BLASTING INFLUENCE ON COMMINUTION

*Dennis Murr[1], Lyall Workman[2], Jack Eloranta[3], and Panagiotis (Takis) Katsabanis[4]

[1]*Barr Engineering Company*
3128 14th Avenue East
Hibbing, Minnesota 55746, USA
*(*Corresponding author: dmurr@barr.com)*

[2]*Barr Engineering Company*
234 West Century Avenue
Bismarck, North Dakota 58503, USA

[3]*Eloranta and Associates*
6485 Koski Road
Tower, Minnesota 55790, USA

[4]*Queen's University*
The Robert M. Buchan Department of Mining
99 University Avenue
Kingston, Ontario K7L 3N6, Canada

BLASTING INFLUENCE ON COMMINUTION

ABSTRACT

The total comminution and processing of hard ores to concentrate consumes a large amount of electrical energy and is theatrically reviewed. In the past two decades, research and case studies have demonstrated a beneficial relationship between explosive consumption and the grindability of ores. Blasting energy and the distribution of that energy appears to affect subsequent comminution beyond crushing. This experience has prompted researchers to attempt to understand and quantify the mechanisms involved. This paper discusses the relationship of drilling and blasting practices to fragment size, particle internal micro cracking, and the energy consumption and throughputs for crushing and grinding.

KEYWORDS

Comminution, drilling, blasting, efficiency, power consumption, powder factor, blast pattern, energy density, fragmentation, micro cracks, grinding mills, grindability, work index

INTRODUCTION

Extracting hard ore from a deposit and processing that ore to a final product consumes a great deal of energy. The largest amount of that is electrical energy dedicated to comminution. In 1998, Roland reported that comminution of ores consumed 2% of the total amount of electrical energy generated in the USA. A small reduction in this significant amount of electrical energy can be a substantial cost savings to the consumer and can have an impact on greenhouse gas emission.

The authors foresee a need to review at a high level the total energy consumption at the mining and processing facility and bracket this review only with a the more conventional crushing and grinding technology. This review will help demonstrate and form a “buy-in” to the comminution possibilities that can be achieved in drilling and blasting practices. This review will look at Bond’s Third Theory of Comminution to get an understanding of the factors that impact energy consumption and the various expressions of efficiency with some of the confusions noted by researchers. Lastly, a focus on the total energy consumption at a facility will show the opportunity to focus on the energy consumed in drilling and blasting.

When optimizing the total comminution, one has to consider the impact of drilling and blasting along with crushing and grinding to evaluate the total process. Higher utilization of blasting energy at its higher efficiency can have a significant impact at lowering the comminution energy in the crushing and grinding circuit downstream.

In the blast, it appears unlikely that the crush zone volume, in the immediate vicinity of each blasthole, is sufficient to account for all the changes in grindability. Estimation of the crushed zone around the powder column is often placed at one to three diameters. This translates to only about 1% of a typical muck pile. The degree of internal damage, experienced by individual fragments as a function of distance from the blasthole, becomes an important parameter to understand, especially for comminution stages beyond primary crushing.

In this paper, we attempt to set forth what is currently known or suggested by evidence. Published case histories are reviewed and analyzed. For example, Vovk (1973) has completed research and postulated a crushed zone much greater than one to three diameters. While his results seem optimistic, the experimental procedure appears worthy of further study.

Energy density and the parameters that affect it appear to be crucial in an effort to increase the number of micro cracks, and therefore softening, in the blast block. The rock type, explosive selection, blast pattern selection, millisecond delay times, and timing rotation all affect the manner in which energy distributes throughout the rock mass. This is discussed and evaluated.

The authors conclude that energy distribution inside the blast block is of interest and may be a prime contributor to the distribution and frequency of micro cracks. They also concluded that additional research and development work is needed. Recommendations for further work, with an aim to provide the fragmentation engineer and plant engineer with useful tools to optimize grindability and design with the most effective blasts, are presented.

CRUSHING AND GRINDING

Circuits of Interest

The more conventional comminution circuits downstream from the mining process that are the discussion and consideration for this paper will be limited to crushers and grinding mills as listed below:

Crushers

- Gyratory
- Secondary cone
- Tertiary cone

Grinding Mills

- Rod mills
- Ball mills
- Autogenous mills
- Partial autogenous mills
- Semi-autogenous mills

The difference between partial autogenous mills and semi-autogenous mills is the level of the steel ball charge carried in the mill. Partial autogenous mills (Roland, 1964) are normally considered to be mills that carry a small steel ball charge (~5% load) and are used in processing plants to assist in the comminution process, especially used to break up critical size material. Semi-autogenous mills (Roland, 1998) are normally considered to be mills that carry a large steel ball charge (25% to 30% load) to assist in maximum through-put for economic reasons.

Bond's Third Theory of Comminution

The primary focus of this section will be the "Bond's Third Theory of Comminution," as described by Bond and used by Roland and many other researchers, scientists, and engineers. We recognize that others have successfully developed other theories and have presented compelling narratives to the applicability and accuracy of these theories and their ability to provide better analysis. But looking from a big picture point of view, Bond's Third Theory of Comminution can still provide means to evaluate a measure of grindability and level of circuit performance (Roland, 2008). For this purpose, Bond's Third Theory of Comminution is considered by us as the standard.

The Bond equation (Bond, 1960) determines the energy required to produce a required particle size reduction.

$$W = 10W_i/P^{0.5} – 10W_i/F^{0.5}$$

Where:
W is the power requirement (kWh/t)
W_i is the work index, a measure of power to break the material
P is the product size in micrometers which 80% passes
F is the feed size in micrometers which 80% passes

The work index can be calculated from either the Bond grindability test or can be calculated from accurate plant operating data.

Basically, Bond's Third Theory of Comminution has two functions for determining the energy for comminution: work index and particle size reduction. The work index function is a hardness factor or a degree of hardness and/or toughness of the material being treated and expressed in energy per ton treated. The particle size reduction is expressed as the feed size (F_{80}) and the product size (P_{80}) for the respective particle size distribution analysis.

Particle Size

The particle size reduction function is fairly straight forward and easily measured from samples taken from the feed material to the comminution vessel and from the product material. The samples are processed for a standard particle size distribution analysis and an 80% passing size noted. The 80% passing size is reported in micron units. The relationship of particle size on the power consumption is non-linear due to the inverse of the square root, with the finer sizes having a more significant impact on power consumption.

The desired degree of particle size reduction is ultimately determined by the liberation characteristics of the mineral and the separation techniques applied. The various crushing and grinding equipment employed is determined by the effectiveness of the equipment on the particle size at the various stages of reduction.

Work Index

The work index is a different kind of function than particle size and is dependent on the hardness and/or toughness on the material. As mentioned previously, the work index can be measured by a test of the material or from operating data. The required work for comminution is directly proportional to the work index. Softer material will have a lower work index and harder material will have a higher work index. The effect of Work Index on the required SAG mill power draw is shown in Figure 1. For the example calculation, a 10.4 meter diameter by 5.2 meter long mill, with a 25% steel ball charge of 12.7 cm diameter and a constant feed rate of 2500 ton per hour is considered.

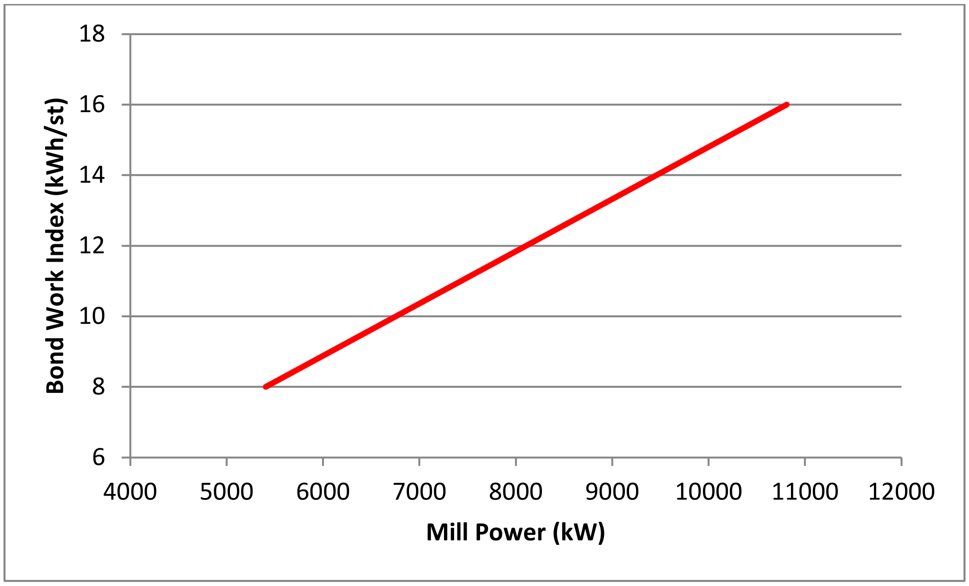

Figure 1 – Effect of mill power on a SAG mill by the change in Word Index parameter only

As the graph illustrates, a material with a Work Index of 8.0 for a typical SAG mill will consume 5,400 kWh/t and a material with a Work Index of 14.0 will consume 9,500 kWh/t. The relationship is linear and the impact of Work Index on power consumption is significant.

Efficiencies

The efficiency of comminution machines in converting electrical energy to actual size reduction has been reported (Roland, 1998) to be poor. It is significant to note that when discussing efficiency, there are three commonly referred to efficiencies: theoretical efficiency, operating efficiency, and economic efficiency.

To avoid confusion, the definitions of these three efficiencies are discussed below.

Theoretical

Research reveals that there have been numerous attempts to hypothesize on the relative efficiencies of comminution processes. Roland (1998) cited theoretical efficiency as one of the efficiencies for consideration, defining it as “the actual energy consumed in a comminution machine compared to the theoretical energy required to perform the size reduction.”

Theoretical efficiency is the most important efficiency to consider when evaluating energy consumed in the size reduction of particles. When making choices on where to expend energy in total comminution, one should focus on areas which result in high values for maximum impact to achieve the lowest cost of energy in the form that is the lowest cost.

Also in his paper, Roland (1998) made reference to a report published by the National Materials Advisory Research Council (1981), which indicated that their studies showed that only 1% of the energy available for size reduction in grinding is actually used for that purpose. The remaining 99% of that energy is expended on moving machinery and generation of noise and heat. Others have reported efficiencies as shown in Table 1.

Table 1 – Theoretical efficiencies of various form of comminution

Process	Efficiency	Reported
Blasting	20.0%	Brinkman (1987)
Crushing	70% to 80.0%	Morrell (1992)
Grinding	1.0%	Willis (1988), Hukki (1975)

Nielsen and Kristiansen (1995) summarized, “Current comminution technology is both energy intensive and often inefficient, with only about 1% of the total energy consumed in conventional grinding being used to actually create new surface (Willis, 1988). The power draw in the grinding mill is mainly caused by moving the mill charge, most of which consists of the grinding media. Size reduction may therefore be viewed as a byproduct of moving the charge in the mill.

The size reduction mechanisms of crushers differs from those of grinding mills. The power draw of a crusher is dependent upon the order the rate in the size reduction across the machine. Crushers are much more energy efficient than mills…crushers have been estimated to be in the range of 70 to 80% (Morrell, 1992).

Use of explosives is also not very energy efficient. Brinkman (1987) reported that up to 20% of the explosive energy may be transmitted to the surrounding rock is elastic strain energy.”

Evertsson (1995) wrote the following concerning crushing: “Most of the energy input into crushing machines is not possible to use for the creation of new free surfaces. A relatively large part is absorbed in the material due to friction losses during the crushing stroke. A minor part is absorbed by the machine itself due to mechanical losses. Only a small fraction, a few percent, of the total energy is utilized for breakage of the material.”

Further, L. López, et al. (2002) states, “There are important discrepancies among different authors about the fraction of the available energy employed in rock fragmentation (as large as 0.6% to 50%). The values obtained in this work range from 4.1 % using heat as available energy to 6.6% with useful work to 2000 bar.”

And finally, E. G. Baranov and I. A. Tangeav (1988) specifically list comminution efficiencies as:

Table 2 – Comminution Efficiencies

Process	Efficiency
Blasting	1.4%
Crushing	1.2%
Grinding	0.1-0.15%

As one can see, the reported crushing theoretical energy is quite variable, but when compared to total comminution energy, is not that significant recognizing that the electric motors used to drive crushers are small compared to the downstream motors used on grinding mills. Of additional significance is that the blasting may be only slightly more efficient than crushing, but crushing produces negligible fines and production of fines in grinding is very expensive. Nielsen and Kristiansen (1996) indicate that the production of fines, both in blasting and in crushing, is influenced by how the blast is designed.

Operating

Continuing, Roland (1998) defined operating efficiency as comparing “the operating work index on a comminution machine to the Bond work index of the ore, as determined from bench-scale crushing and grindability tests or pilot-plant tests." Operating efficiency is an important factor when evaluating types and sizes of grinding mills, but is not considered in this paper.

Economic

Finally, Roland (1998) defined economic efficiency as comparing "income from production to predicted income." For this discussion, we will assume the income is a fixed number and based on the commodity price of the product. Therefore, evaluating and reducing the cost factors can lead to maximizing profits when utilizing various forms of energy. Eloranta (1997) has presented a comparison of unit cost of the various forms of comminution as shown in Table 3.

Table 3 – Unit operating cost of comminution processes

Process	kW-Hr/Lton	$kW-Hr	$/Lton
Blasting	0.43	$0.38	$0.16
Crushing	3.24	$0.07	$0.23
Grinding	17.82	$0.07	$1.25

Combining the unit cost factors with the theoretical efficiency results in blasting, as a form of comminution, to be the most economic form of comminution. Pending the absolute vales of these efficiencies, a factor of 15:1 (Eloranta, 1997) can be realized by blasting compared to grinding.

In summary, based on consideration of all the definitions of efficiency, the following can be concluded:

1. All of blasting, crushing, and grinding are of low efficiency.
2. Blasting is considerably more efficient than grinding.
3. Blasting is likely more efficient than crushing, but to a lesser degree than when compared to grinding.
4. Blasting is the most effective and economic way to produce fines due to direct production, its effect on fines production at crushing, and in easing the creation of fines in grinding.

Electrical Energy Consumption

Examining energy consumption in each unit operation at a typical hard rock mining and processing facility leads to an important understanding of how energy is used in the mining operation. A study (DOE, 2007) identified all the forms of energy as a percent of total and is shown in figure 2. Grinding is shown as 40% and crushing is shown at 4%, for a total electrical energy consumption of 44%. This compares to drilling at 5% and blasting at 2%, for a total of energy of 7%. This is a significant difference. It suggests an area to focus on for optimization is to apply more energy at blasting where it is more efficiently used, in order to reduce energy consumption ay crushing and grinding. The energy for drilling is electrical but in some cases could be diesel. All the energy for blasting is contained in the blasting agents used (powder, primers, and cord).

Optimization of drilling and blasting practices by incorporating best available technology will not necessarily increase the cost to the total facility if savings in crushing and grinding comminution are realized. A small increase in blasting energy (if directed into more comminution) can create a significant reduction in crushing and grinding comminution costs. Utilization of best available drilling and blasting technology is discussed later in this paper.

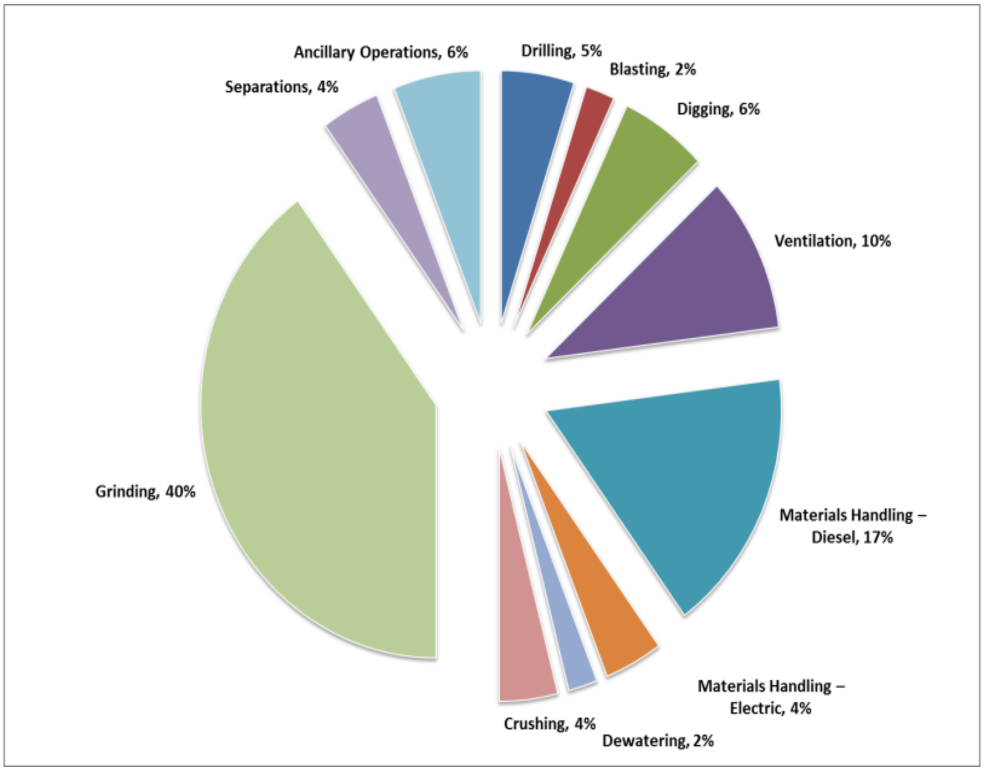

Figure 2 – Distribution of energy consumption (DOE, 2007) at a hard rock mining facility

Limits to Crushing

As shown in Figure 2, crushing contributes only 4% of the total energy at the mining and processing facility. Savings in crushing electrical energy can be obtained by improvements in drilling and blasting, but are expected to be minor in amount. Therefore, efforts should be directed to grinding electrical energy in the processing facility. At the crusher, the principal benefit of optimized blasting will likely be improved throughput.

DRILLING AND BLASTING

Despite advances across a broad front in the understanding of rock fragmentation by blasting, much remains to be established. Even where lab and a small bench results have been successfully conducted and conclusions reached, scaling up to production blasting has remained difficult. One of the principal obstacles lies in rock mass characterization. In metal mining, ore body models are based on diamond drilling, which is often done on a grid of 100 m x 100 m. The recovered drill core is assayed to provide grade/tonnage estimates and to schedule a uniform ore blend to the crusher and subsequent milling processes. Typically, drill core does not undergo testing for geo-mechanical properties. The principal exception to this is in areas where wall stability is a limiting factor. In addition there are issues associated with small scale testing, in terms of energy losses due to poor confinement of the charge that adversely affect scale-up. Experimentation at a larger scale continues to be needed to improve the capability to scale-up results (Eloranta, Katsabanis, and Workman, 2015).

Measure-While-Drilling

The value of measured-while-drilling (MWD) parameters has been demonstrated. Modern rotary drills are often fitted with sensors which monitor the following parameters: penetration rates, rotary amps, pull-down pressure, RPM, vibration, and air pressure, along with precise GPS coordinates. Telemetry systems are capable of making this data available in sub-second frequency to blasting engineers in real time. The sampling rate for a 10 m x 10 m pattern exceeds diamond drill hole data in two dimensions by two orders of magnitude. In the vertical dimension, the sampling rate is at least an order of magnitude greater, resulting in a net increase of data density of three orders of magnitude. The authors took the opportunity at a recent SME trade show to canvass suppliers of MWD technology. While no questionnaire or standard reporting method was attempted, it appeared that of customers who have already installed MWD technology, only about 5% of the capabilities are actually being exploited. Adoption of MWD technology which was introduced in the early 1980s has been slow.

MWD-based rock property data would be of value, especially when used in concert with online particle size analyzers (OPSA).OPSA output has been used by a number of authors in mine/mill fragmentation studies. OPSA measurements are highly reproducible and relatively inexpensive to acquire.

The weakness of all OPSA technologies lies in the fact that it is a WYSIWYG system (what you see is what you get). The lens sees only the surface material and only those particles of resolvable size. In practical terms, that means down to about 10 cm. There are schemes allowing increased resolution, but that can limit the upper end of measurable sizes.

Blasting Aids Milling

The conundrum centers on the assumption that blasting aids milling in two ways: an increase in the production of sub-grate fines; and a reduction of the work indices (Wi) of the fragments as a result of individual fragment internal softening. However, OPSA technology is not suited to measure micro cracking and will have difficulty accurately measuring finer material below a certain size. Therefore OPSA systems are very valuable but cannot fully characterize drill to mill parameters.

Criteria for blasting design have evolved with specific objectives in mind. Therefore, it is instructive to know how we arrived at the current blast design basis before we discuss how best to blast for optimized milling.

Two cardinal requirements of drilling and blasting are: to free the rock mass from earth; and to reduce that rock to a fragment size that allows for loading, hauling, and crushing. In addition, blast optimization can also mean: establishing and maintaining level floors; controlling unwanted damage to back walls; controlling environmental effects (vibration, orange smoke, air blast, and fly rock); and minimizing the required drilling footage.

In the past five years, there has been a surge of research into mechanisms underlying the production of fines and weakened rock and their distribution within a muck pile. Forward-looking operations are proceeding even though the science is not yet fully understood. They recognize the potential of tens of millions of dollars of annual savings without major capital expenditure. Three popular strategies that have received attention include:

1. Increasing powder factor
2. Increasing velocity of detonation (VOD) of blasting agents
3. Improving distribution of blast energy

Steps for Improvements

So, what specific steps can an operation take to determine whether or not enhanced blast fragmentation can improve mill performance?

Assemble the data

Before hiring a consultant, commencing additional physical testing programs, or acquiring other new technology, an operation should take time to assemble available data. This can be done by a single person or a team with knowledge of geology, production history, flow sheet changes, drilling, blasting, mining engineering, crushing, grinding, and instrumentation. Begin with monthly data from day one of plant operations, if possible. Even old information, which may predate flow sheet revamps, should be included. Monthly weather records from the closest National Weather Service station are important. Accounting summaries with unit cost/ton results are key. Excel spreadsheets may not have all the functionality of a dedicated database, but can provide a good start. Data, properly analyzed, is the source of information and knowledge.

Conduct a simple breakeven analysis

This step will help calibrate expectations for the operation. A speaker at a recent seminar indicated that a 7% improvement in mill tons per hour would pay for a doubling of drilling and blasting costs. By creating a table using current costs, one will be able to bracket the scope of opportunities available.

Review best practices in drilling and blasting

Past efforts to cut drilling and blasting costs may have resulted in expedited Standard Operating Procedures (SOPs). Deviation from best practice that may have made sense in a narrow definition of blast optimization may not when a full consideration of downstream opportunities is performed. The adoption of a broader definition of fragmentation optimization requires a revisiting of the SOP's. There is a cumulative effect of many small shortcuts. Some have termed this "a death by 1000 duck bites." An audit of drilling and blasting practices may reveal shortcomings in pattern cleanup, drilling accuracy, re-drilling procedure, powder placement, stemming, and blast timing. With the results of the previous breakeven analysis in hand, the cost of rectifying best practice deviations can be put into context.

Pattern designs

To incorporate higher powder factors, higher VOD products, and improved energy distribution, changes may be required in pattern geometry. Here again, the breakeven analysis can help in scoping such trials. Major changes in design such as reduced hole diameter and associated tighter blast patterns, as well as substantial changes in powder factor, are often envisioned in this stage of thinking. However, it is important to always begin with small steps, changing as few parameters as possible each time. Remember that seemingly small changes may be larger than they seem. A change of drill bit diameter of just one centimeter from 40.6 cm to 38 cm is a reduction in area from 1,297 cm² to 1,142 cm². That is a 12% change and, for the same column length of explosive, 12% less volume in which explosive can be placed. However, changes need to be large enough to provide results that can be clearly distinguished from variations caused by working in rock, which is an inexact medium.

Not all crushing and grinding circuits are the same and different fragmentation distributions may be required depending on the methods employed. It is important to understand that there are things that can be done in blast design to address such requirements as media rock for grinding, while at the same time designing to decrease energy consumption and increase throughput.

The degree to which blasting conditions the ore for crushing and grinding is not just a product of the powder factor. The manner in which energy distributes throughout the rock mass is also important. The distribution depends on numerous variables related to the rock mass, explosive, and blast design. Important among these are the spatial arrangement of holes and the length of stemming material placed at the top of the explosive column to retain explosion gases in the blasthole, while allowing full breakage to the top surface of the blasted area.

It is well known that damage to the rock mass from blasting (as evidenced by cracks and micro cracks) is greater closer to the blasthole than further away. Therefore, energy distribution inside the blast block becomes important. Energy density and the parameters that affect it, such as charge distribution, distance, explosive properties, timing, and rock properties can be crucial in achieving the best fragmentation and maximizing the number of micro cracks within a fragment. Figure 3 illustrates how stresses attenuate as distance from the blasthole increases for two explosives with different detonation velocities.

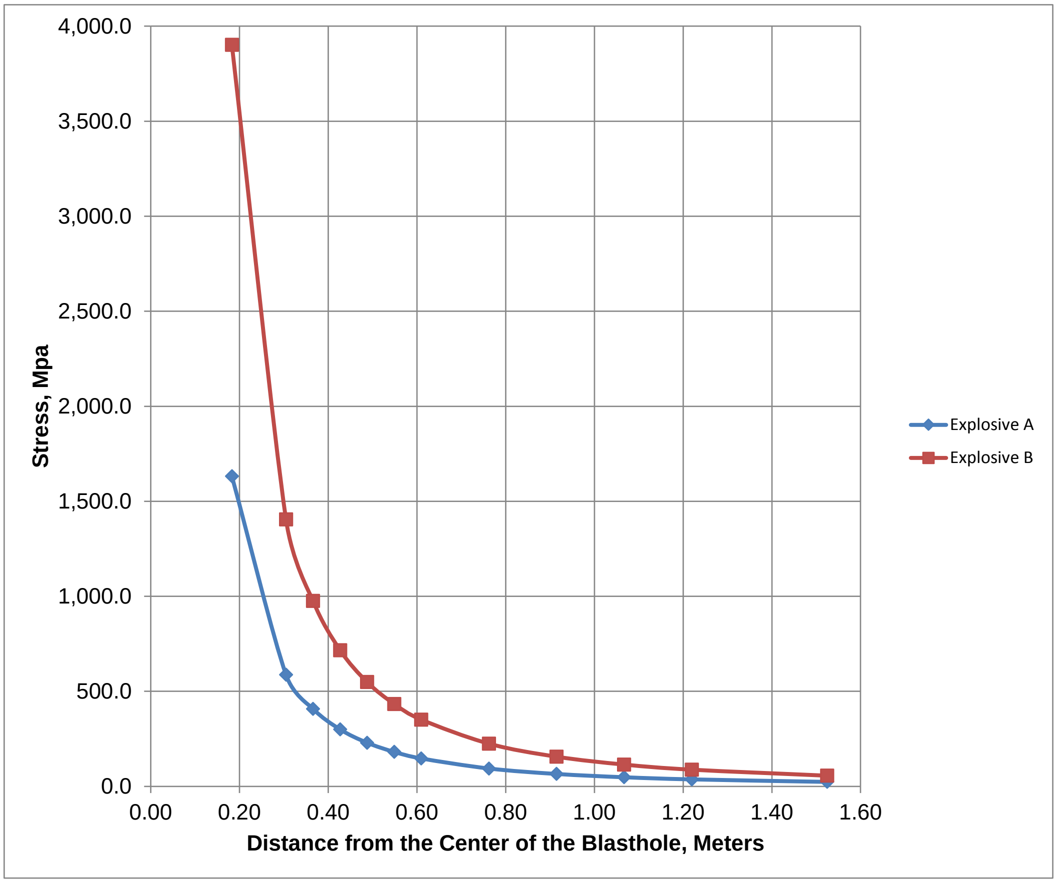

Figure 3 – Effect of distance from a blasthole on stress

Within the broader goal, adjustments to the blast design parameters can provide a way to obtain different fragmentation distributions and degree of fragment softening that best meet the needs of crushing and grinding employed at a particular mining operation. In other words, each operation must be considered on its merits and blast design provides a way to cater for differences.

There are a large variety of possible blast patterns, both square and rectangular. Normally the burden (distance between successive rows of blastholes) is equal to or larger than the spacing between holes in a row. Common among these are the square pattern, staggered square pattern, and the equilateral pattern (which may also be staggered). The distribution of energy throughout the blast differs for each of these patterns.

For example, consider a square pattern and a staggered equilateral pattern having the same area of influence around a blasthole. In this example, the square pattern is 7.6 by 7.6 meters and the staggered equilateral pattern is 7.1 by 8.2 meters. Each has an area of influence of approximately 58 meters. Figures 4 and 5 show the dimensions of the square and staggered patterns respectively.

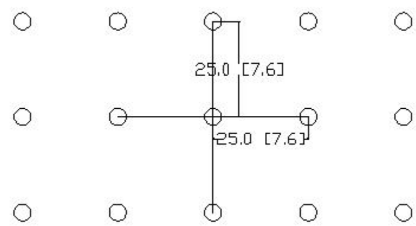

Figure 4 – Arrangement of blastholes for square pattern

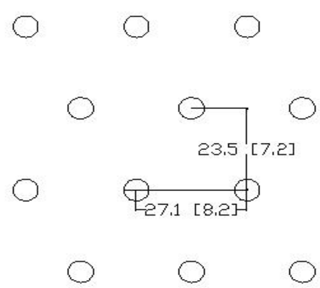

Figure 5 – Arrangement of blastholes for staggered equilateral pattern

The area of influence around a blasthole is the same in both the cases. However, the distance furthest from a blasthole is not the same. Figure 6 shows that the furthest distance from a hole for the square pattern is 5.4 meters. By contrast, Figure 7 demonstrates that if the staggered equilateral pattern is used, the furthest distance from a blasthole is 4.8 meters. The rate of decay of energy density leaving a columnar blasthole varies as the square of the distance from the hole. Comparison of the two examples shows that there is a 21% difference in the energy density at the furthest distance from a blasthole. Therefore, there is likelihood that the lowest energy density for the square pattern will be approximately 21% lower than for the equivalent equilateral pattern. With this in mind, there is reason to believe that fragmentation will be finer for the equilateral pattern and individual fragments may be less resistant to crushing and grinding due to increases in internal micro cracking.

When the square pattern is also staggered, the difference in energy at the furthest point is much less. In this example, the difference would be about 3%. The result with this spatial arrangement may then be similar to that obtained with the equilateral pattern, but perhaps a little coarser or less softened.

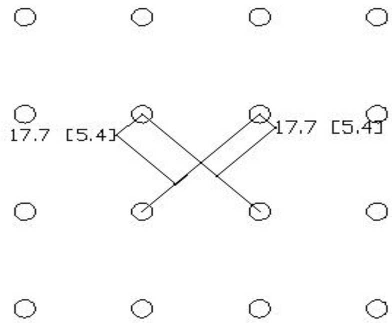

Figure 6 – Furthest distance from a blasthole for a 7.6 x 7.6 meter square pattern

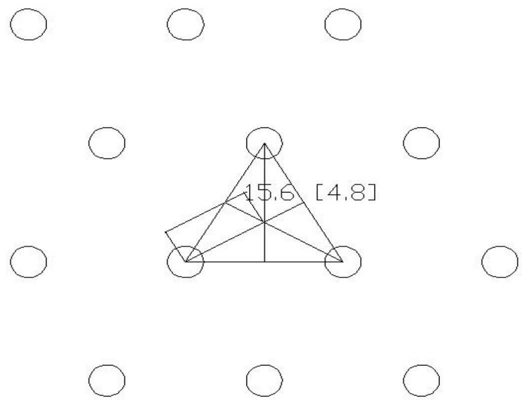

Figure 7 – Furthest distance from a blasthole for a 7.1 x 8.2 meter staggered equilateral pattern

These examples demonstrate that blast designs with varying spatial arrangements of holes can lead to different results, even when the area of influence around a hole remains the same. Therefore, these are important blast design tools that may be employed to generate a fragmentation distribution most suited to the crushing and grinding circuit in use, while seeking to minimize energy consumption and maximize throughput.

Similarly, adjusting the stemming height above the explosive column may assist in achieving a required fragmentation distribution for a given grinding circuit. Stemming is material placed above the explosive column to hold explosion gases in the hole long enough to do work on the surrounding rock and will also help prevent unwanted flyrock.

It is true that most coarser fragment in a muckpile comes from the front and top of the blast. This is largely due to backbreak into the ore behind the blasted block and subgrade damage at the top of the bench from blasting that occurred on the bench above.

Some grinding mills require a sufficient amount of coarser ore in the feed to act as grinding media in order to break up the fragments entering the mill. Others may not require the coarser material, in which case blasting as finely as possible may be the best approach. For those circuits which require a percentage of coarser rock, much of this will come from processing rock at the front and top of the muckpile.

Adjusting the stemming height in the blastholes will also affect the fragmentation at the top of the blast. For a given rock, blasthole diameter, and explosive type, there is a length of stemming that will provide optimum fragmentation. Within limits, if less stemming is employed, the fragmentation will become finer and there will be more displacement from the top of the holes. Conversely, if the length of the stemming column is increased, the top fragmentation will become coarser and displacement will decrease.

Figure 8 demonstrates that fragmentation is not uniform throughout a blast, but that there are zones related to proximity to the blastholes, stemming heights, and backbreak from previous blasting.

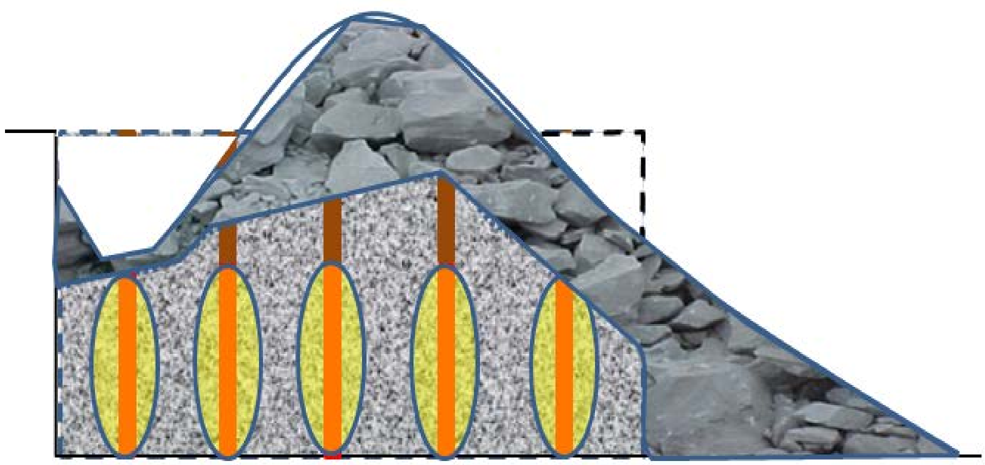

Figure 8 – Representation of fragmentation zones within a blast

This figure demonstrates that within a few radii of the blasthole (inside the yellow ovals) the material is pulverized by very high stresses and is very fine. Beyond the crushing zone is the main body of the fragmented ore. This material will be readily diggable and processed in a well-designed blast. Most of the coarser fragmentation is illustrated to come from the top and front of the blast due to backbreak, subgrade breakage, and the stemming height selected.

It is important to understand that by changing the stemming height, the blasting or fragmentation engineer can to some degree adjust the amount of larger fragments produced. If, for example, there is too little media rock, the stemming height can be increased. Conversely, if there is an excess of coarse ore in the mill feed than required, the stemming height can be decreased to create a finer distribution. It should be noted that design controls related to stemming height will be more effective if backbreak and subgrade breakage are kept to a minimum.

The forgoing discussion of blast design parameters demonstrates that drill to mill blast optimization is not an “either/or” proposition. The drill to mill goals of energy consumption reduction and throughput maximization can be addressed, while also developing the blast designs in a way that recognizes the feed requirements of a specific grinding circuit.

<u>Changes in product formulation</u>

Energy partitioning is a term used to define the relative amounts of shock energy versus gas bubble energy produced in a detonation. Increasing the detonation velocity may improve milling performance. It is postulated that high shock energy enhances the fracture network. Nielsen (1995) found as much as a 65% reduction in grinding energy in diorite samples that were exposed to blasting. The response of the rock also plays a role. Vovk (1980) found a greater area of fragmentation around the borehole for harder formations. Detonation velocity testing can be difficult in production scale trials. Clean data is often only available from the first hole of a blast. Subsequent holes tend to be noisy, possibly due to dead pressing, gas jets, or offsets. The focus must be on effective VOD in the blasthole, not ideal VOD.

Some have suggested the addition of sensitizers in large diameter holes. Sensitizers such as glass micro balloons and phenolic spheres are adiabatically compressed during detonation, which adds intense heat and speeds the reaction. Chemical gassing has become the preferred sensitizer. Capitalizing on a reaction similar to vinegar and baking soda, tiny bubbles are created in the bulk product. This economically attractive sensitizer requires rigid field controls and properly trained operators. Due to the potential for migration and coalescing of chemically produced gas bubbles, micro balloons may be a better choice when a consistent, high quality result is required. Extra sensitivity is necessary in small diameter blasting, but not so in large diameter applications. However, rock shifting during the blast can lead to disrupted powder columns. When shifting is severe, sensitivity may become a limiting factor. A drop in sensitivity may lead to a drop in velocity, which in turn can reduce the fracture network with an end result of the lowering grinding performance.

Blast timing

It would make little sense to raise powder factors without first ensuring that maximum utilization of current blast energy is being exploited. Recent modeling published by Preece (2008) sheds light on optimizing delay times. It appears that insufficient delay times may result in the quenching of developing fracture networks when a subsequent hole fire is too soon. On the other hand, excessive delay time introduces a likelihood of holes becoming offset or entirely cut off due to shifting. Therefore, the window for timing is narrow. Furthermore, conventional pyrotechnic delays are increasingly coming under scrutiny, with questions about their ability to provide desired performance. Electronic delays are considerably more accurate than pyrotechnic units and may well provide better results in a blasting context that requires a high degree of quality control to meet goals.

MICRO CRACKING

The impact of blasting on downstream operations has been discussed extensively over the last 20 years. Literature has suggested that there are two types of benefits: throughput and energy requirements. The latter is of significant interest, given the poor efficiency of grinding. Through small scale testing, Nielsen and Kristiansen (1996) suggested significant changes of the work index when samples had been subjected to blasting energy. These tests showed that fines increased when using explosives with larger diameters holes or explosives with high detonation velocity, while both crushability and grindability were increased with a higher powder factor. Nielsen (1999) attributed these changes to the generation of microcracks in the rock due to stress wave propagation during the blast. Katsabanis et al. (2003) conducted small scale blasts in granodiorite and limestone blocks. The change of the work index, determined using Bond tests, was insignificant. Subsequent tests (Katsabanis et al., 2004) showed a more significant change in the case of limestone. Results were often inconclusive, frequently because of the small change of the work index, but also because industrial samples were variable (Hikita, 2008). Further work, reported by Katsabanis et al. (2008) and Kim (2010), concentrated on granites, obtained from dimensional stone operations. These samples had not suffered any blast induced damage prior to their testing at Queen's University. These researchers conducted small scale blasts, using detonating cord placed in small boreholes in blocks having dimensions of 0.25 m x 0.25 m x 0.25 m. The fragments were then subjected to impact energy and determined the impact breakage parameters. Katsabanis and Kim (2011) expressed the effect of powder factor on the impact fracturing of rock in a convenient relationship between progeny size, impact energy, and powder factor used in obtaining the primary fragmentation.

In order to model grinding mills, it is often convenient to consider the effect of the energy of impact on the fraction of the material that is reduced below 1/10th of the original size. This method has been used extensively by JKMRC (Napier-Munn et al., 1996) and the following equation is used:

$$t_{10} = A(1 - e^{-bE_{CS}})$$

Where
t_{10} *is the fraction of the material less than 1/10th of the original size*
E_{CS} *is the specific impact energy (typically expressed in kWh/t)*
A and b are the breakage constants

The values of constants A and b obtained by Kim (2010) at different powder factors, q, expressed in kg of PETN (a high explosive often used in detonating cord and cast primers) per m^3 of rock and the three different granites used are shown in Table 4.

Table 4 – Breakage parameters for three different granites (Kim, 2010) and various powder factors

	Stanstead				Laurentian				Barre			
q, kg/m^3	0	0.39	0.78	1.17	0	0.39	0.78	1.17	0	0.39	0.78	1.17
A	86.56	70.0	69.6	66.03	100	61.9	57.7	65.8	100	61	57.4	58.8
b	0.50	1.56	2.13	2.45	0.21	0.75	1.07	0.92	0.33	1.02	1.3	1.4
Ab	43	109	148	161	21	46	61	60	30	62	75	82

It is evident that the breakage parameters are affected by the explosives energy consumption (powder factor). Of importance is the product Ab, which is the slope of the $t_{10}(E_{CS})$ relationship at zero input of E_{CS}, and is considered an indicator of grindability. This changes with powder factor. However, at increased powder factors there appears to be less change with powder factor, especially in the case of Laurentian granite.

To examine the effect of the changes in A and b, these parameters were used in a hypothetical circuit, similar to the one used by Michaux and Djordjevic (2005). The operation was simulated using JKSimMet software (version 6.01, 2014). The circuit consisted of a single SAG mill fed with ore having a F80 of 212 mm. The SAG mill had an internal diameter of 12 m, length of 6 m, and grate size of 20 mm. The ball load was set at 12% by volume and the ball top size to 125 mm. The mill discharged at 70% solids to a screen with a 12 mm aperture.

The flowsheet modeled in JKSimMet is shown in Figure 9.

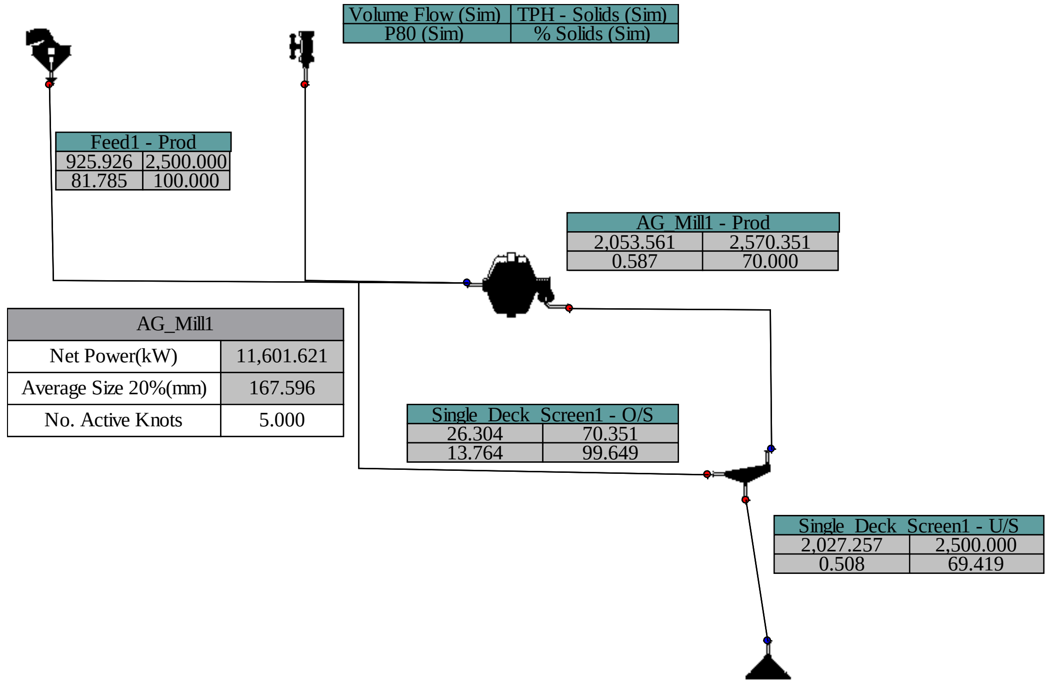

Figure 9 – Simplified flowchart

The simulation was run using the breakage parameters in Table 4, describing the material and was optimized by trial and error, increasing the feed rate to the SAG mill until the circulating load became too large for the mill to process. At this point the net power of the mill was obtained. This is reported in Tables 5 through 7 together with the feed rate, providing energy consumption per ton of material.

Table 5 – Mill productivity vs. powder factor for Stanstead granite

	Stanstead			
q, kg/m^3	0	0.39	0.78	1.17
Net power (kWh)	11578	11644	11665	11668
Feed (tph)	2075	3325	3775	3875
Specific energy, kWh/t	5.58	3.50	3.1	3.01

Table 6 – Mill productivity vs. powder factor for Laurentian granite

	Laurentian			
q, kg/m^3	0	0.39	0.78	1.17
Net power (kWh)	11511	11569	11597	11582
Feed (tph)	1300	2100	2500	2400
Specific energy, kWh/t	8.85	5.51	4.64	4.83

Table 7 – Mill productivity vs. powder factor for Barre granite

	Barre			
q, kg/m^3	0	0.39	0.78	1.17
Net power (kWh)	11538	11597	11602	11619
Feed (tph)	1700	2500	2700	2900
Specific energy, kWh/t	6.79	4.64	4.30	4.01

Clearly, the effect of increased powder factor is to reduce energy requirements at the mill. A significant decrease occurs at the first step, from unblasted material to the powder factor of 0.39 kg/m^3. While there is no unblasted material in a blast, ore far from detonating boreholes, or isolated by discontinuities or due to bad blasting practices may be not be affected by the blast and, thus, it may exhibit larger energy requirements during grinding. On the other hand, it appears that there is a limit to the benefits of blasting in the case of Laurentian granite. Whether this is true, or a result of limited observations, is unknown at this point.

CASE STUDIES

Two long-term, large-scale case histories in iron ore suggest a strong relationship between powder factor and mill performance. Eloranta (1995) compared mill throughput to blasting powder factors in a conventional grinding flowsheet for some 250,000,000 tons of production over a five year period. In the second study (Gertsch, 2005), he looked at a 12 year period involving roughly the same tonnage for a fully autogenous flowsheet.

The annual data are compiled in Figure 10. The two data sets are plotted along with the trend line of laboratory blasting/grinding investigations done by Michaux. He observed milling throughput increases of “360 t/h for every kJ/kg increase in explosives energy over the range (1.5 kJ/kg, 1430 t/h) to (2.7 kJ/kg, 1870 t/h). The implication was that the SAG mill power draw remained at 15.9 MW; hence energy consumption fell from 11 to 8.5 kWh/t, a decrease of 23%” (Michaux, 2005).

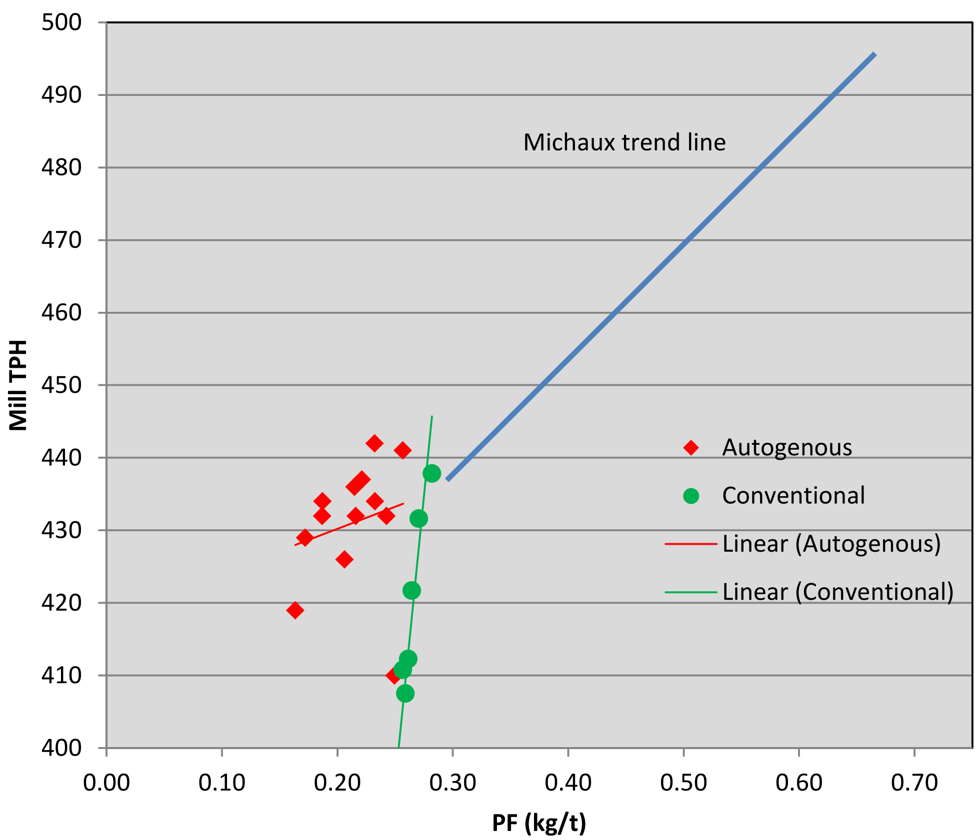

Figure 10 – Mill tons per hour vs. powder factor for conventional and autogenous grinding compared to the trend line from laboratory study by Michaux

Conventional milling shows a steeper slope than the trend line of lab studies. The fully autogenous grinding has a flatter slope, but that may be due to a single outlier. A second hypothesis is that the benefits of increased fines and of material softening may be offset due to the deprivation of media rock. In any case, the upward trend shown by the lab samples could potentially justify a doubling of powder factors.

SUMMARY

The following conclusions are made:

- Drilling and blasting is the first stage of the comminution process. Therefore, it will have an impact on subsequent stages of comminution. The amount of comminution of in-place material taking place in a blast is a significant part of the total comminution required to liberate the valuable mineral for extraction.
- Significant variations exist among authors as to the efficiency of blasting, crushing and grinding. Almost all agree that grinding efficiencies are very small and much less than blasting. Crushing appears to fall in between these two. Blasting is attractive because it can produce more fines more efficiently and it impacts subsequent stages of comminution both in energy savings and productivity.
- For total optimization of comminution energy, a global understanding of the operation's mining and processing facility is required. This is achieved by reviewing all available data and by careful monitoring of results as changes are made.
- Drilling and blasting can be designed to provide improved downstream results. Designs can be varied to provide size distributions specific to the requirements of different types of grinding equipment.
- Blasting optimized for downstream benefit is a more sophisticated process and requires a high degree of quality control to provide consistent results. The increasing availability of technology enables understanding and control of the process.
- The benefit of drill and blast optimization is not just due to achieving an optimum fragmentation curve. It also involves softening of individual fragments by micro cracking. This is especially true for stages downstream of primary crushing. Research involving small scale testing demonstrates that increasing powder factor reduces energy consumption at the mill in two of three granites tested. Because of energy losses in small scale testing, larger scale experiments are needed to further characterize this effect.
- Additional study of the role of micro cracking and maximizing of such fractures is needed with the goal of being able to provide blasting and fragmentation engineers' techniques for optimizing this aspect of blasting results.
- Technical challenges to the successful implementation of a drill to mill optimization program can be resolved by assembling a team of internal and external experts to work together on addressing technical aspects of the implementation and to provide overall coordination of the effort.
- However, the challenges are not only technical. During implementation, significant culture change will be necessary. It is not possible to develop and sustain a holistic drill to mill blast optimization process from departmental silos. General management must be committed and lead others. While departmental goals and budgets are important, what ultimately matters is achieving the best total cost to put the mineral commodity on-board for shipment and to maximize production during times of high commodity demand.

REFERENCES

Baranov E. G. & Tangeav I. A. (1988). *Energy principles for analysis and optimization of mining and ore preparation processes.* doi: 622.271:3:658.5.012.1 (p. 342).

Bond, F. C. (1960). Crushing and grinding calculations. *British Chemical Engineering, 1960,* 378-385 and 543-548.

Brinkman, J.R. (1987). Separating shock waves and gas expansion breakage mechanisms. W.L. Fourney & R.D. Dick (Eds.), *2nd International Symposium on Fragmentation by Blasting (Fragblast 2*), (pp. 6-15). Sydney, Australia: Society for Experimental Mechanics.

Department of Energy (2007). *Mining energy bandwidth study*. U.S. Department of Energy Industrial Technologies Program: BCS Corporation.

Eloranta, J.W. (1997). Efficiency of blasting vs. crushing and grinding. *Proceedings of the 23rd Conference of Explosives and Blasting Technique.* Las Vegas, NV: International Society of Explosives Engineers.

Eloranta, J., Katsabanis, P., & Workman, L. (2015). Considerations in blasting influence on grindability. *Proceedings of the 41st Conference on Explosives and Blasting Technique*. New Orleans, LA.

Evertsson, C. M. (1995). Prediction of size Distributions from Compressing Crusher Machines. *Proceedings of Explo95 Conference*, (pp. 173-180). Brisbane, Qld, Australia.

Gertsch, L., Eloranta, J., & Gertsch, R. (2005, March*). Ore characterization of process control: an update of a Mesabi Range project.* Presented at the Society for Mining, Metallurgy & Exploration Annual Meeting.

Hikita, D.H. (2008). *The influence of blasting on Kemess Hypogene ore milling* (Master's thesis). Department of Mining Engineering, Queen's University, Kingston, ON.

Hukki, R.T. (1975). The principles of comminution: an analytical summary. *Engineering and Mining Journal, 176*, 106-110.

Katsabanis, P.D., Gregersen, S., Kunzel, G., Pollanen, M., Pelley, C., & Kelebek, S. (2003). *Effects of blasting on damage and grindability of impacted rock.* Presented at CIM 105th AGM, Montreal, Quebec.

Katsabanis, P.D., Kelebek, S., Pelley, C., & Pollanen, M. (2004). Blasting effects on the grindability of rocks. *Proceedings of the 30th ISEE Annual Conference on Explosives and Blasting Technique, 1*.

Katsabanis, P.D., Kim, S., Tawadrous, A., & Sigler, J. (2008). Effect of powder factor and timing on the impact breakage of rocks. *Proceedings of the 34th Annual Conference on Explosives and Blasting Technique*, 173-184.

Katsabanis, P.D. & Kim, S. (2011). Effect of blasting on impact breakage of the resulting fragments – results from small scale tests. *Blasting and Fragmentation, 5*(2), 87-108.

Kim, S. (2010). *An experimental investigation on the effect of blasting on the impact breakage or rocks*. (Master's thesis). Department of Mining Engineering, Queen's University, Kingston, ON.

López L., Hamdi E., Sanchidrián J., & du Mouza J. (2002). On explosive useful work and rock mass fragmentation energy. *Proceedings of the 28th Annual Conference on Explosives and Blasting Technique,* 1, 2002G.

Michaux, S. & Djordjevic, N. (2005). Influence of explosive energy on the strength of the rock fragments and SAG mill throughput. *Minerals Engineering, 18,* 39-448.

Morrell S., et al. (1992). The prediction of power draw in comminution machines. *Comminution – Theory and Practice* (pp. 233-247). Littleton, Colorado: International Society of Mining Engineers.

Napier-Munn, T.J., Morell, S., Morrison, R.D., & Kojovic, T. (1996). Mineral comminution circuits. Their operation and optimization. *JKMRC Monograph Series in Mining and Mineral Processing.* University of Queensland, Australia.

National Materials Advisory Board (1981). *Report of committee on comminution and energy consumption.* National Academy of Sciences, Publication NMAB 1981.

Nielsen, K. & Kristiansen J. (1995). Blasting and grinding - an integrated comminution system *Proceedings of Explo95 Conference*, (pp. 113-117), Brisbane, Qld, Australia.

Nielsen, K. & Kristiansen, J. (1996). Blasting-crushing-grinding: Optimisation of an integrated comminution. *Rock Fragmentation by Blasting, FRAGBLAST-5*, (pp. 269-277), Montreal, Quebec.

Nielsen, K. (1999). Mine through mill reconciliation. Can we really make it happen? *Minnesota's First Blasting Conf. – MINNBLAST 99*, (pp. 125-141), Duluth, MN.

Preece D. & Lownds C. (2008). 3D computer simulation of bench blasting with precise delay timing. *Proceedings of the 34th Annual Conference on Explosives and Blasting Technique*, 2, 2008G. New Orleans, LA.

Rowland, C.A. (1998). Using the Bond work index to measure operating comminution efficiency. *Minerals & Metallurgical Processing, 15*(4), 32-36.

Rowland, Jr., C.A. (2008). The Bond standard for comminution efficiency. *SME Annual Meeting.* Salt Lake City, UT: SME.

Rowland, C.A. (1964). Why intermediate autogenous grinding? *Proceedings of the Annual Meeting of the American Institute of Mining, Metallurgical, and Petroleum Engineers Inc.*

Vovk, A.A., Mikhalyuk, A.V., & Belinskii, I.V. (1973). Development of fracture zones in rocks during camouflet blasting. *Soviet Mining Science. V9, N4*, pp. 383-387.

Willis, B.A. (1988), Enhancement of mineral liberation. *XVI International Minerals Processing Conference*, (pp. 293-297). Elsevier, Amsterdam.