How electronics can release the imagination

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Synopsis

It is self-evident that economic pressure demands that today's mines stay ahead and stay competitive. The challenge, however, is to find fresh approaches to the pursuit of efficiency and operational effectiveness. Rather than focusing on individual activities in isolation, a process that can lead to poor investment decisions affecting other critical areas of operation, a key concept is optimization of the whole value-adding process of mining. This concept is often called 'mine to mill'. Whereas it is never easy to establish optimal conditions across a whole mining operation, the quality and consistency of the blasted rock strongly affects all operations. In many instances an inability to control rock breaking has been unchallenged, leading to significant investment in time and money to manage the consequences of poor and/or inconsistent rock breaking. This paper discusses how electronic initiation systems can play a major role in optimizing the whole mining operation. Electronically programmed detonators provide not only the ability to tightly control a key parameter, namely timing, but also the opportunity to extract blast data for a continuous improvement process. The ability to alter predictably, using feedback from the downstream processes, blasting variables such as fragmentation, throw, wall stability, and vibration, is a huge advantage. The current understanding of the effect of timing, accuracy, and scatter on rock fragmentation is reviewed and offers reasons why there is significant progress in controlling blast results. Two case studies are examined, which demonstrate the benefits of the technology on the economics of the operations under review.

Keywords
Blasting, electronic, detonators, mine to mill, blasting timing, continuous improvement, optimization, productivity, electronic initiation systems, mine process optimization.

Introduction

In an increasingly competitive world, mines must continuously find new ways to remain competitive, because decades of doing the same thing, with pure cost-reduction drives and optimizing of secluded processes, produces diminishing returns. A key development has been viewing the activities on a mine as an integrated, interlinked process: phrases such as 'mine to mill' encapsulate this concept. The goal of mine to mill is to identify the contribution of each component in the entire value-adding chain and then to manage these to maintain the most effective, efficient, and profitable balance.

Blasting is usually the single most critical operation affecting the entire mining cycle. However, conventional explosive initiation systems, while having low cost and ease of use, harness pre-digital technology, which severely limits what can be achieved, either in terms of control over blasting effects or capturing critical information. Only coarse adjustments of timing are possible with fixed, low precision pyrotechnic delays. Standardized, workable solutions are the only option with these systems; little is or can be done to meet changing conditions and requirements.

With the advent of electronic initiation systems, it is now possible not only to have far more precise delays and flexibility in their choice, but also to store and process a broad spectrum of critical information. This has revolutionary implications for the whole mining operation.

Figure 1 is a graphic representation of the timing improvement of initiation systems over the last 100 years, the timing scatter contracting from about 10 seconds to about a millisecond.

Technically, control over blast timing increases influence over blasting results such as fragmentation, throw, and impact on the environment, with downstream benefits for overburden removal, ore recovery, and life of resource.

Whereas the principle of adjusting mining activity to try to optimize the overall process has been applied for many years, lack of control over blast results and difficulties in capturing or measuring its impact has limited

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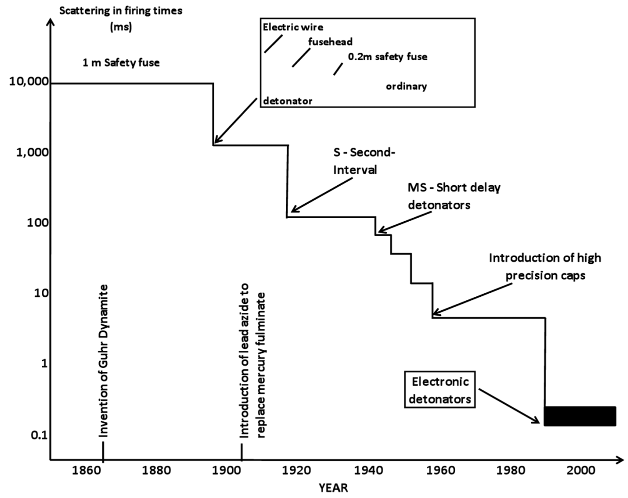

Figure 1—The evolution of explosives initiation system capability's timing accuracy over the last 100 years, Persson *et al.*[1]

the application of these techniques. The mine to mill concept enables blasting parameters to be integrated with operational and mineral processing requirements, benefiting the entire value chain of a mine.

What is possible with electronic initiation of blasts?

Cyclic demand for minerals, and the resulting price fluctuation, constantly changes the priorities in mining. Information and control are key to adapting to the changing needs and lead to improved management processes, better use of current methods, and upgrading of technology. These are necessary for providing fundamental, sustainable, competitive advantage. Electronic blast initiation can contribute both to improving blasting efficiency and adjusting fragmentation, thus improving mineral recovery and profitability.

Optimizing the complete process from rock breaking to the sale of a mineral requires the integration of, and increased information transfer between, individual mining disciplines, from geology to mineral processing. The golden thread that links all these activities is the quality of the rock liberated or left behind by blasting. Unit costs of blasting, versus costs of loading, hauling, crushing, and grinding, with the influence of blasting fragmentation on downstream costs and ultimate mill material feed size, need to be balanced against metallurgical properties in the ore feed and ultimate recovery, life of resource, and handling of waste. The blast should not therefore be viewed as merely fragmenting the solid rock to make it loadable, but as the first step of beneficiation that leads to an optimized mining value chain.

Process optimization

Firstly, optimization must focus on waste removal to expose value-bearing ore. Waste (or low-grade) removal generally involves vast quantities of material and is a leading cost contributor. Blasting influences the economic and environmentally acceptable handling and placing of waste, as well as the long-term integrity of pit walls and the effectiveness of rehabilitation. In a world that is increasingly sceptical about the environmental impact of mining operations, reducing noise and vibration from blasting is a particularly important benefit of using accurate, well-designed initiation systems.

Secondly, the ore itself should be fragmented to achieve the best compromise, among several often conflicting requirements along the journey of successive ore refining activities. An iterative process involves activity outputs being measured, communicated between departments, and evaluated with the aim of total process optimization. The resulting virtuous spiral of expanding knowledge enables a management process to focus on reducing mill feed variability while increasing process predictability. The centre of attention becomes the quality and quantity of saleable product that the operation produces, not the tonnage the mine delivers or the volume the mill treats.

What are the potential benefits of this optimization? Craig Imrie[2] states in a paper on ore flow optimization that leading operators, applying close management of knowledge of rock hardness, blast design, and grinding parameters, obtained a 2% to 5% improvement in recovery rates, improved mill throughput by 5% to 15%, and upped concentrate grade by 2%. In the study these improvements were observed in metal mines around the globe, with more specific details provided from Mount Isa Mines in Australia and Highland Valley Copper Mines in Canada. (See Figure 2.)

In mines where this approach is followed, the more standard functional activity approach is replaced by a more overall model that recognizes the value impact of one activity on another, and adjusts each to achieve the best overall economic result. Figure 2 also illustrates the additional benefit possible from accelerated process understanding brought about when data availability leads to cost breakthroughs in areas that were previously viewed as sufficiently optimized.

To reach and remain at an optimized state, each function needs the ability to recycle data quickly, extracting the required knowledge to make appropriate changes. The operation also needs collective memory to understand the effect of the changes.

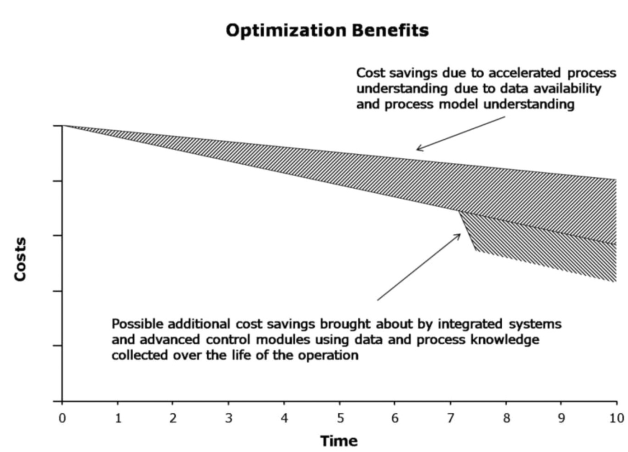

Figure 2—Benefits achieved through continuous learning and holistic knowledge integration, according to Craig Imrie[2]

What changed with electronic initiation?

In a holistic process control model, the fragmentation of the broken rock needs to meet the best compromise across the needs of load and haul, crushing, milling and mineral beneficiation, as well as pit wall quality, rock vibration, and air shock.

The medium in which blasting takes place is highly variable in nature, since rock properties and geological structures can change over very short distances. This means that the ability to adapt blast design to changing conditions offers real benefit. However, control over blasting processes is possible only when blasting input variables are flexible, easily adjustable, and accurate.

To date, the adjustment and fine-tuning of blast parameters has been fairly limited. Some key parameters could (and can) be adjusted only with difficulty. At the mine design stage, the bench heights are set and drilling equipment selected. Subsequently, the only parameters to play with are hole positioning, adjustment of hole diameter within the range of drill bit diameters, the explosive (usually only changed with difficulty), and very limited options for timing the holes.

Explosives properties are not endlessly changeable and are mostly set once the explosive delivery system is selected for an operation. Notwithstanding varying rock properties, the practicalities and regulation of explosive loading normally mean that the same explosive is used for all holes on a blast bench, and for all strata intersected by a single blast hole. Shock tube initiation units also offer standardized timing brackets from which a workable compromise is selected. Shock tube inter-hole delays are factory determined at typically 17 ms, 25 ms, 33 ms, 42 ms and 50 ms (and longer) delays for inter-hole and inter-row timing. When the blasting results do not suit the value chain, the operation is forced to accept the result, with consequent penalties for down line processes. This inability to fine-tune the primary rock-breaking process has been changed with the introduction of high precision, adjustable electronic delay detonators and control equipment. Much better control is possible, providing the enhanced opportunity to optimize all downstream activities.

Benefits of electronic initiation of blasts

Electronic blast initiation provides engineers and supervisors greater levels of control and higher levels of certainty over the outcome of a blast. Electronic initiation systems are completely flexible: any timing range for any blast can be selected. At any time before the blast is initiated, changes can be made to the originally allocated timing. Electronically captured pre-blast information from the system provides the blaster with accurate information on the timing and status of each detonator. If a detonator is not ready, it can be reprogrammed or repaired before the blast is taken.

The precision of electronic detonators is orders of magnitude higher than shock tube detonators, providing certainty of consistent inter-hole time intervals. Each blast log tracks the time of blasting, the detonators used, and the delays. This kind of record is completely beyond what can be done with pyrotechnic initiators, and enables continuous adjustment and fine-tuning of blast designs. It also allows adjustment to cater for changes in the geology, hardness, and rock structure. The records facilitate process improvement by providing accurate blast records for comparison with loading and hauling rates, breaker, and crusher power consumption, secondary-blast lost time, mill feed quality, and savings to mill time and recovery rates.

In order to prevent blast cut-offs from ground movement and flyrock, shock tube systems employ a long period delay down-hole detonator, so that detonators are 'cooking' in the hole ahead of the initiation front on surface. Unfortunately this increases the scatter of firing times for each hole. With electronic detonators, the timing sequence is programmed into the in-hole detonator, eliminating the need for a burning front, since all the detonators are 'cooking' before the first initiates. This is particularly important for the long delays needed for throw blasting, which can result in short burning fronts for shock tube systems. Throw also depends on cooperation between holes in a row, so electronic detonators are able to achieve improved results in terms of movement. Better control over the throw of material reduces pre- and post-blast machinery movement, which shortens the waiting time before re-engagement.

Finally, a real benefit is that safety improves, since information on a possible misfire is available before the blast. The position in a muckpile of a misfire is then known and measures can be taken well in advance before reaching the zone of danger. Fly rock is reduced, since out-of-sequence firing is eliminated, and for the same reason, rockfalls tend also to reduce. Long-term effects such as pit wall stability are benefits that will last the life of the mine, although appreciated only once slope stability is lacking. In the absence of slope stability problems, the positive contribution of better initiation is less apparent, but the moment it does occur the logic of investing preventatively makes sound economic sense.

Why are electronic detonators providing better operational excellence compared to pyrotechnic systems?

Blasting is a complex physical process that starts with the detonating explosive generating a concentrically expanding strain wave in the rock, tracked by crack formation and gaseous rock mass expansion to finally settle as a pile of fragmented rock. The interface between rock and air is called a free face and accommodates the swell of the post-breakage fragmented rock, as defined by Cruise[3]. A V-shaped groove is created in the free face parallel to the blasthole. Figure 3 shows different scenarios and explains them schematically.

When two holes are fired simultaneously, one hole cannot relieve the next by creating an additional free face, and large flaky boulders result, as illustrated in Figure 3(b).

The more faces of freedom into which the blast can expand, the more efficient the blasting tends to be and the better the fragmentation. Initially at least one free face is available, but as the blast progresses into the solid, more free face is opened up by each blast hole. If the holes are separated by the right time delay, breakage mechanisms interact and better fragmentation is generally the result. When Figure 3 is studied, it is clear that the inter-hole and intra-row timing during blasting is critical to create good fragmentation.

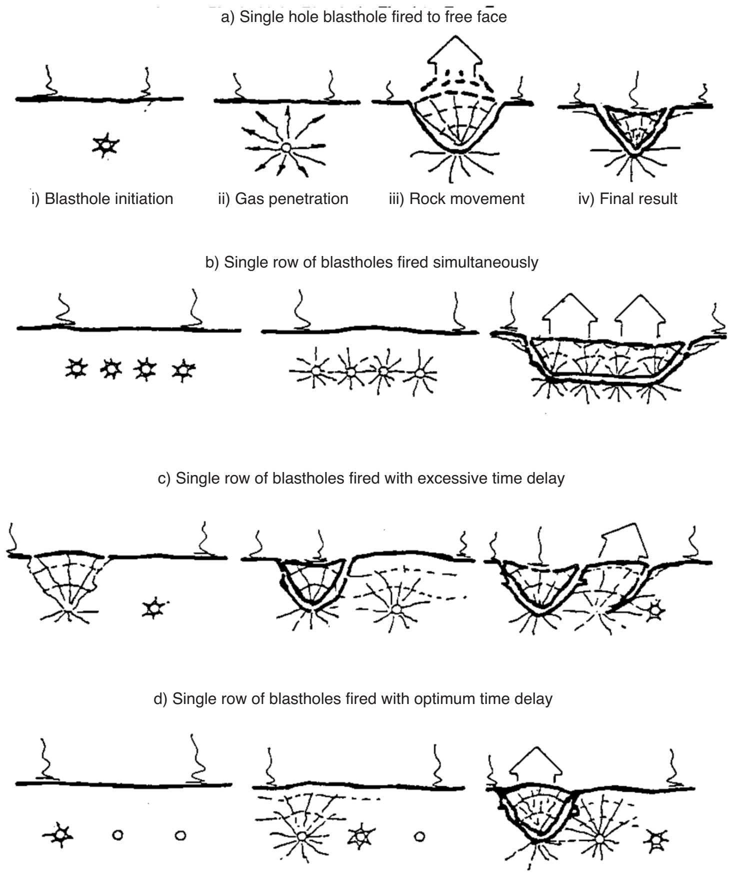

Figure 3—A simple schematic illustration explaining the effect of timing on free face formation and fragmentation, Ireland[4]

Cunningham[5] explains that the different aspects of the blast result are greatly influenced by whether the relevant breakage mechanisms are active when holes in the same row and holes in the rows around it detonate. The time period between shots he defines as 'intervals', as opposed to 'delays', which are the time periods from the beginning of the blasting process. These periods of opportunity to exploit the mechanisms he calls 'windows'. Windows exist for influencing fragmentation, movement, vibration, and splitting.

Inter-hole fragmentation windows typically occur between 0 ms/m and 6 ms/m. Intra-row windows, typically affecting movement, act through various regimes, within 10 ms/m, 100 ms/m or 1 000 ms/m. The blast results obtained can differ widely, depending on the extent of the windows interacting. See Table I.

When inter-hole delays are long, the ground addressed by a preceding hole has moved away and cannot be affected by the active hole. When inter-hole timing is reduced, the windows of activity start to overlap and the breakage mechanisms start to interact. Different blast results for these different timing regimes can thus be expected.

According to Winzer *et al.*[6] short delay-interval initiation systems were introduced into production practice in the USA in 1946. Short delay meant timing intervals measured in milliseconds, whereas long period delays meant intervals above a half-second. Users across the industry noted that they could improve fragmentation and reduce ground vibrations with the new millisecond delay capability.

Bergman *et al.*[7] did work in large homogeneous granite blocks using rectangular blast patterns of not more than two rows of small diameter holes. An optimum delay time of 3.3 ms/m (1 ms/ft) to 6.6 ms/m (2 ms/ft) of burden was established, a standard that laid the foundation for design of delay times in most hard rock types. They noted that the optimum delay interval was achieved when the crack network around the first fired hole was just fully developed before the next hole fired. They also found that fragmentation deteriorated for very short delays, with the worst results obtained for zero delay intervals, as well as for very long delays. These results were more recently confirmed in a study done by Katsabanis *et al.*[8], where the use of very fast firing times for improved fragmentation was questioned.

Table I

Duration of rock-breaking mechanisms which forms windows of activity and are influenced by the interval time selected between blast holes, Cunningham[5]

Mechanism	Inter-hole T_h ms/m window	Intra-row T_r ms/m window	Comment
Splitting	0–1	+30	
Fragmentation	0–6	+10, +100, +1000	Various regimes
Movement	0–10	6–100, +1000	Various regimes
Vibration	0–5	5–20	Continuous effect

The studies that Winzer *et al.*[6] did in limestone blocks with structural discontinuities using very short inter-hole delays, indicated that the shorter delays (450 microseconds) provided better fragmentation results compared to longer delays. These represented a delay ratio of 1.5 ms/m (0.45 ms/ft) of burden and the crack network progressed only halfway between adjacent holes. The results in these two sets of studies contradict each other to some extent, but they confirm that all blasting situations are different and specific timing solutions are required for the delivery of optimum fragmentation. The difficulty of finding the ideal timing sequence for a specific deposit or part of it is thus a learning process, which smart blasters engage in to fine-tune the blast designs. Most importantly, they require timing flexibility offered by electronic delay detonators without the time delay restrictions of present pyrotechnic initiation systems.

Cunningham[5] proceeds to explain that the scatter in down-hole pyrotechnic delays is so great that a measure of control is possible only over the very slowest mechanisms of breakage such as rock movement. This lack of control over the timing regime explains much of the variation experienced in blasting measurements.

To a large extent the blasting science, rules of thumb, and practices that guide blast design are based on experience with pyrotechnic initiation systems. After all, most of the empirical work that underlies blasting knowledge was done using timing systems with unpredictable, highly variable timing intervals, which would have masked key information. The ability to adjust timing, combined with accurate timing and certainty of operation, provides the opportunity for operators to gain knowledge of, and control over, the rock-breaking process. This allows integration of blasting as a controlled activity, leading to a state of total mine process optimization. Flexibility, testability, and timing accuracy of initiation systems, therefore merit close consideration.

Flexibility

Shock tube time delays are achieved by burning delay elements containing various lengths of different pyrotechnic compositions. Burning fronts are achieved by using long, identical delay in-hole detonators, which, before firing, enable the short 'out-of-hole' delays to initiate down-hole detonators in neighbouring holes . The surface delays determine the inter-hole and intra-row delays, and the longer these delays, the less the burning front between detonating holes and units being initiated.

All pyrotechnic delays are limited to the range offered by the supplier. This system is widely used, but the fixed nature of timing options limits the flexibility of what can be achieved with both burning front and timing in blast designs. Flexibility is also limited by the logistics of stocking and controlling different delay units within the constrained storage requirements of explosives magazines. A standard timing regime is thus imposed across all situations, with a limited ability to adapt as geology, rock structure, and operational requirements change.

All of this changes with electronic initiation systems. A typical system contains an application specific integrated circuit (ASIC), which allows the detonator to be given a time of detonation from a zero timeline. Since the timing information is stored inside the detonator before the blast command is activated, the burning front is infinite. In addition, each identical detonator can be given a unique delay. Depending on how the system is set up, time can be changed at will anytime before the blast. The blast design is thus unrestricted, offering full control for optimizing time regimes among decks, holes, and rows. This flexibility is achieved without the need to stock different delay units, and in fact halves the number of detonators stocked, since no out-of-hole units are used.

For normal blast situations where a consistent inter-hole timing pattern is required, the electronic systems provide for automatic delay duplication as the detonators are linked. Additionally, because the detonators can electronically store and process information, linked blast design software can be used to design and archive the blast, or to directly allocate delays.

Testability

Shock tube initiation systems are not testable in any way except by destruction. Misfires are discovered only after the blast, often during loading operations.

All electronic detonators are connected to a control system and continuously online during hook-up. In advanced systems, two-way communication allows the integrity and required set-up of every linked detonator to be verified. Should a problem manifest before blasting, personnel can either repair the problem or, if it is down a stemmed hole, proceed to blast anyhow, advising production personnel of the location of the uninitiated detonator. A post-blast log can be extracted in some electronic initiation systems together with a record of each blast. If the blast parameters are compared with blast output measurements, such as loading rates, hauling costs, or secondary breakage figures, a strong basis is formed for continual improvement of rock breaking.

As noted above, not all manufacturers of electronic initiation systems allow for testability. This is an important aspect to consider when a system is selected. Without this capability, a significant benefit is lost.

Timing accuracy, nominal times, and scatter around the mean

Blasting requires an initiation system to trigger the blasts from a safe distance at a selected time. The simplest systems consist of an in-hole detonator, a trigger mechanism (shot exploder) positioned at a point of safety, and a medium linking the two. The medium transfers the signal to the detonator, causing it to activate.

Electric initiation systems require an electric power source generating a potential difference, causing an electric current in a conductor to ignite a fuse head in the detonator. The fuse head ignites a primary explosives such as lead azide $Pb(N_3)_2$ which in turn ignites a secondary explosive such as pentaerythritol tetranitrate $C_5H_8N_4O_{12}$ (PETN). The exploding PETN ignites the targeted in-hole explosives charge. Pyrotechnic systems exploit trigger mechanisms such as an open flame to start either a deflagrating or detonating chemical reaction held in cords or tubes as a means of conveying the impulse to the detonator.

As outlined above, the outcomes from blasting are usually strongly influenced by the intervals between the blastholes, and changing the delays changes the way that the blast breaks, digs, and affects the environment. Pyrotechnic delays severely limit timing options because of issues with burning front and range availability. However, precision of timing adds a critical additional element to the potential to gain continuous improvement in blasting results through adopting an electronic delay detonator system.

As indicated by Figure 1, all timing devices are subject to scatter, but there is a step-change in precision between those systems depending on the burning rates of pyrotechnic powders, and those using digital technology. The firing times of pyrotechnic delay detonators vary widely around their nominal values, and to some extent vary in mean times, due to unavoidable variations in delay element length, powder composition, and compaction.

Figure 4 shows the normal distributions of two sequential in-hole electronic detonators ignited 17 ms apart versus a normal distribution for two sequential in-hole shock tube detonators, each of 500 ms nominal delay, also ignited 17 ms apart. The electronic detonators have a zero probability of firing out of sequence, whereas the shock tube detonators have not only a high probability of crowding but also a significant probability of firing out of sequence.

The consequence is that with electronic detonators the blast engineer has great certainty that the holes will ignite when intended, but for pyrotechnic systems great uncertainty is introduced. It is certain with pyrotechnics that a number of the holes deeper into the solid will ignite before the relieving holes ignite. This lack of control with pyrotechnic systems leads to inconsistent fragmentation, with a percentage of large boulders usually present.

Physical factors during application of detonators in a blast can also influence pyrotechnic delay accuracy. A stress preconditioning pulse from surrounding holes or different decks in the same hole can radically alter the actual timing of a blasthole being ignited compared to the intended timing. Figure 5 illustrates the effect of an underwater pre-shock by a Pentolite booster on the firing time of a 500 ms shock tube detonator, as described by Mohanty[9]. It is clear that the intended ignition time is influenced by previous blastholes, which diminishes control over the blast design even more. Similar underwater pre-shock tests revealed that the accuracy of an electronic detonator is far less susceptible to timing deviation due to shock preconditioning. For the detonator tested, the first time effect was noticed at a pressure of 309 MPa (44 851 psi), more than four times that of pyrotechnic elements, as reported by van der Walt[10].

The lack of precision of shock tube systems evidenced above, resulting in not only excessive or insufficient intervals between holes, or even out of sequence firing, means that reduced burdened drilling patterns and increased powder factors are necessary to achieve effective blasting results and even then tend to result in excessive overbreak, vibration, and flyrock. Practically this means that as soon as electronic delay detonators are introduced on a bench, even with the same timing pattern retained, burden and spacing can be increased, reducing drilling cost and still resulting in improved fragmentation and control.

In the next section two case studies are discussed to illustrate the dramatic impact that the ability to control timing has on the economic outcome of operations, confirming mine to mill thinking as the key to lifting mining operations to the next level of efficiency and effectiveness.

The positive economic influence of rock fragmentation on downstream activities—two case studies

In the first study, a quarry needed to produce finer fragmentation so as to meet a shift in market demands. Secondly, a gold mine's attempt to improve grade control in order to optimize its metallurgical processes was investigated. Both studies demonstrate massive improvement in results due to control over fragmentation and availability of information.

Balancing market demands by adjusting quarry blast output

In 1993, the building sector in the Western Cape region of South Africa started to experience a shortage of building sand due to the depletion of natural deposits in the region. With the resulting market demand, Peak Quarry of Lafarge (Pty) Ltd. went through a process of adjusting crusher output to generate more fines. The cost of increased comminution proved to be excessive, so alternative methods for producing more fines at an acceptable cost had to be found.

Blasting

The obvious route was to put more focus on blasting methods rather than to pursue expensive alterations to the

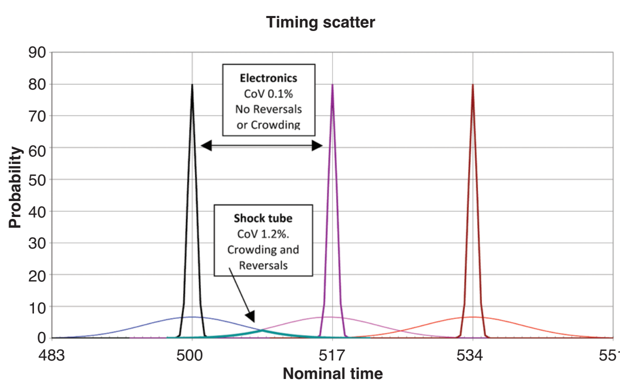

Figure 4—Distribution of actual firing time of pyrotechnic delay detonators, illustrating the risk of overlap compared to electronic delay detonators, which have no risk of timing overlaps

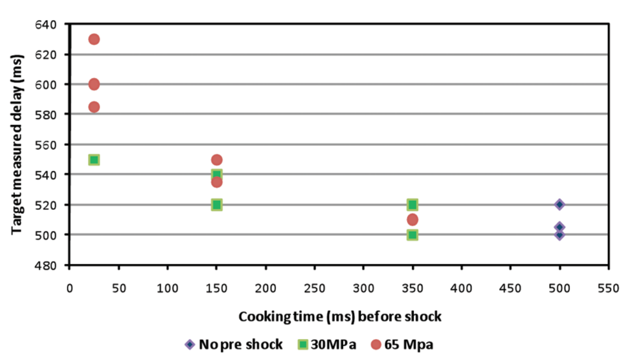

Figure 5—Variation of firing times of a 500 ms pyrotechnic delay shock tube detonator as a function of pre-compression and 'cooking time', reproduced from Mohanty[9]

crushing plant. Bedser[11] observed in his study that fragmentation research had been directed more at crusher efficiencies than blasting practices. Blasting was viewed an extraction process and not as a crushing stage. By viewing the blast output as the first stage of crushing, modelling indicated that a substantially improved production plant return could be achieved if a balanced feed could be achieved by blasting. The savings observed were in reduced crusher power and metal consumption. Although the comminution theory he used was based on index parameters from simple laboratory tests, the modelling pointed to exciting possibilities for future use in other Lafarge operations.

The blast design objective was to provide a high yield of fine material from the blast, and optimize crushing efficiency in terms of energy requirements, sustaining both plant throughput and mining pit parameters such as wall stability and back break.

Peak Quarry is situated in the Cape metropole surrounded by different categories of urban land use. Hornfels rock, part of the Tygerberg formation in the Malmesbury group, dips between 70 and 90 degrees. Residential structures 1 500 m from the quarry introduce some limitation to blast design in that vibration frequencies were restricted to between 13 and 20 Hz, with peak particle velocity limited to 9 mm/s. Noise levels were limited to be below 120 dB for periods not longer than two seconds. Local requirements limited the amount of explosives detonated to 230 kg per delay period and the powder factor to below 0.42 kg/m^3.

Management objectives were (a) to reduce oversize to 1% of blast volume from benches 13 m to 26 m high and 20 m wide; (b) to achieve downstream cost savings exceeding 3% of budget; and (c) not to lose flexibility for changing the future product mix as the market dictated. Table II provides further information.

Initially, the blast was changed from a rectangular to a staggered pattern; the blast direction was modified; and timing with pyrotechnic delays was slowed from 17–25 ms to 35–42 ms. With the introduction of electronic delay detonators, delay times were increased progressively towards the tight end of the blast, as illustrated in Figure 6.

Results

The run of mine fragmentation fed to the in-pit crusher reduced in mean size from 53 mm to 26.5 mm, with the overall product results depicted in Figure 7. Fines, including dust production, increased from 13% to 33%. The primary crusher power setting was reduced by 10%, while the crusher throughput rate was maintained. The frequency and cost of primary crusher liner changes was halved. At the secondary crusher, which treated 35% of run of mine volume, the power setting was reduced by 25% without compromising plant throughput. The face shape improved and less backbreak occurred, while drill string wear reduced by 8% and drill rate increased by 13%.

The environmental impact reduced dramatically, with noise and vibration within the required limits 150 m from the blast. Operational variables improved, with faster load cycles and larger fill factors. This led to the reduction of the haul fleet by one truck.

These results illustrate well how blast results were improved by the flexibility and accuracy of electronic delay detonators, and how positively the total mine to mill economics benefited.

Optimizing a gold ore roaster and autoclave with smart blasting techniques

Barrick Goldstrike Mines in Nevada USA conducted a detailed

Table II

Peak Quarry blast parameters, Western Cape, South Africa, Bedser[11]

Blast description	
Hole diameter	110 mm
Hole angle	80°
Burden and spacing	3.5 m x 4.0 m
Average hole depth	26 m
Pattern	Staggered and 2 free faces
Number of holes	20 holes per row, 3 rows

(12)

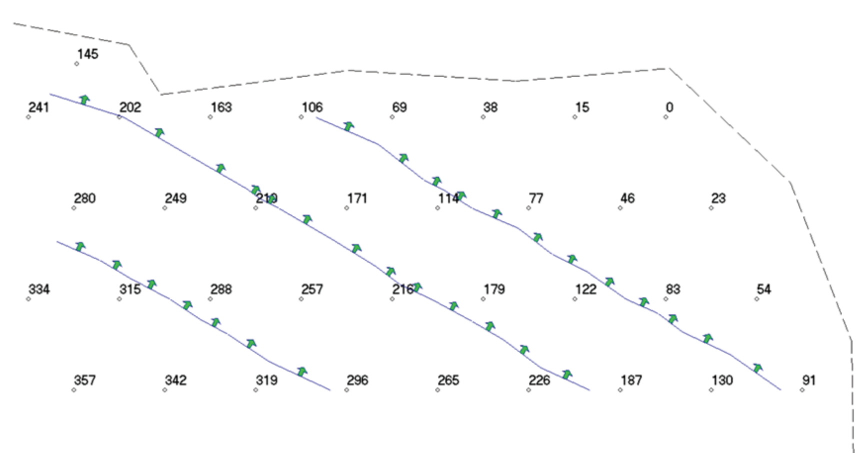

Figure 6—A typical electronic blast design at Peak Quarry, as reported by Bedser[11]

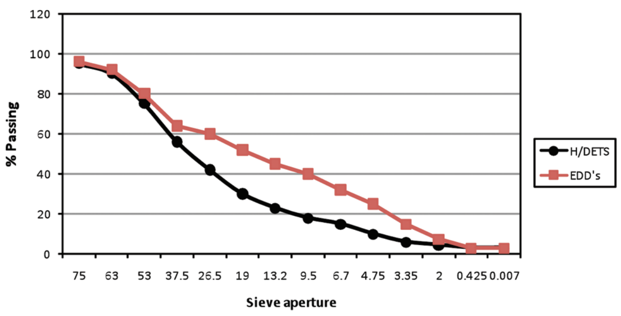

Figure 7—Run of mine product size reduction after introduction of electronic delay detonators at Peak Quarry, Western Cape, South Africa, according to Bedser[11]

study in 2001 to quantify the benefits of the use of electronic detonators on excavation, crushing and ore processing operations. Blast evaluations were conducted to determine the effect of electronic delay detonator use on fragmentation, excavator productivity, vibration control, and mill throughput. Of particular interest in this work reported by McKinstry *et al.*[12], is an investigation into the potential to improve ore grading on the bench with the help of good timing.

Blasting

Geology played a dominant role in blast design and dictated the timing sequence aimed at optimizing both ore dilution and fragmentation. Detonators were not located inside blastholes due to the frequently hot conditions caused by sulphide ore. Prior to loading, hole temperatures were taken and polyethylene liners were placed in any hot holes to insulate the explosives from the blasthole walls. Detonating cord was used with in-hole boosters and an inhibited emulsion blend explosive. The latter inhibits exothermic reaction between sulphide ores and the ammonium nitrate content of the explosives. The electronic detonators were finally connected to each detonating cord down line, programmed, and the blast taken. The blast crews found the transition from pyrotechnic to electronic detonation relatively easy.

For normal production blasts, the established pyrotechnic delay sequence of 17 ms inter-hole and 25 ms intra-row timing was not changed or experimented with. A chevron configuration was used to concentrate the ore in the centre of the blast. Electronic delay detonators increased total blast cost by 6.5% over that of pyrotechnic blasts.

Results

For pyrotechnic blasting, ninety per cent of the particle size was less than 177 mm (7.07 inches), but for electronic ignition it reduced to 100 mm (4 inches). See Table III.

The muckpile was easier to dig and a consequent improvement in excavation productivity was observed. The interval time from the first loader bucket being dumped into a truck until truck release was measured as a productivity rate of tons per hour. This improved by approximately 11% after electronic detonators were introduced. The average loader dig cycle improved by 4%, leading to the conclusion that the bucket fill factor had improved. The dig cycle was also more consistent over time compared to what was experienced with pyrotechnic initiation systems.

The efficiency of the gold recovery process at Goldstrike is highly sensitive to blast-induced dilution. The geology of the ore also differs and there are 14 routing schemes for ore and 4 for waste. Ore boundaries are staked clearly, but with conventional blast timing different material types often moved unpredictably, leading to inaccurate placement of ore boundary stakes. With electronic blasting much greater accuracy for muckpile movement became possible.

The flexibility of electronic delays allowed blast designs that limited dilution and piled, in distinct grade heaps, different grade zones within a single blast. This dramatically reduced dilution. An advanced application of the technique, where four distinct material types were separated in four piles on the same blast, is shown in Figure 8.

As a result of the flexibility provided by electronic initiation, blasting has changed from an inflexible activity, to which the rest of the mine must inevitably adjust, to an integrated operation that can be modified to suit the total mine to mill value chain.

Apart from the in-pit operational benefits for loading and hauling, the productivity of the milling and roasting operations, as well as the effectiveness of the autoclave operation, were to be balanced with grade and feed quality. Unfortunately the full economic effects were not quantified in this study, but it is evident that the scale of benefit handsomely outweighed the cost of creating it. It was determined that a recovery increase of just seven-hundredths of a per cent was needed to offset the additional cost incurred.

Conclusion

As mining operations increase in competitiveness, optimizing individual processes in isolation leads to short-sighted fixes that may not allow the best business solution. The mine to mill concept leads to total process optimization, since activities are not optimized in isolation but integrated to deliver an optimal process, even if the result is that individual activities become more costly.

The particle size distribution and muckpile shape and displacement delivered by blasting affect productivity and recovery. Productivity improves through increases in loading rates, fill factors, crusher and grinding plant throughputs, and costs. Recovery improvements arise from better grade control and a reduction in dilution during blasting. Heugh[13] summarized it well that, ‘the goal is to achieve fragmentation by design, consistently and repetitively’.

Table III

Cumulative fragmentation data at Goldstrike, Mckinsty *et al.*[12]

Per cent passing	Pyrotechnic blast	Electronic blast	Difference
10	25 mm (0.99’)	36 mm (1.44’)	45%
25	45 mm (1.78’)	54 mm (2.15’)	21%
50	73 mm (2.92’)	72 mm (2.87’)	-2%
75	112 mm (4.46’)	89 mm (3.55’)	-20%
80 (interpreted)	128 mm (5.10’)	93 mm (3.70’)	-27%
90	177 mm (7.07’)	99 mm (3.98’)	-44%

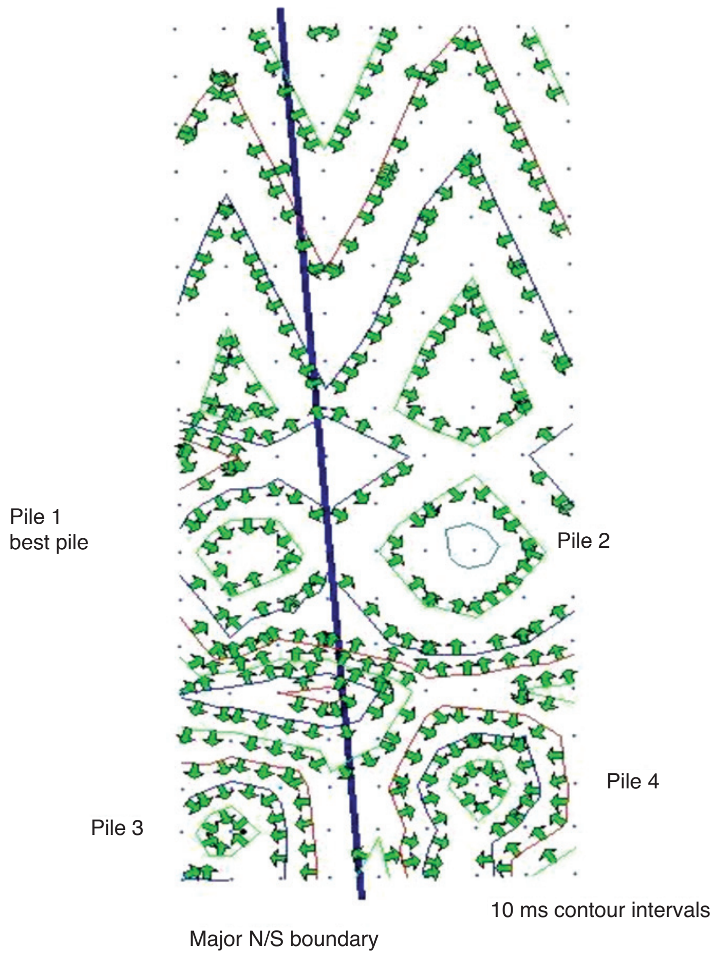

Figure 8—Ore grade control with electronic blasting at the Barrick Goldstrike mine in Nevada, with four distinct piles created on the same bench, each with different grade characteristics. The image is a DetNet ViewShot™ interpretation of the original, as reported by McKinstry *et al*.[12]

The ability to tailor blasting results for downstream operations, such as loading and hauling, crushing, grinding, milling, and recovery, has been hugely expanded by the introduction of electronic initiation systems, with their flexibility, testability, accuracy, safety, and information feedback capabilities. They have completed a feedback loop that allows continuous improvement and fine-tuning of the entire value chain and business process.

Electronic initiation of blasts represents a new enabling technology that not only increases the overall balance and integrated effectiveness of mineral liberation, but is a key to stimulate the imagination and ingenuity of all those who manage and operate mines.

References

1. Persson, J., Holmerg, P., and Lee, R. *Rock Blasting and Explosives Engineering*. s.l. CRC Press, 1993.
2. Craig Imrie, J.O. *Ore Flow Optimization—Mine to Mill*. s.l. Hatch, 2001.
3. Cruise, J.A. Rock breaking—a science, not an art. *Drilling and Blasting School*. Johannesburg, The Southern African Institute of Mining and Metallurgy, 2010.
4. Ireland, K. Initiation and timing of blasts, Chapter 4. Surface Mining Explosives Engineering Training Course. Modderfontein, Johannesburg , AEL Pty Ltd, 2000.
5. Cunningham, C.V.B. The effect of timing precision on control of blasting effects. *Explosive and Blasting Technique*, R. Holmberg (ed.). Rotterdam, Balkema, 2000.
6. Winzer, A.P. and Ritter, S.R. Effect of delays on fragmentation in large limestone blocks. Martin-Marietta Laboratories. s.l. National Science Foundation, 1980.
7. Bergman, O.R., Wu, F.C., and Edl, J.W. Model rock blasting measures effect of delays and hole patterns on rock fragmentation. *Engineering Mining Journal*. Washington, s.n., 1974.
8. Katsabanis, P.D., Tawadrous, A., Braun, C., and Kenedy, C. Timing effects on fragmentation. *Society of Explosives Engineers*, vol. 2. 2006.
9. Mohanty, B. Intra-hole and inter-hole effects in typical blast designs and their implications on explosives energy release and detonator delay time—a critical review. *Rock Fragmentation by Blasting*, J. A. Sanchidrián (ed.). s.l.: Taylor & Francis Group, London, 2010.
10. Van der Walt, H. Electronic detonator timing accuracy. Internal report, DetNet (Pty) Ltd. South Africa, s.n., 2010.
11. Bedser, G. In Search of Fines. Internal Lafarge Study Document. Cape Town, Lafarge (Pty) Ltd., 1993.
12. McKinstry, R., Floyd, J., and Bartley, D. Electronic detonator performance evaluation. The Journal of Explosives Engineering. s.l.: *International Society of Explosives Engineers*, 2002. vol. May/June 2002.
13. Heugh, D. Development of explosives, explosive products and blasting scince during the last decade. *Eigth International Symposia on Rock Fragmention by Blasting*—Fragblast 8. Santiago: s.n., 2006. ◆