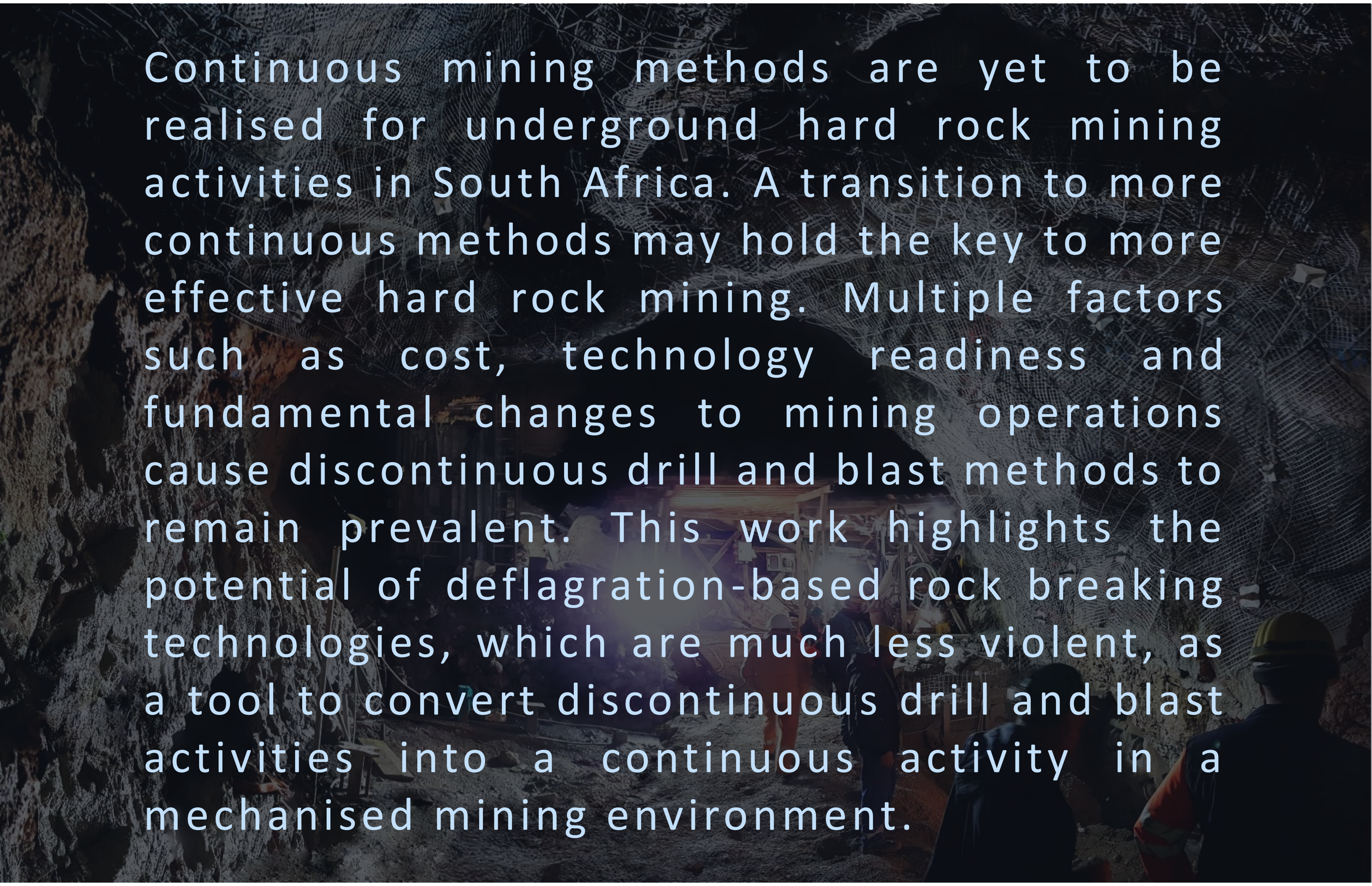
TOWARDS CONTINUOUS UNDERGROUND BLASTING IN MECHANISED MINING (DRAFT)

PROGRAMME	MECHANISED MINING SYSTEMS
PROGRAMME MANAGER	M PRETORIUS
RESEARCH AGENCY	UNIVERSITY OF PRETORIA
RESEARCH CENTRE	RESEARCH ACTIVITY IN MECHANISED MINING SYSTEMS (RAMMS)
DATE	07-02-2024
REVISION	1.0
AUTHOR(S)	LD VAN EYK, DF MALAN, PS HEYNS
PROJECT TEAM	LD VAN EYK, J WANNENBURG, DF MALAN, PS HEYNS

MANDELA MINING PRECINCT
MINDS FOR MINES

AD DESTINATUM PERSEQUOR



Continuous mining methods are yet to be realised for underground hard rock mining activities in South Africa. A transition to more continuous methods may hold the key to more effective hard rock mining. Multiple factors such as cost, technology readiness and fundamental changes to mining operations cause discontinuous drill and blast methods to remain prevalent. This work highlights the potential of deflagration-based rock breaking technologies, which are much less violent, as a tool to convert discontinuous drill and blast activities into a continuous activity in a mechanised mining environment.

1 INTRODUCTION

The underground hard rock mining landscape in South Africa is predominantly shaped by the drill and blast method, currently the most economically feasible option (Rostami, 2023). Despite its prevalence, many mines are nearing the end of their economic viability, necessitating innovation to extend their lifespans. Mechanisation of the existing drilling and blasting processes may show the necessary improvements, but these efforts are fundamentally limited by the batch mode that blasting with high explosives induce. This batch mode comprises drilling, blasting, cleaning and support operations.

These operations create inefficiencies that are fundamentally linked to the rigid timing windows associated with batch processes. Completion of drilling, cleaning, or support operations before the batch ends results in wasted time, while delays in these processes lead to missed blast windows. Vogt (2016) identifies a transition to continuous processes as the key to improving productivity in underground hard rock mining.

The pursuit of a continuous underground mining process has centred on mechanization, particularly in rock cutting. Although successful in softer rock coal mining, widespread adoption in hard rock applications remains a challenge, requiring further development and a departure from the drill and blast norm (Vogt, 2016).

While research into continuous methods such as hard rock cutting is vital, this work proposes an existing technology to bridge the gap between batch and continuous processes. This work explores non-detonating rock breaking methods for ore extraction. These methods operate in a similar manner as conventional drill and blast but have potential to facilitate more continuous processing. This technology is therefore positioned as a method of transitioning existing underground hard rock mines from batch to continuous processing with minimal changes to existing mining operations required.

The subsequent chapter examines the challenges faced by current drill and blast methods, highlighting factors related to safety and overall production cost. The following section summarises the proposed deflagration technologies, namely pyrotechnic and carbon dioxide (CO_2) blasting. Subsequent chapters explore how deflagration-based methods address the challenges of the current drill and blast method, whilst simultaneously indicating shortcomings of this technology, which lead to conclusions and research recommendations.

We would like to acknowledge Andre van Dyk (https://www.linkedin.com/in/andre-van-dyk-8a40a824/) of AVD Consulting for sharing his ideas around non-detonating rock breaking methods – specifically pyrotechnic rock breaking. Many of his ideas were used as a basis for the arguments formulated throughout this report.

2 THE STATUS QUO: DRILLING AND BLASTING

Rock breaking underground primarily occurs through two methods: drilling and blasting and rock cutting (Tuck & Loomis, 2023). While rock cutting is favored for its ability to enable continuous mining and improve process efficiency (Vogt, 2016), it remains challenging in hard rock environments. As a result, drilling and blasting, known for high productivity (Wei et al., 2023) and relative cost-effectiveness (Al-Bakri & Hefni, 2021), remains the method of choice.

In the current South African mining landscape, achieving more efficient mining processes is crucial for extending the life of existing mines. This section sheds light on the significant challenges associated with drill and blast techniques, with a focus on proposing potential solutions in susequent sections. The identified challenges fall into four main categories:

- Rock fragmentation, fines generation and dilution of ore
- Dust, fumes and ventilation implications
- Structural impacts
- Batch processing

These challenges are explored in terms of their impact on operational cost and efficiency, as well as safety of mining personnel and equipment. A key aspect, related to deep seismically active mines, is that the blast triggers most of the seismic activity and a much lower backgound level of seismicity is typically experienced duing the shift when the workers are in the mine (Malan & Napier, 2018). For a continuous mining operation, this benefit of a "blast window" with higher levels of seismicity will disappear and this may expose the workers to a higher seismic risk. This work is, however, beyond the scope of this initial report. It is also not a problem in the shallow and intermediate depth platinum and chrome mines.

2.1 ROCK FRAGMENTATION, FINES GENERATION AND DILUTION OF ORE

Xingwana (2016) underscores the critical impact of fragmentation on mining efficiency in gold mines. Poorly optimized fragmentation can result in the production of excessive fines, leading to gold loss for several reasons (Vogt, 2016). Gold particles, often as small as 0,001 mm, may be present in these fines, which become airborne and are lost through ventilation. Additionally, fines can be washed into cracks, forming what is known as free gold, a persistent issue in underground mining (Xingwana, 2016). As ore progresses along the processing pipeline, fines are generated as coarse particles are crushed, dispersing potential gold-rich dust throughout the pipeline. Overcharging is identified as a contributor to increased fragmentation, leading to the production of excess fines.

These fines pose hazards to underground workers, causing health issues such as silicosis and tuberculosis (Xingwana, 2016). To mitigate these risks, fines must be ventilated out of the working area, consequently increasing the ventilation load and operational costs.

Lusk et al. (2023) offer remedial advice for reducing fines generated by blasting, suggesting measures like increasing burden and spacing between charges. However, this approach comes with a trade-off – while it decreases fines, it simultaneously increases the vibration of the explosion, potentially causing more damage to the surrounding rock, necessitating a balance between safety and fragmentation size.

Another challenge in rock fragmentation is the generation of waste rock along with the ore. Ore dilution occurs when low-grade or waste material mixes with the ore. Despite careful mining practices to extract only the reef, there is inevitably waste rock that dilutes the ore sent to the processing mill, diminishing mining efficiency and increasing processing costs (Xingwana, 2016).

2.2 DUST, FUMES AND VENTILATION IMPACTS

The blasting process generate fumes, such as nitrogen monoxide (NO), nitrogen dioxide (NO_2) and carbon monoxide (CO), all of which are toxic at low parts per million (Lusk et al., 2023). A review from Al-Bakri and Hefni (2021) highlights that blasting emissions contribute significantly to NO_x emissions in mining, second only to haul trucks, with blasting emissions being half that of haul trucks. These toxic gases, therefore, substantially increase the ventilation load in the mine. Ventilation costs form a considerable part of a mine's overall operating expenses (Tuck & Loomis, 2023). Consequently, blasting emissions alone have a significant impact on a mine's operating costs.

Beyond the financial aspect, the ventilation process itself introduces further challenges. After blasting, toxic fumes must be ventilated before work can resume, perpetuating the batch nature of drill and blast mining and exacerbating operational costs. Minimizing or nullifying fumes could therefore lead to more cost-effective mining practices. Tuck and Loomis (2023) suggest that non-explosive alternatives could reduce dust and fumes.

2.3 STRUCTURAL IMPACTS

During blasting, violent and rapid chemical reactions occur, unleashing high-energy, high-speed detonation waves in the surrounding rock. In open-pit blasting, up to 85% of the energy is wasted, with only 15% effectively breaking rock. It is likely that similar energy waste occurs in underground scenarios, impacting the stability and safety of the surrounding rock mass (Al-Bakri & Hefni, 2021).

Ground vibrations (Lusk et al., 2023) and flyrock (Al-Bakri & Hefni, 2021) are the biggest concerns to structural damage underground. The MHSC (2023) reports that blast-on support units, such as mine poles, hydraulic props and other pre-stressed elongates are affected by blasting. They indicate that the blast-out rate for these support units is very high, especially for mine poles. The MHSC mentions that techniques which minimise the blast-out rate of these support accessories, without compromising blast efficiency, is worth investigating.

If high vibrations are present during blasting, minimizing them may come at the cost of finer fragmentation (Lusk et al., 2023), thereby impacting productivity and potentially leading to greater losses. This underscores the need for a balanced approach to ensure both safety and operational efficiency.

2.4 BATCH PROCESSING

The process of blasting introduces a cyclical nature into mining operations, requiring the evacuation of personnel and equipment (Al-Bakri & Hefni, 2021). In larger mines where blasting is synchronized, inefficiencies become inevitable. If drilling, cleaning, and supporting operations finish ahead of schedule, time is lost waiting for the blasting window. Conversely, if these tasks exceed the allotted time, an entire shift is wasted, needing completion after the blasting window. Unless these operations are synchronized, time is wasted (Vogt, 2016). The ventilation of dust and toxic fumes post-blast also consumes time that could otherwise be utilized for mining. Owing to these factors, Vogt (2016) argues that continuous processes are the key to improved productivity in underground mines.

Beyond operational inefficiencies, batch processes raise safety concerns. Evacuations related to blasting introduce more relative movement between people and machines compared to continuous mining efforts. Increased relative movement heightens the risk of machine-related injuries (Rostami, 2023). Therefore, minimizing batch processes aligns with both efficiency and safety objectives in underground mining.

3 NON-DETONATING TECHNOLOGIES

The preceding chapter outlined the limitations associated with traditional drill and blast rock-breaking methods. While technological advancements may address many of these issues, the inherent challenge of the batch process remains due to the explosive and violent nature of blasts, necessitating personnel and equipment evacuation before each blast. The act of blasting is violent because the chemicals used in the process, detonate after being ignited. Detonation refers to a reaction within an explosive which propagates faster than the sonic velocity of the material within the explosive (Lusk et al., 2023).

This section explores non-detonating alternatives, which may overcome many of the shortcomings of detonation-based blasting. Among various alternatives, two methods stand out:

- Pyrotechnic methods
- CO_2 methods

Both of these technologies operate on the principle of deflagration, where the propagation velocity in the explosive material is sub-sonic (Lusk et al., 2023). This has the implication that explosions[1] are much less violent, potentially eliminating the need for large scale mine evacuation, minimising or completely removing the need for a batch process.

Deflagration-based techniques present a possible intermediary technology that maintains the core operations of underground hard rock mining (drill, charge, blast) while facilitating a transition towards more continuous processes. This technology holds the promise of guiding existing mines toward continuous operations, laying the groundwork for fully continuous mechanical methods in the future.

Notably, certain alternative rock-breaking methods such as hydraulic (Wei et al., 2023), plasma (Zhou et al., 2018) and expansive cements (De Silva et al., 2016) were not explored due to perceived integration complexities into existing mines. Mechanical methods were also excluded, as Vogt (2016) has previously conducted a comprehensive study and determined that although these methods allow for continuous mining, they are not yet mature enough for the current mining landscape.

Subsequent sub-sections will provide detailed descriptions of the two deflagration technologies, emphasizing their potential in enhancing underground hard-rock mining operations.

3.1 PYROTECHNIC ROCK BREAKING

According to the United Nations (UN) (ILO, 2023), a pyrotechnic substance is a substance which is designed to produce an effect by heat, light, sound, gas, smoke or a combination of these, as a result of non-detonative, self-sustaining exothermic reactions. In rock breaking applications, pyrotechnic technologies can be used in a similar fashion to detonation-based explosives (also referred to as “high explosives”). A plastic cartridge is filled with pyrotechnic substances (see Figure 1) mainly containing a mixture of Ammonium Nitrate, Nitro Cellulose as a propellant and Dibuthylphthalate (Gupta, 2016).

Cartridges, equipped with igniters, are placed in drilled holes, and stemmed. Upon ignition, the substances undergo sub-sonic chemical reactions (deflagration), generating high-energy gas, mainly nitrogen, CO_2, and steam. The borehole

[1] It is important to take note of terminology. The word “explosion” is used quite loosely in literature and can therefore be confusing. The United Nations (UN) broadly defines an explosive substance as a solid or liquid substance which may through chemical reaction, produce gas at a temperature and pressure such as to cause damage to the surroundings (http://tinyurl.com/MMS-UN-DEF). This definition is adopted throughout this report. This definition of “explosive” includes two sub-categories, namely detonations and deflagrations. Therefore, these deflagration-based technologies are most accurately described as non-detonating.

pressure, considerably lower at 300 MPa compared to conventional explosives (1500 to 15000 MPa), opens pre-existing cracks and fractures in the rock, causing the rock mass to heave rather than violently eject (Gupta, 2016).

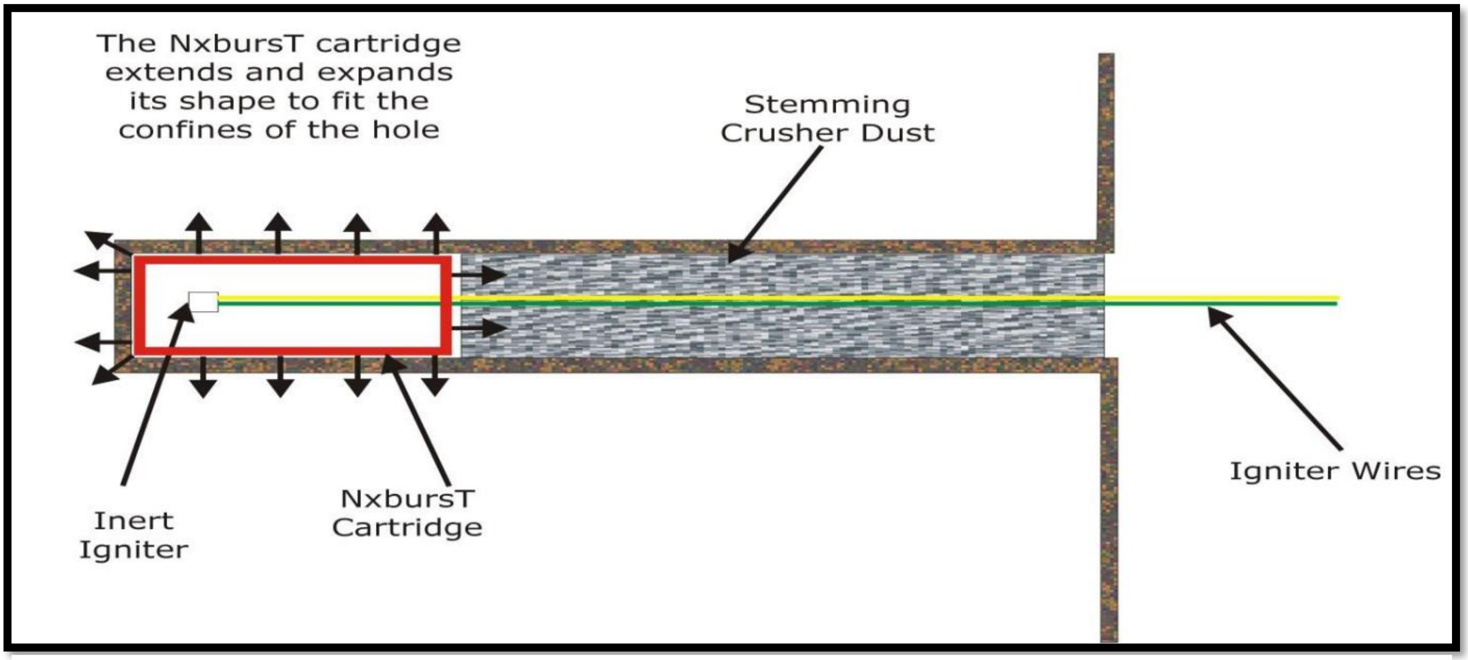


Figure 1 Illustration of a pyrotechnic cartridge and its placement with stemming in a borehole. Image courtesy of https://www.nxburst.co.nz/wp-content/uploads/2020/05/nz_NxbursT_manual_full.pdf

Due to their non-violent nature, pyrotechnic charges find applications where safety, low ground vibrations, and minimal noise are essential (Rhino Rock Breakers, 2024). They have also seen use in underground mining, predominantly in applications where rock breaking is necessary near critical infrastructure, and flyrock needs to be avoided. Gupta (2016) identifies companies manufacturing these charges, including NoneX, Royex, Pyroblast and Autostem.

The UN classifies these types of pyrotechnic charges under Division 1.4 Compatibility Group S Chemicals, indicating that they present no significant hazard and only pose a small hazard in the event of ignition during transport. This classification allows for the transportation of pyrotechnic cartridges by commercial aircraft and, in quantities less than 250 kg, by vehicles not registered as explosive vehicles (NXCO, 2023a).

3.2 CARBON DIOXIDE ROCK BREAKING

Carbon dioxide (CO2) rock breaking technology relies on the rapid phase change of CO_2 from liquid to gas (Zhou et al., 2018). This method of blasting does not undergo any chemical reaction and is therefore classified not only as non-detonating, but also as a non-explosive. CO_2 cartridges are employed similarly to high explosives or pyrotechnic technologies. In this method, holes are drilled, cartridges with ignition wires are placed and stemmed into the hole, and an ignitor initiates the blasting process. There are two types of CO_2 cartridges: reusable and disposable. The construction varies slightly depending on the chosen cartridge type, as depicted in Figure 2.

Reusable cartridges feature thicker cylindrical walls (10 mm or more) and include a filling head for CO_2, a shear rupture disc to control desired pressure, and a releasing head for gas to escape after rupturing. Importantly, the venting holes on the pressure release heads can be customized for the task at hand, allowing for optimization of rock fragmentation (Chen et al., 2022).

Disposable cartridges have thin walls (1,5 mm) and come pre-packaged with the CO_2 liquid and heating element. Thus, when the element is heated, pressure builds within the tube until it ruptures, releasing the high-pressure gas into the borehole.

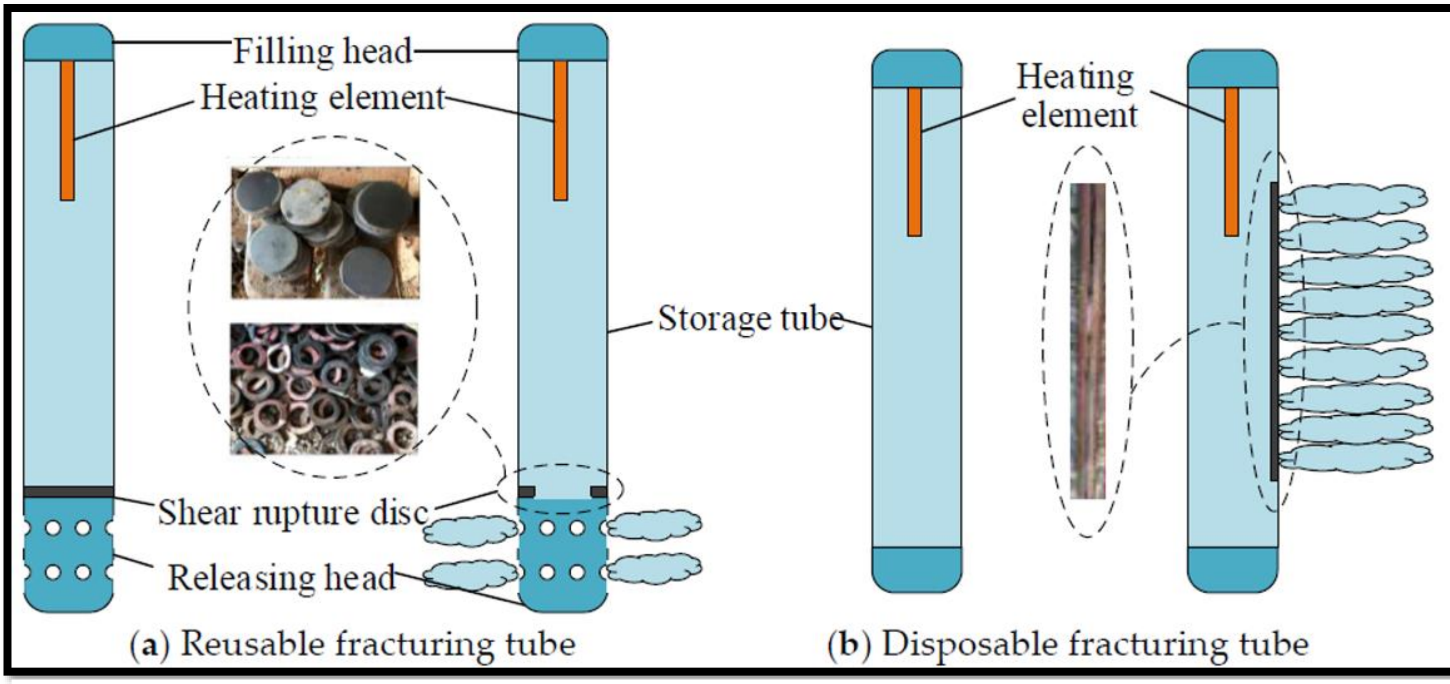


Figure 2 Illustration of the two types of CO2 blasting cannisters. On the left a reusable variant is shown and, on the right, a disposable variant is shown. Image courtesy of Chen et al. (2022).

In both cartridge types, when an electric current is passed through the heating element, the CO_2 liquid within the storage chamber is heated. As the temperature increases, CO_2 vaporizes rapidly, expanding its volume by 660 times. At this point, the vessel or rupture disc ruptures, releasing high-energy gas (approximately 100 MPa (Hu et al., 2019)) into the surrounding borehole. The pressure infiltrates existing cracks, fragmenting the rock, and the rupture event is accompanied by a shock wave, creating fractures around the blasting hole. The high-energy gas not only expands existing cracks but also forms new cracks, aiding in fragmentation (Chen et al., 2022; Hu et al., 2019).

CO_2 rock breaking technology is not new and dates back to at least the 1940s, where it contributed to 25% of coal output in United States coal mines (Chen et al., 2022). Gupta (2016) indicates although it was still used into the 1950s in British and Indian coal mines, the advancement of mechanized coal mining led to its gradual withdrawal from the coal mining industry. Instead it found applications in urban earth and rock blasting and cement industry blockage removal (Chen et al., 2022). Hu et al. (2019) further indicate that CO_2 is utilised in fields such as tunnelling and municipal transportation.

4 THE POTENTIAL FOR DEFLAGRATION TECHNOLOGIES

Pyrotechnic and CO_2 methods, though slightly different, share a common characteristic: they operate in a significantly less violent manner compared to high explosives. High explosives detonate upon exploding, generating shock waves that pose safety, production, and cost challenges in an underground mining environment, as discussed in Section 2.3.

The fundamental challenge posed by detonation-based explosives is their introduction of a cyclical process into mining, resulting in batch processes that are less efficient than more continuous methods. This section aims to underscore the potential benefits and drawbacks associated with less violent, deflagration-based rock-breaking techniques in an underground hard-rock mining environment. These methods hold promise for transitioning from batch processes to more continuous ones without a significant impact on existing production lines.

The first sub-section contrasts the two deflagration techniques with detonation-based explosives, emphasizing potential safety, cost, and productivity improvements resulting from the switch to deflagration-based methods. The subsequent sub-section delves into the current challenges associated with these deflagration methods, shedding light on the prominent obstacles hindering their widespread adoption.

4.1 POTENTIAL ADVANTAGES OF DEFLAGRATION TECHNOLOGIES OVER DETONATION-BASED TECHNIQUES

Detonation-based explosives pose numerous challenges for miners in underground operations. This section explores the potential of deflagration-based explosives to mitigate or eliminate these challenges, particularly in terms of mine safety, efficiency, and profitability.

Deflagration-based techniques offer the prospect of transitioning away from batch processes in underground mining operations. Literature on pyrotechnic and CO_2 rock-breaking suggests that mine evacuation might not be necessary, given the non-violent nature of the explosion. This implies the elimination of the batch process associated with evacuating people and equipment, resulting in a potential improvement in mining efficiency. Peake et al. (2003) note a fivefold improvement in advance rate for deflagration-based alternatives.

Another advantage of deflagration rock-breaking technologies is the production of minimal to no toxic fumes and reduced dust due to improved fragmentation. This means that personnel only need to evacuate the immediate blasting area during ventilation of any toxic fumes and dust.

The true potential of deflagration techniques lies in their similarity to conventional drilling and blasting. Transitioning to this technology would minimally impact existing mining operations, as it can be trialled alongside existing high explosives. Moreover, mining staff would not be replaced, and the skills of blasting teams would likely be easily transferable. This makes the change management around such a technology much simpler than technologies that replace workers or require a fundamental change in skill sets.

If deflagration-based rock-breaking techniques prove to be equally or more effective, they could replace all high explosives without requiring major process overhauls. Once all blasting activities adopt deflagration-based methods, more continuous processes can be implemented, thereby enhancing mining efficiency.

At the extreme end, mechanization of deflagration technology could lead to a scenario where machines drill holes, place cartridges, stem holes, and blast rock—all while being remotely controlled by an operator. While existing drill and blast operations also have this potential, the violent nature of high explosives complicates blasting, necessitating additional machine evacuation steps and lowering mining efficiency.

Such mechanization could serve as a transition towards hard rock cutting methods if and when they become viable. Directly transitioning from the current batch-process drill and blast methods to continuous hard-rock cutting methods will have major impacts on the processing line of mines, increasing resistance to the adoption of these technologies. However, gradually transitioning from batch processes to more continuous deflagration methods would minimize the impact on existing mining operations, making subsequent transitions smoother.

While the primary focus of this report is to highlight the potential of deflagration technologies for expanding existing hard-rock mining operations to more continuous processes, even their partial adoption in certain mine areas is expected to yield economic and safety benefits, as discussed in the following sub-sections.

4.1.1 IMPROVING GOLD RECOVERY

In Section 2.1 we highlighted that the violent nature of high explosives produces fines associated with gold losses. Deflagration-based rock-breaking methods are less violent, and therefore, fragmentation is expected to generate fewer fines, potentially increasing gold recovery (Peake et al., 2003). Additionally, detonation-based explosives damage surrounding rock, creating cracks where gold fines can seep (free gold) and become challenging to recover. Deflagration-based explosives are likely to cause less damage to the rock, reducing the chance of free gold seepage into cracks.

Xingwana (2016) highlighted a challenge associated with detonation-based explosives, namely the dilution of ore. Henning and Mitri (2007) mention blast-induced overbreak as a contributing factor to ore dilution underground. Deflagration-based techniques could improve this challenge in two ways. Firstly, deflagration-based explosions, being less violent, are expected to result in less overbreak. Secondly, as deflagration-based explosions may not require full mine evacuations, more blasts per day become feasible. This flexibility allows mine planners to blast ore and waste sections separately, potentially reducing ore dilution.

The use of less energetic explosives, therefore, holds the potential for improved rock fragmentation, less free gold loss, and reduced ore dilution, ultimately enhancing gold recovery rates.

4.1.2 REDUCING OVERALL COSTS

Ventilation costs related to fines, dust, and toxic fumes from explosive blasting were discussed in Section 2.2. Pyrotechnic or CO_2 methods, leading to better fragmentation (less fines and dust) and minimal toxic fumes, can help minimize these costs. Furthermore, blow-out of supporting structures, highlighted by the MHSC as a large issue (MHSC, 2023), would no longer occur, saving costs on replacement structures. Although the overall cost-saving contribution of these two elements is not known, they are seemingly large enough issues that they have received attention in the literature.

4.1.3 IMPROVING UNDERGROUND SAFETY

Mine safety is of great importance, and a goal of “zero harm” is being pursued in South Africa (Macnamara, 2023). Deflagration-based technologies can contribute to this goal on multiple fronts. These technologies, designed with safety and limited environmental impact in mind, are inherently safer than high explosives.

The less violent nature of deflagration-based rock breaking is expected to decrease damage to the surrounding rock, reducing potential fall-of-ground events related to blasting (Peake et al., 2003). Additionally, damage to supporting structures in the mine is likely to be reduced or eliminated, lowering the risk of critical safety infrastructure damage. Underground mines already employ deflagration-based techniques for exactly this purpose (NXCO, 2023b).

Deflagration-based rock breaking, as mentioned before, has the potential to transition existing mines to more continuous mining operations. This has the benefit that drilling and blasting equipment can stay near the face, as blasting events are not as violent. This in turn reduces the number of times workers and machines move past one another, increasing overall safety in the mine.

4.2 CURRENT CHALLENGES WITH DEFLAGRATION TECHNOLOGIES

While the potential advantages of pyrotechnic and CO2 rock-breaking methods have been underscored, it is essential to acknowledge the challenges these methods face. Every technology has its limitations, and deflagration-based rock breaking is no exception. Here, we explore the primary challenges associated with these methods.

The foremost constraint for deflagration-based rock-breaking technologies is likely their cost. Comparative material costs between pyrotechnic/CO_2 technologies and high explosives are not precisely known. Chen et al. (2022) estimate CO_2 to be 1.5 times more expensive when compared to conventional explosives, although specific factors included in this calculation are not known.

Gupta (2016) estimates pyrotechnic charges to be roughly 20% more expensive per cubic metre blasted. However, Peake et al. (2003) suggest that lower energy techniques may require twice as many holes, implying twice as much pyrotechnic explosive. This would put cost estimates around 1.4x higher compared to conventional explosives. When factoring in the cost of the extra holes, Peake et al. (2003) come to an estimate of 6x as expensive, although their work is based on low-energy explosives, which are described as a different but related technology compared to pyrotechnic explosives. Related to the issue of more blasting holes, is fragmentation. Although deflagration-based techniques produce less fines, the question remains whether the rock fragments are perhaps too large, requiring closer spacing between cartridges, increasing the overall cost of blasting too much.

Reliability is another critical challenge for deflagration technologies. Peake et al. (2003) note that these lower energy technologies demand high reliability, as even a single misfire necessitates redoing the entire blast, thereby increasing operational costs. Maintaining reliability often involves decreasing hole spacing, which in turn raises drilling and material costs. Reliability is therefore closely intertwined with cost-effectiveness. Furthermore, the suitability of these technologies in very deep South African mines is not yet reported in literature. Although the less violent nature of blasts is mostly beneficial, it is sensible to question whether the lower energy blast can break the deepest, hardest rock underground in South African mines, further raising concerns around reliability of these methods.

Peake et al. (2003) highlights downstream processing as another challenge. The handling systems for rock will likely be more expensive, requiring adjustments to accommodate larger rock fragments and greater advance rates expected with more continuous deflagration-based methods. Additionally, greater advance rates are also associated with increased seismicity in deep underground mines (Malan & Napier, 2018), creating a greater safety risk compared to batch processes.

In summary, while cost stands out as a major challenge for the adoption of deflagration technologies, it is crucial to weigh these costs against the benefits previously outlined. Factors such as decreased ventilation costs, enhanced advance rates, improved fragmentation, and reduced dilution need thorough consideration before making conclusions solely based on cost.

5 CONCLUSIONS AND RESEARCH RECOMMENDATIONS:

Detonation-based blasting induces a batch process into underground hard-rock mining environments, limiting mining efficiency. Further challenges surrounding rock fragmentation, fines, dilution of ore, dust, toxic fumes, ventilation, and mine safety are also currently prevalent.

This report highlighted two promising deflagration-based blasting technologies, namely pyrotechnic and CO_2 rock breaking. Deflagration technologies are much less violent, removing the need to evacuate personnel and machinery from the mine during blasting. This fundamental difference allows operations to become more continuous, creating the potential for improved mining efficiency.

The similarities in the operational processes between deflagration- and detonation-based explosives allow for a gradual integration of deflagration-based explosives into existing drill and blast operations with minimal retraining requirements. The similarity of operation allows the technology to be adopted into operations slowly over time. This phased adoption reduces investment risks and allows mining operations to become more continuous over time. The benefits of deflagration technologies extend beyond their continuous nature, showing potential for improving gold recovery, lowering mine process costs, and enhancing mine safety.

However, the report acknowledges existing challenges, particularly the higher costs associated with deflagration methods, influenced by factors such as increased hole numbers, unreliability, and downstream processing effects. It calls for further research to address these challenges and evaluate whether the positive factors, including lower transportation and ventilation costs, offset the overall expenses.

From an industrial research standpoint, one would like to ascertain the biggest unknown factor to this technology: Cost. A small-scale practical implementation of these technologies in an existing underground mine could be constructed. Such an implementation would cause minimal disruptions, as detonation-based blasting operations could continue as usual. Ore extraction efficiencies can be compared between the detonation- and deflagration-based methods. Impacts on process costs can be monitored for both technologies, allowing the downstream cost implications to be better understood. Furthermore, questions around the viability of the technology on the hardest rocks and the seismicity risk deep underground could be addressed.

From a research standpoint, multiple facets may be explored. However, because reliability of these methods is still a large challenge, research in this field would likely generate the most immediate value. For example, optimisation of hole geometries using finite element or discrete element models could help advance blasting reliability, decreasing the average cost per blast.

The cost implications of deflagration methods over the entire production line are not yet understood and therefore this is another facet that may benefit from academic research. A statistical model can be developed which simulates various mine processes for both detonation- and deflagration-based explosives. Such a model may serve as a first indication of expected economic limitations or benefits when employing deflagration-based rock breaking method. Such a model could also simulate the feasibility of jointly using deflagration- and detonation-based explosives in a mine, better understanding what a transition from batch to continuous processes could look like.

In conclusion, the report aims to raise awareness about existing deflagration technologies as potential solutions for transitioning underground hard-rock mines to more continuous methods. It emphasizes the need for further research to determine the economic viability of these technologies in the context of underground hard-rock mining.

6 REFERENCES

Al-Bakri, A., & Hefni, M. (2021). A review of some nonexplosive alternative methods to conventional rock blasting. *Open Geosciences*, *13*(1), 431-442. https://doi.org/10.1515/geo-2020-0245

Breakers, R. R. (2024). *Nonex*. https://www.rhino-rock-breakers.co.za/p/929697/nonex

Chen, Z., Yuan, Y., Yan, C., Wang, W., & Qin, Z. (2022). A Novel Carbon Dioxide Phase Transition Rock Breaking Technology: Theory and Application of Non-Explosive Blasting. *Processes*, *10*(11). https://doi.org/10.3390/pr10112434

De Silva, R., Pathegama Gamage, R., & Anne Perera, M. (2016). An Alternative to Conventional Rock Fragmentation Methods Using SCDA: A Review. *Energies*, *9*(11). https://doi.org/10.3390/en9110958

Gupta, R. N. (2016). Emerging explosives and initiation devices for increased safety, reliability, and performance for excavation in weak rocks, mining and close to surface structures. https://doi.org/10.2991/rare-16.2016.57

Henning, J., & Mitri, H. (2007). Numerical modelling of ore dilution in blasthole stoping. *International Journal of Rock Mechanics and Mining Sciences*, *44*(5), 692-703. https://doi.org/https://doi.org/10.1016/j.ijrmms.2006.11.002

Hu, S., Pang, S., & Yan, Z. (2019). A new dynamic fracturing method: deflagration fracturing technology with carbon dioxide. *International Journal of Fracture*, *220*(1), 99-111. https://doi.org/10.1007/s10704-019-00403-8

ILO. (2023). Explosives. (pp. 1-44). https://www.ilo.org/static/english/protection/safework/ghs/ghsfinal/ghsc1528.pdf

Lusk, B., Perry, K., Rouse, N., & Castro, J. (2023). Underground Blasting. In *SME Underground Mining Handbook* (pp. 467-500). Society for Mining, Metallurgy & Exploration, Incorporated. https://books.google.co.za/books?id=XuaLzwEACAAJ

Macnamara, S. (2023). *SA Mining Safety Initiatives Targeting 'zero harm' gain traction*. https://www.africanmining.co.za/2023/04/01/sa-mining-safety-initiatives-targeting-zero-harm-gain-traction/

Malan, D., & Napier, J. (2018). A limit equilibrium fracture zone model to investigate seismicity in coal mines. *International Journal of Mining Science and Technology*, *28*(5), 745-753. https://doi.org/10.1016/j.ijmst.2018.08.003

MHSC. (2023). *Operational constraints of temporary and face area support systems*. https://mhsc.org.za/sites/default/files/public/research_documents/Chap5%20Final.pdf

NXCO. (2023a). *About Us*. https://nxco.co.za/about/

NXCO. (2023b). *Application*. https://nxco.co.za/application/

Peake, G. M., Rupprecht, A. V., & Rapson, S. M. (2003). The challenges facing Continuous Mining, using low energy rock breaking technologies. *Journal of the Southern African Institute of Mining and Metallurgy*, *103*(1), 29-33. https://doi.org/doi:10.10520/AJA0038223X_2880

Rostami, J. (2023). Mechanical Rock Breaking. In *SME Underground Mining Handbook* (pp. 417-445). Society for Mining, Metallurgy & Exploration, Incorporated. https://books.google.co.za/books?id=XuaLzwEACAAJ

Tuck, M., & Loomis, I. (2023). Mine Ventilation. In *SME Underground Mining Handbook* (pp. 551-571). Society for Mining, Metallurgy & Exploration, Incorporated. https://books.google.co.za/books?id=XuaLzwEACAAJ

Vogt, D. (2016). A review of rock cutting for underground mining: past, present, and future. *Journal of the Southern African Institute of Mining and Metallurgy*, *116*(11), 1011-1026. https://doi.org/10.17159/2411-9717/2016/v116n11a3

Wei, X., Wang, X., Wu, G., Liu, Q., & Zhang, Y. (2023). Research and Application of High-Energy Gas Fracturing Mechanism Based on CT Scanning Technology. *Rock Mechanics and Rock Engineering*, *56*(11), 7981-7996. https://doi.org/10.1007/s00603-023-03487-w

Xingwana, L. (2016). Monitoring ore loss and dilution for mine-to-mill integration in deep gold mines: A survey-based investigation. *Journal of the Southern African Institute of Mining and Metallurgy*, *116*(2). https://doi.org/10.17159/2411-9717/2016/v116n2a6

Zhou, H., Xie, X., & Feng, Y. (2018). Rock breaking methods to replace blasting. *IOP Conference Series: Materials Science and Engineering*, *322*, 022014. https://doi.org/10.1088/1757-899x/322/2/022014