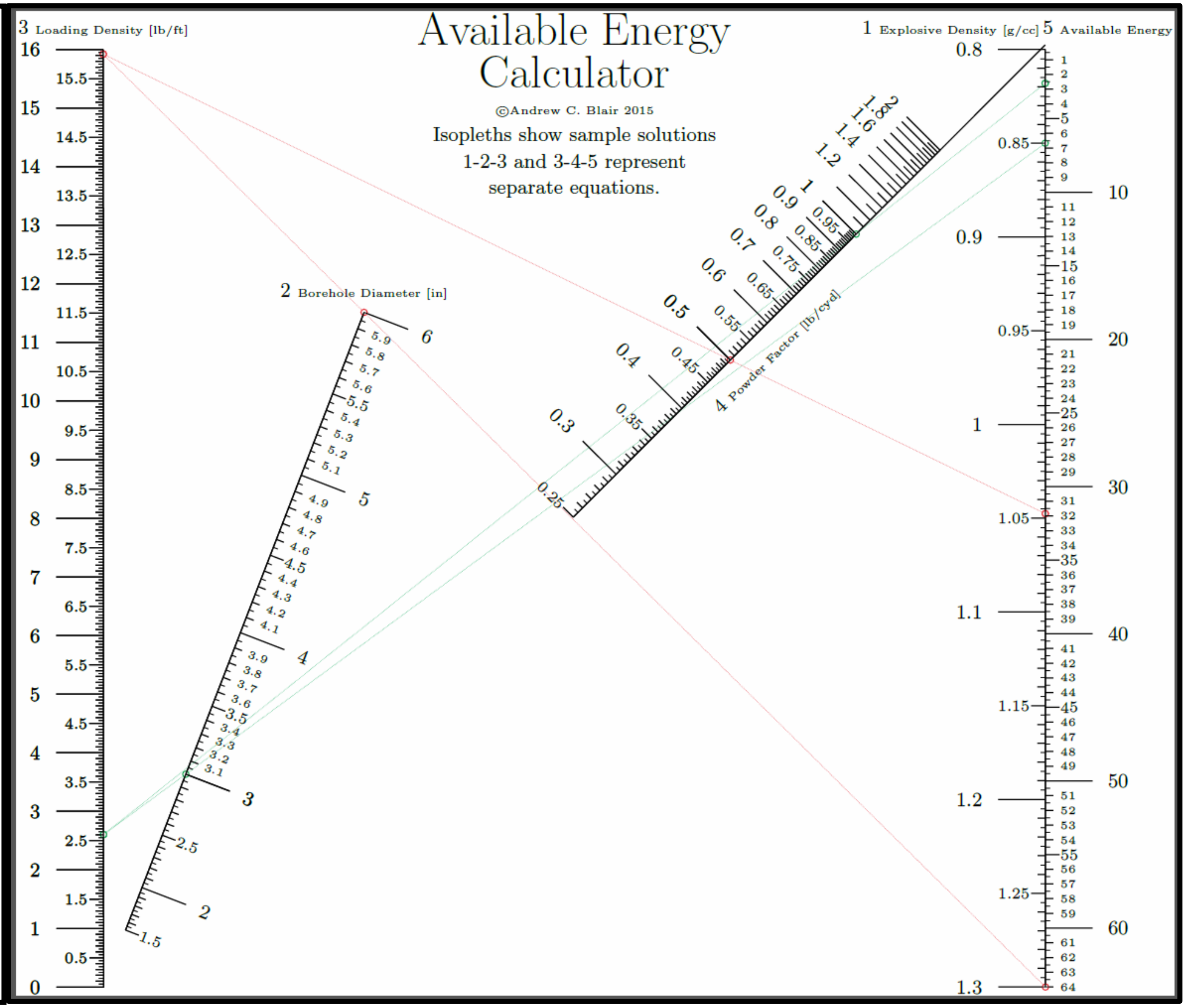


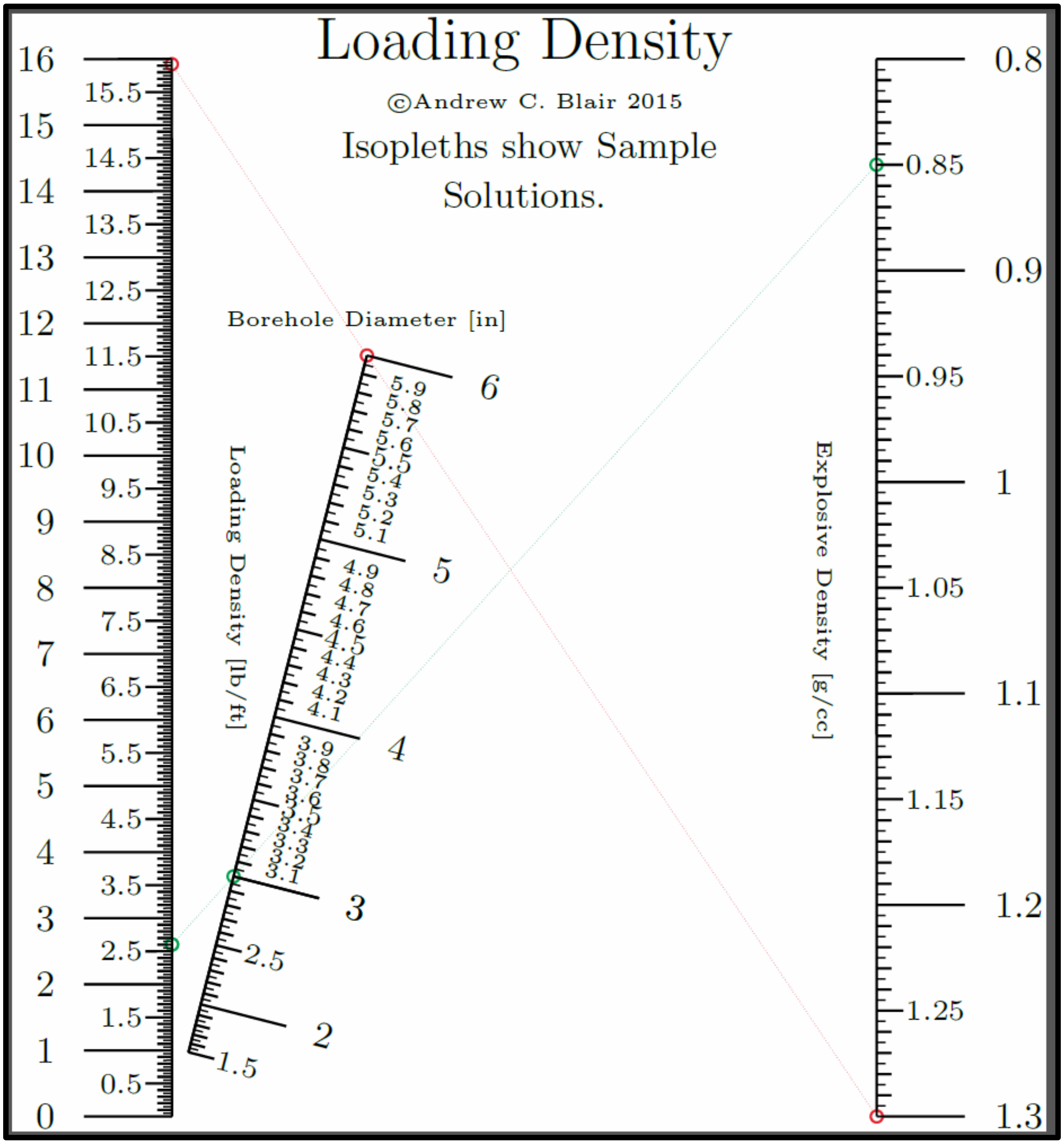


The above nomograph is a wide range Loading Density calculator, covering the range from 0.8-1.3 g/cc explosives and 1.5”-13” borehole diameters.

This Available Energy Calculator allows the user to generate a loading density and calculate the AE value for various powder factors.

It differs from the previous AE Calculator by focusing on a smaller range of borehole diameters more suitable for quarry blasting.





The above nomograph is also a Loading Density calculator, but is focused on smaller borehole diameters more likely to be used in quarries.

APPENDIX C
DERIVATION OF AVAILABLE ENERGY FORMULAS

Developing the AE method is a process that has taken place over several years. The original goal was to create an excellent powder factor based volumetric blast design method.

Several years ago, this author was a teaching assistant for the introductory blast design course at Missouri S&T and knew there had to be a simpler way to teach detailed blast design. Traditionally, blast design at S&T is taught by introducing Ash's burden equations, and then presenting a simplified Rules of Thumb approach to get the user to a safe and efficient starting point for design. After working through the traditional methodology where powder factor is calculated at the end of design, a simple powder factor based blast design method is introduced. This method is simplistic, and uses fixed relationships for stemming and subdrill based on borehole diameter. The problem with the presented powder factor method was that no adjustment of stemming for varying levels of energy (higher or lower powder factor) was possible without iteration of the design process. Essentially, by fixing the stemming and subdrilling on borehole diameter with no explosive energy scaling (which is present in most design methods where stemming is dependent on burden), the presented method gave up some flexibility in the interest of a rapid solution.

To this author, volumetric blast design makes sense. Visualizing a volume is much easier than visualizing a weight (which requires density information and would be necessary for weight based blast design methods), and using volume allows the user to use dimensional analysis for many of the design steps. For the typical blast design student in a university setting, dimensional analysis and volume calculations will be familiar practices, and for industry students, these concepts are quicker to illustrate and explain than weight, density and volume relationships. In any case, weight conversions are easily completed at the end of the design process if necessary, so the focus was placed on volumetric design.

Some of the early researchers did not feel that powder factor was a suitable criteria for blast design, despite its use for accounting purposes. This hesitation is likely based in the possibility that users would not properly understand the application of powder factor and may be tempted to ignore geologic and geometric concerns if powder factor was a design criteria. These are well-founded concerns and should still be considered. However, today's blasting environment enjoys a widespread use of powder factor ratios for accounting purposes, and the great majority of sites will have a target powder factor for individual shot types. The separation of accounting and design criteria places the blaster in the uncomfortable position of trying to unify disparate standards. Early versions of the volumetric powder factor based blast design method were iterative processes – it was necessary to slightly inflate the target powder factor to compensate for the presence of stemming in the borehole so that the final design would arrive precisely at the desired powder factor. Several steps in this development took place while the author was completing a Mining Engineering B.S. and taking graduate courses.

In Spring 2011, the author began work as a truck/shovel engineer in Wyoming's Powder River Basin ("PRB"). Two previous internships had laid a foundation of understanding for surface mine operations, and the author's work involved short range design and scheduling for the truck/shovel fleet. Short range scheduling illustrated the production bottleneck created by the drilling process, and discussing blast design with other employees exposed potential areas of improvement in blasting processes with respect to maintaining a consistent powder factor. Solving problems is an engineer's job, and the author considered the multi-faceted nature of Large Surface Coal Mine ("LSCM") operations and realized that bench blasting was an ideal area to apply volumetric design principles already considered by the author.

After returning to S&T in Fall 2013, the author continued to improve the iterative design process, and consider what tools would be helpful for LSCM bench blasters. Discussions with James Hawkins in Spring 2014 concerning tools for blasters pushed the author toward nomography for reliable and effective information dissemination, and continued explorations of nomography showed the value of simple formulas. The fewer variables in an equation, the easier it is to represent the formula graphically in a nomograph. Shortly thereafter in the summer and fall of 2014, the Available Energy ("AE") concept was developed as an attempt to condense the number of variables required for blast design.

First, iteration was required in earlier versions of the volumetric blast design method because of a dependence on burden to calculate stemming. Essentially, the earlier methods would use an assumed target powder factor in an attempt to calculate a burden that would generate a stemming length that would arrive at the desired actual powder factor. This process was time consuming and only suitable for spreadsheet analysis. Usually the design would reach the desired actual powder factor, but occasionally it would not. Dependence on burden created a complex solution method. Second, bench blasting in the PRB did not look like quarry blasting – the target domain of most existing major methods of blast design. Quarry blasting usually has relatively few long rows with plenty of room for movement. LSCM bench blasting has many shorter rows with much less room for movement. In quarrying an immediate descent to a band of ore under waste material is not required since the blasted material is the ore. In LSCM bench blasting at strip mines, the majority of material blasted is waste material in an effort to reach the band of ore. This primary difference places additional restrictions on blasting because of the usual method of attack. Quarries often mine along the long faces of their benches and have plenty of room to run down the length of the bench. This situation is affordable for quarries because they are selling the material they are blasting. To minimize capital investment at LSCM operations, bench widths are kept narrow to minimize the volume mined before reaching coal, since the waste material does not add profit to the company, only expense. This fundamental difference leads LSCM operators to minimize offset between benches, typically forcing cuts to be mined from one end to the other across their short dimension, rather than down the long face. Additionally, the reduction in width between the toe of the existing bench and the crest of the bench below leaves less room for material movement when blasting – a quite different situation from quarries. These differences also are reflected in challenges faced by drillers. Shovels mining narrow cut widths move rapidly down the cut and can quickly get to the minimum safe distance for blasting, meaning that if the drill and blast ("D&B") team does not blast material far in advance of the shovel, they may have to walk the shovel back from the face to blast, which introduces unnecessary delays. Combine this with the typical bottleneck of moving drills from one pit to the next, and D&B teams drill and shoot as much as possible at each location while the drill is there. Conversely, quarries often have longer dig faces, so the loader can be working at one end of the cut while the D&B team is at the other end. The separation distance between D&B and the loader minimizes delay time for blasting, and allows more efficient operations with similar volumes of blasted material. The final result of these differences is that while quarry blasting traditionally moves material out from the bench due to the small number of rows, LSCM bench blasting traditionally moves the material up due to the large number of rows. This difference in material movement implies that the primary criteria of design should also be different. Quarries focus on burden because it is the direction of movement and the shortest distance to relief; similarly, LSCM operations should focus on the surface area of borehole influence ("surface area") which is defined by burden times spacing.

Playing with the AE concept brought out some interesting relationships. AE is a unit depth design method – the AE value represents the volume of material that can be blasted by a unit depth of borehole filled with explosive. AE is almost equal to a surface area, but the AE value assumes the entire borehole is filled with explosive – it does not compensate for stemming or subdrill. Therefore, a design's AE will always be larger than the design's surface area by a small margin depending on the magnitude of stemming, assuming that the traditional guideline of less subdrill than stemming is followed. It became apparent that with some changes, the iterations previously required because of stemming could be removed.

The AE formula itself is shown below:

$$Available\ Energy = \frac{(0.3402 * Explosive\ Density\ * Borehole\ Diameter^2)\left[\frac{Lb/Exp}{Ft\ of\ Borehole}\right]}{Powder\ Factor\ \left[\frac{lb}{cyd}\right]}$$

The next step in the design process is to calculate stemming:

$$Stemming = \left(\sqrt{AE * 27}\right) * St_F$$

The AE stemming calculation is a significant deviation from traditionally accepted thought concerning stemming calculation. Traditionally, stemming is directly dependent

$$Subdrill = Stemming * Su_F$$

$$Surface\ Area = AE * \left(\frac{1 - (Stemming - Subdrilling)}{Face\ Height}\right) * 27$$

on burden, represented as a percentage of burden. For LSCM bench blasting, surface area is more important that burden, and the big benefit of calculating stemming based on AE is apparent when viewing the following equations:

Subdrill is a percentage of stemming (if present), and surface area shows the importance of a new way of calculating stemming. Stemming is essential for the calculation of surface area. Essentially, the surface area calculation takes AE converted to cubic feet and multiplies it by the percentage of borehole full of explosive to compensate for the presence of stemming. If stemming was based on surface area instead of AE, the design process would iterate since the user would need surface area to calculate stemming and stemming to calculate surface area. Using AE to calculate stemming is a logical next step since AE parallels surface area, differing only because of the presence of stemming and subdrill.

$$Number\ of\ Rows = \frac{Cut\ Width}{\sqrt{Surface\ Area}}$$

Once surface area is calculated, the remaining steps are straightforward. This specific implementation of the AE design philosophy integrates cut width in the design process. The following equation uses cut width divided by a first guess at spacing (for a square pattern with burden and spacing equal, the square root of the surface area is equal to both burden and spacing) to generate a rough number of rows. This value will not likely be an integer, and will represent some fractional number of rows – say 14.34. The final spacing equation avoids the problem of fractional rows by dividing cut width by a rounded number of rows – to continue the above example, 14 rows – to arrive at a spacing value that is a factor of the cut width.

$$Spacing = \frac{Cut\ Width}{ROUND(Number\ of\ Rows)}$$

After spacing is calculated, burden is simply the other leg of surface area.

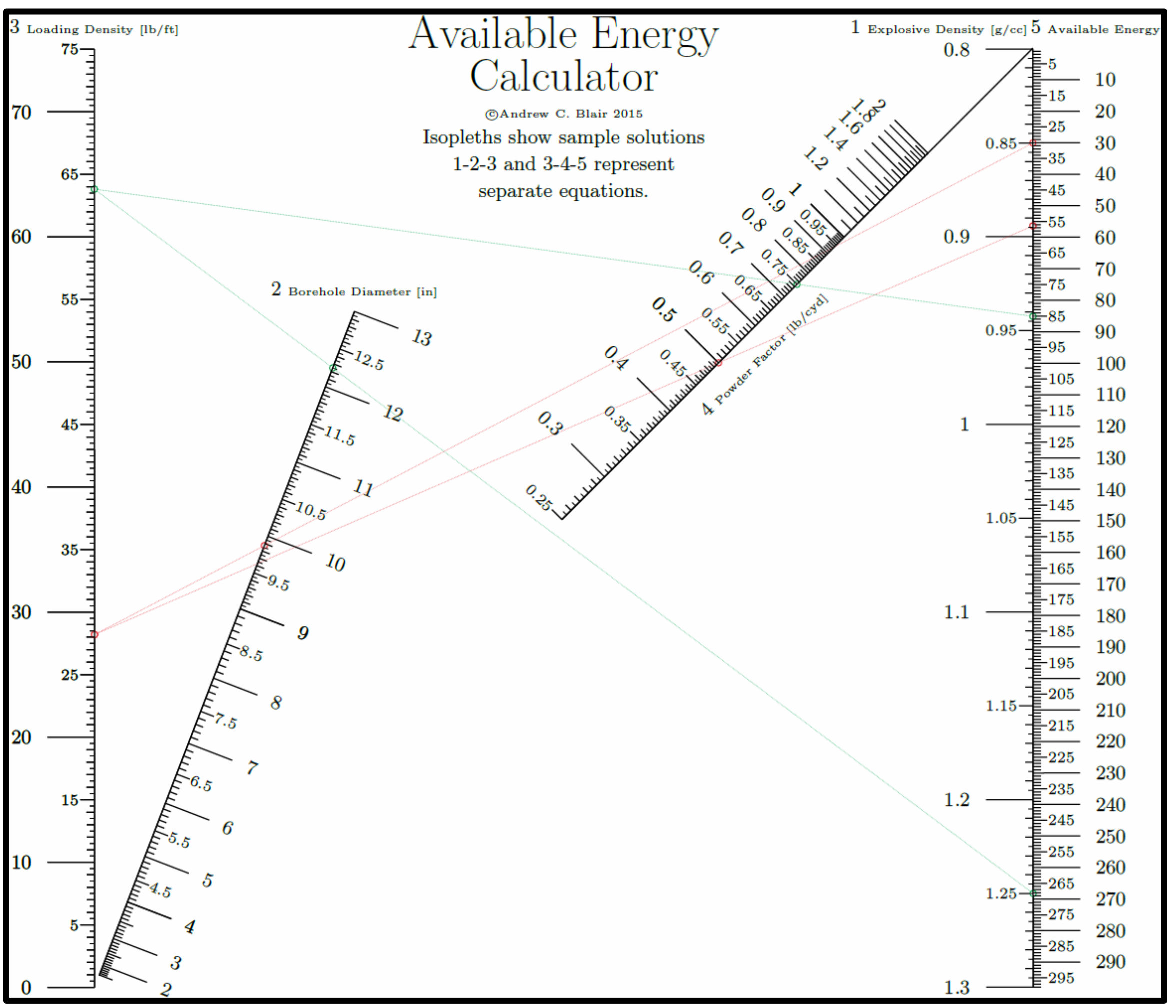
$$Burden = \frac{Surface\ Area}{Spacing}$$

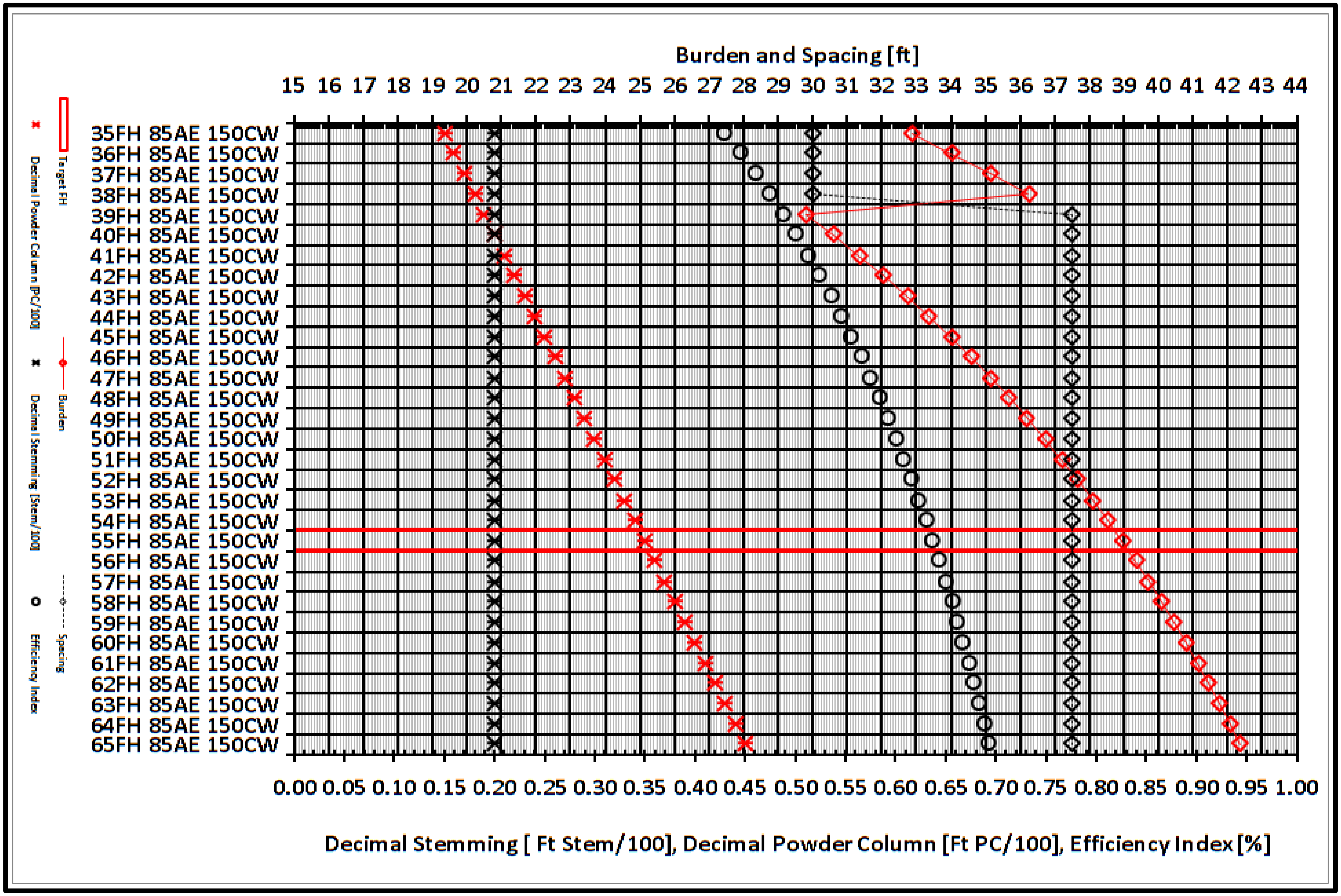
The final AE method is simple, employing straightforward formulas and logical progressions from known entities to final solutions. However, this simplicity hides years of consideration and adaptation to deliver the final product. Future work and targeted expansions are shown in the dissertation.

APPENDIX D
BLAST DESIGN USING A SAMPLE AE NOMOGRAPH

The following text illustrates the use of the AE nomograph as presented in this research. The design nomograph on the following page is identical to Figure 6.7 in the dissertation.

The nomograph is tailored for a cut width of one hundred and fifty feet (150’), face heights from thirty-five feet (35’) to eighty-five feet (85’), and an AE level of 85. No subdrill is shown on this specific example, although subdrill values could be easily integrated using the same process as stemming. This AE value can be calculated using the following nomograph:




Burden and Spacing [ft]
15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44
35FH 85AE 150CW
36FH 85AE 150CW
37FH 85AE 150CW
38FH 85AE 150CW
39FH 85AE 150CW
40FH 85AE 150CW
41FH 85AE 150CW
42FH 85AE 150CW
43FH 85AE 150CW
44FH 85AE 150CW
45FH 85AE 150CW
46FH 85AE 150CW
47FH 85AE 150CW
48FH 85AE 150CW
49FH 85AE 150CW
50FH 85AE 150CW
51FH 85AE 150CW
52FH 85AE 150CW
53FH 85AE 150CW
54FH 85AE 150CW
55FH 85AE 150CW
56FH 85AE 150CW
57FH 85AE 150CW
58FH 85AE 150CW
59FH 85AE 150CW
60FH 85AE 150CW
61FH 85AE 150CW
62FH 85AE 150CW
63FH 85AE 150CW
64FH 85AE 150CW
65FH 85AE 150CW
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00
Decimal Stemming [Ft Stem/100], Decimal Powder Column [Ft PC/100], Efficiency Index [%]
Target FH
Decimal Powder Column [PC/100]
Burden
Decimal Stemming [Stem/100]
Spacing
Efficiency Index

In this case, the 85 AE represents a borehole diameter of 9.875", explosive density of 1.285g/cc, a 70/30 ANFO Emulsion blend with ANFO density of 1.3g/cc and emulsion density of 1.25 g/cc, and powder factor of 0.5 lb/cyd. When the AE value is calculated, the number is actually 85.26, and the solutions on the graph are calculated using that value. In the interests of readability, the AE value was rounded to the nearest whole number.

For the AE design nomograph as shown above, the process of designing a blast for a fifty-five foot (55') face height is as follows:

1. Familiarize yourself with the legend at the far left.
    a. Stemming is a black crossed X, and Powder Column is a red crossed X; neither of these variables have connecting lines, and both are expressed in decimals
    b. The Efficiency Index is represented by black circles, and is expressed in decimals – where the decimal value equals %/100
    c. Burden is a red diamond and Spacing is a black diamond
        i. Both values have connecting lines to differentiate themselves from Stemming and Powder Column
        ii. Because Spacing varies to match cut widths, the Spacing values will look like a step function, meaning that Spacing will switch magnitudes suddenly and maintain the same magnitude for several face height values
        iii. The Burden values are more likely to show gradual changes in magnitude to compensate for the increased efficiency of the longer boreholes
2. Determine the average face height for the row
3. Find the average face height on the left Y-axis of the graph
4. Trace to the right along the row represented by the average face height
5. Stemming is the first item encountered
    a. Trace down to the lower X-axis, and multiply the value by 100 to calculate the length of stemming in feet
6. Powder Column is the second item
    a. Trace down to the lower X-axis, and multiply the value by 100 to calculate the powder column length in feet
7. The Efficiency Index is the third item from the left

   a. Trace down to the lower X-axis, and read the Efficiency Index as a percentage by mentally multiplying the decimal value by 100.
8. Spacing is the fourth item
   a. Trace up to the upper X-axis and read the magnitude of the Spacing dimension
   b. Black major gridlines are in units of feet, and gray minor gridlines represent inches
9. Burden is the fifth and final item on the graph
   a. Trace up to the upper X-axis and read the magnitude of the Burden dimension
   b. Black major gridlines are in units of feet, and gray minor gridlines represent inches
10. Final Notes:
    a. The red box denoting "Target FH" is meant to draw the eye of the user toward the planned face height and speed up the process of locating the appropriate face height
    b. The directions above denote an order of operations for a specific nomograph
    c. It is possible that the values may be shown in different orders for different design solutions – referencing the legend will help the user successfully complete the blast design.

APPENDIX E
GUIDELINES FOR USE OF AVAILABLE ENERGY METHOD

The ultimate goal of using the AE method is similar to most blast design methods: a safe and efficient blast for field conditions. However, there are some critical differences between the AE method and existing major methods of blast design such as those put forward by Ash and Konya. Existing major methods were created to be used for initial blasting across a wide range of conditions – safe and effective for blast design where no blasting had been done before. This concept of use focuses on each individual blast design as a singular occurrence.

The AE method was formulated with the understanding that blasting is a continual process. Large mine sites shoot large volumes of material every day, and have a more process-based mentality than smaller operations where a single large shot may last for weeks of production. The Large Surface Coal Mine AE method is not designed for initial blast design at sites where no blasting has been done before – rather, this presentation of the AE method is designed to allow existing operators to adapt and improve their current design practices (borehole diameter, explosive density, powder factor, face height, and cut width) based on whatever safe and effective blast design method is currently in use. With additional research, this author believes that the AE method can be used for many additional types of blasting and in the hands of skilled and experienced blasters may be useful for initial blast design at this time. However, at present, the AE method has not yet been field tested to verify this author's expectation of broad usability. As such, this author recommends caution in using the AE method for initial design practices and suggests comparing AE design values with established blasting practices for any initial design use prior to drilling any boreholes.

The following list discusses some potential pitfalls of blast design using the AE method. Users are encouraged to read and consider the points listed below; as the AE process is fundamentally different than most blast design methods. Primary points of concern are as follows:

1. Understanding the effects of Powder Factor on blast pattern dimensions
    a. The Available Energy ("AE") method integrates powder factor into the design process itself, which may be a new concept for some users. In general terms, the higher the powder factor, the greater the quantity of explosive used per unit of volume. Typically, this additional energy causes the final product to be more finely broken than lower powder factors. In simple terms, high powder factors make little rocks, and low powder factors make big rocks.
    b. It is important to remember that when changing powder factor for pattern designs where face height and explosive quantity are held constant, the burden and/or spacing of the pattern will change. Essentially, high powder factors generate small surface areas, and low powder factors generate large surface areas.
    c. For the AE method, surface area scales proportionally to AE in contrast to the inverse relationship of powder factor and surface area. For users who modify pattern size to compensate for powder factor using an inverse relationship, the initial switch to the AE technique may require a short adjustment period.
    d. The mechanism of adjustment that allows variation of powder factor is typically modifying either burden or spacing length. Since powder factor is a ratio, adjusting either explosive weight or the material volume will change the powder factor.
        i. Explosive weight can be adjusted through varying explosive densities or the height of the powder column (the portion of the borehole full of explosives). Powder column height can be varied through length of stemming or addition of decking.
            1. Adjustment of powder factor using explosive density is not recommended on an individual borehole basis. Changing the weight of explosive in the borehole changes scaled distance requirements that may place the blaster in violation of federal, state, or local regulations. Any change in the weight of explosives in the borehole should be checked against acceptable scaled distance values for the individual site.
        ii. Typically, traditional methods adjust powder factor by varying spacing, although changes to burden will also adjust powder factor. The AE method

as developed for Large Surface Coal Mines controls spacing for cut width adaptation, and adjusts burden to vary powder factor.

2. Adequate Burden and Spacing,
   a. The nature of the Large Surface Coal Mine AE method focuses on surface area more than burden, but burden is still an important component of blast design. Burden and spacing scale in proportion with borehole diameter.
   b. Excessive burden or spacing increases the volume of material affected by the fixed quantity of explosive in the borehole, and effectively lowers the powder factor. Low powder factors may cause cratering around the borehole, and/or stemming to be blown free of the borehole (known as "rifling"), creation of flyrock, and/or excess ground vibrations since the borehole does not contain enough explosive energy to effectively break the rock surrounding the borehole.
   c. Inadequate burden or spacing near an exposed face can result in flyrock, since generally speaking, explosive energy follows the path of least resistance. If burden or spacing is too short, a smaller volume of material is affected by the fixed quantity of explosive in the borehole, effectively raising the powder factor.
   d. Rough faces may create areas of inadequate burden or spacing, which can focus the explosive energy in specific areas resulting in flyrock, excessive airblast, and uneven breakage.
3. Monitor Stemming and Subdrill
   a. The AE method is designed to allow the user to calculate an appropriate stemming height through use of a stemming factor. This stemming factor can be back-calculated using safe site practices to match current stemming values in use, and it is strongly recommended that the user begin use of the new method with a stemming length known to be safe at the user's site.
      i. Adequate stemming is critical for efficient use of explosive energy. The required quantity of stemming for efficient use of explosive energy depends on the quality of stemming (whether using crushed rock or drill cuttings), and should be safely determined for individual sites by an experienced blaster in closely monitored and controlled conditions
         1. Inadequate stemming results in borehole rifling where explosive energy pushes the stemming free of the borehole rather than breaking through the burden. Rifling creates excess noise and fails to break the material as desired. Rifling also creates unsafe conditions due to flying stemming and the potential for some explosive material to be expelled from the hole prior to detonation
         2. Excessive stemming lowers the amount of explosive placed in the borehole which limits the quantity of material that can be blasted by

that borehole for a given powder factor. Lowering the powder factor due to excessive stemming requires additional boreholes to shoot the bench to the desired powder factor, which increases drilling and initiation costs.

ii. The ideal quantity of stemming would always contain the explosive energy safely while maximizing the footage of borehole used for explosives. Determining the safest and most efficient length of stemming for a site should be done by an experienced blaster. As a general rule, it is the opinion of this author that if there is any question about the ability of the stemming to contain the explosive energy, add more stemming.

iii. Inadequate subdrill may fail to break the toe of the bench near the dig face. Experienced blasters may determine that additional subdrill is necessary to attain desired breakage. AE method subdrill factors have been determined in accordance with subdrill factors recommended by Ash and Konya. Users should determine site-specific subdrill factors to replicate safe and efficient subdrill values currently in use.

iv. Excessive subdrill leads to damage of lower benches and increases drilling complications. Experienced blasters may determine that excessive subdrill is causing unwanted breakage. AE method subdrill factors have been determined in accordance with subdrill factors recommended by Ash and Konya. Users should determine site-specific subdrill factors to replicate safe and efficient subdrill values currently in use.

b. The AE method matches powder factor with a target value supplied by the user. By definition, powder factor is explosive weight divided by quantity of material blasted. **Target powder factors can be attained with both inadequate and excessive stemming and subdrill values.**

i. Inadequate stemming and subdrill will result in rifling and poor breakage, as outlined in previous points.

ii. Excessive stemming and subdrill can create a condition where overall powder factor is correct while the actual explosive powder column is split between the target bench and a lower future bench. If a blast pattern is loaded and shot in these conditions, two benches will be severely damaged as the explosive product will be unable to adequately break the target bench and will damage the lower bench due to excessive subdrill. Excessive ground vibrations may also be possible due to increased confinement. Always monitor stemming and subdrill lengths and maintain values shown to be reasonable by safe and efficient site-specific practices.

4. Appropriate borehole diameter choices with respect to face height

a. Often, companies specify borehole diameters based on economics and time constraints rather than pattern geometry. These choices lead to less-than-theoretically-ideal pattern configurations, but do not automatically mean current site practices are unsafe or unduly inefficient.

b. A good rule of thumb is to use one inch (1”) of borehole diameter for every ten feet (10’) of face height. For a thirty foot (30’) face, use a three inch (3”) borehole; a fifty foot (50’) face can start with a five inch (5”) borehole. These diameters can be varied successfully depending on the accuracy of drilling equipment and speed of drilling required.

c. Experience may show that the above guideline can be safely modified for specific site practices – for instance, the author would drill a ten (10’) or fifteen (15’) foot bench with a three inch (3”) borehole and consider the practice safe if adequately stemmed (with potential use of blast mats if necessary). Additionally, thirty (30’) to fifty (50’) foot face heights are routinely blasted safely with borehole diameters greater than nine inches (9”) at several strip mines in Wyoming’s Powder River Basin. The key factor in these cases is experience. Novice blasters who are unsure of conditions or safe practices are strongly encouraged to seek out professional opinions from other more experienced blasters and technical services personnel from the site and/or professional independent contractors.

Use of AE for Different Types of Blasting

At present, the AE method has been formulated for LSCM bench blasting in Wyoming’s PRB. Questions have been raised concerning the applicability of this method for other sorts of blasting such as surface gold, copper, or taconite mining.

This author focused the AE method presented in this research toward LSCM bench blasting because of personal experience. Numerically and theoretically, there is no reason to expect that the AE method would have any difficulty in designing blasts for a wide range of materials other than coal and its associated overburden.

Additionally, the Quarry AE method shown in Appendix F may open the door for AE use in quarries or other areas where varying rectangular pattern geometry is highly valued. Such an extension of this research is welcomed and planned as future work. At present, if the reader is considering using the AE method for a type of blasting not explicitly prescribed in the dissertation, keep these points in mind:

- LSCM bench blasting is largely in low density materials such as dirt, weak shales, sandstones, and coal
    - Applying AE blast design principles to different material types will require changes in powder factor
    - Harder materials such as taconite will require greatly increased powder factors compared to typical LSCM overburden blasts
    - If softer materials are encountered, lower powder factors are advisable
- Geologic discontinuities are a problem for all blast design methods, and the best mitigation techniques for discontinuities should be shared between blast design methods
    - In the case of joint sets, continue current site practices to deal with oversize or flyrock issues
    - Continue to carefully place boreholes to deal with geologic discontinuities
    - Voids can be dealt with in the same manner as any other blast design method
- In all cases, any completed AE design should be compared with current best practices for the individual site until experienced blasters are confident in their understanding of the AE method and judge the AE method safe for use at the individual site
- Blasters are discouraged from making drastic changes to pattern design or loading practices at any time
    - Small changes are less likely to result in major safety hazards
    - All changes made to a blasting program at any operation should be done only under the supervision of experienced blasters who understand their responsibility for the results of their actions
- It is unlikely that the AE method will immediately deliver large savings in blasting costs
    - The author expects incremental changes to be the most likely vehicle of savings – saving a few dollars at a time through the stabilization of powder factor from shot to shot
- Ultimate responsibility for the blast rests with the blaster at the site; the author cannot and will not certify that the Available Energy blast design method is suitable for use in all times and at all places, or at any time or any place. The AE method is presented as a tool for today’s blaster; and as with any tool, must be used intelligently for best results.

Any persons using the AE method for blasting at their site are encouraged to contact the author to discuss the performance of the AE method.

APPENDIX F
AVAILABLE ENERGY QUARRY METHOD

The current research effort focuses on LSCM bench blasting in Wyoming's PRB. However, it became apparent during the testing process that the AE method could easily be adapted to generate pattern geometries similar to Ash and Konya. Some preliminary testing using the methods discussed in the dissertation has shown that the AE method can come very close to matching Ash for quarry geometry blast design.

Quarry AE comparison testing was done using Ash's design method as Ash has explicit spacing factors while Konya has more complicated relationships. This testing should be thought of as high-level proof of concept testing, not detailed testing for immediate use.

Six tests with narrow face height ranges were conducted:

1. Wide spacing factor range, no subdrill
2. Wide spacing factor range, subdrill
3. 1.2 spacing factor, subdrill
4. 1.4 spacing factor, subdrill
5. 1.4 spacing factor, no subdrill
6. 1.2 spacing factor, no subdrill

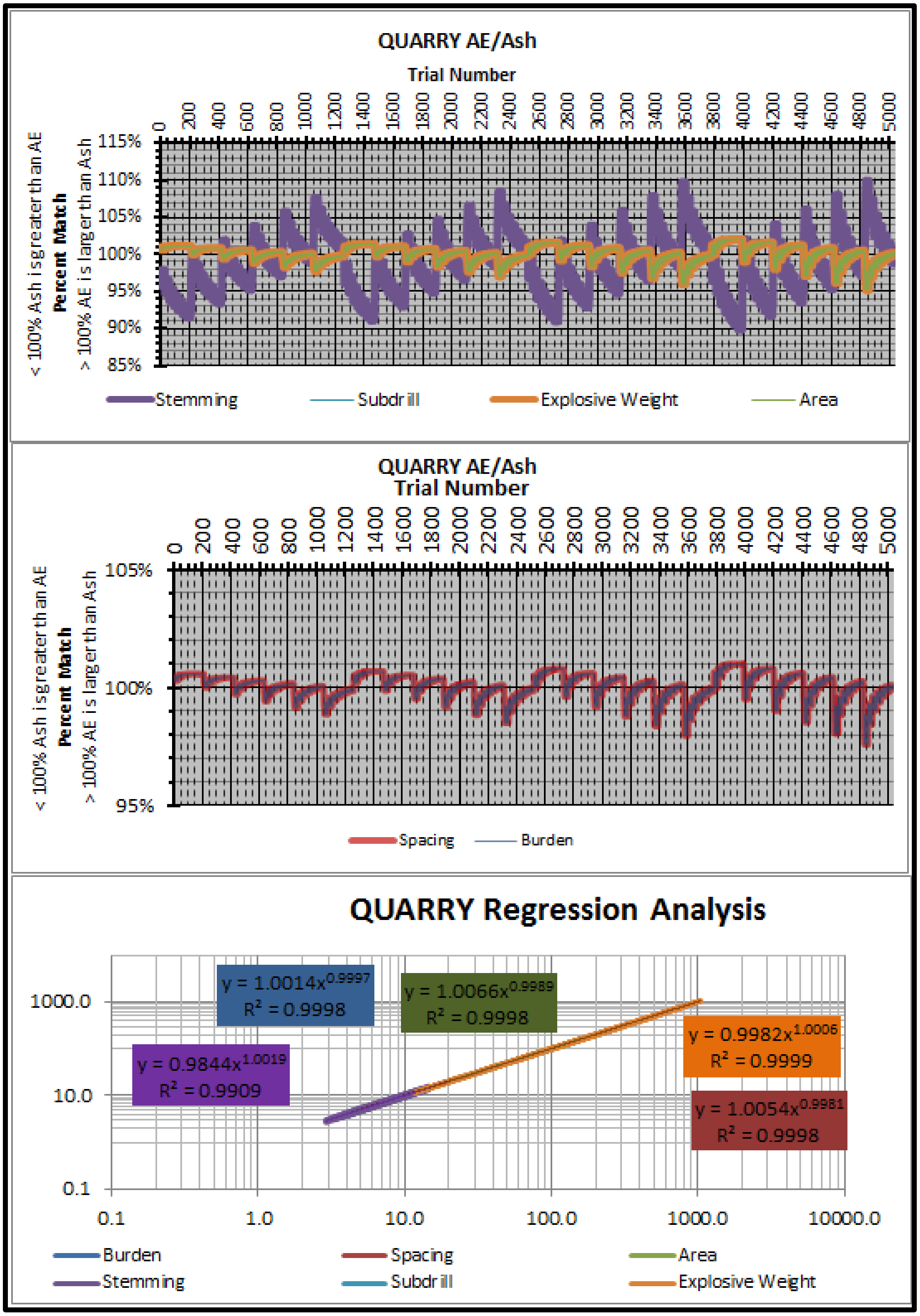
Adapting the AE method to quarry blasting was simple, removing an entire formula from the calculation process. Standard AE calculations were used up to Surface Area, then the method solved for burden and finally spacing.

AE Quarry Method				
F	G	H	I	J
6	Inputs 1	Borehole Diameter	9.875	9.875
7		Product Density	0.8	0.8
8		Powder Factor	1	1
9	Output 1	AE	26.56	=(0.3405*J7*J6^2)/J8
10	Inputs 2	AE	26.56	=J9
11		Face Height	60	60
12		Spacing as % of Burden	1.4	1.4
13		Stemming Factor	1	1
14		Subdrill Factor	0.4	0.4
15	Outputs 2	Stemming Factor	26.78	=((J9*27)^(1/2))*J13
16		Subdrill Factor	10.71	=J15*J14
17		Surface Area	525.13	=J9*(1-((J15-J16)/J11))*27
18		AE Burden	19.37	=(J17/J12)^(1/2)
19		AE Spacing	27.11	=J17/J18

Replacing Cut Width with a spacing factor represented as a percentage of burden adds the necessary information for the design process. The Number of Rows formula is no longer needed. The burden formula is the square root of surface area divided by the spacing factor, and spacing is surface area divided by burden. Those changes create a quarry geometry AE method for blast design. The results of the testing are shown on the following pages using the same general format as Appendix A. Note that variations in spacing factor lead to less accurate matches – by determining appropriate spacing and subdrilling factors for individual spacing factors much better matches are attainable.

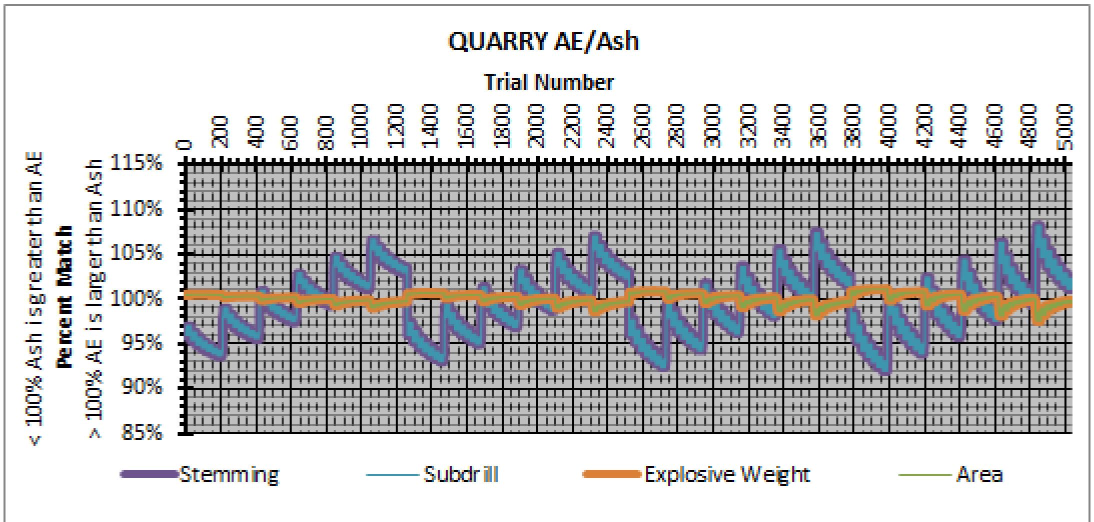
Quarry AE Test 1

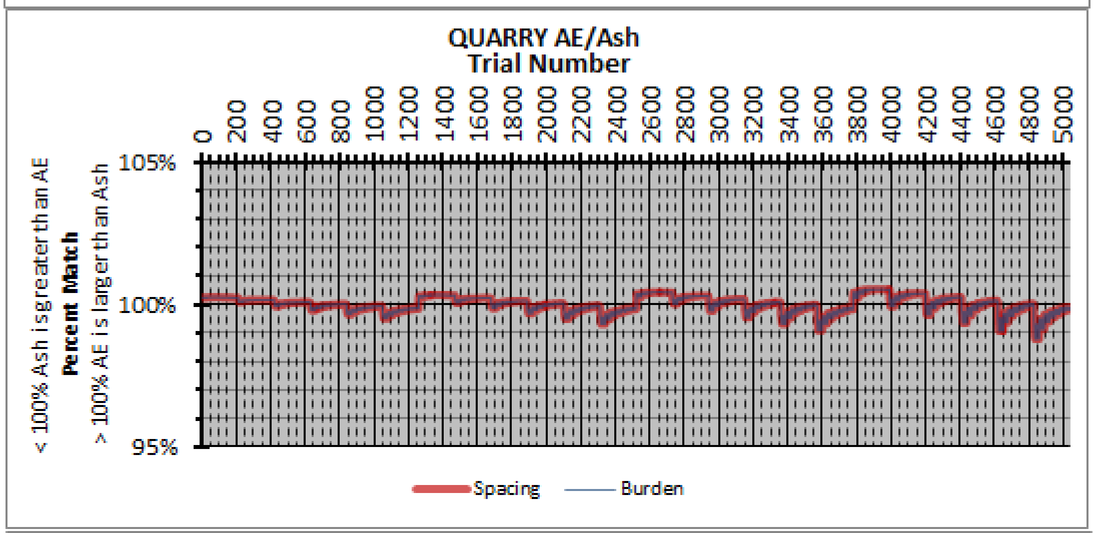
Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.550	0	0.000
0.80	0.620	0	0.000
0.90	0.690	0	0.000
1.00	0.750	0	0.000
Spacing Factor	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	
1.20	2	75%	
1.25	3	83%	
1.30	4	92%	
1.35	5	100%	
1.40	6	108%	
1.45		117%	
		125%	

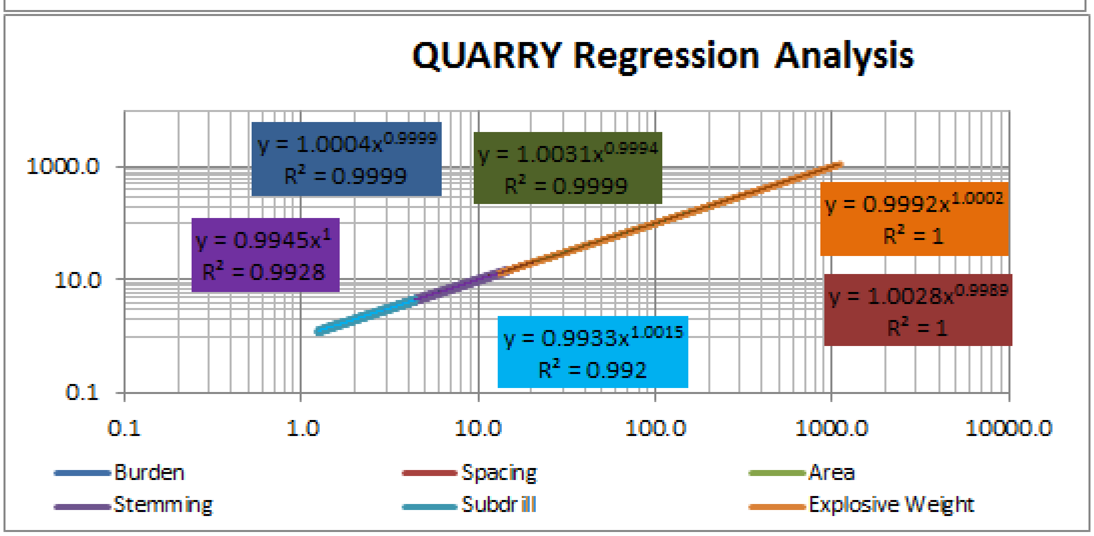

QUARRY AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area
QUARRY AE/Ash
Trial Number
Spacing
Burden
QUARRY Regression Analysis
y = 1.0014x^0.9997
R² = 0.9998
y = 1.0066x^0.9989
R² = 0.9998
y = 0.9844x^1.0019
R² = 0.9909
y = 0.9982x^1.0006
R² = 0.9999
y = 1.0054x^0.9981
R² = 0.9998
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

Quarry AE Test 2

Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.578	0.3	0.429
0.80	0.651	0.3	0.375
0.90	0.721	0.3	0.333
1.00	0.790	0.3	0.300
Spacing Factor	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	
1.20	2	75%	
1.25	3	83%	
1.30	4	92%	
1.35	5	100%	
1.40	6	108%	
1.45		117%	
		125%	

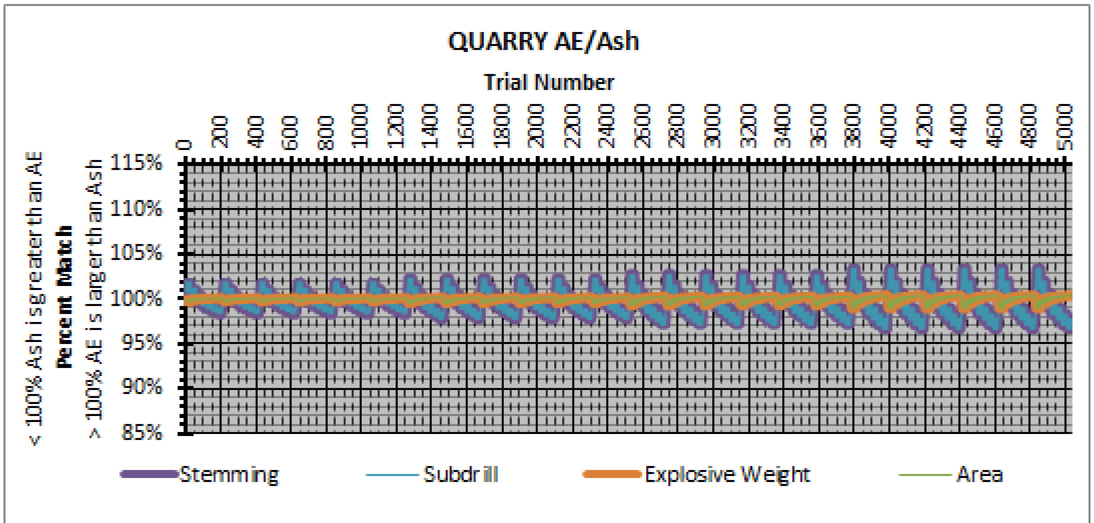

QUARRY AE/Ash
Trial Number
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000
115% 110% 105% 100% 95% 90% 85%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than an Ash
Stemming
Subdrill
Explosive Weight
Area

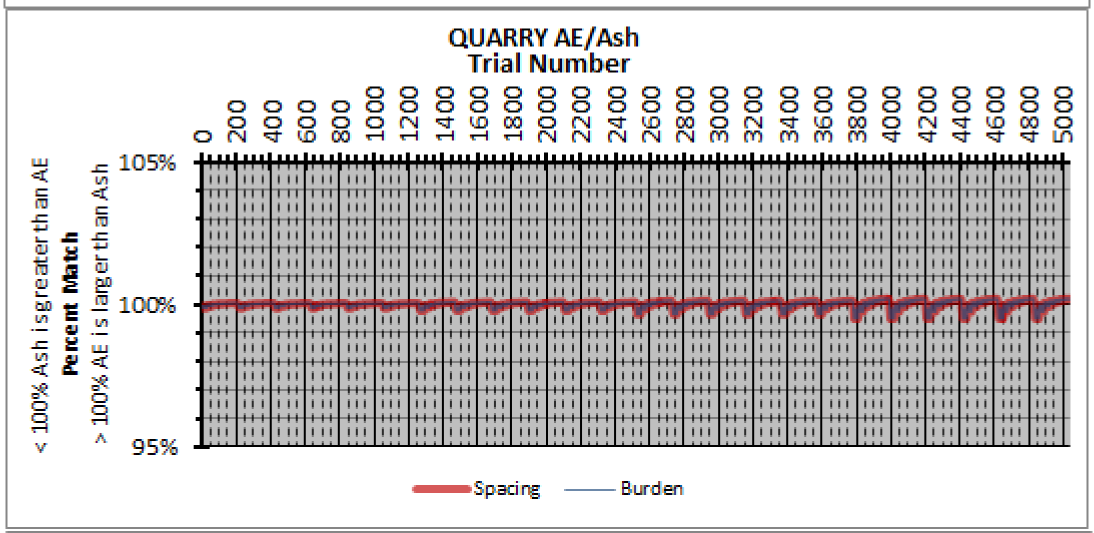

QUARRY AE/Ash
Trial Number
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000
105% 100% 95%
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than an Ash
Spacing
Burden

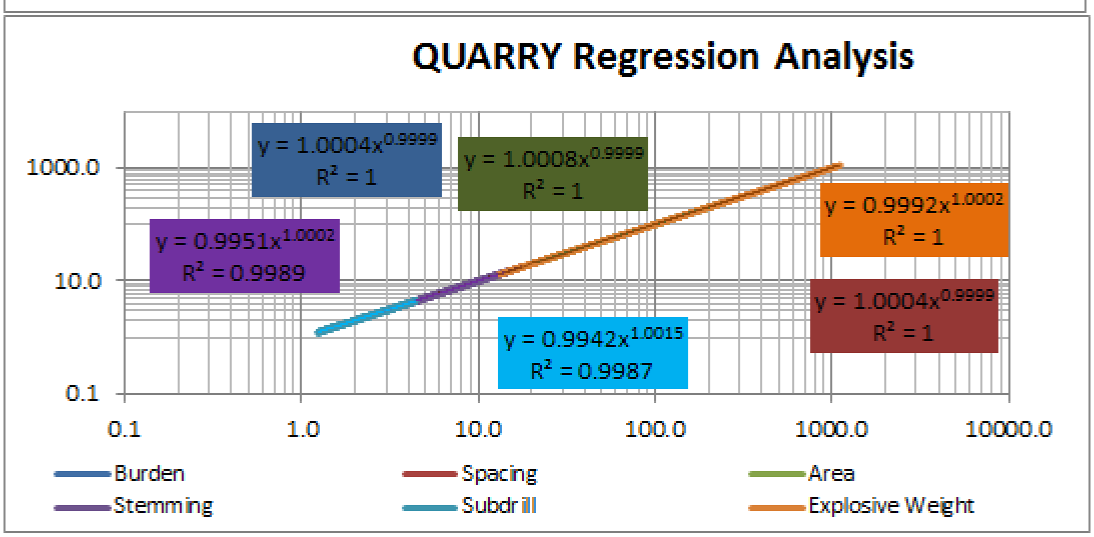

QUARRY Regression Analysis
1000.0
10.0
0.1
0.1 1.0 10.0 100.0 1000.0 10000.0
y = 1.0004x^0.9999
R² = 0.9999
y = 1.0031x^0.9994
R² = 0.9999
y = 0.9945x^1
R² = 0.9928
y = 0.9992x^1.0002
R² = 1
y = 1.0028x^0.9989
R² = 1
y = 0.9933x^1.0015
R² = 0.992
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

Quarry AE Test 3

Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.607	0.3	0.429
0.80	0.684	0.3	0.375
0.90	0.758	0.3	0.333
1.00	0.830	0.3	0.300
Spacing Factor	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	
1.20	2	75%	
1.20	3	83%	
1.20	4	92%	
1.20	5	100%	
1.20	6	108%	
1.20		117%	
		125%	

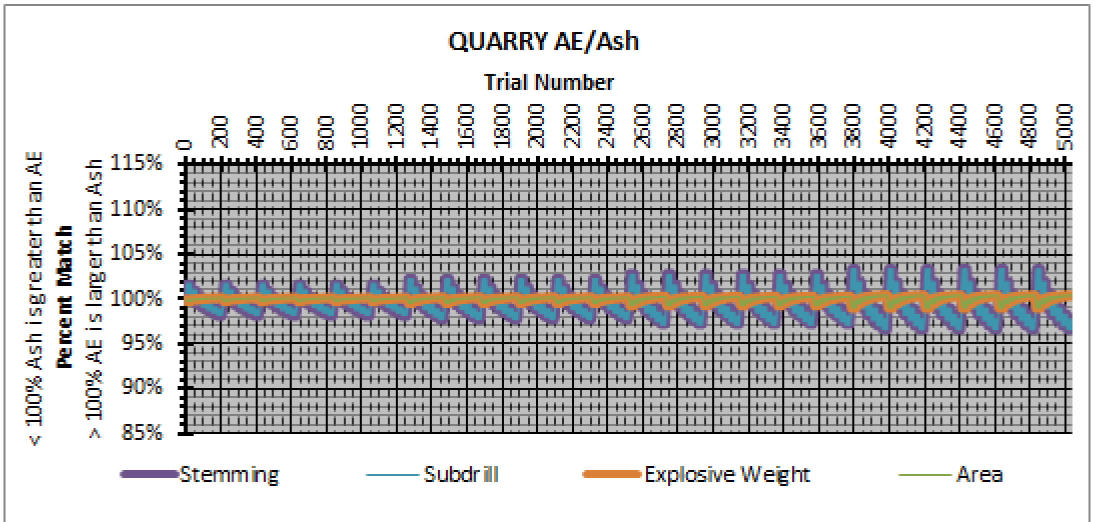

QUARRY AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Stemming
Subdrill
Explosive Weight
Area

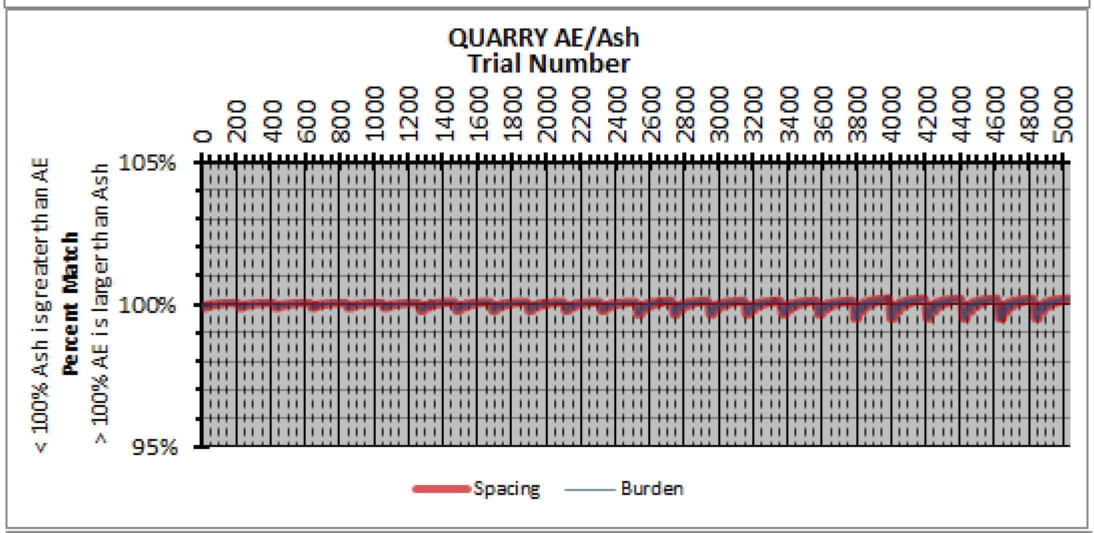

QUARRY AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
Spacing
Burden

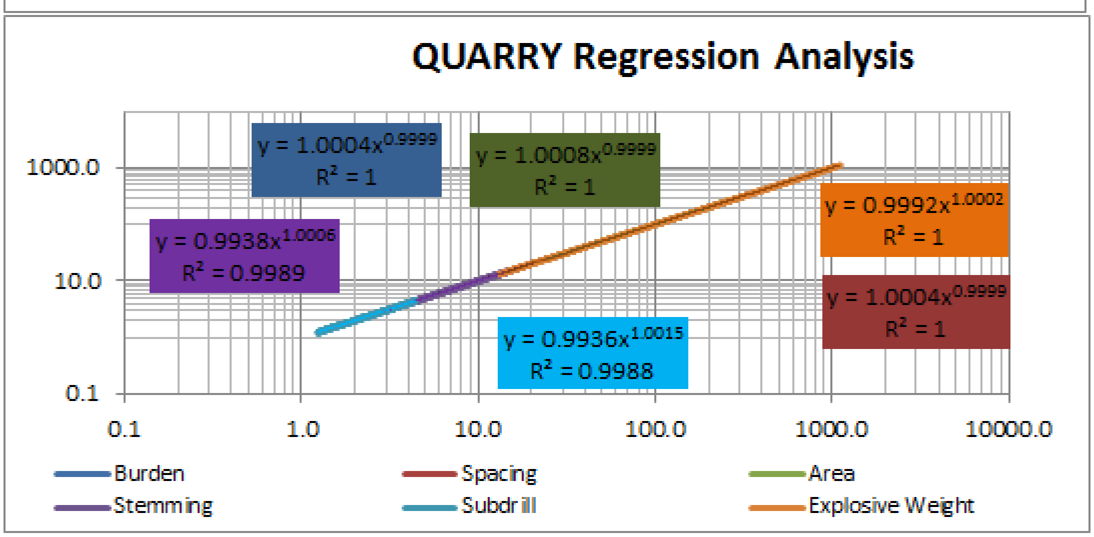

QUARRY Regression Analysis
y = 1.0004x^0.9999 R² = 1
y = 1.0008x^0.9999 R² = 1
y = 0.9992x^1.0002 R² = 1
y = 0.9951x^1.0002 R² = 0.9989
y = 1.0004x^0.9999 R² = 1
y = 0.9942x^1.0015 R² = 0.9987
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

Quarry AE Test 4

Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.561	0.3	0.429
0.80	0.633	0.3	0.375
0.90	0.702	0.3	0.333
1.00	0.768	0.3	0.300
Spacing Factor	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	
1.40	2	75%	
1.40	3	83%	
1.40	4	92%	
1.40	5	100%	
1.40	6	108%	
1.40		117%	
		125%	

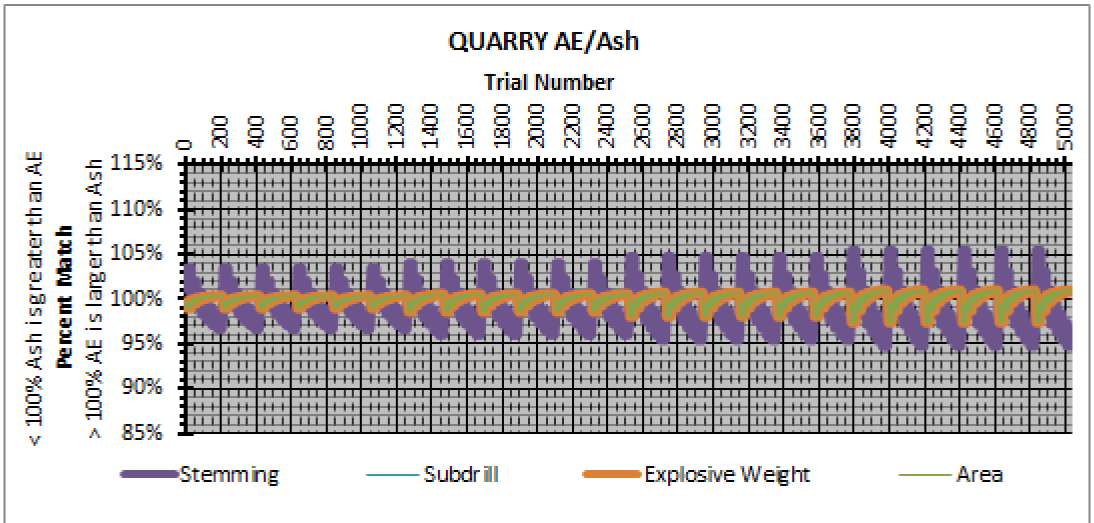

QUARRY AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
115%
110%
105%
100%
95%
90%
85%
Stemming
Subdrill
Explosive Weight
Area

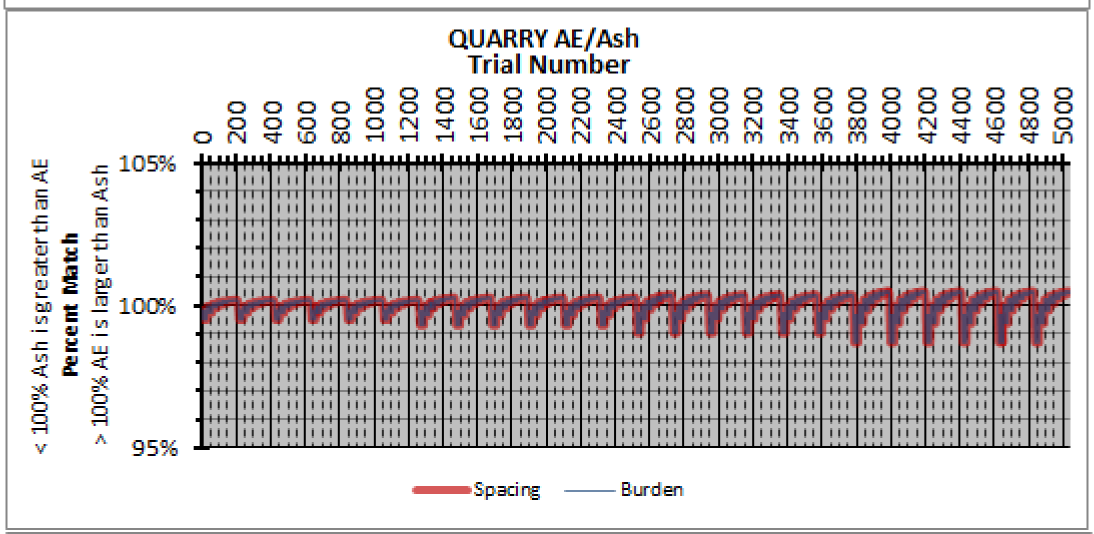

QUARRY AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
105%
100%
95%
Spacing
Burden

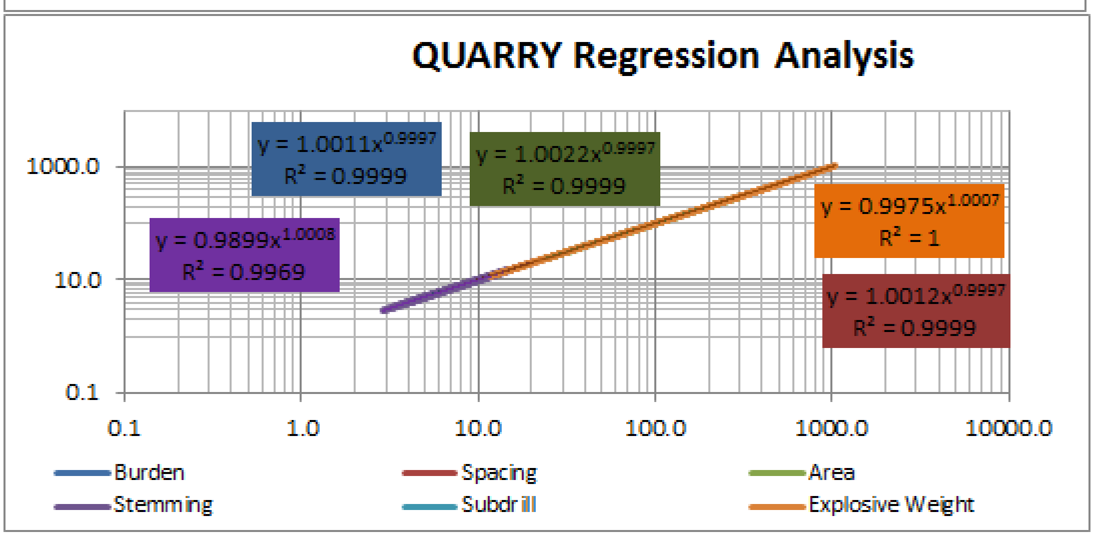

QUARRY Regression Analysis
y = 1.0004x^0.9999
R² = 1
y = 1.0008x^0.9999
R² = 1
y = 0.9938x^1.0006
R² = 0.9989
y = 0.9992x^1.0002
R² = 1
y = 1.0004x^0.9999
R² = 1
y = 0.9936x^1.0015
R² = 0.9988
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

Quarry AE Test 5

Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.538	0	0.000
0.80	0.605	0	0.000
0.90	0.670	0	0.000
1.00	0.732	0	0.000
Spacing Factor	Borehole Diameters [in]	Face Height Multipliers [% of 10*D]	
1.40	2	75%	
1.40	3	83%	
1.40	4	92%	
1.40	5	100%	
1.40	6	108%	
1.40		117%	
		125%	

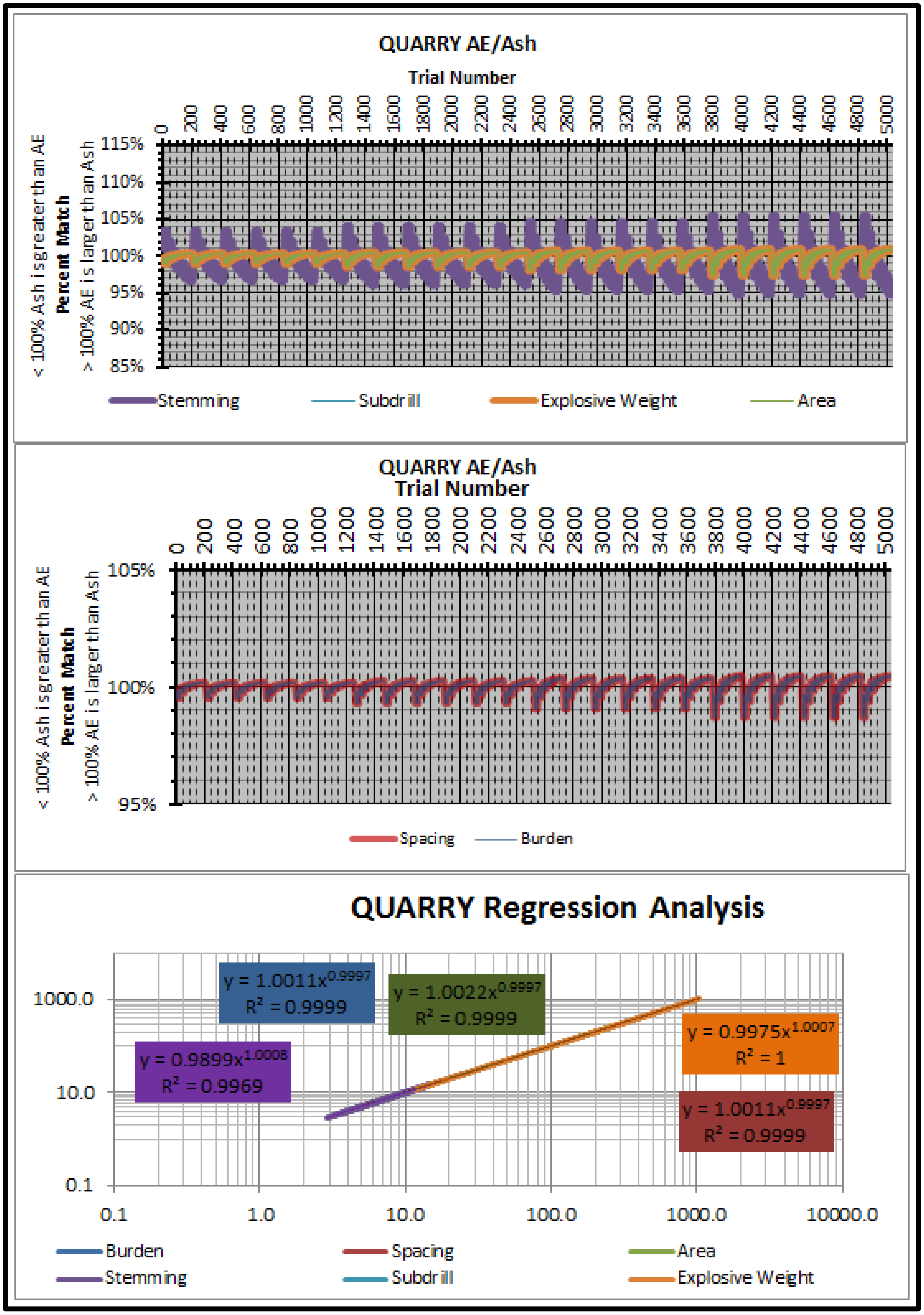

QUARRY AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
115%
110%
105%
100%
95%
90%
85%
Stemming
Subdrill
Explosive Weight
Area


QUARRY AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
105%
100%
95%
Spacing
Burden


QUARRY Regression Analysis
y = 1.0011x^0.9997
R² = 0.9999
y = 1.0022x^0.9997
R² = 0.9999
y = 0.9975x^1.0007
R² = 1
y = 0.9899x^1.0008
R² = 0.9969
y = 1.0012x^0.9997
R² = 0.9999
1000.0
10.0
0.1
0.1
1.0
10.0
100.0
1000.0
10000.0
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

Quarry AE Test 6

Ash - Available Energy Comparison Test			
Ash Stem Factor	AE Stem Factor	Ash Subdrill Factor	AE Subdrill Factor
0.70	0.581	0	0.000
0.80	0.654	0	0.000
0.90	0.723	0	0.000
1.00	0.791	0	0.000
Spacing Factor	Borehole Diameters [in]	Face Height Multipliers [% of 10"D]	
1.20	2	75%	
1.20	3	83%	
1.20	4	92%	
1.20	5	100%	
1.20	6	108%	
1.20		117%	
		125%	


QUARRY AE/Ash
Trial Number
< 100% Ash is greater than AE
Percent Match
> 100% AE is larger than Ash
115%
110%
105%
100%
95%
90%
85%
Stemming
Subdrill
Explosive Weight
Area
QUARRY AE/Ash
Trial Number
105%
100%
95%
Spacing
Burden
QUARRY Regression Analysis
y = 1.0011x^0.9997
R² = 0.9999
y = 1.0022x^0.9997
R² = 0.9999
y = 0.9899x^1.0008
R² = 0.9969
y = 0.9975x^1.0007
R² = 1
y = 1.0011x^0.9997
R² = 0.9999
1000.0
10.0
0.1
1.0
100.0
10000.0
Burden
Spacing
Area
Stemming
Subdrill
Explosive Weight

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Andrew Clifford Blair was born on March 8, 1988 in southwest Missouri. Andrew earned a Bachelor of Science, Cum Laude, in Mining Engineering at Missouri University of Science and Technology (formerly UMR) in May 2009, a Master of Science degree in Explosives Engineering at Missouri S&T in December 2011, and a PhD in Mining Engineering at Missouri S&T in May 2015.

Andrew has worked as a Teaching Assistant and Graduate Teaching Assistant while attending Missouri S&T, and taught Explosives Engineering courses as a Lecturer at Missouri S&T in the Spring, Summer, and Fall semesters of 2014.

Andrew has worked in the mining industry as an intern in the Southeast Missouri lead mines; and as both an intern and full time Truck/Shovel engineer in Wyoming's Powder River Basin, reaching Engineer II before returning to S&T to complete his PhD degree.

Andrew joined the staff of the International Society of Explosives Engineers as Director, Training and Education in April 2015.