NEDERBURG MINER

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Abstract
Research into the mechanisation of ore winning from the very narrow reefs characteristic of South African gold mines has been conducted from as early as 1964 through the Chamber of Mines Research Organisation (COMRO) but with limited success. However, the Council for Scientific and Industrial Research (CSIR) has recently re-evaluated the potential for the mechanisation for the narrow tabular gold mines. It has been determined that there are approximately 22 000 tonnes of gold left in-situ in channel widths of less than 500 mm in thickness. The extraction of ore from such reefs requires a complete paradigm shift in that the current mining cycle (drilling, blasting, cleaning and supporting) is not feasible since such a stoping width would not allow the workers entry into the stope. Consequently, a non-entry form of mining is required. With this target in mind CSIR has invested in a project called the Nederburg Miner which seeks to identify new technologies for drilling, rock breaking, cleaning, and materials handling, the application of which will enable non-entry mining of very narrow ore bodies. The intention is to develop a fully automated system that will not require human involvement at the stope face. The outcomes of research into this proposed system will not only extend the life of South African gold mines but will also enhance South Africa’s reputation for excellence in mining research.

This paper presents the new technologies under consideration and potential methods for their application into an integrated non-entry mining system.

1.0 Introduction
So called because it was conceived to be the size of a bottle of wine, the Nederburg Miner is a new approach to the development of a mechanized mining system for very narrow stopes. The technology is targeted to be small, low cost and locally made. It is designed to extract narrow reefs that are currently uneconomic because the minimum stoping width has to accommodate the people operating the conventional or mechanized mining system. The small size represents a change in philosophy: rather than miniaturizing conventional machines for narrow stopes, this system will be conceived and developed from the ground up for its intended purpose. This implies that operation must be truly remote - there is no place for an operator. By contrast, current low profile equipment that is remotely controlled is still controlled from within visual range.

However noble the Nederburg Miner is as a concept, two questions remain to be answered:
- Is there an economic justification for the concept?
- What is the CSIR going to do differently that COMRO did not consider in its mechanization activities in the mid 1970s?

If these two questions can be adequately addressed then a number of further questions arise that must be answered to realize the Nederburg miner system.
• How is the rock to be broken and transported?
• How is the machine to be powered?
• How will the machine know where it is?
• How does the machine follow the ore body?

Each of these questions leads to a host of further questions as the problem is broken into manageable tasks. If all of the tasks can be successfully completed, the result will be a revolutionary mining system. If not, there is still tremendous learning that can be derived from solving even a single challenge. For example, solving the problem of navigation that is essential to the Nederburg Miner will enable other innovations.

2.0 The Economics

A resource is the quantity of a mineral in the ground. For example, the total gold resource in the Witwatersrand, past and present, is variously estimated at 150 000 tonnes. A reserve is the quantity of gold that can be expected to be removed from the ground. A reserve discounts gold resources lost for any reason, for example because the grade is too low, or because gold bearing rock has to be left in-situ to support the excavation.

The reserve therefore, is a function of the mining method. For example, in a coal mine a room and pillar method is often employed, where the rooms are mined out and the pillars are left behind to support the roof. The maximum extraction in room and pillar is about 70%. By contrast, a longwall coal mine will remove all the coal in an area, allowing the roof to collapse behind the mining face. Given the same resource, longwalling will yield a higher reserve.

![Figure 1 Additional reserves within the Middelvlei reef](Schweitzer:2006)

The question for the Nederburg Miner is the size of the reserve. A study was commissioned from Shango Solutions, a geological consulting company, to answer that question. Shango
were directed to consider a mining machine that could extract reefs of less than 50 cm in areas where conventional mining is sub-economic, at mining heights of greater than 80 cm. Using the Middelvlei reef as an example as presented in Figure 1 it can be seen that any mining system capable of economically mining reefs at a stoping width of less than 0.5 m significantly increases the reserves from any existing resource.

Applying a similar analysis to all the South African gold resources results in an additional estimated reserve of 19 000 tonnes of gold based on an a cut of grade of 5g/ton. Should the Nederburg Miner system be capable of economically mining lower grades then a commensurately larger increase in reserves would be achievable as demonstrated in Figure 2.

Figure 2 Total additional resources in all un-mined reefs <0.5m vs pay limit for Nederburg Miner [Schweitzer 2006]

Table 1 Distribution of additional Nederburg Miner reserves between gold field, depth and extent of previous mining.

<table>
<thead>
<tr>
<th>Gold field</th>
<th>Total Tons Au</th>
<th>Tons of Gold</th>
<th></th>
<th>Extensive Previous Mining</th>
<th>No Previous Mining</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Depth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;900m</td>
<td>&gt;900m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Welkom</td>
<td>3 172</td>
<td>150</td>
<td>3 022</td>
<td>2 279</td>
<td>317</td>
</tr>
<tr>
<td>Bothaville Gap</td>
<td>317</td>
<td>-</td>
<td>317</td>
<td>-</td>
<td>317</td>
</tr>
<tr>
<td>Klerksdorp</td>
<td>2 164</td>
<td>100</td>
<td>2 064</td>
<td>1 450</td>
<td>714</td>
</tr>
<tr>
<td>Potchestroom Gap</td>
<td>5 980</td>
<td>-</td>
<td>5 980</td>
<td>-</td>
<td>5 980</td>
</tr>
<tr>
<td>Carletonville/West Rand</td>
<td>7 910</td>
<td>890</td>
<td>7 020</td>
<td>6 100</td>
<td>1 810</td>
</tr>
<tr>
<td>Central Rand</td>
<td>1 860</td>
<td>510</td>
<td>1 350</td>
<td>1 290</td>
<td>570</td>
</tr>
<tr>
<td>East Rand</td>
<td>200</td>
<td>-</td>
<td>200</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td>South Rand</td>
<td>190</td>
<td>90</td>
<td>100</td>
<td>-</td>
<td>190</td>
</tr>
<tr>
<td>Evander</td>
<td>825</td>
<td>125</td>
<td>700</td>
<td>100</td>
<td>725</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>22 618</strong></td>
<td><strong>1 865</strong></td>
<td><strong>20 753</strong></td>
<td><strong>11 419</strong></td>
<td><strong>11 199</strong></td>
</tr>
</tbody>
</table>
At a gold price of $900 per ounce and a Rand to Dollar exchange rate of 8 the additional reserves are equivalent to R5.6 trillion.

To put this into perspective, the total of all the gold removed from the Witwatersrand to date is estimated at 40 000 tonnes, and current mining is extracting about 350 tonnes per year. In other words, the Nederburg Miner can create a new gold reserve comparable to the Witwatersrand itself.

3.0 A Different Approach

From 1974, COMRO (the predecessor of the Mining competency in NRE) undertook a ten-year initiative to introduce mechanization to the gold mines of the Witwatersrand [Pogue: 2006]. It failed to introduce a new system so what will be different this time round?

The COMRO mechanization programme was subject to an intense internal technical review in 1987, which strove to identify, which of the previous technologies identified and used in the mechanization programme would benefit from more recent developments and innovations. The results of the review were presented in a series of documents collectively referred to as the “Review of the Stoping Problem – GS” [COMRO:1988]. In essence, CSIR has re-visited and re-evaluated the findings of the stoping review in the context of current and near future national and international technological developments.

Consider for example, the impact of new technologies on the stope coring method evaluated by COMRO: also under consideration for the Nederburg Miner. Essentially, a boring machine drills a series of parallel holes in the reef plane, removing rock. This approach was considered in 1975 by COMRO, but, it was assumed that because the boring machine was not readily steer-able the holes would have to be straight. Because the reef is not planar, having significant rolls and faults, and therefore the bored hole has to have a large diameter to ensure that it will mine the entire reef that is available [Jaeger:1975]. In contrast, with recently developed small diameter steer-able down-hole water-powered drills a much smaller diameter hole can be cut and steered to remain within the reef. By doing so, the size of the hole is far closer to the thickness of the target, meaning that there is less waste rock mined. The drilling technology exists so what is required is an automated system to identify the reef and steer the drill.

The work by COMRO [COMRO 1988a] did establish many of the fundamental requirements of a mechanized /automated mining system such as:

- The stress required to break rock in tension is 6-15 percent of the stress required in compression.
- There is an inverse relationship between the specific energy of rock breaking and the particle size produced [Cook 1970].
- The specific energy of rock breaking is much lower when breaking to a free face because the rock is broken in tension.
- Rock breaking alone is insufficient without an integrated rock handling system.
- There are significant economic and operational advantages to be gained from a continuous mining system.
- All of the mechanized systems developed and tested from the Swing Hammer Miner through to the Impact Mining System were subject to similar constraints.
Attacking the face from the front required very high energy levels, which in turn necessitated either massive machines or large staking forces.

The transfer of energy to the rock was inefficient resulting in large amounts of energy having to be absorbed by the machine.

If the machine could not produce a smooth footwall, advancing the machine after cutting the face was problematic.

The machines had to be able to mine their own length resulting in complex advancing arrangements.

There were many more requirements addressing issues of cost, design, operation, implementation, health and safety and costs.

In recognising that the fundamental element of any mining system is the breaking of the rock, the first stage of the Nederburg project focussed on the identification of new rock breaking methods commensurate with the Nederburg requirements. Several rock-breaking technologies were identified, some existing and others at various stages of development from laboratory demonstrator through to a working production prototype. It was also recognised that to facilitate rock removal, material handling and navigation and manipulation of any rock-breaking device a smooth regular footwall would be advantageous. As a result the following technologies were considered worthy of further investigations:

- Wire rope cutting;
- Controlled foam injection;
- Micro-wave drilling;
- Electric rock breaking; and.
- Rock breaking in tension (a laboratory feasibility study to verify the generation of sub-surface tensile stresses via the interaction of stress waves produced by the impact of a disc shaped impactor)

Because the distribution of grade within any one reef is so varied from concentration within 10mm in the carbon leader to almost uniform distributions in other reefs it was considered unrealistic for any one technology to economically mine all reefs. Consequently various combinations of the identified potential rock breaking technologies were considered to mine at stoping widths of up to 20 mm, 20-250 mm and 250-500 mm.

The target for the 2007-8 Nederburg project was to establish local technology demonstrators of the identified technologies and to commence preliminary studies on control systems, materials handling, cooling and ventilation, mine layouts, economics and health and safety. An overview of the 2007-8 Nederburg project is shown on Figure 3.
4.0 Novel Rock Breaking

4.1 Controlled Foam Injection

Various forms of rock fracturing via the pressurization of a drilled hole have been studied resulting in a fundamental understanding of the process requirements and limitations [Young:1999]. Simply put a pressurization of 75 to 500 MPa attained in 0.02 to 0.25 milliseconds and maintained for 0.05 to 0.1 milliseconds [Brinkmann:1986] would be sufficient to induce and propagate multiple fractures in constrained quartzite. While the pressurization levels and rise time can be achieved using water hydraulic methods the problem has always been the inability to maintain the pressurization sufficiently long to propagate the fractures. A review of these controlled rock fracture methods has been presented by Young [Young:1999] and led to the development of a new method [Young:1999 and 1999a]. This method is based upon the use of high pressure foam as the fracturing medium and is referred to as Controlled Foam Injection (CFI) fracturing.

A hydraulic rock breaking method should have the ability to pressurize a controlled fracture (or system of fractures) in such a manner that pressures required to adequately propagate the fractures are maintained. In order to maintain the pressurization a fluid of the necessary viscosity and compressibility is required to store sufficient energy to maintain the required pressure as the fluid expands into the developing fracture system. Young concluded that a water-based foam would have all of the requisite properties.
Foam, which is a two-phase mixture of a liquid and a gas, can be made with a viscosity several orders of magnitude higher than a gas or even water, and hence will escape from a developing fracture system more slowly than a gas or water. With a much slower escape of the fracture pressurizing medium, the pressures required to initiate, extend and develop the desired fractures can be much lower than if a gas alone is used. The use of water alone is not sufficient because this relatively incompressible liquid will rapidly lose pressure as the fracture volume increases with fracture growth. The fracturing process usually occurs so rapidly that the pressure cannot be maintained by injecting additional liquid down the injection tube or barrel. Foam, in contrast, can maintain the pressures for efficient fracturing due to the expansion of the gaseous phase of the fluid. Thus, foam has the ability to provide the pressures for efficient controlled fracturing without requiring the excessively high pressures associated with explosives, propellants, water cannons or electrical discharge.

One of the common difficulties encountered in the fluid pressurization of holes for rock-breaking is that of producing and maintaining a seal between the pressurization device and the drilled hole. Applied Geodynamics Inc. have resolved this problem by using an injection tube with a bulb enlargement at its tip and an annular hydraulic piston acting around the smaller barrel of the tube, as illustrated in Figure 4. The crushing of an annulus of deformable material between the bulb tip and the annular piston effects sealing. The crushing of this material along the axis of the hole causes it to expand radially and seal against the sides close to the bottom of the hole.

The CFI breaker operates as follows. Once the device reservoir is charged with foam at the required pressure, the foam is released into the pre-drilled hole by means of a rapid acting reverse firing poppet valve. A reverse acting poppet (RAP) valve, as indicated in Figures 4 and 5 is used to initiate the high-pressure foam injection because the valve has only one moving part, the poppet, which opens very rapidly when the pressure in the RAP control tube behind the poppet is released. As soon as the poppet moves, the reservoir foam pressure will act on the full sealing face of the poppet causing it to retract or open quite rapidly. The high-pressure foam will then be rapidly delivered to the bottom of the hole to effect a controlled...
fracturing of the rock. Rapid opening is important so that the bottom of the pre-drilled hole may be brought to a high enough pressure rapidly enough to induce the desired combination of hole-bottom fracturing and radial fracturing needed to achieve complete fragmentation.

Having an effective seal at the bottom of the hole provides advantages beyond ensuring the rapid pressurization of the hole. The sealing method provides a significant amount of resistance to the reaction forces enabling the system to be mounted on simple light carrier systems (ref Figure 7) and could possibly be used to pull rock from the face if fracturing does not fully extend to the free face. Having an effective seal also maintains hole pressurization should the rock not fracture enabling further shots at increasing pressure until fracturing is achieved.

All the ancillary equipment to operate the CFI breaker including the foam generator, pressure intensifier and foam reservoir can be readily accommodated on the carrier system as shown in Figure 6.

A fully remote controlled CFI rock breaking system mounted on a tracked carrier has been effectively used by SECO-Rail to non-explosively produce refuge bays in the Fréjus rail tunnel between France and Italy.

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Figure 5 General arrangement of the CFI breaker in operation.
Figure 6 CFI ancillary equipment shown mounted on a tracked carrier.

Figure 7 CFI Breaker mounted on the reverse of drill slide mounted on a carrier boom

4.2 Electric Rock-Breaking
Previous work on non-percussive electric drilling had focused on the plasma drilling process developed by Tetra Corporation of Albuquerque, New Mexico, and referred to within South Africa as the Plasma Hole-Maker(Figure 8). However, more recently, Tetra have, during their investigations into methods for the enhancement of oil exploration drilling, developed a
significantly different approach to that of the Plasma Hole-Maker. Tetra to Plasma hole-making as Electric Hydraulic Drilling (EHD) and to their latest technology as Electric Discharge Drilling (EDD).

In EHD it was surmised that the electric discharge produced a plasma in the surrounding water which resulted in a high pressure shock wave which subsequently broke the rock. However, during investigations into the use of electric discharge to enhance rotary well drilling, high speed photography seemed to indicate the formation of a plasma streamer just below the surface of the rock being drilled. Figure 9 is a schematic of the general arrangement of the drilling bit and figure 10 shows the evidence of a sub-surface plasma streamer.
Data presented by Tetra indicated a rock removal rate by EDD of typically 0.5 to 2.5 cc per pulse with frequencies of 20 to 200 pulses per second being possible. The specific energy of rock breaking for the EDD process was found to be lower than conventional percussive drilling as shown in Figure 11. Material removal rates of 0.075 m$^3$/min have been reported, which, if confirmed, would be sufficient for a practical electric mining machine.

Work conducted by Ilgner has confirmed the amenability of South African host rock to electric discharge breaking and CSIR is continuing investigations into the mechanisms of rock breaking by electric discharge [Ilgner:2006].
A lot of the previous work by Noranda and others into electric rock breaking did not develop into a practical rock breaking system. However a recent review of electric rock breaking by Jacques Nantel concluded that electric rock breaking should be re-evaluated as a non-explosive mining method. In this vein Natural Resources Canada, in collaboration with industry partners is actively pursuing an “Explosive-Free Rock Breakage Initiative”

4.3 Microwave Drilling
Professor E Jerbi of the University of Tel Aviv has published several papers on the use of microwaves for drilling non-metallic materials [Jerby:2001.] The technique is currently only operational at a laboratory scale and used for further research but has demonstrated an ability to drill in some South African host rocks. Microwaves are guided along a metal pin to produce localised heating and melting ahead of the pin. The molten material is displaced by the advancing pin (Figure 12). For thermal runaway to occur and the heating to remain localised requires a combination of temperature dependant material properties as shown in Figure 13. A schematic representation of the application of micro-wave radiation to drilling is shown in figure 14 whereas figure 15 shows an early laboratory system for drilling in concrete.

![Microwave Drilling Concept](image)

Figure 12 Micro-wave drilling concept

While significant development remains before this technology can be used for mining applications it is unlikely that it will become a stand alone system for drilling, more likely is its application to assist and improve conventional rotary drilling or even to provide access to a point beyond the rock face to facilitate the fracturing of the rock by the application of tension stresses i.e. to pull the rock off the face.
The Microwave-Matter Interaction –
A Localized Thermal-Runaway Instability

Figure 13 Micro-wave matter interactions

Rectangular-Waveguide Microwave Drill

Figure 14 Rectangular waveguide microwave drill
4.4 Diamond Sawing

Anglo American Corporation (AAC) initially investigated this technology for the underground mining of narrow-reef orebodies. The wire consists of diamond-impregnated cutting elements threaded onto a steel cable. The space between the cutting beads is covered by a plastic sleeve to protect the cable from abrasive wear. The object of the wire saw is to separate the economic reef from the surrounding host rock by cutting slots above and below the channel [Buyens:1993]. The reef located between the slots can then be extracted by explosive or mechanical means to give a very pure product. Initially, the cable of the wire saw is threaded through holes drilled close to the upper and lower contacts between two parallel gullies. A continuous loop is established round the pulley of the wire-saw machine. The wire is then rotated at high speed and pulled through the rockmass across the face to be cut, as indicated in Figure 16.

Table 2 Diamond rope cutting data [Buyens:1993]

<table>
<thead>
<tr>
<th>Data for a typical diamond-wire saw cut slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area cut</td>
</tr>
<tr>
<td>Cutting time</td>
</tr>
<tr>
<td>Cutting rate</td>
</tr>
<tr>
<td>Penetration rate</td>
</tr>
<tr>
<td>Wire tension</td>
</tr>
<tr>
<td>Wire velocity</td>
</tr>
</tbody>
</table>

Table 2 provides information on the cutting rates achieved at Freddies in respect of a typical slot cut with the Technical & Development Services Mark I machine. AAC progressed to a third-generation machine which substantially enhanced these rates. The AAC research and development in this area has certainly demonstrated that quartzites can be cut in this way, and that stoping widths of 300 mm can be successfully mined and sustained. The hangingwall and footwall conditions are exceptional, and a very clean product with little to no contamination.
is deliverable. The downstream benefits in terms of transportation, materials handling, metallurgical processing, and recovery are enormous.

However, problems associated with wire wear, closure and trapping of the wire, and effective breaking of the separated reef have hindered the application of this technology. For the Nederburg Miner diamond wire rope cutting is under consideration for the removal of very thin highly localised grade reefs such as the Carbon Leader. In this application the initial holes between the gullies would be steered to remain within the reef and subsequently used to guide the diamond rope to remain within reef thereby enabling the direct extraction by diamond cutting of reef thickness of between 15 and 25 mm. The ability to drill long holes between gullies while remaining within the reef is an essential requirement of this and other Nederburg Miner approaches.

Figure 16 Diamond wire saw cutting methodology [Buyens:1993]

4.5 Stope Coring

As discussed earlier, previous work by COMRO:1998 determined that a stope coring approach was not technically or economically viable. However, a combination of recent developments in drilling technology, ground penetrating radar systems and computer technology offer the ability to drill relatively small diameter holes on reef very accurately.

The development of down-hole water-hydraulically-powered rockdrills offers the opportunity of drilling very long small diameter holes. By drilling a hole between gullies below the reef a borehole radar system can be installed which will guide the drill during the drilling of subsequent overlapping holes with the reef. The number of sub-reef holes required for the radar system will be dependent on the amount of reef roll in the direction of advance but should be fairly evident from a comparison of the reef contact in the gullies.
5.0 Costing

Any mining system has to win ore at an economic rate if it is to be viable. Within the Nederburg Miner system the additional cost of the rock breaking technologies under consideration is compensated by several factors:

- Reduced dilution;
- Continuous mining; and
- Reduced support costs for a non-entry stope

While many of the technologies under consideration are not yet at a production stage, an attempt was made to assess potential mining costs via an adaptation of the economic model of selective blast mining presented by Bock et al [Bock:1998]. Although much of the necessary data had to be estimated the analyses confirmed that at stoping widths of 50-150 mm stope coring by long hole drilling was potentially viable at grades of 5 g/tonne, similarly for stoping widths of 150-500 mm electric rock breaking could be economically viable. The ability to mine sub 50 mm stoping width using diamond rope cutting alone was found to be marginally economic at grades of five gm/ton although potentially viable for the carbon leader reefs.

Work by Pickering et al [Pickering:2001] indicates that a CFI device in combination with a carrier capable of material handling and cleaning, could provide an advance of 300 m/month.
in a fifteen square metre end at an operating cost lower than that of a mechanized drill and blast system. Such a performance is certainly sufficient to advance the gullies in a Nederburg mining system thereby providing for an integrated non-explosive continuous mining system with non entry stopes.

6.0 Conclusion
Provided technologies such as controlled foam injection rock-breaking, in combination with electric rock-breaking and steer-able long-hole drilling with radar guidance can be developed through to a production level then an integrated, continuous, non-explosive, non-entry mining system is feasible. Such a system could then be further developed to a fully mechanized and automated system. However, such an undertaking is of the same order of magnitude as the mechanization and water hydraulic technology programmes of COMRO in the 1970’s and 1980’s about which Pogue [Pogue:2006] asserts “Despite valid criticisms of COMRO itself, without a similar stakeholder in the sector’s system of innovation, it is virtually certain that no equipment supplier would ever undertake the development of a systemic alternative technology …”.

There is no doubt the potential rewards of a successful Nederburg Miner system are substantial, offering increased reserves at a magnitude close to the Witwatersrand itself and a mining system that can be fully mechanised and automated whilst providing increased levels of operator health and safety. However, the effective development of a Nederburg Miner system through to a production reality will require the collective, integrated, and managed input and support of all stakeholders.

REFERENCES


