Executive summary

The timeline imposed by the Mine Health and Safety Committee’s (MHSC) milestones set during their 2003 annual summit poses severe limitations on the introduction of new or alternative technologies by December 2008 and December 2013. In order to meet the 2008 milestone of no more than ten per cent deterioration in hearing among occupationally exposed individuals, any new technology envisioned for use must already be in the advanced prototype stage of development. The 2013 milestone of less than 110 dB sound pressure levels at any place in the workplace is a marginally better time frame for the introduction of new technology, although the identified equipment would again need to be in a relatively advanced form of concept demonstrator or newly emerging prototype. *It is thus inconceivable that the total replacement of the South African de facto tool for hole-making, the pneumatic rock drill, with a new technology will be achieved within this time period.*

Further implications of the 2008 and 2013 milestones, at a machine specific level, are the unacceptable noise levels emitted by unsilenced pneumatic machines, *rendering these drills immediately in breach of the 2013 milestone.* These machines will need to be revisited and modified, by the minimum addition of mufflers, and it may be expeditious to the prevalence of noise-induced hearing loss (NIHL) to impose an immediate and outright prohibition on the use of unmuffled or unsilenced drills.

Of the equipment currently available, only the electric, muffled pneumatic and water-hydraulic drills have the potential to repeatedly emit less than 110 dB in an underground environment. However, the use of multiple drills in a stope, while increasing the incident sound pressure levels, offers an approach to the issue concerning equivalent operator exposure, viz:

- An optimum point exists in the number of drills required to complete the panel versus the equivalent noise level exposure (at higher incident pressure levels for shorter duration) experienced by the drilling crew.

- Placing more drills in a stope will increase the cost of hole production, in terms of increased capital expenditure, maintenance and labour costs.

*The first bulleted point above may in fact disregard the 2013 milestone of the MHSC. Unless exemption is obtained in terms of proven equivalent operator exposure, this scenario may not be viable. Further, and implicit in the above discussion is a demand that the workforce is equipped with adequate hearing protection and educated in such a way that the ramifications of ignoring personal safety and of the long term effects of NIHL are understood and internalised.*

Examining the spectrum of sound emitted from an unmuffled pneumatic and an electric drill, sensitivity analyses show that the greatest influence on sound pressure levels is obtained by addressing the higher frequencies, i.e. those above 2 000 Hz. This frequency is characterised by ringing of the drill steel, resonance of steel components within the drill and the expansion of air from the exhaust ports of a pneumatic machine. It is also noted that the drill steel is common to all drills, irrespective of the motive power, and concentrated research into this factor may facilitate an immediate and industry-wide acceptable reduction in noise levels.

The outcomes from a facilitated workshop with the affected industry highlighted several key issues, viz:

- Buying-on-price was highlighted as hindering the introduction of quieter drills to the marketplace. Contracts were being awarded, despite the publication of the MHSC milestones, for unmuffled drills, as these are cheaper options to their muffled counterparts.
• Buying-on-price has a minimizing effect on the drill manufacturer’s ability to generate funding to support research and development activities. Similarly, manufacturers were not prepared to self-fund the development of alternatives that were unlikely to be purchased by mines. The basic principles of business predominate.

• From the foregoing, access to state research and development (R&D) funding could prevent the symbiotic mine-manufacturer-R&D relationship.

• The basis of measurement by the inspectorate for compliance with the MHSC milestones was raised as a concern, and the need was alluded to for the publication of standard methods and codes of practice. The manufacturers require these in order to gauge development and product compliance, while the mines need clarity on the ways in which they will be judged.

• The general culture within the mining industry is of concern, and extends beyond the drill operator to include production bonus schemes, supervision of drillers, maintenance of equipment (particularly that of the air-supply lines and provision of adequate air pressure), purchasing procedures, and the management of noise in general.

The workshop concluded with a matrix of results to be achieved against known issues and concerns. The overarching drivers to this matrix are the MHSC milestones, as published, and are taken as the overall desired results to achieve and enabling statements. While the matrix (shown in full in appendix 2) is extensive and all points must be taken cognisance of, the following four functions were derived as the critical minimum that will achieve the greatest benefit:

- Changes to the industry culture;
- The management of time-equivalent exposure to drill noise;
- The application of technologies to reduce noise; and
- The application of appropriate standards, both for the measurement of noise and the specification of equipment.

While technology is only one of the four functions recognised in the holistic noise management process, it can also be seen as having a causal function; i.e. the deployment of alternate technology allows the development of new standards, the management of noise exposure, and the potential to change culture among the users of that technology.

*Technology is therefore a key element to the management of noise-induced hearing loss.*

Addressing the technologies available that hold promise for development and eventual deployment as viable mining tools, it is reiterated for emphasis that work must continue on the currently available pneumatic, water-hydraulic and electric drills. Specific areas for research centre on the need to reduce frequencies in the higher end of the emission spectrum, typically associated with exhaust noise (pneumatic) and the resonance of the steel components. Implicitly included here is the continuation of previously sponsored MHSC work on totally enclosed and remotely operated drills. In terms of emerging or new technologies, the following have been identified for study, with appropriate indications of expediency for implementation (Table1):
Table 1: Identified technologies for development

<table>
<thead>
<tr>
<th>No.</th>
<th>Method / technology</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Near term research areas</th>
<th>Long term research areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Pneumatic rotary percussive.</td>
<td>• Best penetration rate;</td>
<td>• Noise levels;</td>
<td>• Effective muffling of exhaust noise;</td>
<td>• Damping / elimination of mechanical noise.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Common standard.</td>
<td>• Performance dependent on air pressure.</td>
<td>• Damping of drill steel;</td>
<td>• Towards items 3 and 4 below.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Qualitative acceptance criteria (compulsory standards).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Electric drills.</td>
<td>• Relatively quiet (101 dBA);</td>
<td>• Low penetration rate;</td>
<td>• Damping of drill steel;</td>
<td>• Reductions / elimination of mechanical noise;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Independence from air supply.</td>
<td>• Require specialised bits.</td>
<td>• Qualitative acceptance criteria (compulsory standards).</td>
<td>• Towards items 3 and 4 below.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Enclosed “quiet rock drills”.</td>
<td>• Potential to go below ±90 dB(A);</td>
<td>• Size and manoeuvrability;</td>
<td>• Telecontrol needs underground evaluation;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Worker acceptance.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Remotely operated rigs and jigs.</td>
<td>• Removal of operator from high noise and unsupported areas.</td>
<td>• Time to set up;</td>
<td>• Development of rigs, jigs and control systems.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Bulkiness.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Down-the-hole (DTH) percussive drills.</td>
<td>• Diminishing noise with penetration.</td>
<td>• Large diameter, limited by size of percussion elements;</td>
<td>• Monitor technology offering from established manufacturers.</td>
<td>• Investigate alternative percussion methodologies.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Not established for SA hard rock conditions.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Method / technology</td>
<td>Advantages</td>
<td>Disadvantages</td>
<td>Near term research areas</td>
<td>Long term research areas</td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------</td>
<td>-------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>6.</td>
<td>Microwave drilling.</td>
<td>• Silent / little noise;</td>
<td>• Unestablished performance in SA formations;</td>
<td>• Conduct laboratory scale tests with SA rocks;</td>
<td>• Develop for deployment as commercial hole-making device.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Compact (roof bolts);</td>
<td>• Concerns over safety (radiation plus applications in fiery mines).</td>
<td>• Investigate collaborative effort with IP/patent holder;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Relatively low power.</td>
<td></td>
<td>• Conduct risk assessment for development potential.</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Plasma drilling.</td>
<td>• Compact size;</td>
<td>• Reliability of capacitor storage;</td>
<td>• Re-establish contact with IP/patent holder;</td>
<td>• Develop for deployment as commercial hole-making device.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Proven in large diameters;</td>
<td>• Ability to scale to appropriate sized holes?</td>
<td>• Conduct risk assessment for development potential.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• SA researchers are familiar with technology.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Ultrasonic.</td>
<td>• Relatively silent?</td>
<td>• Unknown effects on human physiology (hearing and hand-arm vibration syndrome, HAVS).</td>
<td>• Investigate effects on human physiology;</td>
<td>• Develop understanding of the influence of frequency and amplitude of vibration on SA rocks;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Smart material enable small diameter, compact equipment?</td>
<td></td>
<td>• Establish suitability for providing percussive energy (DTH drilling).</td>
<td>• Develop for use as a hole-making device.</td>
</tr>
<tr>
<td>9.</td>
<td>Active and passive suppression.</td>
<td>• Complementary technology to all above.</td>
<td>• Need quantification by recognized experts.</td>
<td>• Quantification of potential for application.</td>
<td>• Develop appropriate technologies in parallel with all of the above.</td>
</tr>
</tbody>
</table>
Table 1 includes pneumatic machines, as these cannot be discarded as equipment for use in the drilling of blast- and support-holes for some considerable time to come. Their inclusion is to highlight that work needs to be conducted to reduce their noise emissions, even if this is a simple regulation that forbids the use of unmuffled machines within the South African mining industry.

The combination of the workshop-derived critical four points and Table 1 allows the development of the proposed structure for future work, as illustrated in Figure 1. The predominantly technology-orientated thrust must be supported by occupational health studies to complement or reject technologies, and assist with the determination of work aimed at developing standards and cultural changes within the industry.

![Figure 1: Research cross-cutting relationship](image)

**Figure 1:** Research cross-cutting relationship

### Programme of work and project structure

Considering the number of technologies envisaged (Table 1) and the relatively short time frame for the implementation of the milestones (2008 and 2013), a fast-tracked, multi-tasked programme of work is recommended. This programme of work can essentially be split into two broad categories on the basis of the maturity of the technology, and each will have separate development tracks and time frames. The two categories selected for this purpose are:

- Concept / laboratory scale (technology) demonstrator; and
- Pre-production prototype.

Pre-production prototypes are those technologies that have the greatest probability of having reached commercial production by the expiration of the 2008 milestone, and the following summary applies to these technologies:

- Modifications to existing drills (items one to four of Table 1), including –
  - Muffling of the exhaust expansion from pneumatic drills;
  - The commercialisation of enclosed quiet rock drills; and
  - The development of remotely operated rigs and jigs.
- Drill steel damping. Common to all drills is the drill steel, and a collaborative effort across the manufacturing industry to address damping and the use of chuck bush inserts offers an area for concerted effort with a relatively short time to realisation.
Muffling the exhaust expansion from pneumatic drills is beneficial from a NIHL perspective, and mechanisms can be put in place to assist the user industry with the purchase of drills that meet a pre-determined exhaust-noise emission level. Envisioned mechanisms are the prohibition of unmuffled machines, controlled by a minimum compulsory standard administered by the established regulatory bodies already in existence within South Africa. An analogy to this type of approach is the inspection and test process already in place for self-contained self rescuers and steel wire hoist ropes.

*In parallel with the above is a concerted education and enforcement effort amongst the affected workforce, concentrating on producing internalisation of the need to wear personal hearing protection devices (HPDs). Given the current state of the technological offerings, it is improbable that any totally silent hole-making device will be available by 2008, and thus the modus operandi to meet the first milestone must be a combination of technological offering and a workforce-driven culture of compliance with recommendations.*

Addressing the technologies already at the advanced concept-demonstration stage of development, the microwave and plasma drilling technologies hold the greatest potential for being fast tracked (items six and seven of Table 1). While these two hole-making methods appear, superficially, to be able to offer a solution in time for the 2013 milestone, the possibility exists that they may be fast tracked to be available, at least as field-trial machines, by 2008.

The remaining entries in Table 1 (ultrasonic excitation and active and passive suppression) are either insufficiently advanced, or require expert analysis before an informed decision can be made regarding their inclusion on the immediate timeline. The recommendation is to enable a programme of work to examine these technologies in greater technical detail, coupled with base-line experimental work to determine any potential benefit to the mining industry. It is envisaged that this (largely academic) work will span approximately 12 months and result in recommendations that will either enable further development, or at least conclusively exclude the candidate technologies from immediate consideration.

*Figure 2 illustrates the proposed conceptual technical structure of the project to address NIHL.*
Figure 2: Technical project structure

Evident in Table 1 is the large number and diversity of technologies under consideration. In response to a resource concern for the management of such a project, it is envisioned that the current Technical Advisory Committees (TACs) will require considerable technical assistance and advice with the control of multiple, fast tracked, technical projects. This is particularly so if these TAC members are burdened with concurrent additional (“non-noise”) research programmes and especially in view of the fact that the industry representatives on the TACs are largely co-opted and, therefore, have additional regular employment duties to attend to.

In this light, it is recommended that a drilling (or noise) advisory panel be established whose sole mandate is to administer and lead the drilling noise reduction programme, and that a full time project leader be contracted to direct technical matters. While this technical leader need not be an expert in all technological disciplines under consideration, this person must, of necessity, be at least conversant with the technical concepts under investigation, as well as being familiar with the manufacturing, drilling and mining industries.

Addressing the timing of the project, it cannot be stated for certain what the eventual outcomes will be of this dedicated programme of research. Given these uncertainties, it is proposed that each technology thrust be developed through a dedicated technical evaluation, followed by a risk assessment before a full programme of work can be individually detailed. Inter alia, this process specifically requires the development of a high level technical and functional specification for the intended device or technology, which will assist with determining the overall time and resource allocation. This is illustrated in Figure 3.
Figure 3: Technology evaluation process
Acknowledgements

Mr G van den Berg of Anglo Platinum is thanked and acknowledged for his support, and encouragement, in particular the use of the comparative drill test results.

The MHSC is thanked for its patience and the granting of an extension to this project to enable the covering of the comparative test work.

The following persons are acknowledged for either their time given during interviews or for their participation in the workshop of 2005-11-17:

Mr W. Masztalerz of the Department of Minerals and Energy;
Messrs D. Amidzic and A. Gumbie from the Mine Health and Safety Council;
Mr G. van den Berg of Anglo Platinum;
Messrs P. Fletcher, M. O’Connor and G. Engelbrecht of Sulzer HydroMining;
Messrs J. Oerson, N. Roberts and W.J. Murray of Boart Longyear;
Mr R. Buchwane of South Deep;
Mr A. De Villiers-White of ERPM;
Messrs K. Moxham and M. Diedericks from Lonmin Platinum;
Messrs R. Constable, D. Ford, R.F. Matong and F. Tiedt of Harmony Gold Mine;
Messrs M. Franz, G. Güler, K van Zyl and Ms T. van Dyk of the CSIR;
Messrs J. Jordaan and Emil of Hilti SA;
Messrs D. O’Brien and H. van Eck of Victoria Engineering;
Messrs W. Jenkins, N. Stewart and M. Pedersen of Atlas Copco South Africa (Pty) Ltd.;
Messrs T. Wikström and P. Forsberg of Atlas Copco Construction Tools AB;
Mr T. Zaniewski of AngloGold Ashanti;
Messrs R. Kendall, M. Erasmus and H. Bear of Northam Platinum Mine;
Mr H. Smith of Impala Platinum Mines Ltd.;
Mr R.G.B. Pickering of Sandvik Tamrock SA.
Mr J. Wills of Novatek;
# Table of contents

Executive summary .................................................................................................................. 2
Acknowledgements .................................................................................................................. 10
List of Figures ........................................................................................................................... 12
List of tables ............................................................................................................................. 13
1. Introduction ......................................................................................................................... 14
2. Methodology ......................................................................................................................... 14
3. Review of previous MHSC sponsored work ........................................................................ 15
   3.1 Noise attenuation with distance ......................................................................................... 15
   3.2 Control of noise at the drill ............................................................................................... 17
   3.2.1 Drill steel damping ...................................................................................................... 19
   3.2.2 Later versions of rock drill technology ....................................................................... 20
   3.3 Operator isolation from the noise zone ............................................................................ 25
   3.3.1 Hearing protection devices ......................................................................................... 27
   3.4 Summary of previous MHSC sponsored work ............................................................... 28
4. New work and alternative technologies ............................................................................. 29
   4.1 Rotary percussive ............................................................................................................. 29
   4.1.1 DTH and Churn drilling ............................................................................................ 30
   4.1.2 Summary of new rotary percussive work .................................................................. 31
   4.2 Drag-bit cutting .............................................................................................................. 31
   4.2.1 Rotary drilling ........................................................................................................... 32
   4.2.2 Novel techniques ...................................................................................................... 33
   4.2.3 Summary of rotary drilling ...................................................................................... 34
   4.3 Fluid jet .......................................................................................................................... 34
   4.3.1 Novel applications of fluid jet cutting ....................................................................... 37
   4.3.2 Summary of fluid jet drilling ..................................................................................... 37
   4.4 Thermal .......................................................................................................................... 38
   4.4.1 Rock melting ............................................................................................................. 38
   4.4.2 Thermal spalling ....................................................................................................... 41
   4.4.3 Laser ........................................................................................................................ 43
   4.4.4 Thermal jets ............................................................................................................. 45
   4.4.5 Microwave ............................................................................................................... 46
   4.4.6 Miscellaneous thermal methods .............................................................................. 48
   4.4.7 Summary of thermal drilling .................................................................................... 49
   4.5 Plasma drilling .............................................................................................................. 50
   4.6 Ultrasonic ....................................................................................................................... 51
   4.6.1 HAVS and NIHL at ultra high frequencies ................................................................. 53
   4.6.2 Summary of ultrasonic drilling ................................................................................ 56
   4.7 Active and passive noise suppression ........................................................................... 57
   4.7.1 Noise barriers ........................................................................................................... 57
   4.7.2 Active noise attenuation ......................................................................................... 59
   4.7.3 Summary of active and passive noise suppression .................................................... 61
5. Comparative testing of rock drills ....................................................................................... 62
   5.1 Surface trials .................................................................................................................... 62
   5.2 Underground trials ....................................................................................................... 68
   5.3 Multiple drills .............................................................................................................. 74
   5.4 Discussion ....................................................................................................................... 76
6. Discussion and recommendations ....................................................................................... 79
   6.1 Programme of work ....................................................................................................... 85
   6.2 Project administration and timeline ............................................................................. 87
7. References ........................................................................................................................... 89
   7.1 Internet references ......................................................................................................... 95
   7.2 Personal communications ............................................................................................. 96
Appendix 1 Drill steel noise (Pemberton, 2005) ..................................................................... 97
Appendix 2 Report – workshop of 2005-11-17 ..................................................................... 106
Appendix 3 Conditions pertaining to the use of this report .................................................. 118
List of Figures

Figure 3.1.1: Noise attenuation with distance (after Franz et al., 1996) ........................................16
Figure 3.2.1: Average equivalent sound levels (after Franz et al., 1996) ....................................17
Figure 3.2.2: Typical rock drill emission sources ......................................................................18
Figure 3.2.3: Hard rock drill (after Maneylaws et al., 1997) ................................................... 19
Figure 3.2.4: Concentric drill steel arrangement (after Maneylaws et al., 1997) ....................... 20
Figure 3.2.5: Pi-reactive muffler details (after De Woody et al. 1964) ....................................... 21
Figure 3.2.6: Experimental Rock Drill (after Otterman et al. 2001a) ....................................... 22
Figure 3.2.7: Sound measurement position (after Heyns, 2003) ............................................ 23
Figure 3.2.8: Comparative SPL’s (after Franz et al., 1996; and Heyns, 2003) ......................... 24
Figure 4.4.1: Transient response of rock to a heat source ...................................................... 40
Figure 4.4.2: Specific energy versus laser power (after Gahan et al., 2001) ............................. 44
Figure 4.4.3: Hard rock thermal spallation cavity maker (after US DOE http://www.netl.doe.gov/) .......................... 46
Figure 4.4.4: Microwave concentrator (after Jerby and Dikhtyar, 2001) .................................... 47
Figure 4.5.1: PHM roof bolter (after Haase, 1995) ................................................................. 50
Figure 4.6.1: Ultrasonic material removal rate (after Wiercigroch et al., 2005) ....................... 52
Figure 4.6.2: Curves for exposure times of percentiles of population groups to suffer mild effects on tip of finger (after ISO 5349.2: 1986) ................................................... 54
Figure 5.1.1: Surface SPL, unmuffled pneumatic drill (UA) ................................................... 63
Figure 5.1.2: Surface SPL, Electric drills (E1 and E2) .......................................................... 64
Figure 5.1.3: Comparison of pneumatic and electric drills: surface ....................................... 65
Figure 5.1.4: Sound pressure and air-supply pressure relationship: surface ........................... 66
Figure 5.1.5: Comparison of drill sound spectra (surface; 350 kPa) ....................................... 67
Figure 5.1.6: Comparison of drill sound spectra (surface; 500 kPa) ....................................... 68
Figure 5.2.1: Comparison of electric and pneumatic drills: underground .............................. 69
Figure 5.2.2: Sound pressure and air-supply pressure relationship: underground ................ 70
Figure 5.2.3: Comparison of drill sound spectra (underground; 350 kPa) .............................. 71
Figure 5.2.4: Comparison of drill sound spectra (underground; 550 kPa) .............................. 71
Figure 5.2.5: Difference in frequency spectrum, drill UA .................................................... 72
Figure 5.2.6: Difference in frequency spectrum, drill MA .................................................... 72
Figure 5.2.7: Difference in frequency spectrum, drill MB .................................................... 73
Figure 5.2.8: Difference in frequency spectrum, electric drill .............................................. 73
Figure 5.3.1: Data for drill UA at 450 kPa (no HPDs) ........................................................... 74
Figure 5.3.2: Spatial sound distribution, three UA drills, 450 kPa .......................................... 75
Figure 5.3.3: Data for drill UA at 450 kPa (wearing muffs) .................................................... 75
Figure 5.3.4: LAeq as a function of penetration rate (operator wearing muffs) ...................... 76
Figure 5.4.1: Comparisons with water-hydraulic drill (after Franz et al., 1996) .................... 78
Figure 6.1: Noise management ............................................................................................... 82
Figure 6.2: Research cross-cutting relationship .................................................................... 85
Figure 6.1.1: Proposed technical project structure ............................................................... 86
Figure 6.2.1: Initial technology evaluation process ............................................................... 88
List of tables

Table 1: Identified technologies for development .................................................................4
Table 3.1.1: A typical mining cycle in gold/platinum conventional mining .......................16
Table 3.2.1: Sound pressure levels – drill comparison (after Heyns, 2003) .......................23
Table 3.3.1: Remote operation systems (after Kononov, 1994) .......................................25
Table 3.3.2: Hearing protection devices (after Franz et al., 1996) .....................................27
Table 3.3.3: Remote operation systems (after Kononov, 1994) .......................................25
Table 3.3.4: Hearing protection devices (after Franz et al., 1996) ....................................27
Table 3.4.1: Principal findings: previous MHSC work .....................................................29
Table 4.1.1: Summary of rotary percussive drilling technologies ....................................31
Table 4.2.1: Comparison of rotary drill bit types in quartzite (after Haase, 1989) ...............32
Table 4.3.1: Comparison of water jet technologies (after Kollé, 1999) ................................36
Table 4.4.1: Thermal properties of South African rock ......................................................38
Table 4.4.2: Variation in energy of melting ...................................................................39
Table 4.4.3: Mechanical properties of South African rock ..............................................42
Table 4.4.4: Tensile properties of Bushveld igneous complex rocks ...............................42
Table 4.4.5: Summary of thermal drilling technologies ..................................................49
Table 5.1: Test drill designation ......................................................................................62
Table 5.1.1: Background noise (surface) .......................................................................62
Table 5.1.2: Pneumatic rock drill frequency spectrum ..................................................66
Table 5.2.1: Background noise (underground) ...............................................................68
Table 5.4.1: Theoretical attenuation with frequency band .............................................78
Table 6.1: Drilling technologies for development .............................................................83
1. Introduction

The Mine Health and Safety Council (MHSC) set two milestones for the reduction of sound level exposure of mine workers, namely (Safety in Mines Research Advisory Council, 2005):

- By 2008, the hearing conservation programmes implemented by industry must demonstrate a deterioration in hearing of not greater than ten per cent in occupationally exposed workers. Essentially, this implies no new incidents of compensable hearing loss.
- By 2013, the total noise emitted by all equipment installed in the workplace must not exceed a sound pressure level of 110 decibels (dB) at any location in the workplace.

The pneumatic-powered rotary percussive rock drill is the most widely used device for drilling blast and support holes in the South African mining industry. While considerable development has taken place since its adoption as the de facto hole-making machine, in areas such as metallurgical refinements for better service life and the adoption of drill steels with concentric flushing bores, little significant change to the basic principle of operation has occurred (Harper, 2004). Of importance to the work conducted for this project is the fact that the noise emitted by rock drills has received comparatively little funding or attention, with the exception of recent work conducted by CSIR Natural Resources and the Environment (NRE) and the University of Pretoria, working under grants for the MHSC. Whist this work culminated in the design of a machine that emitted sound pressures in the 85 dB range, the actual device made use of a relatively conventional pneumatic rock drill that was housed inside a sound-isolating container.

Similarly, the recent two years have seen the commercial introduction of an electric rock drill to the gold and platinum mines of South Africa, with claimed sound emissions in the upper 90 dB range. With the motive power being provided by electricity, the noisy expansion of exhaust air is avoided, enabling a modest improvement to be offered to noise pollution over the typical 110 dB to 115 dB range of conventional pneumatic machines.

With these latter two machines, the individual noise emissions may be below the milestone set by the MHSC, but it must be noted that the sound-level measurements were conducted in free space and not in the reverberant conditions encountered underground. Harper (2004) indicated that the typical stoping environment, with multiple drills in operation, would require individual machines to operate at significantly lower sound pressure levels to meet the MHSC requirements.

The purpose of the work described in this document, therefore, was to examine the previous work done on sound emissions from rock drills, and to search the national international literature for alternative technologies that hold potential for development as hole-making devices.

2. Methodology

The methodology adopted in the execution of this project was a threefold approach, namely the evaluation of available literature; a survey of the industry in general; and the final workshopping of inputs from the previous activities to gain consensus on the way forward.

The literature survey was divided into two sub-tasks. The first of these was the review of work previously sponsored by the MHSC on noise related issues with rock drills, to establish any avenues for further research. The second sub-task was to survey the national and international literature for new developments in the field of quiet hole-generation.

An opportunity arose during the execution of this work to study the comparative performance of pneumatic and electric rock drills in a surface (free field) and underground environment. The results of this work are reported on in Section five.
3. Review of previous MHSC sponsored work

Equipment responsible for noise in mining can be categorised into four main areas: mineral winning, tunnel development, ventilation, and transport systems. Mineral-winning machinery includes rock drills (both hand-held and track or rail mounted), longwall machinery, continuous miners, and some trackless vehicles, all of which make a substantial contribution to noise during production hours of the mining cycle. Maneylaws et al. (1997: 3) indicated that operators of rock drills, whether pneumatic or hydraulic were the most at risk of noise induced hearing loss (NIHL). This was most prevalent in the hard rock mining industry, owing to the higher number in use relative to the other mining sectors, and the predominance of mechanical mining techniques in the coal industry (111 dB(A) for a pneumatic rock drill operator versus 100 dB(A) for a shearer operator).

The MHSC has sponsored several projects within the last decade to research and develop methods to reduce noise emissions from machinery. These studies have encompassed key noise generation aspects of the machines themselves, as well as established noise-reduction techniques. Maneylaws et al. (1997: 15) list two primary methods for noise reduction, namely:

- Noise control at source; and
- Noise control remote from the source.

The former action is often only accomplished by extensive re-engineering of the product, which demands intimate knowledge of the working of the machine. The second technique does not require detailed engineering information of the machine but requires knowledge of the sound spectrum produced (Maneylaws et al., 1997: 15). Redesign of machines to eliminate noise has the potential to enhance performance by increasing efficiency (thereby reducing the conversion of lost energy to sound), but there is also the risk of reducing performance. Noise control remote from the source includes the fitting of silencers, mufflers and enclosures, for example, or, alternatively, shielding the exposed personnel via personal protective equipment (PPE), sound proof booths or distance as examples. Muffling, particularly of exhaust expansions from pneumatic driven machines almost invariably carries with it a cost in terms of performance.

Returning to the work previously sponsored by the MHSC, this will be examined in the following sections, and will concentrate primarily on the work conducted on rock drills. The examination of this work will be split into two sections: work done on the drill itself, and work done in attempts to protect the operator, either by moving the operator away from the noise source, or providing hearing protection devices (HPDs). Before this examination, however, it is worth looking at the stoping environment and the influence of a noise source and its attenuation with distance.

3.1 Noise attenuation with distance

The stoping teams experience the most sound pressure levels from their respective operations. Table 3.1.1 shows a typical gold/platinum conventional three-shift mining cycle, the activities performed and their duration, as well as the typical number of people performing those particular tasks.
Table 3.1.1: A typical mining cycle in gold/platinum conventional mining

<table>
<thead>
<tr>
<th>Day Shift</th>
<th>3 Day Mining Cycle</th>
<th>Night Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>3 Day Mining Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Night Shift</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Nb: Each division under each shift represents one hour
The number in brackets is the approximate number of employees
Drilling may be 4 or 5 hours
Blasting takes place after charging

Rock drills can be singled out as the major contributors of high noise pressure levels in the stopes (Franz et al., 1997).

Franz et al. (1996) conducted studies on the attenuation of noise with distance from source using both silenced and unsilenced pneumatic rock drills and a water-hydraulic machine, allowing the generation of Figure 3.1.1.

![Figure 3.1.1: Noise attenuation with distance (after Franz et al., 1996)](image)

Figure 3.1.1 shows both the influence of air pressure on the sound emissions from pneumatic drills as well as the attenuation of sound pressure with distance from the drill. The water-hydraulic rock drill used for this test was run at 17 MPa and is shown falling between the attenuation lines for the silenced pneumatic machine at pressures of 600 kPa and 400 kPa.

Superimposed on Figure 3.1.1 is the equivalent eight hour exposure limit for workers, 85 dB(A), and it is evident that none of the machines studied by Franz et al. (1996) met that requirement, even in the back areas of the stope at a distance of ten metres from the machine. This scenario remains valid in the current mining climate, and may even become worse with the reduction of stoping widths in the modern and deeper mine layouts.
3.2 Control of noise at the drill

Franz et al. (1996) studied the emissions and performance of fourteen hand-held rock drills from different manufacturers, including seven silenced pneumatics, four unsilenced pneumatics and three water-hydraulic drills in the development and or stoping environment. The results are shown in Figure 3.2.1 below for stoping drills (after Franz et al., 1996).

![Figure 3.2.1: Average equivalent sound levels (after Franz et al., 1996)](image)

Figure 3.2.1 shows the averages for the different types of drills used by Franz et al. (1996). Of interest is that while the exhaust noise of the water-hydraulic rock drill is substantially less than that of the high-expansion pneumatic exhausts, the sound level of the silenced pneumatic at 400 kPa operating pressure is lower than that of the hydraulic. However, 400 kPa air pressure must be recognised as approaching the lower bound of acceptable performance for the typical pneumatic machine.

Maneylaws et al. (1997: 24), reporting on studies conducted by the US Bureau of Mines (USBM), the British Coal Board, and other researchers, identified three sources of noise in hand held rock drills, namely the exhaust, the drill steel itself, and noise emanating from the body of the drill. Drill body noise is created by the moving and impacting of parts inside the drill. Hydraulic rock drills have similar noise sources to pneumatic rock drills except that hydraulic machines lack noise generated by rapidly expanding exhaust air.

The source of noise from pneumatic rock-drills was expanded upon by Scanlon and Harper (1998) who diagrammatically depicted these emissions as in Figure 3.2.2.
Figure 3.2.2: Typical rock drill emission sources

Figure 3.2.2 shows the almost uniform emission of noise throughout the mechanical design of the drill, implying that the reduction of emission from one source allows another noise source to become dominant. The systematic reduction of individual noise sources is typical of the iterative and incremental approach usually necessary when attempts to control noise remote from the source are made. However, it must be noted that Harper and Scanlon (1997) indicate that as the drill penetrates the rock, the noise emission for the drill steel / rock interface will diminish with depth drilled.

Attempts to silence pneumatic rock drills from the 1960s onwards were made by the University of Queensland (Australia), USBM, Compair and the Steel Engineering Company, for example, with limited success as there were performance losses (up to 45 per cent in some cases) and mass additions accompanying any noise reduction. During the 1970s and 1980s, the USBM, UK and other EU countries, partially funded from the European Coal and Steel Community (ECSC) developed techniques to reduce noise levels in mining equipment. This work to develop “quieter” versions of the equipment was either in retrofit treatment or in redesign (controlling noise at source). Retrofit treatment was largely the application of acoustic principles (insulation, damping, isolation, absorption and enclosure).

Maneylaws et al. (1997) summarises this work as follows:

- The drill steel rotation mechanism was redesigned to have independent rotation through the introduction of a separate air motor and gear arrangement. This meant that the rotation was independent of thrust force. Many internal impact rattle points were eliminated, thus reducing the high frequency rattling noise of stoper drills.

- A compact muffler/enclosure was designed to consist of a series of “ring” shaped baffles placed along the drill, covered by a layer of aluminium, which was in turn covered by an outer layer of EAR Isodamp 1002 polymer. This design attenuated both drill body noise and air exhaust noise.
• A shroud tube made of steel tube designed to fit 25 mm hexagonal drill steel and 35 mm to 44.5 mm drill bits was connected to the drill body by a rubber sleeve to provide isolation from drill-body vibration.

• Drill controls were positioned on the feed leg to allow the operator to be further away from the drill as compared to conventional pneumatic rock drills.

Underground testing of these machine showed an overall improvement of 15 dB(A), indicating an equivalent level of 102 dB(A). Maneylaws et al., 1997 stated that the primary disadvantage of this design was that the drill steel shroud tube had to be removed at each drill steel change, which implies an increase in overall drilling time.

The success of these coal stoper tests allowed Maneylaws et al. (1997: 29) to study noise attenuation in hard rock drills. While the principal isolation techniques used to quieten the coal stoper were employed, the hard rock version required a redesign of the piston to achieve the blow energies required for the harder drilled material. Nonetheless, these researchers achieved an overall equivalent sound level of 104 dB(A) with a drill steel shroud and 107 dB(A) without the shroud. Figure 3.2.3 shows the relatively compact design of the hard rock drill.

Figure 3.2.3: Hard rock drill (after Maneylaws et al., 1997)

Once again, the drill steel shroud was identified as being detrimental to production, as it was abraded by the rock, while the viscoelastic bond between it and the steel failed regularly, allowing the shroud to oscillate up and down the drill steel.

3.2.1: Drill steel damping

With their relative success with damping the mechanical sound of the drill, as illustrated in the preceding section, the researchers reported on by Maneylaws et al. (1997) turned their attention to the drill steel itself, this work being largely sponsored by the USBM. The reasons for this were the significant levels in noise reduction which were marred by practical and production limitations. Recapping on the findings reported by Maneylaws et al. (1997) with the shrouded drill steel:

• The shroud hid the operator’s view of the rotation of the actual drill steel, thus impairing the judgement of the optimum thrust;

• The shroud decreased the clearance between drill steel and the drilled hole, thus hindering chip removal; and
The shroud tube and retainer increased the complexity of steel changes, thus lowering production rates.

To overcome these shortfalls, the USBM began the development of “concentric” drill steels (Maneylaws et al., 1997). The basic design comprised an inner rod to transfer percussion pulse to the bit and an outer tube for the transmission of torque. The premise for this construction was that the outer tube acted as a cover for the inner rod and contained sound waves generated by the inner rod from bending stresses resulting from the percussion. The reduction in noise was due to the degree of containment of the inner rod and transmitted vibrations exciting the outer tube. The flushing medium was conveyed through an annulus between the two concentric rods. Figure 3.2.4 illustrates the construction of steels for hand held drills.

![Figure 3.2.4: Concentric drill steel arrangement (after Maneylaws et al., 1997)](image)

Field tests of drifter concentric drill steels showed measurements of 107-109 dB(A) as opposed to the 110-112 dB(A) for conventional drill steels. Penetration rates averaged 600 mm/min for the drifter concentric drill steel and about 500 mm/min for the conventional drill, although endurance tests highlighted problems with the uncoupling forces required and the service life of the threads (drifter steels).

For the hand-held concentric drill steels, noise levels of 104 dB(A) were recorded at the operator’s ears as opposed to 107 dB(A) for the conventional drill steel. Drilling rates for the two types of drill steels were comparable.

Maneylaws et al. (1997: 33) concluded that the concentric drill steel concept showed promise of noise reduction, but needed substantial development to overcome technical shortfalls. It must also be noted that the increased complexity of such steels will necessitate an increased cost in production.

### 3.2.2 Later versions of rock drill technology

Harper and Scanlon (1997: 21 on), working in parallel with Maneylaws et al. (1997) - both works sponsored by MHSC - addressed the performance losses of silenced machines by attempting to optimise the thrust delivered to the bit. Citing Hustralid (1971), Harper and Scanlon (1997) state that the thrust required was independent of rock type and bit diameter. Further, in under-thrust situations, the incident stress wave transmitted from the piston to the drill steel to the bit / rock may cause the bit to temporarily leave intimate contact with the rock upon reflection of the stress wave. This free-end effect caused a stress wave to be reflected up the drill string of
approximately the same amplitude as the initial percussion propagated stress wave, which would be larger in amplitude than the reflected wave if the bit was in contact with the rock. While Harper and Scanlon (1997) were more concerned with the fatigue effects of this scenario, it is also plausible to speculate that these reflected waves have the propensity to produce sound waves of a greater power than those produced when the bit is in contact with the rock, by dint of the greater wave amplitude.

Harper and Scanlon (1977) considered the work done by the USBM and elected to construct a fully enclosed machine, making additional use of constrained layer damping to reduce the sound emissions from the drill string. The full enclosure was designed to make use of the “Pi-reactive” silencer concept to reduce exhaust air noise.

![Figure 3.2.5: Pi-reactive muffler details (after De Woody et al: 1964)](image)

The pi-reactive silencer is simply two volumes connected by a small tube of determined impedance as shown in Figure 3.2.5 above. Through the use of this model, the requisite muffler geometry was developed by cylindrical enclosures around the percussion and rotation sections of the drill, with the lengths of each enclosure being modified to provide the required volume. A standard SECO 215 rock drill was modified and mounted inside a plastic (HDPE) tube. This tube that encapsulated the drill represented the primary chamber in the reactive muffler system. The tube containing the drill was then mounted within a second aluminium tube, which became the secondary chamber of the system. The exhaust air was channelled in this way from the primary chamber through a series of holes, representing the impedance tubes of the system, into the main tube.

The constrained-layer damping system used consisted of a thin-walled tubular metal cover bonded to the drill steel by a viscoelastic material that adhered well to both surfaces. Two prototypes were developed under this work by Harper and Scanlon (1997) and both were tested in Norite.

While little mechanical modifications were made to the drill per se, the first prototype reduced noise levels from the original 115 dB to 93 dB during drilling, but with reduced performance because of backpressure problems caused by the restriction of flow to the exhaust air. Harper and Scanlon (1997) further noted that of the six drills manufactured to the first prototype specification, some of the drills were under-thrusted and produced poor penetration rates. These drills made use of a modified back plate to the drill, which acted as a piston inside the drill-housing tube to provide the thrusting arrangement. After modification to improve the rate of air flow to this piston and testing, an examination of the complex seal arrangements indicated severe degradation caused by hysteresis heating.

Further modifications of this prototype resulted in a second model, which proved noisier than the first, emitting 102 dB, but drilling at penetration rates similar to those of the unmodified
Following this attempt, it was decided to discontinue the project, although the main recommendation was to determine a suitable thrust system since pneumatic thrusting techniques faced technical and practical challenges.

Scanlon and Harper (1998) continued with the initial work of Harper and Scanlon (1997), and developed a thrust method consisting of a reciprocating mechanism based on a standard beam crawler. Prototypes were developed and manufactured and tested on surface drilling into Norite. The prototypes retained the noise and performance of previous prototypes but the thrust mechanisms proved limited in available thrust and endurance, with failures of small plastic elements within the pneumatic circuit. The project concluded with proof of the possibility of a quiet drill concept and that, with further work, the concept could be taken to full commercialisation.

Otterman et al. (2001a) continued with the basic work conducted by Harper and Scanlon (1997) and Scanlon and Harper (1998) and again considered the total encapsulation of the drill and drill steel in a soundproof housing. Two encapsulation concepts were evaluated by these authors, one being a flexible bellows and the second a composite material tube. From qualitative analysis, the latter was selected, as the primary concerns about a bellows arrangement centred on it having insufficient sound-attenuation properties, which may diminish when the bellows was stretched. Manufacturing and durability considerations were also dominant considerations in the dropping of the bellows concept, enabling the pursuit of the composite tube enclosure. In addressing the thrusting mechanism, Otterman et al. (2001a) elected to use a geared air motor and lead-screw arrangement.

Different drill support options for the back end and rock face were also evaluated, from which, a height adjustable A-frame leg was chosen for the front end and a modified ‘camlock’ roof support for the back end.

![Experimental Rock Drill (after Otterman et al. 2001a)](image)

Figure 3.2.6: Experimental Rock Drill (after Otterman et al. 2001a)

A Seco 215 pneumatic rock drill was also chosen for modification in this project. Figure 3.2.6 shows details of the design of the developed model. Surface tests in Norite showed reduced sound pressure levels (110 dB to 90 dB), while the penetration rate was measured to be 500 mm/min for both the original/unmodified drill and the modified versions. Underground tests showed values of 115 dB and 118 dB measured near the operator’s head, which Otterman et al.
(2001a) concluded may have been caused by sound reflections from the foot- and hangingwall of the 1,2 m stope and air leaks from an inspection lid and depth indicator.

Numerous shortfalls in the design (known as the experimental rock drill, XRD) were noted by Otterman et al. (2001a), the most significant of which were the machine’s weight and associated handling difficulties; corrosion of metallic parts; a build up of water inside the tube and excessive air exhaust back pressure (both also observed in the machine of Harper and Scanlon, 1997), and an inability to reach the bottom footwall corner during drilling (manoeuvrability).

Despite these difficulties, Otterman et al. (2001a) proved the concept and noted that, with further development, the machine had the potential to be developed to the point where one operator could manage several jig-mounted machines simultaneously. In this guise, the further advantage would be that the operator could be located further away from the noise source.

Heyns (2003), reported on the comparative testing of four different types of rock drill, namely the Quiet Rock Drill (similar to the XRD) with normal and cladded drill steel, a muffled and standard pneumatic machine, a hydraulic drill, and an electric drill. All these drills were tested in an artificial stope to establish the sound and vibration levels for each as part of MHSC project Health 806. Sound level measurements were taken for each drill at varying positions on a radial grid around the drill during drilling, as in Figure 3.2.7, and allowed the comparison of the drills as given in Table 3.2.1 (after Heyns, 2003), for positions 13, 25 and 27.

**Table 3.2.1: Sound pressure levels – drill comparison (after Heyns, 2003)**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>L_{Aeq}</th>
<th>Sound pressure level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet drill with standard steel</td>
<td>88,7</td>
<td>84,9</td>
</tr>
<tr>
<td>Quiet drill with cladded steel</td>
<td>84,1</td>
<td>86,1</td>
</tr>
<tr>
<td>Pneumatic drill, standard configuration</td>
<td>104,4</td>
<td>107,9</td>
</tr>
<tr>
<td>Pneumatic drill, muffled configuration</td>
<td>100,5</td>
<td>103,8</td>
</tr>
</tbody>
</table>
As anticipated, the unmuffled pneumatic drill emitted the greatest sound pressure levels at the three measurement positions. On examination of the sound levels at position 13, just behind where the operator would be, the Quiet Rock Drill with the cladded steel was recorded at marginally below the 85 dB eight-hour exposure limit. Interestingly, this sound level increased at positions 25 and 27 to levels above those of the unclad steel. This is contrary to expectations, and Heyns (2003) offers no explanation, other than that as position 13 was directly behind the operator, some of the results from this recording station may have been shielded by the operator’s body.

Again, and as anticipated, the electric and hydraulic machines respectively recorded the next lowest sound levels behind the operator respectively. This is most likely owing to the absence of noise due to the rapid expansion of air, as would be the case for the pneumatic drills, although it must be stated that no information is given for the hydraulic machine, as to whether it was of the closed or open loop type. Figure 3.2.8 graphically compares the values of Franz et al. (1996) and Heyns (2003).

<table>
<thead>
<tr>
<th>Drill Type</th>
<th>Position 13</th>
<th>Position 25</th>
<th>Position 27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic drill</td>
<td>98,9</td>
<td>103,4</td>
<td>98,1</td>
</tr>
<tr>
<td>Electric drill</td>
<td>92,4</td>
<td>94,7</td>
<td>94,6</td>
</tr>
</tbody>
</table>

**Figure 3.2.8: Comparative SPL’s (after Franz et al., 1996; and Heyns, 2003)**

Figure 3.2.8 shows the results of tests conducted some seven years apart, and under differing conditions. While it can be seen that the results recorded by Franz et al. (1996) are substantially higher than those recorded by Heyns (2003), the following points must be taken into consideration when interpreting this data:

- Heyns (2003) conducted tests in an “artificial stope”, being a test area enclosed by a roof but open on the sides of the test area, apart from the block of rock used as the test piece. Hence, sound waves are able to escape and attenuate from the sides of the
artificial stope, without reflection and reverberation.

- Franz et al. (1996) conducted tests underground, where the drill is effectively enclosed on all sides by a combination of rock, packs, sticks and props, and the effects of this will be to effect reflection of the sound waves, leading to an increase in measured sound pressure levels.

- No description is available of the technological advances made to the machines in the years intervening between the studies mentioned above.

- The sound-pressure levels reported by Heyns (2003) are taken from position 13 in Figure 3.2.7, i.e. some two metres from the sound source and behind the drill operator. Similarly, the figures used in Figure 3.2.8 for the data presented by Franz et al. (1996) are also from a distance of two metres away from the sound source (as per Figure 3.1.1). Franz et al. (1996) makes no mention of shielding by the operator.

On the basis of the above arguments, Figure 3.2.8 is, therefore at best illustrative of the need to rigidly control sound-field testing so as to prevent unwanted and spurious effects from skewing the data.

Finally, and importantly, Heyns (2003) concludes that the muffling of the pneumatic machines accounts for a drop in some four decibels, and that the individual situations in the underground environment could lead to different recordings for each machine.

3.3 Operator isolation from the noise zone

Kononov (1994) introduced the term “telecontrol” to describe any form of “non-on-board” control system, and cited communication channels between the controller and the machine to include physical lines (hydraulic hose, wires, optic fibres and power cables), wireless (radio and infra red), or any combination of the above.

The findings of Kononov (1994) are summarised, for the purposes of this study, in Table 3.3.1:

<table>
<thead>
<tr>
<th>Method</th>
<th>Principle of operation</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line systems</td>
<td>Transmission of signals down existing power cables or hydraulic hoses or dedicated fibre optic and signal cables.</td>
<td>• Low cost and simple.</td>
<td>• Restriction of machine and operator’s movement; safety (cut cable; electrocution; operators dragged into machinery).</td>
</tr>
</tbody>
</table>
| Wireless systems | Radio control. Transmission of and reception of signals via electromagnetic waves, either through the air or suitable waveguides (e.g. armoured braiding on hydraulic hose) | • Easy to install;  
• Moderate maintenance costs;  
• Reasonably rugged. | • Propagation of waves can be unstable;  
• Interference caused by closely located conductors;  
• Potential for cross-activation with multiple systems; |
<table>
<thead>
<tr>
<th>Method</th>
<th>Principle of operation</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Infra red. Transmission and reception of control signals via the infra red light spectrum.</td>
<td>• Independence from mining or technological conditions; • Relatively immune from electromagnetic interference; • Low cost; • Harmless to humans; • Potential for delimitation of the control area.</td>
<td>• Generally line-of-sight only; • Potential for cross-activation; • Periodic cleaning of lenses required.</td>
</tr>
</tbody>
</table>

Kononov (1994) reports, amongst other things, on the use of a telecontrolled long hole drill at Outokumpu Finnmines Enonkoski mine, where at least one hole is drilled by remote control during lunch breaks and at shift changeover, to increase production.

Kononov (1994) continues to describe the base requirements of a telecontrol system as being:

- Intrinsically safe and flame proof;
- Capable of withstanding the harsh mine environment, including the provision for repair and maintenance underground;
- Not impairing in any way the ability of the machine to be manually controlled;
- Designed to allow for quick switching between manual and telecontrol; and
- Ergonomically acceptable to the operators within the mining environment envisaged.

Talbot and Rushforth (1998) conducted an international investigation into the safety and health benefits and problems associated with stand-off controls, and provide an expanded and detailed list of ergonomically critical dimensions and features for control elements, such as push buttons, toggle switches, joysticks, and levers. These authors concluded that the differences in risk factors between conventional operation and stand-off control were related to the operator position and the potential for the controlled machine to undergo uncontrolled and / or unexpected movements. Among their conclusions is the need to conduct rigorous risk assessments with the actual conditions in mind.

Otterman et al. (2001b) considered the use of a telecontrol system for the XRD of section 3.2.2, and defined the system as requiring the following control elements:

- Control drilling operation from portable controller:
  - Activate forward motion;
  - Apply thrust;
  - Activate water / air;
  - Activate reverse;
  - Stop;
- Control of two machines simultaneously;
- Range of portable controller: 2 - 5 m;
- Drills must be capable of operating simultaneously and independently;
- Stop in the case of a communication channel interruption between the portable controller
and the drill;
- Sense position of drill (drilling depth indicator);
- Drilling cycle complete indicator;
- Drill jammed indicator;
- Selection of and calibration for different drill rod lengths; and
- End position switch in the front of the drilling unit to prevent overtravel.

Owing to the identified need to control two machines simultaneously, Otterman et al. (2001b) elected to utilise radio as opposed to infra red control. As for the latter, the infra-red transmitter would need to provide an exceedingly wide-angle beam in order for both machines to receive the signal. Similarly, the use of trailing lines was discounted, as these were considered to be too delicate and restrictive for a stoping environment. A radio-control system was therefore selected as the desired medium of communication and developed accordingly to fulfil the control requirements listed above. The system was developed and fitted to the XRD of Otterman et al. (2001a), and proved to work during surface trials. The authors stated that the electronics were not designed to meet the harsh in-mine conditions, and therefore no underground trials were conducted.

### 3.3.1 Hearing protection devices

Conventional hearing protection devices (HPDs) are another example of passive devices for the attenuation of sound. Franz et al. (1996) list the attenuation of seven combinations of HPD and equate their attenuation properties, as reporting to the wearer’s ears, to the noise emissions from silenced and unsilenced pneumatic drills and a water-hydraulic drill. These results are summarised in Tables 3.3.2 and 3.3.3.

#### Table 3.3.2: Hearing protection devices (after Franz et al., 1996)

<table>
<thead>
<tr>
<th>Designation</th>
<th>HPD Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>Muffs and band mounted plugs / caps</em></td>
</tr>
<tr>
<td>HPD1</td>
<td>Conventional muff</td>
</tr>
<tr>
<td>HPD2</td>
<td>Helmet mounted muff</td>
</tr>
<tr>
<td>HPD3</td>
<td>Caps, semi-aural, band worn under chin</td>
</tr>
<tr>
<td></td>
<td><em>Muffs worn over plugs</em></td>
</tr>
<tr>
<td>HPD4</td>
<td>Muffs with foam plugs</td>
</tr>
<tr>
<td></td>
<td><em>Reusable plugs</em></td>
</tr>
<tr>
<td>HPD5</td>
<td>Plugs</td>
</tr>
<tr>
<td></td>
<td><em>Disposable plugs</em></td>
</tr>
<tr>
<td>HPD6</td>
<td>Foam plugs</td>
</tr>
<tr>
<td></td>
<td><em>Custom-moulded plugs</em></td>
</tr>
<tr>
<td>HPD7</td>
<td>Adjusted to maximum attenuation</td>
</tr>
</tbody>
</table>

#### Table 3.3.3: Attenuation with HPDs (after Franz et al., 1996)

<table>
<thead>
<tr>
<th>Drill type</th>
<th>LAeq (dB)</th>
<th>Mean $N_{eq}$ (dB) for 150 min of stope drilling</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>HPD1</td>
<td>HPD2</td>
</tr>
</tbody>
</table>
Table 3.3.3 gives the worst-case scenario for pneumatic drills, i.e. when operating at 600 kPa supply pressure. Only the custom-moulded plugs, or the use of muffs worn over plugs, are adequate in attenuating the noise levels to below 85 dB for all scenarios of drilling studied.

Additionally, it can be seen that the moderate reductions in sound pressure levels offered by the silenced pneumatic machines and the hydraulic are sufficient to enable the vast majority of HPDs to bring the noise at the ear of the operator to below the critical 85 dB mark.

### 3.4 Summary of previous MHSC sponsored work

Maneylaws et al. (1997) showed that the damping of the drill steel resonance has the ability to reduce operator incident noise levels considerably, but that the use of shrouding and cladding has detrimental effects on the operator’s ability to see the rotation and judge the optimum thrust.

These drawbacks were addressed by the work of Harper and Scanlon (1997), Scanlon and Harper (1998) and Otterman et al. (2001a), who demonstrated the ability to reduce sound power levels emitted by totally enclosing the drill and providing a separate thrust mechanism. The drill developments reported on by Otterman et al. (2001a) achieved comparable penetration rates to a conventional drill, and showed noise emissions below the maximum permissible 110 dB stated in the MHSC milestone for 2003.

However, the aspect of size and manoeuvrability of these drills in a confined stoping environment remains the largest drawback, as well as cultural issues surrounding their implementation. Harper and Scanlon (1997: 17) report that there was resistance to the muffled drills they studied in the workplace, because the drills did not “sound right, therefore could not be drilling right”. The operators did not comment on the approximately one kilogram of additional weight, nor the slightly decreased penetration rate. In one instance, an entire batch of silenced drills was returned to the manufacturer owing to this operator resistance.

The use of telecontrols and mounting these larger drills on a rig or jig has been addressed, with Otterman et al. (2001b) reporting the successful surface demonstration of remotely controlled drills. This methodology not only reduces incident sound levels received by the operator, but also removes drilling personnel from the dangerous unsupported face area. However, the time required to set the drills up increases.

Returning to the manoeuvrability issues, the need to totally enclose the steel is apparent from the sound pressure level reductions achievable. To reduce this barrier to implementation, it is possible to terminate the encapsulation at the chuck, and resort to alternative methods of drill steel ring attenuation.

In conclusion, earlier MHSC-sponsored work on rock drills has examined practical methods of muffling emissions from commercially available pneumatic rock drills. These endeavours have resulted in working prototypes which, while displaying shortfalls, have potential for real deployment and commercialisation. However, all these studies have centred on ways of quietening commercially available drills, and little work has been conducted on sourcing alternative hole-making methods nor the redesign of the actual drill. Table 3.4.1 summarises...
the principle findings of rock drill specific work.

**Table 3.4.1: Principal findings: previous MHSC work**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Maturity</th>
<th>Advantages / drawbacks</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill steel cladding.</td>
<td>Demonstrated.</td>
<td>• Reported attenuation of ±4 dB;</td>
<td>• Pursue for commercial application.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Clearance for chip removal;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Complexity (drill changes);</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Operator vision;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Cost.</td>
<td></td>
</tr>
<tr>
<td>Concentric drill steels.</td>
<td>Demonstrated.</td>
<td>• Reported attenuation of ±4 dB;</td>
<td>• Pursue for commercial application.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Cost.</td>
<td></td>
</tr>
<tr>
<td>Totally enclosed drill.</td>
<td>Demonstrated.</td>
<td>• Meets MHSC 2003 milestone;</td>
<td>• Pursue for commercial application;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Size;</td>
<td>• Investigate shortening of tube and quiet drill steels;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Cultural issues (quiet, therefore not right).</td>
<td>• Programme to educate operators.</td>
</tr>
</tbody>
</table>

4. New work and alternative technologies

4.1 Rotary percussive

The literature contains many references to the study of rotary percussive drilling, but most studies are concerned with the understanding of the transmission of the stress waves from the hammer (or piston) to the rock / bit interface. While an understanding of these mechanical principles is paramount to the design of efficient machinery, little work appears to have been done on noise itself.

It can be argued that an in-depth understanding of these mechanics has the potential to increase the efficiency of transmission of the percussive energy, which will diminish the inefficiencies or lost energy, which have the potential to be converted to sound energy. However, in relation to the brief of this project, this detail of study is precluded, and the literature has been searched for public and CSIR-alliance partner work specifically and directly aimed at noise reduction.

Pemberton (2005, personal communications, transcribed in Appendix 1) indicates that work to address the damping of drill steel noise, for example, terminated in the 1980s (other than the work described in Section 3.2). This sound energy transmitted from the drill steel constitutes some 12 per cent of the total sound pressure emitted by a drill, and only anecdotal evidence exists for the deliberations surrounding the use of a high-frequency short-pulse wave, versus a low-frequency long-pulse wave. Pemberton (2005) states that Seco has developed the “Nova” machine, a 3,5 kW, independent rotation hand-held drill that operates at 53 Herz and delivers 66 Joules of blow energy. During testing of this machine, Pemberton (2005) states that the
rock-removal (penetration) rate per kilo Watt of power was the same as for a rifle bar machine operating at 35 Herz and 97 Joules blow energy.

Pemberton (2005), however, also states that there is evidence of a trend for some manufacturers to move toward a higher-frequency lower-blow-energy machine design, with Tamrock (2004), for example, issuing a press release indicating the development of the “KHZ” machine. This is stated to operate in the kilo Herz range with a variable blow frequency that can be tailored to the rock being drilled. This machine is further reported to have achieved five metres per minute in hard granite, although this machine appears to be a large drifter type of drill and not a hand-held drill.

Returning to the drill steel, Pemberton (2005) indicates that it is the transverse waves set up in the drill steel that is the predominant source of drill-steel noise. Further, the understanding of the mechanics of generation of these transverse waves is little understood, thus vindicating the use of damping material to reduce them as opposed to designing noise out at source.

Harper (2005, personal communications) indicates that the use of nylon chuck bush inserts has the ability to decrease sound pressure levels by approximately two decibels. These inserts were shaped in cross section similar to a chord of a circle, and lined the shank of the drill steel along the grips of the chuck. Being of an elastic nature, they damped out the rattling caused by misfits and wear between the steel and the drill, and also served to prevent abrasion of the two surfaces. Harper (2005) states that in addition to the noise attenuation from the drill / steel interface, wear on the shank of the steel was almost eliminated by these disposable and relatively inexpensive inserts, which were intended to be changed at every drill steel change. However, the retrofitting of these to a drill required modifications to the drill chuck itself, which the manufacturers claimed was not cost effective.

When considering the overall perspective of noise induced hearing loss (NIHL), an aspect that deserves consideration is the length of time that operators are exposed to the noise. A time-weighted equivalent level of 85 dB(A) is considered the upper limit for an eight-hour exposure, and many researchers have shown the interrelation between time exposure and sound pressure level. The current levels of emission from silenced rock drills, as per Franz et al. (1996, Figure 3.1.1), say three metres from a machine operating at 400 kPa, allows an upper exposure limit of 30 minutes per eight-hour shift (Otterman et al. 2001a: 10). Therefore potential exists for the development of fast machines that may or may not emit significant sound pressure levels, and which drill at rates that limit the exposure of the operator by decreasing the time required to complete a panel.

4.1.1 DTH and Churn drilling

A method of reducing the sound pressure incident on the ears of the operator is to move the noise source into the hole as it is developed. Down-the-hole (DTH) drills have been used in the oil and gas industry for some time, the primary consideration being the loss of energy associated with transmitting a percussive stress wave over considerable distances of drill string. Since the percussive mechanism is located in the bore of the well, the minimum diameters achievable for this form of drilling are generally considerably larger than required for typical in-stope blast- and support-hole generation. This limitation is imposed by the optimum dimensions of the piston so as to maintain acceptable blow energies within the range of commonly available material limitations (Murray, 2005, personal communications). Typical rock drills used in South Africa, where the percussive element is outside the hole, are known as top-hole drills.

With DTH drilling, the piston or hammer impacts directly onto the drill bit, and Lundberg and Okrouhlik (2001: 7) indicate that a sharp peak in efficiency occurs when the length of the piston and the length of the bit are equal. With churn drilling, the bit acts as the piston and is simply and directly accelerated into the rock. If a DTH drill is operated at an equivalent bit – rock
distance as a churn drill, the two are identical in performance. However, under optimal thrust considerations, Lundberg and Okrouhlik (2001: 15) indicate that (theoretically) DTH and churn drilling are more efficient than conventional top-hole drills for rocks with low penetration resistance. At higher penetration resistances, the three (top-hole, DTH and churn) drills approximate one another.

In addressing the aspect of dimensions, the recent advances in magnetostrictive steels and piezoelectric elements may indicate the use of these for down-the-hole purposes (as discussed with Swart, 2005, personal communications and elaborated on in Section 4.6), allowing the potential to reduce the diameter of the in-hole percussive components. With the potential for this form of drilling to be quieter than top-hole drilling, on an exposure-equivalent basis, it is recommended that the design of such machines be revisited.

4.1.2 Summary of new rotary percussive work

The literature has shown little, or at least only anecdotal work directly related to new concepts for enhancing the performance or low-noise applicability of rotary-percussive drills and techniques. The influence of the percussion frequency on the ability to drill has not been clearly demonstrated in the literature, and optimising this frequency may have the potential to alter the sound pressure level signature of the drill, leading to better or more robust and compact alternatives to muffling and silencing.

Materials science and technologies have now advanced to the point where they are ready for serious investigation for applications in the drilling industry, particularly the magnetostrictive and shape memory alloys, where they show (superficially) the potential to provide percussive energy at high frequencies, for size-limited applications. To this end, the applicability for use in down-the-hole drilling exists, and this is an inherently quieter method from an operator time-exposure basis than top-hole drilling.

Table 4.1.1 summarises the preceding study of rotary percussive drilling.

<table>
<thead>
<tr>
<th>Description</th>
<th>Maturity</th>
<th>Comments</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of percussion.</td>
<td>Anecdotal</td>
<td>• Influence on penetration rate not well defined.</td>
<td>• Requires further investigation.</td>
</tr>
<tr>
<td></td>
<td>evidence.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chuck bush inserts.</td>
<td>Demonstrated.</td>
<td>• Inexpensive, disposable;</td>
<td>• Renew technological evaluation with manufacturers.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Reduce noise and wear.</td>
<td></td>
</tr>
<tr>
<td>Magnetostrictive</td>
<td>Reaching maturity.</td>
<td>• Allows variation of percussive frequency.</td>
<td>• Requires further investigation.</td>
</tr>
<tr>
<td>DTH and churn drilling.</td>
<td>Mature for large diameters.</td>
<td>• Decrease of noise with penetration.</td>
<td>• Requires further investigation.</td>
</tr>
</tbody>
</table>

4.2 Drag-bit cutting

The use of drag-bits, in the form of pure rotary-only drilling is used extensively in the oil and gas industry as well as for geological coring. With no percussive action, there is no drill string ringing nor mechanical noise attributed to a hammer (or piston) striking the drill steel or anvil, nor the release of unused impact energy between the bit and the rock. With the exception of
pneumatic machines, rotary drills tend to be either closed loop oil hydraulic or electrically powered, implying an inherently lower noise emission. However, the major drawback is the need for greater torque at the drill bit and greater thrust force to achieve penetration (hence the generally preferred option of hydraulic power).

4.2.1 Rotary drilling

With reference to the South African situation, a comprehensive literature survey, coupled with laboratory test work, was conducted by Haase (1989), who investigated the use of rotary drilling with diamond tools for the generation of blast holes. Haase (1989: 3) presented a tabulated form of performance figures for various bit configurations, and these are summarised, normalised to (i.e. as a ratio of) the performance and cost of a hydraulic percussive drill, in Table 4.2.1:

Table 4.2.1: Comparison of rotary drill bit types in quartzite (after Haase, 1989)

<table>
<thead>
<tr>
<th>Bit Type</th>
<th>Dimensions</th>
<th>Rate of penetration (m/min)</th>
<th>Maximum thrust (kN)</th>
<th>Bit Costs (R/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic percussive rock drill</td>
<td>40 x 40</td>
<td>1,0</td>
<td>1,0</td>
<td>1,0 (1)</td>
</tr>
<tr>
<td>Impregnated</td>
<td>48 x 32</td>
<td>0,11 – 0,16</td>
<td>25</td>
<td>2,5 – 10,1</td>
</tr>
<tr>
<td></td>
<td>37 x 23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural diamond, surface set</td>
<td>48 x 32</td>
<td>0,07 – 0,11</td>
<td>25</td>
<td>5,0 – 5,9</td>
</tr>
<tr>
<td></td>
<td>37 x 23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polycrystalline diamond, surface set</td>
<td>37 x 23</td>
<td>0,14</td>
<td>8</td>
<td>10,9</td>
</tr>
<tr>
<td></td>
<td>60 x 42</td>
<td>0,55 – 1,27</td>
<td>8</td>
<td>18,5</td>
</tr>
</tbody>
</table>

(1) Cost for the complete drill, thrust leg and bit, based on 1989 Rands (R1,19).

Haase (1989: 3) reports that polycrystalline diamond on a tungsten carbide backing was also considered but was not tested in quartzite and therefore, it is not reported on in Table 4.2.1. Table 4.2.1 is based on costs and available technology from 1989, and includes assumptions and extrapolations used to normalise differing diameters of drill. For this reason, the absolute figures should be used with some caution. However, the relative magnitudes of the figures are of importance, and Haase (1989: 3) states that while the surface set polycrystalline diamond bits are capable of achieving similar performances to percussive drilling, their costs far outweigh their advantages.

It is important to note that Haase (1989: 3) used the cost of a complete hydraulic percussive drill as the base line, and that the costs for the other technologies are for the bit alone, and exclude machinery. With this and the caution given above in mind, examination of Table 4.2.1 reveals, in addition to the cost issues, that the thrust required is considerably higher for rotary drag bit cutting without a percussive component. The implication of this is for more robust thrusting equipment, implying greater cost, greater mechanical complexity, and greater skill level requirement.

Haase (1989: 64) concluded the study by indicating that two potential methods existed for reducing the costs of rotary drag bit cutting; namely, by making use of drilling fluid additives and cavitating jets, either singly or in combination with each other. The best scenario returned a penetration rate variation over hydraulic percussive drilling of between 50 percent and 300 percent and at a cost of from double to eleven times that of conventional rotary drilling. This was
for a combination of jetting and fluid additives, with all the preceding caveats applying. The influence of fluid jects is further discussed in section 4.3.

Despite the work done by Haase (1989), it is generally accepted that pure rotary drilling is confined to the softer formations typically associated with oil- and gas-field reservoir access. Where harder rocks are encountered, it is generally indicated that percussion is required to assist the rock breakage process (Hitchcox, 2005: 8). Pure rotary drilling has received attention primarily in the guise of advances in the tool bit material, particularly as illustrated by Haase (1989) with the use of polycrystalline diamond, and Ersoy (2003), who studied the optimisation of the drilling process by seeking the minimum specific energy at the maximum feed rate. Ersoy (2003) compared polycrystalline diamond composite (PDC) and tungsten carbide (WC) bits, and primarily drilled into typical coal strata (mudstone, siltstone, sandstone and limestone), demonstrating defined minima in the thrust and specific energies for both bits. Nonetheless, it is noted that the thrusts exhibited for the 50 mm diameter bits were of the order of 6 kN (PDC) and 12 kN (WC).

4.2.2 Novel techniques

In developing a drilling system for the exploration of Mars, Hill et al. (2003) conceptualised and prototyped a self-thrusting auger-type drill that dispensed with the conventional drill string and incorporated a down-the-hole motor. The only appendages exiting the bore were a cable for the removal of the chips and cuttings, and the electrical power cable. The principle of operation of the Low Reaction Force Drill (LRFD; U. S. Patent # 5,641,027, 1997) is to act in a manner similar to a conventional “drill and tap” activity used to create screw threads in metals. A pilot hole is drilled using a conventional rotary drill bit acting under the unit’s self weight as the thrust force. When this hole has reached a depth determined by the length of the primary drill rod, a set of cutters slightly larger than the pilot hole is automatically deployed and cuts a helical groove in the rock to the depth of the pilot drill hole. Subsequently, larger-diameter cutters are sequentially deployed, deepening the depth of the helical groove in the rock. Each “helicutter” remains at the bottom of the hole and assists in anchoring the rig in place for the next cutter deployment.

Once the helical groove, or thread, has reached the desired depth, a set of “thread scorers” is deployed from the main drill body, and these then score the threaded helix at the root of the thread. These scorers act in a similar manner to the helicutters, by incrementally scoring the root of the thread, until the “thread” fails and the hole is at its final diameter. Whilst this cutting action is being maintained, an auger or screw conveyor system runs inside a sheath outside the main stem, or pilot drill rod, conveying the chips to a “bailing bucket” located above the drill / helicutter / scorer assembly. This bailing bucket is removed from the hole on completion of the final thread scoring cut, via a cable. Once the chips are removed, the entire assembly is collapsed at the bottom of the hole, the process is repeated, and the hole is deepened in a self-thrusting or propelling manner.

As this device makes use of a down-the-hole motor, noise levels are anticipated to be low (no percussion; electric drive) and to decrease with penetration into the rock. While penetration rates are not given for this device, Hill et al. (2003) indicate a specific energy consumption of 385 MJ/m³, and it is anticipated that the actual penetration rate will be slow, owing to the complex mechanical deployment of cutters and scorers. In comparing hole-generation devices, Hill et al. (2003) give the following comparisons:

<table>
<thead>
<tr>
<th>Excavation method</th>
<th>Rock removal mechanism</th>
<th>Specific energy (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFRD</td>
<td>Shearing and tensile chip generation</td>
<td>100 – 150(1)</td>
</tr>
</tbody>
</table>

(1)
<table>
<thead>
<tr>
<th>Rotary drill</th>
<th>Mechanical chip formation</th>
<th>200 – 500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spark</td>
<td>Mechanical shock</td>
<td>200 – 400</td>
</tr>
<tr>
<td>Water jet</td>
<td>Mechanical erosion</td>
<td>2 000 – 4 000</td>
</tr>
<tr>
<td>Forced flame</td>
<td>Spalling</td>
<td>1 500</td>
</tr>
<tr>
<td>Jet piercing</td>
<td>Spalling</td>
<td>1 500</td>
</tr>
<tr>
<td>Plasma</td>
<td>Spalling</td>
<td>1 500</td>
</tr>
<tr>
<td>Electric arc</td>
<td>Spalling</td>
<td>1 500</td>
</tr>
<tr>
<td>Laser</td>
<td>Spalling / fusion</td>
<td>1 500 – 5 000</td>
</tr>
<tr>
<td>Electron beam</td>
<td>Fusion</td>
<td>5 000</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>Mechanical</td>
<td>20 000</td>
</tr>
</tbody>
</table>

(1) These figures are stated to be projections based on work done by NASA on the LRFD.

### 4.2.3 Summary of rotary drilling

Drag bit cutting is an established technology, predominantly used in the oil- and gas-well industry. Haase (1989) has demonstrated that penetration rates comparable with rotary-percussive drilling can be achieved but that, in order to do this, expensive bits and complementary water jetting are required. Further, the thrust forces required to achieve these penetration rates are considerably higher than those for conventional rotary percussive drilling, implying the use of hydraulic actuators necessary to achieve the required forces. These actuators will add to the complexity of the drilling operation and it is anticipated that, in the absence of remote or gravity-fed hydropower systems, the use of hydraulic power packs will add to the noise levels within the stope.

In summary, it is recommended that this technology be monitored to track progress and technological innovation.

### 4.3 Fluid jet

The use of water jets, with and without abrasive entrainment, has been used for some years, and is reaching maturity in the engineering materials field of application for the cutting and shaping of ceramics, reinforced composites and heat-sensitive metals (Momber, 2001a).

Water-jet cutting has typically three guises, viz:

- Pure water at high pressure, supplied as either a continuous, pulsed or cavitating jet;
- Water at high pressure with entrained abrasive and / or air; and
- Mechanically assisted water-jet cutting, where any of the two above techniques operate in conjunction with a mechanical drill or cutter.

The cutting action of the jet is generally a function of the stagnation pressure as it impinges onto the rock (Vijay, 1985), implying that the actual delivery pressure of the fluid to the nozzle does not necessarily have to exceed the compressive strength of the rock, but is interrelated with the velocity or momentum of the jet. These parameters define what is commonly termed the “threshold pressure” of cutting, or the minimum pressure required to cause fracturing. With mechanically assisted water-jet cutting, Bonge and Wang (1981) indicate that the jet causes a form of strain softening of the rock ahead of the cutter, implying that it may not be necessary to provide as a high a pressure as for pure water-jet cutting. Haase (1989) indicates that the
threshold pressure for damaging typical South African quartzitic rock is 100 MPa. (A theoretical dissertation on the influence of fluid jets and their erosion process is given in detail by Momber, 2001b).

As expected, the typical drawbacks to this form of cutting are the high quantities of water required, as well as the size of the power packs needed to generate the high pressures and jet momentum (flow rate). Equally, and perhaps of greater importance is the influence of water on the underlying geological formations (Kimberlite and coal, for example). From a safety point of view, large amounts of water in a stope can contribute to mud rushes and an increased load on a mine’s dewatering system. When abrasives are being used, these can be expensive and add an additional logistical load to the mine’s transport system, and their recovery post-cutting may prove an additional process burden prior to reaching the dewatering pumps.

Nonetheless, water-jet cutting received prominence in the United States in 1981 with the first water-jet cutting conference, organised by the Water Jet Technology Association held in Golden, Colorado (www.wjta.org). At this conference, Barker and Timmerman (1981) discussed the use of a water-jet drill, operating at 69 MPa with a flow rate of 12 US gallons per minute (45 l/min) to drill holes in a coal seam for the purposes of methane drainage. The drill diameter was six to eight inches (150 - 200 mm), with the jet head assembly rotating at 100 revolutions per minute (RPM). The performance recorded when cutting into clean coal was one foot to two feet per minute (300 – 600 mm/min), although no strength data for the coal is given.

Bonge and Wang (1981) report that the use of water-jet-assisted cutting with conventional tungsten carbide bits resulted in a two- to three-fold increase in penetration rate and necessitated only one sixth of the thrust required for unassisted drilling. In tests conducted in a linear cutting test rig, Haase (1989: 17-24) stated that a tool was deliberately stalled by taking an excessively deep cut, and when two 40 MPa water-jets were switched onto the rock-tool interface, the tool resumed cutting. Haase (1989) derived two hypotheses:

- The water-jets entered the microcracks formed around the tool-rock interface and reduced the crack propagation stress; and
- The water-jet removes fines from the cutting zone, allowing the cutter to bear directly onto the rock. This enables the generation of higher stress concentrations, indicating the application of lower forces to achieve fracturing and chip formation.

However, Haase (1989: 57), in examining anomalous data, further concluded that situations can arise where excessive jet energy can cause detrimental effects to the cutting process. In situations where the crushed material situated around and contributing to the concentration of stress for the formation of cracks is washed away by a high pressure jet, the actual crack-formation process is left entirely to the tool, indicating higher tool forces required to generate the localised stress. Further, considering that the jet is typically directed to impinge just ahead of the cutter, the chip being formed by the tool may be effectively held down by the reaction of the jet, again contributing to a higher tool force.

A comprehensive literature survey and drilling method comparison was conducted by Kollé (1999), who surveyed the literature from 1977 to 1997 listing, where available, reported performances and rock characteristics for pure-water-jet cutting, mechanically assisted water-jet cutting, abrasive slurry jet cutting and rotary mechanical diamond drilling. Of interest is that Kollé (1999) states that for the abrasive slurry drilling, the mass of abrasive used per mass of rock removed is always greater than unity, and may go as high as 20 times that of the displaced rock. Extrapolating from Kollé’s (1999) example given for granite, a blast hole of 34 mm diameter by 1.2 m depth would require 74 kg of abrasive.

Table 4.3.1 lists Kollé’s (1999) main findings on conducting drilling tests in granite with a uniaxial compressive strength (UCS) of 280 MPa.
Table 4.3.1: Comparison of water jet technologies (after Kollé, 1999)

<table>
<thead>
<tr>
<th></th>
<th>Ultra-high-pressure water jet</th>
<th>Mechanically assisted water jet</th>
<th>Abrasive slurry jet</th>
<th>Diamond rotary drill(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate (l/s)</td>
<td>0.16</td>
<td>0.16</td>
<td>1.1</td>
<td>1.0(2)</td>
</tr>
<tr>
<td>Pressure at bit (MPa)</td>
<td>240</td>
<td>240</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>Power at bit (kW)</td>
<td>38</td>
<td>38</td>
<td>19</td>
<td>Mechanical 10 Hydraulic</td>
</tr>
<tr>
<td>Specific energy (J/mm³)</td>
<td>5-100</td>
<td>3-100</td>
<td>70-500</td>
<td>1-10</td>
</tr>
<tr>
<td>Penetration rate (m/h)</td>
<td>3-55</td>
<td>3-80</td>
<td>0.2-2</td>
<td>0.3-3(3)</td>
</tr>
<tr>
<td>Abrasive use (kg/h)</td>
<td>-</td>
<td>-</td>
<td>500-4000</td>
<td>-</td>
</tr>
<tr>
<td>Thrust required (N)</td>
<td>110</td>
<td>400</td>
<td>300</td>
<td>13 000</td>
</tr>
<tr>
<td>Torque required (Nm)</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>80</td>
</tr>
</tbody>
</table>

(1) 50 mm diameter. All others are 25 mm diameter;
(2) Flushing water;
(3) Haase (1989: 3) reports figures ranging from 2.4 m/h for natural diamond to 42 m/h for polycrystalline diamond bits in "average" strength quartzite, at cutter dimensions varying from 37 x 23 mm to 60 x 42 mm.

Kollé (1999) does not elaborate on the interpretation of the upper and lower bounds given in Table 4.3.1, other than for the diamond rotary drilling, where the lower figure of penetration rate is for rock with a UCS of 400 MPa and the higher rate is for rock with a UCS of 280 MPa.

Examining the consumption of abrasive, Xiaohong et al. (2000) report the existence of a minimum in the relationship between this parameter and the abrasive feed rate to the system, with a corresponding minimum in the specific energy of cutting. The implications are that the abrasive consumption can be optimised, although Xiaohong et al. (2000) report that the erosion rate, measured in grams of rock eroded per gram of abrasive supplied is always substantially less than unity (i.e. the inverse of the measurement used by Kollé, 1999, and therefore confirming the findings of Kollé, 1999).

O’Brien et al. (2002) discussed work done within the South African mining industry on water-jet cutting of quartzite. High pressure jets (35 kpsi to 55 kpsi) entrained chromitite particles and were capable of cutting a 200-mm-deep slot in gold-bearing rock, although the penetration rate and / or specific energy consumption was not given. The limiting factors for the PASER (Particule Stream Erosion) system was reported by O’Brien et al. (2002) to be the reliability of the pumps and accumulators in an underground environment, and - confirming the work of Kollé (1999) and Xiaohong et al. (2000) - the large quantities of abrasive chromitite required to produce the slots.

Haase (1989) conducted a literature survey and experimental work aimed at investigating the use of rotary drilling for blast-hole development in South African mines, and defined two scenarios for water-jet-assisted cutting, namely for rock where the jet can penetrate into the rock, and secondly for rocks that cannot be penetrated by the water. For the former scenario, and reporting from the literature, Haase (1989: 19) stated that when the depth of jet penetration...
is equal to or greater than the depth of mechanical cut, tool forces can be reduced by as much as 90 per cent.

Haase (1989) conducted laboratory tests in Norite with a UCS of 300 MPa to investigate the influence of the impingement point of the jets in relation to the cutter. Using a 35-mm-wide tungsten carbide cutter operating at 100 mm/s, and varying jet pressures, Haase (1989: 21) concluded that the jets should be directed as close as possible to the leading edge and towards the inside corners of the tool. At 40 MPa jet pressure, the improvement in the forces in Norite resulted in a doubling of the penetration rate for a given thrust force, while in underground tests in quartzite, the corresponding increase was five times for the same thrust.

When cavitating jets are used at pressures around the rock threshold pressure to assist with the diamond cutting of granite, an unusual situation develops whereby the specific energy of rock removal asymptotes to an almost constant value irrespective of the depth of cut (Haase, 1989: 56-58). This situation applies for larger depths of cut (> ±8 mm), while at shallow depths of cut (2 mm up to ±6 mm), an almost exponential decrease in specific energy occurs.

To test the influence of water jets on rotary percussive drilling, Li et al. (2001) conducted laboratory-scale experiments using polycrystalline diamond compact (PDC) bits in a drop hammer and linear cutting test rig. Water jets were arranged to impinge at varying locations around the PDC bit, and Li et al. (2001) investigated the influence of impact spacing, static preload (weight on bit, or WOB) and impact energy, with and without water jets, on the penetration depth. The jet pressure was maintained at 42 MPa, which, the authors state, was unable to cut the granite used for the tests alone, and they concluded that the influence of the jet was to increase the impact area by washing away chips and fractured or damaged layers of rock. The results generated show an improvement in penetration rate, which is more significant at higher impact energies (the authors used impact energies of 13, 6, 23, 7 and 33, 9 J), and that the influence of the WOB on the penetration rate was insignificant.

### 4.3.1 Novel applications of fluid jet cutting

Kollé and Marvin (2000) conducted jet-assisted rotary drilling using super-critical CO2 instead of water as the fluid. At pressures above its triple point, CO2 exists as a super-critical fluid with a density similar to water, but a much lower viscosity than water, allowing it to behave with the diffusivity of a gas. The authors infer that the mechanism of assistance by this method is caused when the jet fluid penetrates behind the rock grains and causes erosion. Tests conducted by Kollé and Marvin (2000) showed a 42 per cent decrease in specific energy in granite when cutting with super-critical CO2 as compared with water. This decrease can be partly attributed to the 67 per cent drop in threshold pressure recorded by the authors and viewed as the result of the CO2 permeation into the rock lattice.

However, it must be noted that for CO2 to remain in the supercritical state, the ambient pressure at 31°C must be above 7.4 MPa, and Kollé and Marvin (2000) imply that this situation often occurs with oil- and gas-field drilling. It is unlikely that these conditions will ever occur in typical South African mines, and this technology is included here for completeness only.

### 4.3.2 Summary of fluid jet drilling

To summarise, the literature has shown that water jets, whether operated alone, with abrasive particles, or in combination with mechanical drills, can cut rock and improve on penetration rates. From a logistical point of view, the increased volume of water (or fluid) that must both be supplied to the stope at high pressure, and then removed from the mine, will add to equipment capital and operating costs and increase the required skills levels for maintenance and operation. Examining the volumes of fluids involved, if a 30 m panel is considered, with a
burden of 0.5 m requiring some 62 holes, and using the figures shown in Table 4.3.1 for 25 mm hole by 1.2 m depth, the mine must cater for the supply and removal of some 14 m³ of water per panel. This calculation is based on a penetration rate of 3 m/h and a consumption of 0.16 l/s (after Kollé, 1999).

From a noise point of view, jets discharging into air have the potential to generate significant sound pressure levels, although the collimated jet of Savanick et al. (1985) and Xiaohong et al. (2000) are enclosed, and travel into the rock with the generation of the hole. As such, it can be anticipated that sound pressure levels will decrease with penetration. However, the need for high pressure water (typically in excess of 240 MPa) necessitates plunger pumps in the absence of hydropower columns, which will add to the noise load in the environment.

4.4 Thermal

The use of heat to break or crack rock is one of the oldest methods known and has been in use since ancient times by the Egyptians, where the quenching of fire-heated rock would cause the outer layers of rock to spall off, or to cleave along natural faults (McCarthy, 1985). While this cracking was then the prime method of breakage, the concept of using heat to actually melt the rock has been studied and tunnel-boring machines operating on this principle have been brought to concept stage (Robinson et al., 1971). These conceptual designs were based on experimental work carried out at the Los Alamos Scientific Laboratories (LASL, now the Los Alamos National Laboratories, LANL), where electrical-resistance heated drills were plunged into rock. This work was conducted in the early 1960s and culminated in the issuing of a patent in 1965.

4.4.1 Rock melting

The melting temperature of rock is dependent on mineralogical composition and water content, implying that each geological formation will have its own unique set of thermal properties. Further, Seipold and Huenges (1997) indicate that the thermal transport properties of rock are also dependent on stress state and temperature. The following table demonstrates the diversity of typical formations in the South African gold and platinum fields:

**Table 4.4.1 Thermal properties of South African rock**

<table>
<thead>
<tr>
<th>Type of Rock</th>
<th>Thermal conductivity (W/m°C)</th>
<th>Thermal capacity (J/kg°C)</th>
<th>Thermal diffusivity (m²/s)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold mines(1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Witwatersrand quartzite</td>
<td>5.74</td>
<td>837</td>
<td>2.55 x 10⁻⁶</td>
<td>2690</td>
</tr>
<tr>
<td>Ventersdorp lava</td>
<td>3.10</td>
<td>879</td>
<td>1.24 x 10⁻⁶</td>
<td>2850</td>
</tr>
<tr>
<td>Karoo shale</td>
<td>2.39</td>
<td>921</td>
<td>0.99 x 10⁻⁶</td>
<td>2620</td>
</tr>
<tr>
<td>Karoo dolerite</td>
<td>2.01</td>
<td>879</td>
<td>0.77 x 10⁻⁶</td>
<td>2960</td>
</tr>
<tr>
<td>Karoo sandstone</td>
<td>1.97</td>
<td>837</td>
<td>0.95 x 10⁻⁶</td>
<td>2470</td>
</tr>
<tr>
<td>Platinum mines(2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anorthosite and Norite</td>
<td>2.24</td>
<td>815</td>
<td>0.97</td>
<td>2810</td>
</tr>
<tr>
<td>Pyroxenite</td>
<td>3.59</td>
<td>830</td>
<td>1.30</td>
<td>3230</td>
</tr>
<tr>
<td>Type of Rock</td>
<td>Thermal conductivity (W/m°C)</td>
<td>Thermal capacity (J/kg°C)</td>
<td>Thermal diffusivity (m²/s)</td>
<td>Density (kg/m³)</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Dunite / Harzburgite</td>
<td>4,37</td>
<td>865</td>
<td>1,55</td>
<td>3270</td>
</tr>
<tr>
<td>Chromitite</td>
<td>2,47</td>
<td>720</td>
<td>0,83</td>
<td>4140</td>
</tr>
</tbody>
</table>

(2) Joughin et al., 2000.

MSN Encarta (2005) gives a value of some 650°C for the melting temperature of granite, while Robinson et al. (1971) use figures of 1 000°C to 1 150°C. Despite this diversity in reported temperatures, examination of the melting process deserves some consideration.

The University of Texas (Austin) Department of Geological Sciences lecture notes (dated April 30, 2004; http://www.geo.utexas.edu/courses/468k/Clark%20Wilson%20Lectures/G1%20April%2030%20Heatflow.doc), gives the latent heat of melting of igneous rock as 420 kJ/kg. If the average stope face temperature is taken as 30°C, and the hole to be drilled is 34 mm diameter by 1,2 m deep, then the values in Table 4.4.1 allow a comparison of the energies required to melt the hole into the face. Table 4.4.2 summarizes this for a melt temperature of 650°C, and shows that with the parameters given above the variation in energy consumed is considerable for both the gold-bearing formations and the Bushveld igneous complex (BIC).

**Table 4.4.2: Variation in energy of melting**

<table>
<thead>
<tr>
<th>Type of rock</th>
<th>Energy Required (kJ)</th>
<th>Per cent of minimum energy (by formation) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold bearing formations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Witwatersrand quartzite</td>
<td>2 751,8</td>
<td>1,09</td>
</tr>
<tr>
<td>Ventersdorp lava</td>
<td>2 996,3</td>
<td>1,19</td>
</tr>
<tr>
<td>Karoo shale</td>
<td>2 828,9</td>
<td>1,12</td>
</tr>
<tr>
<td><strong>Karoo dolerite</strong></td>
<td><strong>3 112,0</strong></td>
<td><strong>1,23</strong></td>
</tr>
<tr>
<td>Karoo sandstone</td>
<td>2 526,8</td>
<td>1,00</td>
</tr>
<tr>
<td>Bushveld igneous complex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anorthosite and Norite</td>
<td>2 832,8</td>
<td>1,00</td>
</tr>
<tr>
<td>Pyroxenite</td>
<td>3 288,9</td>
<td>1,16</td>
</tr>
<tr>
<td>Dunite / Harzburgite</td>
<td>3 407,0</td>
<td>1,20</td>
</tr>
<tr>
<td><strong>Chromitite</strong></td>
<td><strong>3 907,9</strong></td>
<td><strong>1,38</strong></td>
</tr>
</tbody>
</table>

Further examination of Table 4.4.2 shows that the gold-bearing formations have the lowest energy requirements, while the BIC chromitite requires almost 55 per cent more energy to achieve melting at 650°C than the Karoo sandstone, for the same size of hole.

These energy figures are substantial and indicate that if a melting device could be put into use, then in order to be at least as efficient as the convention pneumatic rotary percussive drill, it
would need to excavate a 1.2 m deep hole in approximately five minutes. This implies a power consumption of 9.2 kW for the Witwatersrand quartzite and 9.4 kW for Norite, as opposed to the typical 2.5 kW delivered to the rock by the conventional pneumatic drill (±70 J blow energy at ±35 Hz).

While the above scenario is a pure and theoretical approach to the thermal melting of rock, another approach is to examine the transient response of rock to the application of heat. Robinson et al. (1971: 33-34) make use of this to examine the temperature gradient within the rock, in terms of multiples of drill rod radius ($r/r_0$) from the heated drill rod surface. Figure 4.4.1 is a representation of this (after the method given by Holman, 1981: 135-136, and Grosglik et al., 2002: 148) and using the physical constants for Witwatersrand quartzite stated previously, for a 34 mm diameter heated hole.

![Figure 4.4.1: Transient response of rock to a heat source](image)

**Figure 4.4.1: Transient response of rock to a heat source**

Figure 4.4.1 depicts the time-related heating of rock with increasing distance from the source, and may be visualised as being an infinite expanse of rock with a 34 mm diameter hole drilled through it, the surface of which is suddenly raised to 1 000°C and maintained at that temperature. The above curves are, therefore, the time-dependent response of the rock to this heating over a period of one minute, one hour, and one day respectively, as a function of distance from the bore surface.

The curves of Figure 4.4.1 differ from those of Robinson et al. (1971: 34), in so much as the diameter of the drill is much smaller and the rock properties are different. Nonetheless, the influence of the insulating properties and thermal inertia of rock are shown, and Robinson et al. (1971: 36) indicate that the exploitation of these properties, i.e. melting only a thin “boundary layer” of rock around the heated penetrator, results in the consumption of approximately 2 W/cm², or some four per cent of the heat flux required for the complete melting of the equivalent volume of rock. Wilson (2003: 5315) corroborates the time-dependent insulating properties of rock by simulating the temperature perturbations on the surface of concrete caused by lightning strikes (with concrete thermal properties very similar to those of rock used...
by Robinson et al., 1971).

Technically transferring this amount of heat to the rock was considered by Robinson et al. (1971: 20 onwards), and the solution offered was to make use of a small nuclear reactor and lithium heat pipes. Holman (1981: 526) refers to this work conducted at LASL on heat pipes, and confirms that these devices are capable of attaining heat fluxes in excess of 2 kW/cm² at temperatures of 1 250°C.

By exploiting the Navier-Stokes equation for incompressible flow, Robinson et al. (1971: 17-19) additionally explored the relationship for the viscosity of molten rock and hence the force required to drive a conical penetrator. Substitution of the appropriate dimensions in the equations given by Robinson et al. (1971: 17-19), yields a force of approximately one kilo Newton for a 34 mm conical penetrator.

Addressing the rate of penetration of this type of device, Krajick (1999) reports that the devices developed at LANL have a penetration rate of approximately one metre per hour, which is considered inadequate for a commercial drilling operation. However, no mention was made of the diameter of the devices tested.

Aside from the low penetration rate, the cooled molten rock, once solidified, formed a glass-like substance (Robinson et al., 1971; Mancinelli, 2000; and McConnell, 2001), which could be forced to extrude into cracks and fissures in the host rock. The original development of the “subterrene” concept was for the boring of large diameter tunnels at great depth, and the formation of this glass was put to good use as a consolidating liner, with McConnell (2001) indicating that it was possible to induce stresses of approximately ten mega Pascals within the liner, sufficient to act as substantial support for deep-level tunnels.

Nonetheless, it remains that there will be amounts of molten rock extruded from the melt zone and that these will require specialised cooling and handling equipment and operations, adding to the complexity of the operation and the energy consumption, particularly in consideration of the cooling and ventilation requirements placed on the mine’s infrastructure. Additionally, the large-scale melting and extrusion of rock poses safety and workforce maturity questions. While this statement may appear contradictory when viewed from the contents of Section 4.4.5, the scale of melting must be considered when analogies are drawn.

4.4.2 Thermal spalling

Shigley (1977: 68) describes the stress generated in the rock under sudden heating or cooling ($\sigma_{th}$) as being given by equation 4.4.1, viz:

$$\sigma_{th} = \frac{\alpha E}{(1-\nu)}(T_0 - T_s)$$

where:
- $\alpha$ is the coefficient of thermal expansion (°C⁻¹);
- $\nu$ is Poisson’s ratio (dimensionless);
- $E$ is Youngs modulus (Pa);
- $T_0$ is the temperature of the undisturbed rock mass (°C); and
- $T_s$ is the temperature of the rock surface (°C).

The coefficient of thermal expansion for granite is given by MATWEB (2005; http://www.matweb.com/) as having a range from 3.7 to 11 µm/m°C, while typical values for quartzite and the Bushveld igneous complex rocks encountered in South African mines (after Ryder 2002: 66) are given in Table 4.4.3:
Substitution of these values into equation 4.4.1 yields that the temperature difference required to spall rock by heat addition varies from 250°C to 830°C for quartzite and 180°C to 590°C for the Bushveld complex rocks.

Given that these temperatures are approaching those of the melting drill described in Section 4.4.1 and by Robinson et al. (1971), it is likely that for this technique the rock will spall before it begins to melt, possibly forming cracks ahead of the penetrator. As concluded in that section, this may be advantageous when molten rock can be extruded into these cracks and allowed to cool, forming a bond between adjacent blocks or delaminated beam elements.

Taking this further and exploiting the relatively low tensile strengths of rock, if rock could be cooled sufficiently rapidly, cracking of the local area will occur (Robinson, 1971: 34). Unpublished test data for the BIC indicates the tensile strengths (by Brazilian disc method) as given in Table 4.4.4 below:

**Table 4.4.4: Tensile properties of Bushveld igneous complex rocks**

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pegmatoidal pyroxenite</td>
<td>8,9</td>
</tr>
<tr>
<td>Norite</td>
<td>13,4</td>
</tr>
<tr>
<td>Chromitite</td>
<td>13,5</td>
</tr>
<tr>
<td>Anorthosite</td>
<td>14,8</td>
</tr>
<tr>
<td>Pyroxenite</td>
<td>20,1</td>
</tr>
</tbody>
</table>

Substitution of these values into equation 4.4.1 reveals a range in temperature differentials of from approximately ten degrees Celsius (pegmatoidal pyroxenite) to 60°C for pyroxenite.

While the temperature differences required for tensile cracking are much lower than those required for compressive spalling, there is little or no literature available that makes use of spot-cooling to achieve localised rock cracking. Cooling by way of heat pipes and heat pipe/adsorber systems has advanced recently to the stage where waste heat is used to produce ice (Wang et al., 2005), but no mention is made in the literature of the uses of this type of device other than for typical heating, ventilation, and air conditioning (HVAC).

Conversely, the use of elevated and concentrated heat sources for drilling has received considerable attention in recent years, most notably in the gas exploration industry and these are discussed in Sections 4.4.3 and 4.4.4.
4.4.3 Laser

The use of lasers to drill through rock is receiving attention from the oil and gas fraternity, where the costs of mechanical drilling deep holes, both on- and offshore is excessive and time consuming. Hatcher (2003) estimated in 2003 that the total cost of drilling onshore in the United States exceeded US$15 billion and, from that point of view, it is appropriate that expensive and high technology equipment should be investigated. As an example of the top end of the laser range, Gahan (2002) states that a six inch (152 mm) beam from the US Army's 900 kW mid infra red advanced chemical laser (MIRACL) removed six pounds (2.7 kg) of sandstone in 4.5 seconds.

While this finding is indicative of the power-density capabilities of lasers, the general maturity of the technology for the underground drilling of (relatively) small diameter holes has not received much attention, although the general premise of operation is becoming better understood. Nagai et al. (2000) indicate that the use of lasers to excavate rock has been studied since the early 1970s, although practical field applications for this technique had not materialised due to the size of the equipment required and the lack of laser power available at the time. These researchers managed to cut granite and sandstone by melting a slot using a continuous CO₂ laser, with power outputs of 1.2 kW, 5 kW and 10 kW. Although no penetration rates were recorded, it was stated that the penetration depth into granite was less than for sandstone, which Nagai et al. (2000) attributed to the higher melting temperature and specific heat and thermal conductivity of granite.

Of significance, Nagai et al. (2000) report that the molten rock formed in the melt pool prevented deep penetration of the laser. Removal of this slag pool, therefore, was paramount to performing continually deeper cuts. However, the authors did note that the rock became embrittled by the heating process, particularly the granite, allowing easy removal of the slag and heat affected zone by mechanical means.

Gahan et al. (2001) noted similar shielding by the melt pool, and quantified their observations by recording that the specific energy increased with duration of exposure to the laser at a given power output. For this work, Gahan et al. (2001) used a 1.6 kW pulsed neodymium yttrium aluminium garnet laser (Nd:YAG), to determine the threshold parameters required to remove the maximum volume of rock. The various threshold parameters that were varied included the beam exposure time to the rock, the pulse width, and the pulse repetition rate. The researchers principal findings were:

- Specific energy rapidly increases with exposure time (melt pool shielding);
- Specific energy decreases for increases in both the pulse repetition rate and pulse width; and
- Results from the cutting of a shale sample indicated that the specific energy reached a minimum in the spallation zone, just before the onset of melting. This results is diagrammatically shown in Figure 4.4.2:
Figure 4.4.2: Specific energy versus laser power (after Gahan et al., 2001)

Figure 4.4.2 is included with non-indicated axes specifically so as to provide an indicative relationship for the parameters, and it is noted that Gahan, et al. (2001) state that different rock compositions will behave in different manners.

Hallada et al. (2001) demonstrated the cutting of three types of rock (massive sulphide, quartz diorite and a disseminated quartz diorite) using a continuous wave infra-red laser beam and also noted the shielding effects of the ablated products of melting as being deleterious to the specific energy of penetration. These researchers used a nitrogen gas purging system to clear the melt pool, but noted that there existed a depth beyond which the gas purge could not reach, thus restricting the influence of this technique. Nonetheless, the performance recorded by Hallada et al. (2001) showed penetration rates varying from 0.32 m/minute to 0.48 m/minute, depending on the sample being drilled, at laser powers of 7.15 kW and 7.75 kW, returning specific energy consumptions of 41.12 kJ/cm³ to 30.41 kJ/cm³ respectively. Interestingly, Hallada et al. (2001) indicate the potential use of lasers in mining by stating that optical fibres could be used to transmit the laser beam from a remote source to multiple sites in the workplace, obviating the need to carry bulky equipment into confined spaces.

Xu et al. (2003), while largely repeating the work of Gahan et al. (2001), used a fibre optic system to deliver the beam to shale and sandstone specimens, and claimed losses of the order of 18 to 57 per cent for the Nd:YAG laser, running at an average power of 1.6 kW. Similar to the specific energy trend reported by Hallada et al. (2001), Xu et al. (2003) recorded a minimum specific energy of 0.508 kJ/cm³ in shale at temperatures just before the onset of melting (Figure 4.4.2).

Gahan and Shiner (2004) discuss the development of doped silica fibre lasers that are diode excited and utilise Bragg gratings written onto the fibres to produce high quality beams. These fibre based lasers are at a stage of development whereby they are produced in sub-assemblies and can be “bundled” together to produce the desired maximum power output required for the
task at hand. Gahan and Shiner (2003) claim that these devices are almost maintenance free and project a diode life of some 100 000 hours.

While the literature reports positively on the use of lasers as a means for drilling rock, whether by spallation, melting or vaporisation, the diameters of beams used are considerably smaller than those required for blast- and support-hole purposes. Nagai et al. (2000) used beams varying from 0.5 mm to 10 mm in diameter; Gahan et al. (2001) used beams between 9.5 mm and 12.7 mm diameter and Hallada et al. (2001) employed a beam of 5.9 mm in diameter. Rao et al. (2005) conducted work on concrete cutting and drilling, using beams of the order of 30 mm to 35 mm in diameter from lasers with up to 10 kW in power. While specific energies were not explicitly given by Rao et al. (2005), it was again noted that the influence of the ablated material was to increase the time required to hole through the concrete blocks.

While research is continuing into the use of lasers in deep oil- and gas-well drilling, the technology is still some way off from commercialisation as a dedicated drilling device. Once commercialisation is achieved, the development of lasers for blast- and support-hole development must be monitored for potential spin-off. It must also be remembered that the safety aspects and highly technical nature of such devices will require a mature and educated work force.

4.4.4 Thermal jets

The web site of Materials Engineering (UK) Ltd., (http://www.meg.co.uk/meg/app10.htm) states that the use of thermal or thermic lances for the cutting and general destruction of concrete has been used since the Second World War. In essence, compressed oxygen is blown down a heated hollow steel tube and the discharge end ignited. The intense heat produced (1 800°C to 2 500°C) consumes the tube, or lance, and is sufficiently high to melt concrete and speciality steels. Materials Engineering (UK) Ltd. indicates that the process does not generate much noise, but that the high temperature and the use of compressed oxygen make the cutting activity dangerous. Good ventilation is required and sufficiently large areas to avoid contact with molten slag.

As an extension of this process, the web site of the US Department of Energy (DOE - http://www.fe.doe.gov/) and the US National Energy Technology Laboratory (NETL; http://www.netl.doe.gov/) report that the Los Alamos National Laboratory (LANL) was funded jointly with the New Mexico Institute of Mining and Technology (NM Tech) to develop and evaluate a “hard rock thermal spallation cavity maker”. The device was developed to open up cavities in hard rock, remotely from surface with no human entrance to the workings. In essence, a hydrocarbon gas was pressurised down one bore of multi-bore coiled tubing and ignited in burners arranged to blow vertically downwards. This flame would then heat the rock, setting up high compressive stresses in the outer layers. In a second bore of the coiled tubing, water would be pumped down and arranged to spray onto the heated rock, causing it to contract and spall off. Debris and gas were ejected from the hole formed this way through an annulus outside of this multi-coiled tubing. The basic process is depicted mounted on the back of a truck in Figure 4.4.3.
Similarly, a patent granted in Slovakia on 1994-11-09, patent number E21B 7/17 (available at http://www.bit.or.at/irc/bbs3.php?ref1=BICBA024&vQuelle) relates to a similar system whereby it is claimed that the combustion of hydrogen in an oxygen atmosphere under the drill creates a high-temperature environment that melts the rock, creates cracks in the immediate vicinity of the melt and then presses the molten glass into these cracks, forming a liner. The theoretical drilling speed of this system is given as between three and five millimetres per second, and the parts undergo little or no wear.

While the use of heat, in the form of energy released from a combustion process, is recognised as being capable of creating holes in rock, it is also noted that the process has the potential to be dangerous, may well produce products of combustion that may have deleterious effects on humans and require an open flame, thus prohibiting their use in methane-rich environments. Similarly, the heat generated by such devices will have negative effects on the climate in a confined working area. For these reasons, this technology is not considered worth pursuing for an underground environment, and the web site search detailed above is considered for completeness of the literature review only.

4.4.5 Microwave

Jerby and Dikhtyar (2001) describe the microwave drill (US patent number 6,114,676) as being capable of drilling into many non-conductive (to electro-magnetic radiation) materials, such as (amongst others) concrete, rocks, ceramics, wood and glass. The principle of operation is to concentrate the microwave energy using a wave guide into a small spot underneath this “near-
field concentrator”, causing a localised hot spot, which melts the material. The pin of the concentrator is then pushed into the melt pool, forming a hole. On retraction of the concentrator pin, the molten material solidifies, leaving a lined aperture. This principle is illustrated in Figure 4.4.4.

![Diagram of microwave concentrator](image)

**Figure 4.4.4: Microwave concentrator (after Jerby and Dikhtyar, 2001)**

Jerby and Dikhtyar (2001) claim to have drilled into concrete using a 600 W microwave drill, creating a two millimetre diameter hole, two centimetres deep, in less than one minute. While the authors claim that the microwave drill is quiet and does not produce dust, there are safety concerns arising from the potential for operator exposure to the microwaves and radio frequency interference to other electronic devices.

Jerby et al. (2002) reiterate this warning, but state that it can be overcome by making use of suitable shielding. In addressing the operation of the drill, the authors state that for the drill to be effective, the thermal conductivity of the rock must be greater than or equal to ten Watts per metre-Kelvin and that the complex dielectric constant of the material should be such that:

\[
\frac{\varepsilon''}{\varepsilon} \geq 0.003
\]  

(4.4.2)

where

\[
\varepsilon = \varepsilon' - j\varepsilon''
\]  

(4.4.3)

In addition, the authors state that the melting temperature of the rock should be less than
2,000°C, and that in order to promote the thermal runaway effect, the thermal conductivity of the material should decrease with temperature, while the dielectric properties should increase. As per Table 4.4.1, it can be seen that the requirement placed on the thermal conductivities of common South African formations are satisfied. Addressing the dielectric constants of rock, the CSIR has conducted numerous experiments to determine these for the purposes of radar penetration. Van Schoor (2005, personal communications) indicates that these values were determined for lower frequencies than those used by the microwave drill, and were measured at constant (ambient) rock temperatures, and therefore are not directly applicable to the evaluation of the parameters according to Jerby et al. (2002). Investigative work would therefore need to be conducted to determine the applicability of this technology to the typical South African formations.

Continuing their work in this field, Jerby et al. (2004) have conducted drilling and melting experiments in basalts, although a full transcript of this article has not been received to date and, therefore, no quantitative analysis of the work can be conducted.

It is noted that the typical diameters of hole drilled by this method are small (sub ten millimetres), although correspondence received from Jerby (2005) has indicated that the technology can be scaled to around 40 mm in diameter, and that it will be capable of drilling into rock that contains electromagnetically conductive trace elements. Jerby (2005, personal communications) has stated that this may be beneficial to the process, as the elements may assist with the absorption of radiation. However, it is noted that the work by Jerby and co-workers examined above does not include quantitative evaluations of penetration rates and specific energies of drilling.

Summarising this technology, it must be noted that the requirement of little or no noise appears to have been met, albeit at the cost of having a localised hot-spot in the working area and a potential risk of worker exposure to microwave radiation. However, correspondence with the technology inventor has indicated that, in addition to the silent operation, the drill has the potential to be developed such that it is small and easily manoeuvred in confined spaces. Unlike thermal lancing, or laser spallation, for example, the hot-spot generated appears to be small, with Jerby and Dikhtyar (2001) indicating that this is much smaller than one wavelength in dimension, and the heat affected zone is of the order of a few millimetres for a two millimetre conductor. In addition, this localised heating travels into the rock with the advance of the penetrator. The possibility of using an inert gas to shield the hot area, such as nitrogen or argon, may alleviate some of the potential for explosion. In non-fiery mines, this technology offers the potential for implementation, provided that suitable radiation protection can be developed.

4.4.6 Miscellaneous thermal methods

Avery et al. (1973, 1975) report on experiments conducted using high power pulsed electron beams to spall rock. For the 1975 tests, the accelerators used were of the order of nine megavolts and fired pulses of 64 kJ per shot, generating 120 mm to 130 mm diameter spalls of between seven and thirteen millimetres depth. The calculated specific energy for this system was reported to be between 0.78 to 1.25 kJ/cm³ in granite, basalt, and greenstone. Since these experiments were conducted on a “one shot” basis, Avery et al. (1975) concluded that had there been a capability to fire rapidly repeated shots at the rock, greater penetrations would have occurred as a result of heating and consequent cracking. This conclusion led Avery and co-workers to design a conceptual tunnel-boring machine based on the data gathered, and predicting a specific energy consumption as low as 250 J/cm³. These researchers finally conceptualised a machine capable of advancing a 6.4 m diameter tunnel at 3.2 m/h.

Schumacher and Smith (1974) conducted similar tests with an electron beam of around 15 kW and postulated that relative to the rock face, the energy of the travelling beam manifests itself
below the surface of the rock, leading to sub-surface thermal stress and eventual breakout. Like Avery et al. (1975), Shumacher and Smith (1974) devised several mining machines and methods, including a blast-hole drill.

While these methods appeared, at the outset, to offer good penetration rates, their development has not been documented in later publications, and the scale of intended operation implies preclusion from further analysis in the context of this study. In addition, electron beams produce x-rays, which are harmful to the operators if they are not properly shielded. The inclusion of these methods is therefore intended only for completeness of the literature survey.

4.4.7 Summary of thermal drilling

The mechanisms of thermal melting and spallation of rock in the pursuit of hole-making are well established. In general, however, pure melting of rock is energy intensive and places the operators and stope personnel at risk of injury from exposure to high temperatures. Additionally, the use of heat sources in fiery mines would be unacceptable.

Lasers, which operate by combinations of spalling, melting and vaporisation, are already being investigated for use in the oil and gas industry. These devices, through the use of optic fibres have the potential to drill at several different locations while being powered from a remote source. However, the general maturity of the technology, when applied to rock drilling is low and, therefore, no immediate application is foreseen.

The demonstration of the potential to drill holes using microwaves shows considerable promise for technological advancement. This technique shows potential for small, low-power devices that offer good potential for roof bolting in narrow stopes, as well as blast hole drilling, but has the disadvantage that the technology is relatively new and only in the concept demonstrator stage. As with melting, the fact that the concentration of microwaves generates a melt pool, the potential for use in fiery mines may also be limited, with the attendant risk of burns and an added risk of injury through microwave radiation. Nonetheless, it is recommended that this technology be investigated in depth for applicability.

Table 4.4.5 summarises thermal rock drilling technologies.

**Table 4.4.5: Summary of thermal drilling technologies**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Maturity</th>
<th>Advantages / drawbacks</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock melting.</td>
<td>Demonstrated.</td>
<td>• Silent;</td>
<td>• None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High energy consumption;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Potential for injury;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Unsuitable for fiery mines.</td>
<td></td>
</tr>
<tr>
<td>Laser.</td>
<td>Demonstrated, investigated for oil and gas.</td>
<td>• Silent;</td>
<td>• Monitor for technological progress.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Potential for use in multiple sites from one machine;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Application maturity low.</td>
<td></td>
</tr>
<tr>
<td>Microwave.</td>
<td>Concept demonstrator.</td>
<td>• Silent;</td>
<td>• Research programme to investigate application.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Acclaimed low energy consumption;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Potential for compact</td>
<td></td>
</tr>
</tbody>
</table>
4.5 Plasma drilling

Haase *et al.* (1995) assessed the potential for use of a new type of rock drill that used the shock wave produced by the generation of a high-frequency, short-rise-time electric discharges generated under water to break rock. This device, known as the plasma hole maker (PHM) is the patent of Mr W. Moeny of Tetra Corporation and several studies of the device have been undertaken by the CSIR. In concept, Haase *et al.* (1995) studied the PHM for use as a roof bolt drill owing to its relatively compact design, its capability for drilling long holes with a low reaction force and, hence, suitability for use in narrow stoping widths.

Haase (1995) indicated that the typically existing in-stope electrical system would be sufficient to power the device, thus obviating the need for any additional electrical infrastructure to the panel. The concept of operation is shown in Figure 4.5.1.

![PHM roof bolter](image)

**Figure 4.5.1: PHM roof bolter (after Haase, 1995)**

Drilling tests using a prototype machine in varying rock types, including quartzite, Merensky reef and hard lavas indicated the potential for its use as a viable hole-drilling machine (Haase, 1997), albeit that varying problems were encountered. Several mechanical improvements were identified, including solutions to mechanical failures due to inappropriate fastening mechanisms loosened by the shock loading of the high frequency pulses, as well as a need to move towards a lower-impedance design. This latter modification involved the placement of capacitors inside the drill stem which necessitated research into suitable capacitive storage devices. Güler *et al.* (2000) document the steps taken to develop the necessary capacitors and proved that the technology was available but needed refinement. Unfortunately, at this point collaborative funding was not forthcoming and the project stagnated.

During the tests conducted by Haase (1997), sound measurements were taken and Haase (1997) states that the A-weighted peak-level measurements recorded indicated some 88,6 dB(A) at a distance of 2,5 m from the device. Bearing in mind that the noise emission is the spark created at the rock interface under water, it can be anticipated that this sound level
will diminish with penetration into the rock. Willis (1998) estimated that the penetration rate of this device could exceed 0.5 m/min under optimal operating conditions.

Recent communication with the intellectual property owner (Moeny, 2005, personal communications) has indicated that the PHM has been redesigned, and that a new patent has been taken out to cover the changes made. Moeny (2005) states that the new design of the PHM is five to ten times more efficient that that tested by Haase (1997), and should consume as little as two to five kilo Watts for the same penetration rates. Moeny (2005) continues to state that sound measurements have been taken during the drilling of a seven inch (178 mm) hole, and recorded 102 dB at three feet (0.91 m) from the machine. Other than stating that the sound-level meter was set to the “slow response” setting, it is not known what weighting scale was used for these measurements. Moeny (2005) further states that for these sound tests, the PHM was firing at one Hertz and operating at 1/22 of the designed power input, recording 85 dB at three feet. The reporting of 102 dB was, therefore, a theoretical scale-up to intended operating diameters, frequency and power.

This technology has been tested and proved capable of drilling in typical formations found in South African mining environments, and offers enormous potential for use as an alternative drilling tool, particularly when considered for roof bolt applications. Addressing the use of a seven inch device, Moeny (2005, personal communications) has stated that the machine, in its new form, is capable of being scaled to meet the typical blast-hole diameter of 34 mm to 38 mm. It is also noted that the sound levels appear to be higher than those recorded by Haase (1997), but it is stressed that the sound level reported by Moeny (2005, personal communications) is a scale-up and that formal testing needs to be done at the intended size, frequency, and power consumption. Reiterating the statement made previously and by Moeny (2005, personal communications), the turbulent action of the water (used as a dielectric and a flushing medium) will mask the noise emissions of the machine as it penetrates the rock, thus lowering the effective exposure of the work force to noise.

In summary, it is recommended that investigations into the use of this technology for hole-making in South African conditions be reopened and actively pursued to its logical conclusion.

4.6 **Ultrasonic**

The advent of space flight, particularly the exploration of Mars, has spawned several innovative methods of drilling and coring rock, with particular emphasis on the search for life-sustaining water. These innovations are born from the need to conserve energy, in particular transport mass, and the need to not contaminate alien planetary rocks with conventional drilling mud and earth water for flushing, cooling and lubricating the bit. Bar-Cohen *et al.* (2000) describe the development of the ultra-sonic drilling and coring system (USDC) developed in response to this inter-planetary sampling campaign.

The USDC developed by Bar-Cohen *et al.* (2000) consists of a piezoelectric stack which is excited to between 20 kHz and 23 kHz. A free-floating end-effector (drill or corer) converts this to a combination of this high frequency and a sonic wave in the 60 Hz to 1 000 Hz frequency spectrum. Bar-Cohen *et al.* (2000) maintain that it is this addition of sonic waves that makes the USDC more efficient than conventional ultrasonic-only drills. Free masses on the opposite end of the piezoelectric stack further enhance the drilling action and springs maintain the contact between the drill and the stack. Sherrit (2005) describes the ultrasonic stack, or horn, and how its configuration amplifies the base displacement of each discrete piezoelectric element to maximise the amplitude of vibration. Bar-Cohen *et al.* (2000) do not provide quantified penetration rates and specific energies of drilling, but do indicate that the USDC is capable of clearing the hole of debris by dint of its ultrasonic vibration, implying that no flushing water or fluid is required.
Addressing the performance of the device, Bar-Cohen et al. (2003) state that the device was capable of drilling a six millimetre hole in basalt to a depth of 25 mm in some two hours, using and average of ten Watts of power (peak at 25 W). While this performance is too slow for a production mine drill, it is interesting to note that the authors claim that the rock fracture method is by shearing and spalling, compared with the compressive fracturing of a conventional drill, and that the axial loading required is low – of the order of ten Newtons, an order of magnitude less than for a conventional corer.

Wiercigroch et al. (2005) applied the established understanding of ultrasonic machining (USM) of engineering materials in an attempt to study the influence of ultrasonic excitation of the pre-load force and its amplitude on the material removal rate (MRR), (measured in cubic millimetres per second) for percussive drilling. Experimental work was carried out on a converted jig borer using diamond-coated tools and with the head / tool holder excited at 21 kHz. Rocks drilled included granite, basalt, sandstone and limestone.

The results obtained experimentally by Wiercigroch et al. (2005) for sandstone indicated a linear increase in MRR with increase in amplitude of excitation up to a saturation point at which amplitude the MRR flattened and became constant. Maintaining the amplitude constant and varying the static load on the bit indicated a harmonic relationship with the MRR, with the second maximum approximately double the first. These influences are illustrated schematically in Figure 4.6.1.

![Figure 4.6.1: Ultrasonic material removal rate (after Wiercigroch et al., 2005)](image_url)

In Figure 4.6.1, the left-hand curve is a schematic representation of the influence of the amplitude of excitation, a, measured in microns, and the right-hand curve represents the influence of the static force, F_{Stat}, measured in Newtons. Figure 4.6.1 indicates that an optimal loading and amplitude of vibration exist for this form of drilling process, implying that experimental work needs to be conducted before an ultrasonic exciter can be designed for a rock drill. The overall improvement to the MRR by varying this static force and optimising the...
amplitude was of the order of ten times the conventional drilling MRR.

Wiercigroch et al. (2005) continued their study by theoretically modelling the dynamic behaviour of the system, and concluded that the observed maxima in the load – MRR relationship existed theoretically. This work further indicated that other, greater maxima existed at higher static loads, which improved the MRR further. However, in between these maxima, the authors found that the MRR could theoretically drop to zero.

Both Bar-Cohen et al. (2000) and Wiercigroch et al. (2005) made use of piezoelectric actuators to achieve ultrasonic excitation of the tools, as this technology is relatively well understood. Discussions with Swart (2005, personal communications) have indicated that these devices may not be durable enough for a mining-type application. Swart (2005) has studied the use of magnetostrictive materials, and suggests that these may be a better alternative for producing ultrasonic excitation. This is particularly so as new materials have been developed that offer very much larger strains and developed forces, known as “giant magnetostrictive” materials. The specification sheet for Terfenol-D obtained from Matweb (www.matweb.com) lists the magnetostrictive strain production as being between 1 500 and 2 000 µm/m. McKnight (2005. aml.seas.ucla.edu/research/areas/magnetostrictive/overview.htm) questions the durability of these materials and indicates that in terms of high-frequency actuation, the eddy currents produced in the solid material under fluctuating magnetic fields limit its use at frequencies above approximately 2 000 Hz. However, McKnight (2005) also states that if the material is manufactured in a particulate form and dispersed in a polymer matrix composite, this eddy-current effect diminishes and the composite may be used at frequencies in excess of 100 kHz.

Human hearing does not register sounds above approximately 20 kHz (Guild et al., 2002, chapter seven), and this threshold frequency decreases with age. Given that materials are available to excite mechanical devices above this frequency, it is arguable that exposure to frequencies above, say, 20 kHz may reduce noise-induced hearing loss. This is examined in greater detail in Section 4.6.1.

Attempts to introduce high-frequency percussion to the drills typically used in South African mining have (anecdotally) been unsuccessful (Murray, 2005, personal communications). The work conducted by Wiercigroch et al. (2005), displaying penetration rate minima in measured results and theoretically predicting zero penetration at certain frequencies, may allude to one reason for this unsuccessful work. Other than this study, however, there is little reporting of work done on drilling at higher frequencies, or the influence of frequency on penetration rate by rock type. Pemberton (2005, personal communications, Appendix 1) indicates that Seco, Tamrock and Atlas Copco are developing, or have offered to the market, drills with (relatively) high blow frequencies (53 Hz, 115 Hz and 102 Hz, respectively), but the reasons for moving to these (marginally) higher frequencies are not clear. It is therefore assumed that the bulk of the research work on the influence of percussion frequency is either incomplete or company confidential.

4.6.1 HAVS and NIHL at ultra high frequencies

In the mining industry, the monitoring of occupational disease has played a significant part in increasing the safety and health of the workforce. Hand Arm Vibration Syndrome (HAVS) is one occupational disease that has only recently been investigated in a South African context, whereas noise-induced hearing loss is one of the most commonly identified and compensated occupational health disease in the mining industry.

HAVS is a multi-system pathology affecting the hand primarily but often extending to include the rest of the upper limb. The nerves, arteries and veins, muscle and joints of the hand are affected in workers using vibration tools. In South Africa, the prevalence rate of HAVS is estimated at 15 per cent of mineworkers exposed to vibration at gold mines.
The disease is contracted when a worker is exposed to high levels of vibration over a prolonged period of time. Vibration produced by hand-held tools is transmitted through the hand and fingers to the arm and elbow. In the UK the recommended level of vibration is 2.5 m/s². Tools found in the South African mining industry, such as rock drills, exceed the UK standards ten times and definitely have the potential of producing HAVS in workers.

The vibration exposures required to cause these disorders are not known, neither with respect to vibration magnitude and frequency spectrum, nor with respect to daily and cumulative exposure duration. The guidance given in ISO 5349: 1986 is derived from limited quantitative data available from both practical experience and laboratory experimentation, and from limited information regarding current exposure conditions. This 1986 standard (ISO 5349) also gives the set of curves shown in Figure 4.6.2 that can determine exposure levels likely to cause the first signs of white finger in workers.

![Figure 4.6.2: Curves for exposure times of percentiles of population groups to suffer mild effects on tip of finger (after ISO 5349.2: 1986)](image)

The horizontal axis in Figure 4.6.2 represents vibration acceleration. This is measured as RMS (Root Mean Square) weighted acceleration in m/s². Weighting accounts for variation in human sensitivity to vibrations of different frequencies and the measured value of acceleration at different frequencies is passed through a weighting filter to obtain a single number as an overall measure of vibration exposure. According to this frequency-weighting filter, people are most sensitive to hand arm vibration in the frequency range of 1/3 octave bands with centre frequency 6.3 to 16 Hz. As frequency increases above this range the sensitivity decreases. The standard provides methods for calculating weighted RMS accelerations and equivalent acceleration values where the level of daily exposure varies with time (Canadian Centre for Occupational Health and Safety web site, www.ccohs.ca).

Rahko et al. (1988) concluded that exposure to high-frequency noise from high-speed drills and other modern dental instrumentation does not appear to be harmful to one's hearing and does not necessitate audiologic screening procedures for dental personnel. Rahko et al. (1988) examined 234 dentists and dental nurses with a normal- and a high-frequency audiometer in high-standard clinical conditions. Their ordinary and high-frequency hearing as compared with the controls showed no significant differences. de Koker (2005, personal communications) agrees with this finding, stating that frequencies above 18 to 20 kHz do not affect the hearing cells of the ear, although de Koker confirmed with senior lecturers at the University of the
Pretoria that little is known about the effect of the sound pressure levels at frequencies above 20 kHz which may affect other parts of the ear, and indirectly affect hearing. For this reason, the effects of ultrasound are discussed below to illustrate this potential.

Ultrasound is produced by various industrial sources, including analytic and testing equipment, welding machines, drills, parts cleaning processes, electrolytic coating processes and catalytic processes. Excess exposure can result in damage to the peripheral nervous and vascular systems, leading to neurovascular syndrome, paresis of the extremities, sensations of cold or numbness, headache, fatigue, dizziness, disturbed sleep, and unsteady gait. Ultrasound at intensities of more than 100 to 110 decibels (dB) may produce functional disorders of the nervous and cardiovascular systems, hearing and vestibular effects, and endocrine and humoral changes. Exposure to levels of 120 to 130 dB or to both airborne and contact ultrasound entails increased risk of health effects (Roscin, 1983; Health Canada web site, www.hc-sc.gc.ca).

The major effects of airborne ultrasound of concern in practice are the result of reception by the ear. Grzesik and Pluta (1983) studied the hearing of 55 ultrasonic cleaner and welder operators. No significant differences in thresholds of hearing between exposed and controls were observed at frequencies between 0.5 and 8.0 kHz. However, the authors claimed significant differences in hearing between exposed and control subjects in the ten to 20 kHz range. They claimed threshold elevations and a decreasing number of subjects responding to stimuli at the highest audible frequencies. In a follow-up of 26 of these workers, Grzesik and Pluta (1986) suggested that a hearing loss of approximately one decibel per year occurs in the frequency range of 13 to 17 kHz due to the occupational exposure of these workers to the acoustic fields created by the ultrasonic cleaners and welders. The acoustic spectra of these devices (Grzesik and Pluta, 1980; 1986) indicated that the sound pressure levels (SPLs) were in the range of 80 to 102 dB at frequencies between ten and 18 kHz, the upper sonic frequencies, whereas the SPLs were in the range of 100 to 116 dB at frequencies greater than 20 kHz. In the absence of a detailed correlation between the acoustic spectra and the measured effects on hearing, it is uncertain which frequencies were responsible for the high-frequency hearing losses. However, it is more likely that the upper sonic rather than the ultrasonic radiation lead to the measured hearing losses in these studies, since high SPLs at upper sonic frequencies were found more frequently than at ultrasonic frequencies (Grzesik and Pluta, 1980, 1986). Also, as noted above, temporary threshold shifts (TTSs) have apparently been observed for subjects exposed to pure tones at upper sonic frequencies between ten and 16 kHz, with SPLs greater than 90 dB. Furthermore, there is no other substantiated evidence for effects on hearing below ultrasonic SPLs of 120 dB.

Other physiological effects of airborne ultrasound are likely to occur only at SPLs greater than or equal to those which would lead to TTS. Knight (1968) and Grigor'eva (1966) found no evidence for any physiological effects at ultrasonic frequencies. Dobroserdov (1967) found significant loss of balance stability and reduced motor response time for exposures to 120 dB at 20 kHz, but the effects were insignificant at 100 dB at the same frequency.

A number of "subjective" effects have been reportedly caused by airborne ultrasound, including fatigue, headache, nausea, tinnitus and disturbance of neuromuscular coordination (Skillern, 1965; Acton and Carson, 1967; Acton 1968; Crabtree and Forshaw, 1977; Herman and Powell, 1981). Skillern (1965) measured the 1/3-octave band spectra from ten to 31.5 kHz from a number of ultrasonic devices and found that subjective effects were associated with devices which produced SPLs greater than 80 dB in this frequency range.

To summarise, exposure to ultrasonic radiation, when sufficiently intense, appears to result in a syndrome involving manifestations of nausea, headache, tinnitus, pain, dizziness, and fatigue. The type of symptom and the degree of severity appear to vary, depending on the actual spectrum of the ultrasonic radiation and the individual susceptibility of the exposed persons, particularly their hearing acuity at high frequencies. A concise summary of the physiological
effects of ultrasound with specific stated exposure conditions has been given by Acton (1974), and is shown in a modified form in Figure 4.6.3.

![Figure 4.6.3: Physiological effects of airborne ultrasound (adapted from Acton, 1974)](image)

4.6.2 Summary of ultrasonic drilling

The use of ultrasonic vibrations applied to tools is an established technology in the precision metal machining industry, and has been demonstrated to be capable of drilling into rock. While the demonstrated holes are small in diameter and little is known of the specific energies of drilling nor penetration rates, the potential for scale-up exists.

Developments in smart materials have demonstrated the ability to provide percussion at ultra-high frequencies. A controversial approach perhaps is to assume that if the frequency of
excitation is moved outside the range of human hearing, little or no damage is done to the auditory system. The literature has shown that there are side effects, but that this subject needs further investigation to prove its safety. Similar to the summary given in Section 4.1.2, the use of smart materials and the influence of frequency on rock breakage requires investigation, in parallel with an occupational health study on the effects of ultrasonic sound on human physiology.

4.7 Active and passive noise suppression

The abatement or attenuation of noise generally falls into two distinct categories, whether the control methods are for personal protection (such as HPDs) or for general work-area isolation of the sound source. Passive noise control or suppression implies that the device draws no energy from any external source, and tends to rely on absorption or reflection of the incident sound waves.

Devices that actively control noise tend to be powered by an energy source, and operate on the principle of measuring the frequency spectrum of the sound wave, inverting it or shifting its phase by 180° and then re-injecting this sound wave at the correct moment to achieve destructive cancellation of the noise. HPDs operating on this principle are used extensively in the military aviation field in pilot’s helmets (Pääkölän et al., 2001). The advantages are that background noise is effectively reduced, but the devices allow the hearing of normal conversation and radio transmissions. Similar devices have been studied for commercial purposes (Sethia, 2002; Narahari, 2003) and are offered for retail sale (http://www.targus.com/; http://www.aircraftspruce.com/, for example).

While HPDs are outside the scope of this study, it is worthwhile to note that the majority of these are passive devices, and while discussed in Section 3.3, new technology is emerging in the passive HPD market that offers tunable attenuation over the entire hearing spectrum (www.noiseclipper.co.za). Test results made available for one such device, the Noise Clipper®, indicate that it is capable of attenuating some 44 dB(A) in the spectrum 125 Hz to eight kilo Herz (SABS, 1997). This HPD, which is custom-fitted to the wearer, appears to offer superior attenuation than the devices listed in Tables 3.3.2 and 3.3.3, and is claimed to be comfortable and hypoallergenic. However, these wearer-specific HPDs are regarded as expensive, and place additional onus on the user for their safe keeping and maintenance in a hygienic state. Regarding price and safe-keeping issues, Steenkamp (2002) indicates that, in one instance, a worker who had been issued with a wearer-specific HPD did not wear it at all for fear of losing it and becoming liable for the replacement cost.

The use of HPDs is ultimately reliant on the user, who, even though issued with HPDs by the employer (free of charge), may elect not to use this protection for a variety of reasons. Ear infections may play a part, making the use of HPDs uncomfortable, and, conversely, inadequate cleaning and disinfection of the devices may cause ear infections. Dimensional changes in the auditory canal, whether through trauma or other causes may hinder the ideal fitment of the device, diminishing its attenuation properties, as may damage to the device itself. Given the above, therefore, engineering the noise out of the device, or attenuation of the noise by means such that workers in the vicinity of the noise source do not have to wear HPDs appears the more tenable option.

4.7.1 Noise barriers

Maneylaw et al. (1997), Harper and Scanlon (1997) and Ottermann et al. (2001a), are some of the researchers who have discussed the use of materials to damp sound waves and minimise their propagation into free space. This form of passive damping of energy (i.e. no additional energy input) is considered as one form of noise control, and is generally the first line of attack when strategies to reduce emission levels are being considered. The addition of silencers and
absorption materials generally, however, tend to add bulk, or dimensional increases, as well as mass to an object.

An alternative to retrofits and design modifications to the machine itself is the use of barriers to deflect or absorb sound emissions and prevent their transmission between areas within the workplace. This practice is commonly used in the civil engineering industry for temporary sound barriers around construction sites, and for abatement of traffic noise in residential or suburban areas. While technical details are not available, SGB (UK) markets the “Defender” acoustic barrier system of panels and claims a reduction of at least 10 dB (www.sgb.co.uk). This is a rigid acoustic barrier and appears (superficially) to be difficult to transport and set up in an underground environment.

Weber and Mehra (http://www.ibp.fhg.de/akustik/ba/schallschutz/foils.pdf) give the mass law of transmission loss of sound as being proportional to the mass per unit area of a foil or membrane, as in equation 4.7.1:

\[
R = 10 \log_{10} \left[ 1 + \left( \frac{2 \pi f m^* \cos \theta}{2 \rho L c L} \right)^2 \right] \text{ (dB)} \quad \text{(4.7.1)}
\]

Where:  
- \( R \) is the transmission loss (dB); 
- \( f \) is the frequency (kHz); 
- \( m^* \) is the mass per unit area of the material (kg/m\(^2\)); 
- \( \theta \) is the angle of sound incidence (radians); and 
- \( \rho L c L \) is the characteristic acoustic impedance of air (≈400 kg/m\(^2\)s).

From equation 4.7.1 it is apparent that one of the fundamental influences on acoustic impedance is the mass per unit area of the material. As such, Sound Reduction Systems Limited (UK) markets a product under the trade name “Soundstop” as an acoustic curtain material, comprising lead sheet clad on either side by an acoustic foam.

Considerable work has been done on the modelling of the insertion losses associated with sound diffractive and absorptive barriers in an acoustic environment. Dance and Shield (2000) discuss the relative accuracies of predictive methods. These authors considered absorbent barriers positioned in an empty factory and compared modelling techniques with recorded attenuation levels around the barrier. They concluded that for predicting the insertion losses and differences, it was necessary to include a diffraction area of two wave lengths either side of the barrier to increase the consistency and accuracy of results.

Yang and Gan (2001) discussed work conducted on an actively controlled sound barrier, which operated by the active cancellation of the sound pressure wave around the diffraction edge of the barrier. Their conclusion was that it was possible to predict the required number of secondary sound sources and error microphones (used to emit and monitor the cancellation wave) by numerical techniques. Importantly, Yang and Gan (2001) state that the most effective method of cancellation is to ensure that the secondary sources (of cancellation sound waves) are placed as close as possible to the primary sound source.

Forssén and Ögren (2002) address the influence of air turbulence on the scattering of sound waves around a thick barrier, with air velocities in the one to three metres per second (“calm” conditions) and at velocities of four to seven metres per second, giving greater turbulence. The “wide” barrier was constructed using two cargo containers placed end-to-end, effectively creating a relatively long barrier with a height to width ratio of 1,05:1. By recording the sound pressures on the lee side of the barrier in response to the varying wind speed and a known sound source, Forssén and Ögren (2002) concluded that the scattering of the sound waves as a result of turbulence can significantly increase the noise level behind the barrier. The increases recorded were up to five decibels at four kilo Herz and approximately ten decibels at eight kilo
Herz. Section Five of this report sets out typical sound spectra for rock drills, and shows that (when read in conjunction with the information presented in Figure 3.2.2), the expanding exhaust air from pneumatic drills and the (general for all drills) resonance of the drill string contribute to the bulk of emissions in these frequencies, generally at the higher sound pressure levels.

While the work of Forssén and Ögren (2002) contains many assumptions, the conclusion must be drawn that the dimensional configuration of any barrier needs to be considered against the ventilation velocities within the stoping environment, in order to preclude amplification of noise.

“Tonal noise” is the term used to describe sound emissions that have one or more dominant frequencies that constitute the bulk of the unwanted noise. Ming (2005) addressed the attenuation of tonal noise emissions from gearboxes installed at a mine drive station and described the development of a novel barrier system to attenuate the noise based on the use of a Helmholtz resonator. The barrier consisted of a purpose designed shaped cavity with sound-absorbent cladding on the inner surface. Measured insertion losses for this barrier system achieved 19.7 dB(A) at 10 m to 5.9 dB(A) at greater than 35 m from the source (510 Hz), and 19.7 dB(A) to 11.1 dB(A) at the same locations for a frequency of 1470 Hz.

Section Five of this report indicates that the noise emitted from drills is generally broad spectrum noise (i.e. not distinctly tonal), and therefore the work of Ming (2005) is not strictly applicable. However, the total noise challenge existing in a mechanically diverse environment such as a mine is comprised of numerous sources, and this work is therefore included here to illustrate methods of alleviating noise from ancillary equipment, such as scrapers, fans and winch drives, which all add to the total sound pressure.

4.7.2 Active noise attenuation

The advent of miniaturised electronic components has increased the capability of adding small and discrete processing devices that can be used to decrease the effective sound pressure levels emitted. The concept of Active Noise Cancellation (ANC, or Active Noise Destruction, AND) of unwanted sound is becoming a mature technology. The detection of a sound waves, either by microphones (or accelerometers measuring structural vibration, Active Structural-Acoustic Control, ASAC), analysing it for amplitude and frequency, and re-injecting a sound or stress wave of the same frequency and amplitude, but out of phase by 180 degrees, show considerable promise for cancelling unwanted noise by addition of the two wave motions (destructive interference).

Jayachandran et al. (1999) indicate that the use of passive techniques (absorption, for example) is inadequate for the lower frequencies of sound (100 Hz to 400 Hz), which view is reinforced by Narahari (2003), who indicates that below 500 Hz, passive devices lose their sound absorption capacity.

Jayachandran et al. (1999) further state that the use of traditional moving coil loudspeakers for the re-injection of these frequencies, using ANC techniques, has the propensity to cause this ancillary equipment to become bulky and heavy. This, the authors state, is due to the efficiency of circular diaphragm speakers being directly proportional to their diameter, and in order to provide adequate fatigue life, the thickness of their materials of construction. In addressing this, Jayachandran et al. (1999) considered piezoelectrically excited conical surfaces, which exhibit greater stiffness and therefore higher flexural rigidity, and give a lighter design for a given component life and power output. Additionally, Jayachandran et al. (1999) indicate that experimentation has shown that piezoelectric actuators have a low electro-acoustic efficiency but that, for the aerospace application under consideration, the lower mass offered a viable solution. While a largely theoretical study, Jayachandran et al. (1999) have indicated that the use of piezoelectric speaker-amplifier systems offers potential for incorporation in aircraft
interiors for sound cancellation, by proposing multiple small systems throughout the fuselage interior.

It must be noted that the interior of an aircraft is of a known, constant dimension and is altered acoustically only by the addition of passengers, while the equivalent properties of an active mining stope will vary considerably on an ongoing basis.

Cuesta and Cobo (2000) examined ways of reducing the noise emitted from a reciprocating engine-generator set, and applied both passive damping and ANC techniques. The authors utilised a total enclosure of the noise source (apart from combustion air, cooling and exhaust duct air gaps), passive elastomeric engine mounts, purpose-designed concentric exhaust ducts and multiple small diameter air intakes to provide the passive damping. The ANC system was dedicated to the exhaust system of the engine, as this then became the dominant noise source. An accelerometer mounted on the air filter cover provided the reference signal, and special high temperature speakers emitted the ANC waves directly into the exhaust duct. An error signal microphone, again located inside the exhaust piping, allowed for control of the overall time-related injection of the cancellation sound waves.

While the overall attenuation of this system is stated as being 33 dB at the second harmonic, it must again be noted that the system is dimensionally and constructionally time-independent. The noise source varies only with a known load characteristic, unlike the collaring and subsequent drilling into varying rock structures with varying operator-machine-rock characteristics.

Continuing up the technology spectrum, it is worth considering the advances made in another noise-generating environment, particularly that of the aerospace industry, where legislation is beginning to dominate the design and commercial release of aircraft. Neise and Enghardt (2003) report on work done on attenuating a purpose designed, noise-intensive, duct-mounted counter-rotating aeroplane propeller system. Rods were mounted immediately upstream of the first propeller to induce a strong tonal field. The ANC system consisted of 96 precision microphones located in the upstream airflow into the duct, followed by 32 error microphones and 32 sound-injection loudspeakers. Two ANC concepts were tested, and the complex analysis revealed a diminishing of the sound power levels of between 24 dB and 34,2 dB. The authors, however, indicate that the loud speakers incurred both weight and space penalties, and that passive lining materials would perhaps have been more economical and operationally simpler, albeit less acoustically efficient.

Magnetostrictive steels are finding their passage into vibration-damping technologies in ways that have the potential to reduce sound levels. The strain transformation ability of these materials under inductive magnetisation and their converse inductive current generation properties under strain conditions are being harnessed to counter vibration pulses.

Addressing the use of smart materials in a drilling context, Kumar et al. (2003a) studied the use of a magnetostrictive layer bonded to an aluminium beam, and used negative velocity feedback to control vibrations within the beam. The counter vibrations were induced by an electromagnetic field applied to a solenoid around the magnetostrictive layer. While primarily a rigorous theoretical study, the authors concluded that the best location for the solenoid-magnetostrictive layer was at the position of maximum beam deflection. They further concluded that the selection of the boundary conditions influenced this (theoretical) result, and that this technique may not control all modes of vibration. No experimental results were recorded.

Section 4.1 of this report indicates that the dynamics of the vibrations induced in the drill rod are not well understood, and that these transverse vibrations are the source of the noise emanating from the drill steel. Similarly, Section 3.2.1 indicates that damping of these vibrations can result in a three-to-four decibel decrease in sound pressure levels (A-weighted). While Kumar et al. (2003a) studied vibration attenuation in a simple beam, Kumar et al. (2003b) extended these
studies to an examination of a cylinder (analogous to a drill steel) with a circumferentially deposited magnetostrictive layer with attendant actuating electromagnetic coil. Again, and with no experimentation, the authors conclude the theoretical study by stating that the indications are that the maximum vibration reducing location for the magnetostrictive shell is at the point of maximum displacement.

Hypothesising a use for this technology applied to a drill steel indicates the location of the sensor-actuator device around the outside (or inside the internal bore) of the drill steel that moves with penetration into the hole being drilled. It is anticipated that the point of maximum vibration will be at some point along the steel between the drill chuck and the rock face, which varies as penetration advances. The practical implications for this are that the device will either need to be extremely small, and / or be exposed to an extremely harsh environment, subject to abrasion and corrosion from contact with the rock and flushing water.

While magnetostrictive steels are one example of “smart” materials, there are many other materials available that display similar characteristics. Moheimani et al. (2004) and Hurlebaus and Gaul (2006) provide concise reviews of these materials and their applications, which range from the vibration control of structures to the harvesting of the energy generated by virtue of a structures displacement under induced vibration. While nothing cited by the authors has direct bearing on drilling, the applications of smart materials science to acoustic and vibration engineering is illustrated as becoming well understood. A detailed evaluation of the application of these smart materials is considered to be outside the scope of this study, and the summaries of Moheimani et al. (2004) and Hurlebaus and Gaul (2006) are therefore noted as reference works for the development of potential drilling-specific applications at a higher research level.

4.7.3 Summary of active and passive noise suppression

The use of sound barriers as a means of noise attenuation is common practice in the engineering fraternity and, as such, these are represented by the tubes used by Harper and Scanlon (1997) and Otterman et al. (2001a) to enclose the standard pneumatic rock drills. In the civil engineering industry, barriers are used to shield residential areas from excessive road noise and construction activities. In a factory environment, barriers are used to partition and shield noisy operations from the remainder of the workforce. In a mining application, the erection of absorptive acoustic barriers around a drilling operation has the potential to reduce reverberation and the unwanted amplification of noise, and to protect other mine personnel in the vicinity from the drill noise. While the prevention of reverberation from the hard and reflective face, hanging, side and footwalls has the potential to reduce the noise received by the operator, it must be stated that the current rock drills will still place the drill operator and assistant at risk of NIHL. As such, barriers are not considered a total solution, unless:

- They completely enclose the drill while allowing the operator to retain control; or
- They are used as part of an overall barrier system used in conjunction with the remote control of the drilling operation.

Active noise control has the ability to cancel the sound waves emanating from a device, and has been demonstrated to offer high attenuation levels under controlled environments. Its application to a mining environment, however, is less certain under continually changing acoustic conditions, but is nonetheless considered worthy of in-depth investigation.

Similarly, the active control of structural vibration shows potential to reduce the transverse vibrations occurring in the drill steel, which have been documented as the primary source of sound from this element within the drilling process. However, the use of actuators placed along a drill steel seems, at the outset, to be at locations that will be subject to damage and deterioration that may negate the benefits from a cost point of view. Nonetheless, this technology is reaching a level of maturity suitable for drilling-specific investigation, and it is
recommended that technological progress be monitored, and an industry expert be engaged to
highlight suitable applications in greater detail.

5. Comparative testing of rock drills

The CSIR was commissioned by a major South African mining concern to investigate the
performance of rock drills. The objective of this study was to determine the performance and
noise emission levels both on surface and in an underground platinum stoping environment.
This latter test regime was to establish the influence of the reverberation and sound-pressure-
level amplification offered by the confinement of the hangingwall, face and footwall, with packs
and support behind the drillers.

The drills tested were:

- Electrically powered at two different rotational speeds (one manufacturer);
- Unmuffled pneumatic machines (one manufacturer);
- Muffled pneumatic machines (two different manufacturers), both with and without (one
  manufacturer) automatic water shutoff functions.

In the context of this report, the results will be compared against the single model of an
unmuffled pneumatic machine, as this can be construed as the current industry standard, and
the subject of the studies covered in Section 3 of this report. In order to maintain the anonymity
of the machines tested, these will be referred to in the remainder of this report according to the
designations given in Table 5.1.

Table 5.1: Test drill designation

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UA</td>
<td>Unmuffled machine, manufacturer A</td>
</tr>
<tr>
<td>MA</td>
<td>Muffled machine, manufacturer A, with automatic water shutoff</td>
</tr>
<tr>
<td>MB</td>
<td>Muffled machine, manufacturer B, with automatic water shutoff</td>
</tr>
<tr>
<td>E1</td>
<td>Electrically operated machine, 405 rpm</td>
</tr>
<tr>
<td>E2</td>
<td>Electrically operated machine, 450 rpm</td>
</tr>
</tbody>
</table>

5.1 Surface trials

Base-line studies involving drilling into a block of Norite were conducted on surface at the CSIR,
Johannesburg premises. The air pressure to the pneumatic machines was varied from 350 kPa
to 500 kPa, and the flow rate, temperature, and pressure recorded, as well as the penetration
rate into the Norite, along with water flow rate, pressure and temperature. Simultaneous with
this, the sound pressure levels were recorded in accordance with SABS ISO 3744:1994 for
each air supply pressure. The electrical machines were monitored for voltage and current
consumption in addition to the water parameters as per the pneumatic machines.

The background noise was measured at the test site, and the spectrum and total sound
pressure level is given in Table 5.1.1.

Table 5.1.1: Background noise (surface)
The total sound pressure level given in Table 5.1.1 is the linear value, which corresponds to 60.3 dB on the A-weighting scale. SABS ISO 3744:1994 makes use of a correction factor, \( K_1 \), when sound levels are interpreted against this background noise, and the base criterion is that if \( K_1 \) is less than or equal to 15 dB then no correction needs to be made. With the exception of the electric drill at the low frequencies (below 250 Hz), no corrections needed to be made to the sound pressure levels recorded while drilling on surface.

Figure 5.1.1 depicts the sound pressure levels recorded during surface tests conducted on the unmuffled machine of manufacturer A, (drill UA), at pressures of 350 kPa, 450 kPa and 500 kPa. While the sound signatures were recorded at these varying pressures for all the drills, this single result is displayed here for illustrative purposes.

The x-axis of Figure 5.1.1 indicates the frequencies at which the sound levels were recorded, with the labelled extreme right data point (column labelled \( L_{pA} \)) being the overall sound pressure level, calculated from these individual spectra points and using the A weighting scale (SABS ISO 3744:1994). Immediately apparent is the increase in sound pressure levels with an increase in air-supply pressure to the drill. This was a common trait for all pneumatic machines tested.

Regarding the electric drills, the difference in speed of rotation and corresponding difference in sound spectrum and pressure levels recorded are depicted in Figure 5.1.2.
Figure 5.1.2: Surface SPL, Electric drills (E1 and E2)

In practical terms, the sound pressure levels recorded for the electric machines at the differing rotational speeds were sufficiently close to one another to be within the bounds of experimental error. As such, the average of both will be used as a single pattern to describe both drills, having an averaged A-weighted sound pressure level of 94.6 dB(A).

Collation of the A-weighted sound pressure levels for all pneumatic drills and the electric drills, allows the derivation of Figure 5.1.3.
Figure 5.1.3: Comparison of pneumatic and electric drills: surface

Owing to the independence of the electric machine from air-supply pressure, this is represented by the solid horizontal line in Figure 5.1.3.

The muffled machines recorded sound pressure levels sufficiently close to each other to use the average as a practical figure. These drills (MA and MB) were some 7.5 dB(A) quieter (average) when running at 350 kPa and 450 kPa, and approximately 10.5 dB(A; average) quieter at 500 kPa than the unmuffled machine. The electric drill recorded a mean A-weighted sound pressure level of 10.9 dB(A) and 18.7 dB(A) below the unmuffled drill running at air-supply pressures of at 350 kPa and 500 kPa respectively.

Addressing the increase in sound pressure levels, as recorded on surface in free air, with increasing pneumatic supply pressure, Figure 5.1.3 can be recast in the guise of Figure 5.1.4. The solid lines are representations of the least squares linear regressions of the air-supply pressure – sound pressure level relationship. While this analysis returned $R^2$ values in excess of 0.9 for each data set, this is attributed to the low number of data points and the use of a polynomial fit of order approaching the number of data points.
Figure 5.1.4: Sound pressure and air-supply pressure relationship: surface

Of interest is the similar nature of the two muffled drills, with slopes of 0.023 and 0.025 dB per kPa respectively and displaced relative to each other by approximately 0.5 dB(A) over the range of supply pressures tested. The sound pressure levels attributed to the unmuffled drill rises at a greater rate per kPa than the two muffled machines.

Harper (2003), citing Miller (1963) gives the frequency distribution of noise from a pneumatic rock drill as in Table 5.1.2:

Table 5.1.2: Pneumatic rock drill frequency spectrum

<table>
<thead>
<tr>
<th>Frequency range (Hz)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 – 100</td>
<td>Impact between the piston and drill steel, and the drill steel and the rock</td>
</tr>
<tr>
<td>100 – 2 000</td>
<td>Exhaust air expanding from the exhaust port(s)</td>
</tr>
<tr>
<td>2 000 and above</td>
<td>Resonance of the drill steel and the steel components</td>
</tr>
</tbody>
</table>

Examination of the individual frequency spectra of all drills tested (Figure 5.1.5) enables an examination of the influence of exhaust muffling.
Figure 5.1.5: Comparison of drill sound spectra (surface; 350 kPa)

All pneumatic drill spectra shown in Figure 5.1.5 are for an inlet pressure of 350 kPa. The uppermost frequency spectrum in Figure 5.1.5 corresponds with the unmuffled pneumatic drill, and displays a generally consistent rise in sound power level with increase in centre frequency. At the lower sound power level, the electric drill, with no exhaust expansion noise, higher frequency of percussion and a different mechanical mechanism, displays a curve shape that is markedly depressed in the 16 Hz to one kilo Her range.

Table 5.1.2 indicates that the percussion between the piston and the drill steel, and the drill steel and the rock accounts for the majority of the 40 Hz to 100 Hz range of noise from a pneumatic drill. The signatures of the three pneumatic drills shown in Figure 5.1.5 tend to coincide with each other at these frequencies (63 Hz centre frequency) and then begin to diverge at 125 Hz, with the muffled drills frequency-power spectra falling below those of the unmuffled drill. Similarly, the 100 Hz to two kilo Herz range is dominated by the expansion of exhaust air (Table 5.1.2), which is evident in Figure 5.1.5 for the muffled machine relative to the unmuffled. Above two kilo Herz, the resonance of the drill steel and metal components dominate the frequency spectra, and it can be observed that the two muffled machines and the electric drill appear to coincide in this frequency range. The reason for these portions of the spectra being below those of the unmuffled pneumatic drill is not apparent, but may possibly be attributed to a lower blow energy for the muffled and electric machines.

These effects are more pronounced at the higher operating air pressures, as shown in Figure 5.1.6 for the pneumatic drills operating at 500 kPa.
Figure 5.1.6: Comparison of drill sound spectra (surface; 500 kPa)

Figure 5.1.6 shows an increasing divergence of the unmuffled pneumatic machine from the muffled counterparts, whose spectra tend to coincide and show increasing divergence from the spectrum of the electric drill.

5.2: Underground trials

The underground testing was conducted in a narrow stope (±0.8 m) of a platinum mine. Owing to the need to adjust the air pressure to ranges equitable with those used during the surface testing, the test work was conducted during the afternoon and night shift, immediately after the blast, fume clearing, and making-safe period. As such, no other equipment was running in the mine, and the background noise measurements taken during this test indicate levels below 80 dB. Table 5.2.1 gives the spectrum of such background noise from a typical platinum mine during the back-shift.

Table 5.2.1: Background noise (underground)

<table>
<thead>
<tr>
<th>Background SPL (dB) at centre frequency (Hz)</th>
<th>Total (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>125</td>
</tr>
<tr>
<td>80,3</td>
<td>76,2</td>
</tr>
</tbody>
</table>

As stated in Section 5.1 for Table 5.1.2, the total sound pressure level quoted in Figure 5.2.1 is the linear value, corresponding to an A-weighted level of 71.4 dB(A). Similarly, the correction factor of SABS ISO 3744:1994, $K_1$, was calculated for these values for all drills tested, and found to be not applicable with the exception of the electric drill at frequencies below 500 Hz.

The air supply during the tests was adjusted in steps of 100 kPa, starting from 350 kPa and terminating at 550 kPa. As expected, significantly higher sound pressure levels were recorded from all drills in this environment, due to the reverberation and reinforcement of the sound.
waves from the face, hanging and footwalls, and the support elements around the drills. This is shown in Figure 5.2.1, where the surface sound levels are superimposed as bars with the same fill pattern, but of lower value to those of the underground tests. Once again, owing to the independence of the electric drills from air-supply pressure, these are shown as solid horizontal lines, the lower line being the surface sound pressure level.

![Figure 5.2.1: Comparison of electric and pneumatic drills: underground](image)

The electric drills returned a constant sound pressure level increase of 6.8 dB(A) due to the underground environment. Drill MA recorded net increases of 10.3 dB(A) and 7.3 dB(A) at 350 kPa and 450 kPa over their surface recordings respectively, while drill MB recorded 5.2 dB(A) and 5.5 dB(A) at the same respective air-supply pressures.

It must be noted that the surface testing of the pneumatic drills was not conducted at 550 kPa, owing to supply limitations. Therefore, the underground test results depicted in Figure 5.2.1 at air pressures of 500 kPa were interpolated for each discreet frequency across the individual drill spectra, and then summed to obtain the equivalent A-weighted sound pressure level.

Similar to Figure 5.1.4, Figure 5.2.1 can be recast to display the direct relationship between the resultant sound pressure level and the air supply to the pneumatic machines. This relationship is displayed in Figure 5.2.2, with the same cautionary notes regarding the least squares fitting of the straight lines to the data, as was given for the development of Figure 5.1.4.
Comparing the regression data for the drills as presented in Figures 5.1.4 and 5.2.2, it can be seen that the unmuffled drill (UA) and the muffled drill of manufacturer B, (MB), differ essentially only in the displacement on the y-axis. In other words, their respective slopes lie close to one another, but the sound pressure levels recorded underground are some 9.3 dB(A) and 3.0 dB(A) higher than those recorded on surface, respectively. Drill MA appears to have been affected by the acoustic environment underground in a different manner, and it can be seen that the rate of rise of sound pressure level with air-supply pressure underground is approximately half that of the surface trial. The implications of this are that the noise emissions from this drill will be less sensitive to pressure increases above 350 kPa.

The relative sound spectra of the drills as measured underground are depicted in Figures 5.2.3 and 5.2.4 for pneumatic air drills running on 350 kPa and 450 kPa respectively.
Figures 5.2.3 and 5.2.4 show similar trends and tendencies to their surface counterpart tests (Figures 5.1.5 and 5.1.6), and draw similar commentary, other than for the obvious increase in emission levels.

This difference in the sound power levels between the underground and surface testing of the drills is shown graphically in Figures 5.2.5 to 5.2.8. It must be noted that these sound power
level differences (additions to the surface spectra) are displayed at the individual frequencies recorded, and are therefore linear power levels and no A-weighted equivalent is calculated.

**Figure 5.2.5:** Difference in frequency spectrum, drill UA

**Figure 5.2.6:** Difference in frequency spectrum, drill MA
Figure 5.2.7: Difference in frequency spectrum, drill MB

Figure 5.2.8: Difference in frequency spectrum, electric drill

Figure 5.2.5 shows that the predominant amplification of the noise levels for the unmuffled drill occurs in the range below two kilo Herz. This indicates that the percussion between the piston and the drill steel, the drill steel and the rock and the exhaust expansion dominate the sound power attributed to the reverberant properties of the stope.
Figures 5.2.6 and 5.2.7 indicate that the mechanical percussive noise from the muffled drills is predominantly amplified (up to 250 Hz centre frequency), and that the muffling of the exhaust expansion (up to two kilo Herz) remains relatively constant for drill MA and decreases for drill MB. The electric drill (Figure 5.2.8) shows a generally uniform increase in sound pressure levels across the spectrum, albeit at a lower level than for the other drills.

5.3 Multiple drills

To address the sound power levels generated with multiple drills running in a stope, the test work conducted as part of this exercise included measurements of sound power levels for three unmuffled (UA) drills running simultaneously underground. During this test, three drills were placed next to each other approximately one metre apart and run simultaneously at 450 kPa. The sound power level recorded behind the operator of the centre drill reached levels of 118.2 dBA, as opposed to the normative 116.9 dB(A) for the single machine, recorded at the operator’s position.

Harper (2005, personal communications) used this information, along with the penetration rates experienced in the underground situation, to calibrate a custom written computer program that analyses the noise generated by multiple sources in a confined environment and computes a spatial sound pressure distribution around the sources. Input data includes the sound pressure spectral distribution, the number of drills running and their location along the face, the location of the operators and assistants relative to the drill and face, the attenuation characteristics of any HPDs that may be worn, as well as the drilling time anticipated as a result of the drill’s penetration rate. The output from the program includes a graphic representation of the sound pressure levels within the area, the exposure of the drill operator(s) and assistants and the anticipated compensation payable should the HPDs be inadequate or not worn.

The input screen used to compute the effects of running three unmuffled drills (UA) at 450 kPa with no hearing protection is given in Figure 5.3.1, with the corresponding spatial distribution of the sound pressure levels in Figure 5.3.2.

---

**Figure 5.3.1: Data for drill UA at 450 kPa (no HPDs)**
Figure 5.3.2: Spatial sound distribution, three UA drills, 450 kPa

Figure 5.3.1 shows three drills and operators located at positions 10 m, 15 m and 20 m along the face, and takes a production rate of 17.5 holes per drill per hour as the penetration rate. This figure was determined during the underground trials.

An equivalent operator exposure of 113.6 dB is predicted by this model (no HPDs being worn), leading to a predicted compensation cost to the mine of some R 1 045 400 per 100 exposed individuals per 25-year period.

Given the same air pressures, drill penetration rates and noise measurements, but using the attenuation properties of simple muff hearing protectors allows the computation shown in Figure 5.3.3.

**Figure 5.3.3: Data for drill UA at 450 kPa (wearing muffs)**

Immediately apparent in the above figure is that the equivalent exposure of the operator has dropped below 87 dB and the corresponding compensation cost has reduced to R 41 000 per 100 exposed individuals over 25 years.
Recalculation of the above scenario for the other drills tested indicates that the use of simple muffs is sufficient to avoid the risk of NIHL, with the proviso that these are worn correctly. While drill UA indicates that there may be some risk of NIHL and compensation with muffs, the relatively high penetration rate of the unmuffled drill into the rock allows the development of Figure 5.3.4, displaying the influence of penetration rate (expressed as total holes per hour of drilling) on the weighted equivalent noise exposure of the operator.

![Figure 5.3.4: LAeq as a function of penetration rate (operator wearing muffs)](image)

The solid line of Figure 5.3.4 at 85 dB(A) indicates the accepted noise level for an eight hour exposure. The upper curve represents the weighted exposure average experienced by the operators with three unmuffled drills (UA) running simultaneously.

### 5.4 Discussion

Sections 5.1 and 5.2 attempt to show the influence of the underground environment on the apparent amplification of the sound power levels of rock drills, generally attributed to the reverberant qualities of hard reflective underground surfaces. However, it is also apparent that the scope of the study conducted was in insufficient detail to show the exact causes of the noise emissions, which would require in-depth mechanical evaluation of all the drills and subsequent complex frequency analysis to discern between true emissions and harmonic frequencies. It must be appreciated that the drills themselves behaved differently during each test conducted, and the preceding sound-power-level spectra displayed are averages of several test runs.

Further, the recording position within the stope itself will affect the reflected sound waves, as will the nature of the rock being drilled, with an anticipation that highly fractured rock will produce differing spectra from more homogeneous formations. Nonetheless, returning to generally observed averages, the following summary can be derived from the tests conducted:

- Surface testing, corresponding to an open air situation (relatively) free of reverberation, shows:
Muffled drills indicate a decrease in sound pressures of 7.5 dB(A) at pressures of 350 kPa and 450 kPa and 10.5 dB(A) at 500 kPa.

The electric drill showed sound pressure levels of 10.9 dB(A) and 18.7 dB(A) below the unmuffled pneumatic drill running at 350 kPa and 500 kPa respectively.

With the exception of the unmuffled drill running at 500 kPa air-supply pressure, all drills tested recorded individual sound pressure levels below 110 dB(A). This limit of 110 dB(A) corresponds to the MHSC milestone set for the maximum permissible emission levels for machinery to be achieved by 2013.

Underground testing, corresponding to a highly reverberant environment showed:

- Unmuffled drills recorded equivalent A-weighted sound pressures levels of between 6.6 dB(A) and 8.6 dB(A) over their respective surface test levels at air-supply pressures of 350 kPa and 450 kPa respectively.

- Muffled drills recorded equivalent A-weighted sound pressures levels of:
  - between 5.2 dB(A) and 10.3 dB(A) over their respective surface test levels at air-supply pressures of 350 kPa; and
  - 5.5 dB(A) to 7.3 dB(A) over the surface tests at 450 kPa supply pressure.

- The electric drill recorded an increase of 6.8 dB(A) over the surface levels.

With the exception of all unmuffled drill tests and drill MA running at 550 kPa underground, the remaining drills attained equivalent sound pressure levels below 110 dB(A).

In attempting to correlate this test work to that conducted in the artificial stope as used for the work covered by GAP 806 (Heyns, 2003; Figure 3.2.8), it must be stated that GAP 806 indicated sound pressure levels recorded some two metres behind the noise source, and that the operator may have shielded the emissions. As such, a quantitative analysis would be misleading in the absence of the raw data, and is thus omitted from further discussion.

However, regarding the work of Franz et al. (1996), the effects of removing the exhaust noise attributed to the rapid expansion of compressed air from the sound spectrum is provided by comparing the emissions from the water-hydraulic rock drill and the electric machine, as illustrated in Figure 5.4.1.
Figure 5.4.1: Comparisons with water-hydraulic drill (after Franz et al., 1996)

All tests depicted in Figure 5.4.1 were conducted in an underground stoping environment.

The almost coincidence of the spectra for the water-hydraulic and the electric machine of Figure 5.4.1 at frequencies below 250 Hz attests to the effects of the air exhaust on the sound levels. The water-hydraulic drills show a sound power level approaching that of the unmuffled pneumatic at frequencies of four kilo Herz, attesting to higher levels of drill-steel resonance associated with the greater blow energy of these water-hydraulic machines.

Examining this further, and taking cognisance of Table 5.1.2, it is possible to consider the theoretical influence on the overall sound pressure levels by attenuating the delineated (principal) frequency bands given by Harper (2003) of 40-100 Hz, 100 Hz – 2 000 Hz and ≥2 000 Hz. As an illustrative example, calculating the potential decrease in sound power levels resulting from the attenuation of these frequency bands, in turn, by a marginal amount, allows the derivation of Table 5.4.1.

Table 5.4.1: Theoretical attenuation with frequency band

<table>
<thead>
<tr>
<th>Drill</th>
<th>Reference SPL (dBA)</th>
<th>Sound pressure level (dBA) after attenuation at frequency band (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>40 – 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Attenuation (5%)</td>
</tr>
<tr>
<td>UA</td>
<td>116,8</td>
<td>116,8</td>
</tr>
<tr>
<td>Electric</td>
<td>101,7</td>
<td>101,7</td>
</tr>
<tr>
<td></td>
<td>Sound pressure level (dBA) after attenuation at frequency band (Hz)</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40 – 100</td>
<td>100 – 2 000</td>
</tr>
<tr>
<td>Water-hydraulic¹</td>
<td>111,1</td>
<td>111,1</td>
</tr>
<tr>
<td>Attenuation (10%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UA</td>
<td>116,8</td>
<td>116,8</td>
</tr>
<tr>
<td>Electric</td>
<td>101,7</td>
<td>101,7</td>
</tr>
<tr>
<td>Water-hydraulic¹</td>
<td>111,1</td>
<td>111,1</td>
</tr>
</tbody>
</table>

1. Data from Franz et al. (1996)

Table 5.4.1 has been calculated from the individual drill frequency spectra recorded in the underground tests for the unmuffled pneumatic drill (drill UA) and the electric drill. These two drills were chosen as they represent the upper and lower levels of sound producers and, therefore, the potential range of noise reductions. The water-hydraulic-drill spectrum was taken from Franz et al. (1996). Table 5.4.1 thus gives an indication of the influence of the frequency spectrum on the overall A-weighted sound pressure level reporting to the ears of the operator. The figures given are the sound pressure levels (dBA) for a percentage reduction in the relevant frequency band only; i.e. the other two frequency bands were maintained at the recorded levels.

As expected, the higher frequencies have the greatest influence, and this, therefore gives an immediate indication of the most effective direction of research in order to promote a speedier implementation of noise reductions from the drills themselves. Attenuating sound transmitted in the 40 Hz to 100 Hz range has little or no influence on the overall sound pressure level recorded by the drills, implying that sound energy resulting from the impacts between the piston and the drill steel, and the bit and the rock are negligible. A five per cent reduction in the mid-range frequencies corresponding to the expansion of air from the exhaust port of the pneumatic machine (100 Hz to two kilo Herz) result in a 2,3 dB(A) reduction in total noise, while a ten per cent attenuation gives some 3,2 dB(A) for drill UA. Similarly significant decreases are noticeable for the water-hydraulic drill, while the electric drill, with lower emissions in this frequency band, is affected to a lesser, but nonetheless significant extent.

Examinining the two kilo Herz and above frequencies shows a more dramatic decrease in total sound pressure emissions, with drill UA recording greater than a three decibel decrease for a five per cent reduction in frequency band emission, while the electric drill recorded approximately the same drop in total sound power level. This frequency, according to Table 5.1.2, is the predominant sound emitted by the resonance of the drill steel and the steel parts of the drill. As the drill steel is, in principle, common to all drills this then appears to offer an area of research that may bring about the greatest and most immediate reduction in overall noise emissions from a single focused research effort.

6. Discussion and recommendations

The timeline imposed by the Mine Health and Safety Committee milestones set during their 2003 annual summit pose severe limitations on the introduction of new or alternative technologies by 2008 and 2013. The technology lifecycle is a lengthy and arduous process from conceptualisation, laboratory scale / concept demonstration, prototyping, field trialling, refinement, manufacturing prototype development, manufacturing, technology transfer, pricing,
marketing and eventual distribution and in-mine service. Added to this, there is already some perceived misconception amongst the workforce, as already highlighted by Harper and Scanlon (1997: 17), who reported that there was resistance to muffled drills in the workplace, because these drills did not sound right, and therefore could not be drilling properly. These cultural issues need to be addressed at the time of prototype development, most likely through an education and technology transfer / ownership programme.

Against this background, in order to meet the 2008 milestone of no more than ten per cent deterioration in hearing amongst occupationally exposed individuals, any new technology envisioned for use must already be in the advanced prototype stage of development. The 2013 milestone of less than 110 dB sound pressure levels at any place in the workplace is a marginally better time frame for the introduction of new technology, although the identified equipment would again need to be in a relatively advanced form of concept demonstrator / newly emerging prototype.

As such, it is inconceivable that the South African mining industry’s de facto tool for blast- and support-hole making, the pneumatic rock drill, will be totally replaced by new technology within this time period.

Further implications of the 2008 and 2013 milestones, at a machine-specific level, are the unacceptable noise levels emitted by unsilenced pneumatic machines, rendering these drills immediately in breach of the 2013 milestone. These machines will need to be revisited and modified, by the minimum addition of mufflers, and the immediate regulated restriction on the use of unmuffled or unsilenced drills may be worthy of consideration.

Of the equipment currently available, only the electric, water-hydraulic and muffled-pneumatic drills have the potential to repeatedly emit less than 110 dB in an underground environment (section 5.2). Again, in order for the muffled pneumatic drills to achieve the prerequisite sound pressure level of 110 dB, the operating air-supply pressure must be controlled appropriately, as detailed in Figure 5.2.2 (i.e. approximately 450 kPa, dependent on the drill used). This is for one single machine operating. However, the use of multiple drills in a stope offers a dual approach to the issue concerning equivalent operator exposure, viz:

- Multiple drills will increase the overall sound pressure levels, but will enable the drilling of an entire panel in a shorter time. There will exist, therefore, an optimum point in the number of drills versus the time taken to complete the panel versus the equivalent noise exposure experienced by the drilling crew.
- Placing more drills in a stope will increase the cost of hole production, in terms of increased capital expenditure, maintenance and labour costs.

The first bulleted point above may in fact disregard the 2013 milestone of the MHSC. Unless exemption is obtained in terms of proven equivalent operator exposure, this scenario may not be tenable.

The above options also implicitly demand that the workforce is equipped with adequate hearing protection, and educated such that the ramifications of ignoring personal safety and of the long term effects of NIHL are understood and internalised.

Examining the spectrum of sound emitted from an unmuffled pneumatic, a water-hydraulic and an electric drill, sensitivity analyses show that the greatest influence on sound pressure levels is obtained by addressing the higher frequencies, i.e. above 2 000 Hz. This frequency is characterised by ringing of the drill steel, resonance of steel components within the drill and the expansion of air from the exhaust ports of a pneumatic machine. It is also noted that the drill steel is common to all drills, irrespective of the motive power, and concentrated acoustic engineering research and development into this component may facilitate an immediate and
industry-wide acceptable reduction in noise levels.

A facilitated workshop was convened to gather information from the affected industries and this was held along established value engineering principles. The objective was to derive methodologies whereby the stipulated MHSC milestones could be achieved. The report received from the facilitators of the workshop, Messrs. VM Services, is included in Appendix 2.

During this workshop, several important aspects of noise and of the drilling industry in general were highlighted, and these are listed below:

- Buying on price was highlighted as being an effect hindering the introduction of quieter drills to the marketplace. Contracts were being awarded, despite the publication of the MHSC guidelines, for unmuffled drills, as these are cheaper options to their muffled counterparts.

- Buying-on-price has a minimising effect on the drill manufacturer’s ability to generate funding to support research and development activities. Synergistically, manufacturers were not prepared to develop alternatives, using their own funding, that were unlikely to be purchased by mines, and therefore remain “on-the-shelf”;

- From the foregoing, access to research and development funding was raised by several representatives of drill manufacturing companies, as this would prevent the above symbiotic price versus sales versus funding for research and development cycle.

- The basis of measurement by the inspectorate for compliance with the MHSC milestones was repeatedly raised as a concern, alluding to the need for the publication of standard methods and codes of practice. The manufacturers require this in order to gauge product development and compliance, and the mines need clarity on ways in which they will be adjudicated.

- The general culture within the mining industry was raised as a concern. This extended beyond the drill operator scenario (as outlined by Harper and Scanlon, 1997) to include broader areas such as the production bonus schemes, supervision of drillers, maintenance of equipment, particularly that of the air-supply lines and provision of adequate air pressure, to the purchasing procedures and management of noise in general.

The workshop concluded by deriving a matrix of results to achieve against known issues and concerns. The overarching drivers to this matrix are the MHSC milestones, as published, and are taken as the overall desired results and enabling statements. While the matrix (appended in full in Appendix 2) is extensive and all points must be taken cognisance of, the following four functions were derived as the critical minimum that will achieve the greatest benefit:

- Changes to the industry culture;
- The management of time-equivalent exposure to drill noise;
- The application of technologies to reduce noise; and
- The application of appropriate standards, both for the measurement of noise and the specification of equipment.

Figure 6.1 presents these primary "pillars of change" graphically:
Figure 6.1: Noise management

In Figure 6.1, the “Apply technology” arrow implies the development of suitable technology, from concept through prototype to commercial application, with the associated intellectual-property protection and sourcing of funding. As such, technology can also be seen as a causal function, in that with appropriate technology comes the development of standards, the management of noise exposure, and the potential to change culture among the users of that technology.

Technology is therefore a key element to the management of noise-induced hearing loss.

In terms of the technologies available that hold promise for development and eventual deployment as viable mining tools, few are at concept-demonstration stage, perhaps with the exception of the totally enclosed drill system initially developed by Harper and co-workers and furthered by Otterman et al. (2001a). Table 6.1 summarises the technologies studied in execution of this work that have the greatest potential for development. In this table, the currently available water-hydraulic machines are taken as having similar characteristics to those of the electric drills, i.e. lower exhaust noise than the muffled pneumatic drills, with the predominant noise emitted in the post-2 000 Hz range.
### Table 6.1: Drilling technologies for development

<table>
<thead>
<tr>
<th>No.</th>
<th>Method / technology</th>
<th>Maturity</th>
<th>Advantages / disadvantages</th>
<th>Research area</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Pneumatic rotary percussive.</td>
<td>Established</td>
<td>• Best penetration rate;</td>
<td>• Muffling;</td>
<td>Unmuffled machines must demonstrate marked increases in penetration rate to reduce the operator-equivalent exposure to meet the 2013 criteria.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Common standard;</td>
<td>• Drill steel damping;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Noise;</td>
<td>• Influence of frequency of percussion;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Chuck bush inserts.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rigs and jigs are established technology.</td>
<td>Rigs and jigs are established technology.</td>
</tr>
<tr>
<td>2.</td>
<td>Electric drills.</td>
<td>Acceptance tests</td>
<td>• Relatively quiet (101 dBA);</td>
<td>• Drill steel damping.</td>
<td>Water-hydraulic machines fall in the same category, with the exception that they do not require specialised bits and emit marginally higher sound pressure levels.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Low penetration rate;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Specialised bits.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Enclosed “quiet rock drills”.</td>
<td>Demonstrated</td>
<td>• Potential to go below ±90 dB(A);</td>
<td>• Enclose up to chuck, use of damped steels;</td>
<td>Telcontrol needs underground evaluation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Size and manoeuvrability;</td>
<td>• Remote operation on rigs and jigs.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Acceptance.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Remotely operated rigs and jigs.</td>
<td>Demonstrated</td>
<td>• Removal of operator from high noise and unsupported areas;</td>
<td>• Underground testing of remote systems;</td>
<td>As per 3 above. Typically cited drawbacks are size and setup time. Rigs and jigs are established technology.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Time to set up;</td>
<td>• Development of rapid deployment systems.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Bulkiness.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Down-the-hole drills.</td>
<td>Established</td>
<td>• Diminishing noise with penetration;</td>
<td>• Use of alternative percussion mechanisms (to decrease diameter).</td>
<td>Currently limited by the size of percussive elements which need to go down the hole.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Large diameter;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Not established for SA hard rock conditions.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Method / technology</td>
<td>Maturity</td>
<td>Advantages / disadvantages</td>
<td>Research area</td>
<td>Comments</td>
</tr>
<tr>
<td>-----</td>
<td>---------------------</td>
<td>----------</td>
<td>----------------------------</td>
<td>---------------</td>
<td>----------</td>
</tr>
<tr>
<td>6.</td>
<td>Microwave drilling.</td>
<td>Concept demonstrator.</td>
<td>• Silent / little noise; • Compact; • Relatively low power; • Unestablished in SA formations; • Safety.</td>
<td>• Suitability for SA formations; • Diameter of drilling; • Safety.</td>
<td>• Penetration rates and specific energies are unreported; • Safety concerns must be addressed.</td>
</tr>
<tr>
<td>7.</td>
<td>Plasma drilling.</td>
<td>Concept demonstrator.</td>
<td>• Compact size; • Proven in large diameters; • Sound levels (102 dB).</td>
<td>• Size reduction for roof bolting.</td>
<td>SA researchers are familiar with technology</td>
</tr>
<tr>
<td>8.</td>
<td>Ultrasonic.</td>
<td>Concept demonstrator.</td>
<td>• Relatively silent; • Small diameter; • Unknown effects on human physiology.</td>
<td>• Effects of frequency on penetration, thrust force etc.; • Effects on human physiology;</td>
<td>Potential to lift sound spectrum above the audible range.</td>
</tr>
<tr>
<td>9.</td>
<td>Active and passive suppression.</td>
<td>Varying</td>
<td>• Complimentary technology to all above.</td>
<td>• Requires dedicated research by technology expert.</td>
<td>This comprises a vast spectrum of technologies that may or may not be of benefit to drilling. The concepts of ASAC may have implications for drill steel damping.</td>
</tr>
</tbody>
</table>
To reiterate, Table 6.1 includes the pneumatic machines, as these cannot be discarded as equipment for use in the drilling of blast- and support-holes for some considerable time to come. Their inclusion is to highlight that work needs to be conducted to reduce their noise emissions, even if this is a simple regulation that forbids the use of unmuffled machines within the South African mining industry.

The combination of Figure 6.1 and Table 6.1 allows the development of the proposed structure for future work, with a predominantly technology-orientated thrust, supported by occupational health studies. These are vital to complement or reject technologies and to assist with the determination of work aimed at developing standards and cultural changes within the industry.

![Research cross-cutting relationship](image)

**Figure 6.2: Research cross-cutting relationship**

### 6.1 Programme of work

Considering the number of technologies envisaged (Table 6.1) and the relatively short time frame for the implementation of the milestones (2008 and 2013), a *fast-tracked, multi-tasked programme of work is recommended*. This programme of work can essentially be split into two broad categories on the basis of the maturity of the technology, and each will have separate development tracks and time frames. The two categories selected for the purposes of this project are:

- Concept / laboratory scale (technology) demonstrator; and
- Pre-production prototype.

Pre-production prototypes are those technologies that have the greatest probability of having reached commercial production by the expiration of the 2008 milestone, and are likely to consist of modifications to existing drills (items one to four of Table 6.1). Common to all drills is the drill steel, and a collaborative effort across the manufacturing industry to address damping and the use of chuck bush inserts offers an area for concerted effort that will assist all manufacturers and users of drills in the mining industry. Similarly, for pneumatic machines, the muffling of the exhaust appears to be beneficial from a NIHL perspective, and mechanisms can be put in place to assist the user industry with the purchase of drills that meet a pre-determined exhaust-noise emission level. Envisioned mechanisms are the prohibition of unmuffled machines, controlled by a minimum *compulsory* standard administered by the established regulatory bodies already in existence within South Africa. An analogy to this type of approach is the inspection and test
process already in place for self-contained self rescuers and steel wire hoist ropes.

In parallel with the above proposal is a concerted education and enforcement effort amongst the affected workforce, concentrating on producing internalisation of the need to wear personal HPDs. Given the current state of the technological offerings, it is improbable that any totally silent hole-making device will be available by 2008, and thus the modus operandi to meet the first milestone must be a combination of technological offering and a workforce-driven culture of compliance to recommendations.

Addressing the technologies already at the advanced concept-demonstration stage of development, the microwave and plasma drilling technologies hold the greatest potential for being fast tracked (items six and seven of Table 6.1). While these two hole-making methods appear, superficially, to be able to offer a solution in time for the 2013 milestone, the possibility exists that they may be fast tracked to be available, at least as field-trial machines, by 2008.

The remaining entries in Table 6.1 (ultrasonic excitation and active and passive suppression) are either insufficiently advanced, or require expert analysis before an informed decision can be made regarding their inclusion on the immediate timeline. The recommendation is to enable a programme of work to examine these technologies in greater technical detail, coupled with base-line experimental work to determine any potential benefit to the mining industry. It is envisaged that this (largely academic) work will span approximately 12 months and result in recommendations that will either enable further development, or at least conclusively exclude the candidate technologies from immediate consideration.

Figure 6.1.1 illustrates the proposed conceptual technical structure of the project to address NIHL.

Figure 6.1.1: Proposed technical project structure
6.2 Project administration and timeline

Considering that the milestone designated by the MHSC for evaluation in December 2013 states that the “total noise emitted by all equipment installed in the workplace must not exceed …110 decibels (dB)...” (SIMRAC, 2005), the indication is that the engineering out of noise emissions from drilling activities is one subtask of an overall and much larger programme of work. Section 6.1 illustrates that the drilling noise subtask is considerable in extent on its own and, due to its diverse nature, will require a dedicated project leader to administer and solely direct drilling-related engineering studies. Given the aforementioned MHSC milestone time constraints, a vital aspect of the leadership of this project will be the setting of realistic milestones and the management of tasks to deliver appropriately against these agreed goals.

Returning to the size of the overall noise-reduction task alluded to by the 2013 MHSC milestone, it is appropriate to discuss the models successfully used to manage large multidisciplinary projects within the mining sector, most notably those of DeepMine, FutureMine and Coaltech 2020. These collaborative research programmes were run through the establishment of Boards of Governance, and in the case of DeepMine, this Board comprised representatives from (http://deepmine.csir.co.za/About/governan.htm, 2005):

- The individual mining houses;
- The CSIR;
- Academic institutions;
- Research fund donor institutions;
- The Chamber of Mines;
- The DME;
- The Department of Trade and Industry (DTI); and
- Organised labour.

Arguably, the above function will be administered (in the case of drilling technology) by the Engineering and Machinery Technical Advisory Committee (EMTAC) and on the occupational health side by OHTAC (Occupational Health Technical Advisory Committee), who both report upwards, through SIMPROSS ultimately to the MHSC (http://www.simrac.co.za, 2005). Given the technical diversity of the disciplines depicted in Figure 6.1.1, these will ultimately multiply for each other noise source identified in pursuit of the 2013 MHSC milestone. Therefore, it is envisioned that the current Technical Advisory Committees (TACs) will require considerable technical assistance and advice with the control of multiple, fast tracked, technical projects. This is particularly so if these TACs are burdened with concurrent additional (“non-noise”) research programmes and given the fact that the industry representatives on the TACs are largely co-opted and therefore have additional regular employment duties to attend to.

In this light, it is recommended that a drilling (or noise) advisory panel be established whose sole mandate is to administer and lead the drilling noise reduction programme, and that a full-time project leader be contracted to direct technical matters. While this technical leader need not be an expert in all technological disciplines under consideration, this person will, of necessity, need to be at least familiar with the technical concepts, as well as with the manufacturing, drilling, and mining industries.

Devolving from this panel, contracts, (on the basis of the familiar and current MHSC tender process) will then be awarded to conduct the individual research thrusts.

Addressing the timing of the project, Table 6.1 and Figure 6.1.1 depict several options for investigation, and it cannot be stated for certain, at this point in time, what the outcomes will be from this dedicated programme of research. Given these uncertainties, it is proposed that each technology thrust be developed through a dedicated technical evaluation, followed by a risk assessment before a full programme of work can be individually detailed. Inter alia, this
process specifically requires the development of a high-level technical and functional specification for the intended device, which will assist with determining the overall time and resource allocation. Graphically, this is illustrated Figure 6.2.1 as part of the programme evaluation and review technique (PERT) and / or process flow diagram:

![Flow Chart]

**Figure 6.2.1: Initial technology evaluation process**

Subsequent to the development of the project plan, with attendant time and resource allocations, the appropriate advisory panel or TAC will be in a position to determine the most appropriate course of action.

To reiterate the estimate given in section 6.1, it is envisaged that this initial phase should take no more than 12 to 18 months, although the maturity and complexity of the technology will dictate the actual time required. It is stressed, however, that the base risk assessment, functional and technical specifications should be developed for each technology considered, as these processes are invaluable for defining any future work. Occupational health and safety evaluations are seen as a concomitant process with the technical studies.

This process, therefore, defines the initial phases of study for the reduction of noise from the drilling process.

In conclusion, it is recommended that a multidisciplinary project be initiated to evaluate and develop the technologies listed in Table 6.1, with cognisance taken of any attendant health and safety issues. Particular reference must be made to the development and publication of necessary standards and codes of practice against which the MHSC milestones will be evaluated. This project must be fast tracked in order to complement and achieve the aforementioned milestones.
7. References


Kollé, J.J. and Marvin, M.H., 2000. Jet-assisted drilling with supercritical carbon dioxide, ©


### 7.1 Internet references

**Active Materials Laboratory (AML) of the University of California, Los Angeles (UCLA).**
http://aml.seas.ucla.edu/home.htm (accessed 2005-06-10);

**Aircraft Spruce and Speciality Company.**
Retailers of Sennheiser headsets for aviation radio communications.

**AMC Consultants.**

**Canadian Centre for Occupational Health and Safety.**
http://www.ccohs.ca/

**Health Canada.**
http://www.hc-sc.gc.ca/

**MATWEB Material Property Data**
Comprehensive material data sheets for engineering materials.
http://www.matweb.com/

**MSN Encarta Online Encyclopaedia.**
"Metamorphic Rock," Microsoft® Encarta® Online Encyclopedia 2005

**The Nineteenth Century in Print, Periodicals.**

**Noise Clipper®, South Africa**
www.noiseclipper.co.za

**SGB Group.**
SGB group of companies associated predominantly with the civil engineering trade.
http://www.sgb.co.uk

**Sound Reduction Systems Limited, UK.**
Supplier of building and construction products for acoustic control
http://www.soundreduction.co.uk/

**Targus Corporation.**
Manufacturers of personal hearing protection devices
Weber, L. and Mehra, S.R.  
Sound insulation of foils and membranes, Fraunhofer Institute of Building Physics (IBP), Stuttgart.  

Wikipedia, the free encyclopedia © 2001-2005  

### 7.2 Personal communications

**de Koker, E., 2005.** Mining audiologist; Correspondence regarding the influence of ultra high frequencies on NIHL.

**Harper, G.S., 2005.** Calibration and use of computer software for the prediction of sound spatial distribution and risk of NIHL to drilling crews; general discussions on rock drilling and noise.

**Jerby, E., University of Tel-Aviv, Israel, October 2005.** Electronic correspondence concerning the scale-up of the microwave drill to diameters of use in the SA mining industry, and the influence of metallic conductors therein.

**Moeny, W., 2005.** Intellectual property owner, Plasma Hole Maker (PHM). Electronic correspondence relating to the current status and developments with the PHM technology.

**Murray, W., 2005.** Discussions related to the development of pneumatic rock drills for South African mining.

**van Schoor, M., CSIR, 2005.** Discussions and electronic correspondence related to the determination of dielectric constants in rock.
Appendix 1  Drill steel noise (Pemberton, 2005)
An Investigation into Noise Reduction from Drill Rods

Prepared for

Mr. Mike O’ Brian

NRE

by

Gavin Pemberton

Hard Engineering Design

21 September

Rep_05_11
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. INTRODUCTION</td>
<td>3</td>
</tr>
<tr>
<td>2. DESCRIPTION OF THE IDEAL DRILLING PROCESS</td>
<td>3</td>
</tr>
<tr>
<td>3. NOISE LEVELS RADIATED FROM DRILL RODS</td>
<td>4</td>
</tr>
<tr>
<td>4. ENERGY TRANSFER FROM DRILL RODS</td>
<td>4</td>
</tr>
<tr>
<td>5. LONGITUDINAL STRESS WAVES IN DRILL RODS</td>
<td>5</td>
</tr>
<tr>
<td>6. BENDING WAVES IN DRILL RODS</td>
<td>5</td>
</tr>
<tr>
<td>7. METHODS OF REDUCING DRILL ROD NOISE</td>
<td>6</td>
</tr>
<tr>
<td>8. NEW TRENDS IN DRILL DESIGN</td>
<td>8</td>
</tr>
<tr>
<td>9. CONCLUSION</td>
<td>9</td>
</tr>
<tr>
<td>10. REFERENCES</td>
<td>10</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

The report was commissioned to investigate the work done on Noise Reduction from Drill Rods. Work published in the public domain, on the reduction of noise radiated from drill steels while drilling holes using hand held drills appears to have ceased in the early 1980’s. References as to the effect of low blow energy high frequency, plus wave form on drill rod noise, were in passing with no substantiated work available.

From the data in the papers presented, noise levels radiated from drill rods in hand drills is in the regime of 110dBa, constituting approximately 12% of the noise power of rifle bar machines. During efficient drilling only 80% of longitudinal energy in the drill rod is used for breaking rock, the balance of 20% is in the form of bending waves, which for comparable stress amplitudes are a more significant noise source than longitudinal waves.

Various forms of damping have been tested to reduce drill rod noise, with the detrimental effect of energy losses of up to 50%.

More recent trends in pneumatic and hydraulic drill development is to produce the power required for the drilling application with lower blow energy and higher frequency.

2. DESCRIPTION OF THE IDEAL DRILLING PROCESS.

Before presenting the work found, done to date on reducing noise levels from drill rods, a brief description of the ideal drilling process of a hand held rock drill follows. At the time of piston impact on the steel, the bit is forced against the rock by the thrust leg. The piston kinetic energy is transferred to the steel as a stress wave, which travels to the interface between the bit and rock. Part of the wave energy goes into breaking the rock and part is reflected back up to the end of the drill rod, where it reflects again down the rod toward the bit, to achieve further penetration. This process may occur several times during each piston blow to the steel, causing the bit to penetrate the rock in a series of jumps as chips are formed. When the force in the stress wave falls below that required to penetrate the rock, the drill rod rebounds, separating from the rock impacting the chuck. During the return stoke of the piston, when the bit is not against the rock the drill rod is rotated. (Hawkes and Wright 1977. Vol 1).
3. NOISE LEVELS RADIATED FROM DRILL RODS

The drill rod is a stressed component transmitting energy. Not all of this energy is used for breaking rock, some remains in the rod causing vibration and ringing which are responsible for the production of large amounts of sound energy. Noise levels radiated from the rods of handheld rifle bar machines being in the regime of 110dBA at 1M. (Stimpson 1981). During the development of a Quite Rock Drill based on a Joy L-47 drill, noise levels from the drill rods in the region of 107dBA to 110dBA were measured (Hawkes and Wright 1977. Vol 1). Similar values for mechanical noise can also be found in studies by (Beiers1966, Pretlove 1969, Summers and Murphy 1974,Visnapuu and Jensen 1975). The noise radiating from the drill rod contributes approximately 12% of the total noise power for rifle bar rotation drills (Holdo 1958).

4. ENERGY TRANSFER FROM DRILL RODS

(Hawks and Chakravarty 1961) presented that up to 20% of the energy in a drill steel can be in the form of bending waves, with 80% of the longitudinal energy used for breaking rock in efficient conditions, confirmed by (Hustrulid and Fairhurst 1971). The condition of the drill bit has a large influence on the energy transmitted to the rock; with a sharp bit the energy transfer from the bit to rock can be as high as 80% according to (Hawkes and Wright 1977. Vol 1). As the bit becomes worn and blunt the energy transferred can fall to as low as 50%. Tests conducted with new taper bits showed that button bits produced more noise than cross bits. “The results show that the button bit was one to two db noisier than cross bits. - - - this is due to greater amounts of low frequency sound radiation with the button bit especially around 2 kHz and below” (Stimpson 1981).

5. LONGITUDINAL STRESS WAVES IN DRILL RODS

The length and shape of longitudinal stress waves are complicated functions of piston shape and dimensions, plus drill rod diameter, and are best calculated using numerical techniques. A
computer program to produce these results for any piston and drill rod configuration based on a program written by (Dutta 1968) could be produced for this purpose (Hawkes, Wright and Dutta 1977. Vol 2). The pistons impact energy can be transmitted along the drill rod in a variety of wave forms, dependent on the piston mass, shape, impact velocity and piston/rod area ratios. Pistons of different shapes, all having the same mass and impact velocity, despite the differences in peak stress levels and wavelength will have the same total wave energy rather than wave form. The problem of relating the stress levels and total energy of stress waves in drill steels to radiated noise does not appear to have been investigated in depth. (Tsao and Musa 1973) made simultaneous recordings of stress waves in rods and resulting radiated noise, but did not correlate the two phenomena. The power of a drill can be produced at high frequency and low blow energy or visa versa; there is neither theory or data from a noise perspective to give preference to either of these alternatives. Also the energy can be transmitted through the drill steel either as a high stress level short pulse or a low stress level long pulse. “We feel it is probable that the later will produce the lowest noise radiation but there are no data to substantiate this hypothesis.” (Hawkes and Wright 1977. Vol 1).

6. BENDING WAVES IN DRILL RODS

Bending waves in drill rods are not well understood, these waves cause the rod particles to vibrate transversely to the steel axis. For comparable stress amplitudes they are a more significant noise source than longitudinal waves. Bending wave theory has not been developed to the extent where vibration amplitudes can be calculated from impact parameters, either for initial impact or steady state vibrations (Hawkes, Wright and Dutta 1977. Vol 2). Factors studied by (Roberts et al 1962) and (Hawkes, Wright and Dutta 1977. Vol 2) appear to represent the bulk of the available data on the subject. From this data the main factors which determine the form and amplitude of the bending waves in drill rods are: piston impact velocity and mass, eccentric impacts caused by chuck wear and misalignment, and rod bending resulting from over thrusting or insufficient support for long drill steels.

(Takata and Shimizu 1960.) showed that the bending wave peak amplitudes increase linearly
with piston impact velocity for impacts having constant eccentricity relative to the piston axis, this was confirmed by (Roberts et al 1962).

Increasing the piston mass for a given impact velocity, all other factors remaining constant, is equivalent to increasing the impact energy that is absorbed by the bending wave (Hawkes, Wright and Dutta 1977. Vol 2). As the impact energy increases so do the lower frequency components of the bending wave, with the stress levels roughly proportional to the square root of the impact energy (Roberts et al 1962).

Bad alignment in the chuck produces an eccentric impact, which generates bending waves. (Roberts et al 1962) showed that typically a clearance of 0.060in, in a worn chuck would give a misalignment of 1.2 degrees, realising stresses in a 7/8in in excess of 20,000psi.

With a typical rifle bar drill it is difficult to optimize the thrust, if the machine is over thrusted the bit drags in the hole during rotation, causing the drill to stall. For smooth operation there is thus a tendency for the operator to under thrust the drill to ensure it remains running. In independent rotation machines, the thrust is not critical to smooth operation so thrust levels can be kept near the optimum, hence drill rod bounce can be kept to a minimum (Hawkes, Wright and Dutta 1977. Vol 2).

7. METHODS OF REDUCING DRILL ROD NOISE

Possible practical ways of reducing drill rod noise are presented in (Hawkes and Wright 1977. Vol 1);

- Match the bit/rock stiffness to the stress wave to ensure that as much energy as possible is used to break rock, leaving a minimum amount in the rod to “ring”.
- Design the drill/bit combination to rapidly damp out residual stress waves between blows.
- Ensure the chuck and drill steel shank design minimize the generation of bending waves.
- Isolate the drill rod collar from the steel to reduce the secondary stress waves generated from the collar impacting against the chuck.
• Damp the transverse drill rod vibration by coating the rod. Shroud the drill rod in order to attenuate the noise radiating from the rod surface.

(Hawkes, Wright and Dutta 1977. Vol 2) implemented the following techniques from those methods presented in volume 1 for reducing drill rod noise, in prototype drills developed for the United States Bureau of mines; using longer shank drill steels, reducing the clearance between the rod shank and chuck bush, mounting rubber collars on the drill rods and optimizing the machine thrust.

Work done by (Stimpson 1981.) and (Stimpson 1982) involved damping treatments to reduce the noise produced by the drill steel during drilling, these treatments were developed in the laboratory and their performance with regards to noise reduction evaluated in field trials, under actual drilling conditions for both hydraulic and hand held pneumatic drills. The damping principals employed were by additive treatments to the drill steel. Two basic damping methods are employed in these treatment processes; friction damping which relies on the energy being dissipated by friction between the steel and damping element. The second being dissipative damping, where the internal energy dissipation is by a highly dissipative material place around the rod.

Various 6ft forged collared 7/8in hex 4 ½ in shank rod combinations, plus a 6ft rubber collar shank steel and shrouded rod were tested;

- Spring dampers of the form of a helical springs wound around the rod.
- Tape wound damper, where a metal tape is wound in tension around the steel.
- A thin walled tube was fitted tightly over the rod as a friction tube.
- An internal friction tube was created was created by tightly fitting an oval stainless steel tube in the water tube hole.
- Dissipative type rods consisting of thick PVC tube tightly around the rod were created.

Energy losses in the five aforementioned damped systems of up to 50% were recorded; this also results in reduced drilling performance.

During these tests noise levels radiated by the 6ft standard forged collar rod were reduced from 110dBa to 112dBa at the start of the hole to around 103dBa at the finish of the hole. The 6ft
rubber collard rod reduces the noise by around 4 to 5dBA. Levels in the regime of 106dBA near the start of the hole falling to around 102dBA were found. In the authors experience penetration rates are reduced by approximately 9% when replacing a forged collar rod with a rubber collared unit.

8. NEW TRENDS IN DRILL DESIGN

In recent times there has been a trend towards higher blow frequencies in both hand held drills and rig mounted hydraulic drifters. An example of such a hand held pneumatic unit, is the SECO Nova, a 3.5kW independent rotation machine, with a blow energy of 66 Joules operating at 53Hz. During testing of the machine at Boart Longyear, when drilling holes of up to 1.4m the author found the penetration rate (volume of rock drilled) to be in the same ratio per kW, as that of a rifle bar machines with blow energies of 97 Joules at 35 Hz. A low energy high frequency hydraulic rig mounted drill is the Tamrock USD 80 suitable for bolt hole and development drilling. The 4kW unit produces 35 Joules of blow energy at an operating frequency of 115Hz. Hex rods as small as 19mm are recommended by the manufacture for use with this drill. The new Atlas Copco Hydraulic Cop 3038 drifter is now operating at 300 Joules 102Hz, the reason being to increase power to 30kW while maintaining the blow energy so as not to overload the drill steel (Mining & Constuction). No publications could be found on these machines with regards to the effect of blow energy and frequency on noise produced in the drill steels.

9. CONCLUSION

The major problem in reducing noise in hand held rock drills is to reduce the noise radiated from the drill rod. The drill rod noise is predominately from bending waves in the drill rod generated by eccentric impacts between the piston and rod and by impacts between the chuck and drill steel collar. Increasing the impact energy increases the lower frequency components in the bending wave.

In order to reduce drill rod noise, the emphasis should be placed on reducing bending waves.
10. REFERENCES


Mining and Costruction, The Dovelopment Of The COP 3038.


Stimpson, G.J. 1981, The Reduction of Noise From Drill Rods Phase 1. Institute of sound & Vibration Research University of Southampton.

Stimpson, G.J 1980, Sound Level Measurements Made at Torque Tension Ltd. Institute of sound & Vibration Research University of Southampton.

Summers, C.R. and Murphy, J.N. 1974, Noise Abatement of Pneumatic Rock Drill. USBM RI 7998


Visnapuu, A. and Jensen, J.W 1975, Noise Reduction of a Pneumatic Rock Drill. USBM RI 8082
Appendix 2  Report – workshop of 2005-11-17
Value Management

Interactive Workshop & Pre-Workshop Report

CSIR Mining Technology,
Carlow Road
Johannesburg

Subject: Rock Drilling Noise Levels

Coordination: Mike O’Brien, CSIR
Pre-Workshop:
Date: 10th November 2005
Venue: CSIR Mining Technology Offices, Johannesburg
Time: 10:00 – 12:20
Participants: Mike O’Brien (CSIR)  
Kurt Huber (VM Services)  
Paul Whitehouse (VM Services).

Background
There is a proposal from the Mine Health & Safety Council to generate a project scope for the development of a low noise drilling system for blast & support holes. Noise induced hearing loss continuous to deprive victims of a quality of life, either in their latter years at work, or in heir retirement. It costs the mining industry over R1000 million annually, in compensation. Legislation will be insisting by 2008 the hearing conservation programmes must ensure no hearing deterioration greater than 10% among occupationally exposed individuals & by 2013 the total noise emitted by all equipment must not exceed 110dB. (the exposure limit in the MHSA is no more than 85dB over an 8 hour exposure period.

Scope setting
Within the context of the above background note.

Purpose Statement: (i.e. Why have a Workshop)
To obtain alignment on the way forward to meet or exceed legislated OHS noise limits, relating to rock drilling, by 2013.

Proposed Objective (i.e. Where we want to get to)
To develop a strategy to address the noise level and concomitant hearing damage associated with the process of rock drilling, for implementation by……….
Issues (perceived key issues that would be confirmed and added to within a Workshop context)

1. Awareness of legislative requirements
2. Resistance to change
3. Operational costs (current Vs new)
4. Social responsibility
5. Use of “best” technologies
6. Ergonomics
7. Non acceptance risk (by Operators)
8. Mining cycle
9. Skilling
10. Blasts/day

(N.B. to be continued within the Workshop…)

Pre-Workshop Conclusions

From the above discussions that centred around the respective elements of the noise generating rock drilling operation, it became clear that one could not ignore the somewhat bigger picture that would encompass the large compensation “bill” of R100m/annum, the mining operating philosophies, the exposure time Vs dB levels diagram, and giving particular consideration to the acceptability or otherwise of change within the current operator staff.

It was agreed that a VM Services Facilitated Workshop, which will follow the Value Engineering methodology of 1 day duration will be conducted, during which time the above Objective will be confirmed, relevant new Issues added, and the Functional criteria will be established, prioritised, and used to objectively measure the effectiveness of the respective solutions.

The Workshop known as; “Noise, rock drilling & the operational environment”, will be conducted at the Mintek offices in Randburg, on the 17th November 2005, commencing 09:30 – 16:00.

Appropriate drawings, diagrams, will be made available for reference during the Workshop.

Mike O’Brien
## Interactive Workshop

### Project Particulars

**Company**: CSIR  
**Purpose**: To obtain alignment on the way forward to meet (or exceed) legislated OHS noise limits. Relating to rock drilling by 2013  
**Date**: 17th November 2005 Commenced ± 10:00  
**Venue**: Mintek Offices, Randburg

**Participants; alphabetically listed**

<table>
<thead>
<tr>
<th>No.</th>
<th>First name</th>
<th>Surname</th>
<th>Organisation</th>
<th>e-mail</th>
<th>Cell No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D</td>
<td>Amidzic</td>
<td>MHSC</td>
<td><a href="mailto:damidzic@mhsc.org.za">damidzic@mhsc.org.za</a></td>
<td>082 781 9971</td>
</tr>
<tr>
<td>2</td>
<td>R</td>
<td>Buchwane</td>
<td>South Deep</td>
<td><a href="mailto:rbuchwane@southdeep.co.za">rbuchwane@southdeep.co.za</a></td>
<td>084 474 0704</td>
</tr>
<tr>
<td>3</td>
<td>Abrie</td>
<td>De Villiers-White</td>
<td>ERPM</td>
<td><a href="mailto:abrie@crowngold.co.za">abrie@crowngold.co.za</a></td>
<td>082 448 5220</td>
</tr>
<tr>
<td>4</td>
<td>Marais</td>
<td>Diedericks</td>
<td>Lonmin</td>
<td><a href="mailto:marais.diedericks@lonplats.com">marais.diedericks@lonplats.com</a></td>
<td>083 321 0468</td>
</tr>
<tr>
<td>5</td>
<td>Paul</td>
<td>Fletcher</td>
<td>Sulzer HydroMining</td>
<td><a href="mailto:paul.fletcher@sulzer.com">paul.fletcher@sulzer.com</a></td>
<td>083 325 6245</td>
</tr>
<tr>
<td>6</td>
<td>Derrick</td>
<td>Ford</td>
<td>Harmony</td>
<td><a href="mailto:derrick.ford@harmony.co.za">derrick.ford@harmony.co.za</a></td>
<td>082 657 5260</td>
</tr>
<tr>
<td>7</td>
<td>Mike</td>
<td>Franz</td>
<td>CSIR</td>
<td><a href="mailto:mfranz@csir.co.za">mfranz@csir.co.za</a></td>
<td>083 628 7592</td>
</tr>
<tr>
<td>8</td>
<td>Gökhan</td>
<td>Güler</td>
<td>CSIR</td>
<td><a href="mailto:gguler@csir.co.za">gguler@csir.co.za</a></td>
<td>082 452 2768</td>
</tr>
<tr>
<td>9</td>
<td>Alec</td>
<td>Gumbie</td>
<td>MHSC</td>
<td><a href="mailto:alec@turgis.co.za">alec@turgis.co.za</a></td>
<td>083 645 0464</td>
</tr>
<tr>
<td>10</td>
<td>Jacques</td>
<td>J</td>
<td>Hilti SA</td>
<td><a href="mailto:jacquesj@hilti.co.za">jacquesj@hilti.co.za</a></td>
<td>082 446 6075</td>
</tr>
<tr>
<td>11</td>
<td>Wiesiek</td>
<td>Masztalerz</td>
<td>DME</td>
<td><a href="mailto:Wiesiek.masztalerz@dme.gov.za">Wiesiek.masztalerz@dme.gov.za</a></td>
<td>084 403 1688</td>
</tr>
<tr>
<td>12</td>
<td>R. Francis</td>
<td>Matong</td>
<td>Harmony</td>
<td><a href="mailto:francis.matong@harmony.co.za">francis.matong@harmony.co.za</a></td>
<td>083 792 7841</td>
</tr>
<tr>
<td>13</td>
<td>W. (Bill)</td>
<td>J. Murray</td>
<td>Boart Longyear</td>
<td><a href="mailto:wmurray@boartlongyear.co.za">wmurray@boartlongyear.co.za</a></td>
<td>082 326 6275</td>
</tr>
<tr>
<td>14</td>
<td>Mike</td>
<td>O’Brien</td>
<td>CSIR</td>
<td><a href="mailto:mobrien@csir.co.za">mobrien@csir.co.za</a></td>
<td>082 896 6878</td>
</tr>
<tr>
<td>15</td>
<td>D.</td>
<td>O’Brien</td>
<td>Victoria Engineering</td>
<td><a href="mailto:vew@global.co.za">vew@global.co.za</a></td>
<td>083 266 2901</td>
</tr>
<tr>
<td>16</td>
<td>Joseph</td>
<td>Oerson</td>
<td>Boart Longyear</td>
<td><a href="mailto:joerson@boartlongyear.co.za">joerson@boartlongyear.co.za</a></td>
<td>011 761 2200</td>
</tr>
<tr>
<td>17</td>
<td>Mark</td>
<td>Pedersen</td>
<td>Atlas Copco</td>
<td><a href="mailto:mark.pedersen@za.atlascopco.com">mark.pedersen@za.atlascopco.com</a></td>
<td>083 633 5218</td>
</tr>
<tr>
<td>18</td>
<td>Neil</td>
<td>Roberts</td>
<td>Boart Longyear</td>
<td><a href="mailto:nroberts@boartlongyear.co.za">nroberts@boartlongyear.co.za</a></td>
<td>083 630 3796</td>
</tr>
<tr>
<td>19</td>
<td>Neville</td>
<td>Stewart</td>
<td>Atlas Copco</td>
<td><a href="mailto:neville.stewart@za.atlascopco.com">neville.stewart@za.atlascopco.com</a></td>
<td>083 650 3796</td>
</tr>
<tr>
<td>20</td>
<td>Felix</td>
<td>Tiedt</td>
<td>Harmony</td>
<td><a href="mailto:felixtiedt@harmony.co.za">felixtiedt@harmony.co.za</a></td>
<td>072 158 8805</td>
</tr>
<tr>
<td>21</td>
<td>Emil</td>
<td>U</td>
<td>Hilti SA</td>
<td><a href="mailto:emilu@hilti.co.za">emilu@hilti.co.za</a></td>
<td>083 645 0481</td>
</tr>
<tr>
<td>22</td>
<td>Gerhard</td>
<td>v/d Berg</td>
<td>Anglo Platinum</td>
<td><a href="mailto:gerhardb@angloplat.com">gerhardb@angloplat.com</a></td>
<td>083 455 7789</td>
</tr>
<tr>
<td>23</td>
<td>Tania</td>
<td>van Dyk</td>
<td>CSIR</td>
<td><a href="mailto:tvandyk@csir.co.za">tvandyk@csir.co.za</a></td>
<td>084 511 8621</td>
</tr>
<tr>
<td>24</td>
<td>Hannes</td>
<td>van Eck</td>
<td>Victoria Engineering</td>
<td><a href="mailto:vew@global.co.za">vew@global.co.za</a></td>
<td>083 635 2099</td>
</tr>
<tr>
<td>25</td>
<td>Kobus</td>
<td>Van Zyl</td>
<td>CSIR</td>
<td>No detail</td>
<td>No detail</td>
</tr>
</tbody>
</table>

**Facilitator**: Paul Whitehouse  
**VM Services (Pty) Ltd**: paul@vmservices.co.za  
**Cell No.**: 083 306 2645
**Issues/Concerns**  
See the Issues/Results to Achieve matrix below

**Purpose (Why?)**  
To obtain alignment on the way forward to meet (or exceed) legislated OHS noise limits. Relating to rock drilling by 2013

**Objective Matrix**

**Objective**  
To develop strategies that will reduce N.I.H.L to legislated levels by 2013 (within the scope of drilling holes).

Noting the following proposed legislation;

*By 2008 no deterioration in hearing greater than 10% amongst occupationally exposed individuals.*

*By December 2013, the total noise emitted by all equipment installed in any workplace must not exceed a sound pressure level of 110 dB at any location in the workplace. (The exposure limit in the MHSA is no more than 85dB over an 8-hr exposure period)*

**Results to Achieve**

1. Details of R100m/Year  
2. Measurement protocol criteria  
3. Commitment to legislation  
4. Self governance (By mining houses)  
5. Change (Driller/Organisation) culture  
6. Reduce percussion noise  
7. Optimise drilling cost  
8. Create noise awareness (N.I.H.L.)  
9. Effective protection devices  
10. Reduce noise exposure time  
11. Research new technologies  
12. Implement technology  
13. Industry standards

**Available Resources**

- CSIR  
- Suppliers  
- (SIMRAC) MHSC  
- International  
- Universities  
- Research  
- Standards  
- H.R. Pool  
- Local Universities  
- Mining Industry  
- Finance (+R100m/Year(Compensation))  
- DME  
- DTI  
- GMRA  
- Research done

**Results to Prevent**

Current rates of N.I.H.L.  
Unclear legislation  
(Job losses)  
(Cost increases)  
Unfair cost burden (if only suppliers)  
> R/Ton  
Inefficiencies  
Contamination of environ  
Further health damage  
Over complication  
Delays

**Constraints**

- Culture  
- Resistance to change  
- Finance  
- Unemployment  
- Time (2013) (7 Years)  
- I.P. Rights  
- Skills (Competencies)  
- Lack of incentive  
- K.I.S.S. Over complication
**Functions (Whats)** developed from the Results to Achieve list

N.B. time precluded prioritising the Functions, however it is apparent the A. Achieve Legislation is the Basic Function and applying process logic would expect all other Functions to be supportive of this achievement, therefore one would not typically address this basic function directly but via the Secondary functions.

Please Note, it is the norm of this methodology to avoid the use of passive verbs, i.e. develop, and instead to use apply, it is a given that anything must be developed before it is able to be applied,

**Cause & Effect**

Applying logic simply ask what function would be achieved with the completion of another, e.g. if this industry is considered technology driven then the nature of the technology developed and applied would have a profound impact and effect of culture, therefore one might propose that Apply Technologies is a causal function and that Change Culture is an effect function. Similarly if one considers Apply Standards, the respective standards, remember these are not the standards associated with legislation but with manufacturing, quality, and application, therefore one again might propose that logically these would be set having established the respective technologies. It is further proposed that noise Vs time is a sub set of technology.

Please note the above view is expressed to both continue and support the synergistic thinking that took place during the interactive workshop, which, due to time constraints was drawn to a hasty conclusion.

**Basic Function:**

A. **Achieve Legislation**

**Secondary:**

B. **Change culture** (effect?)

C. **Manage Noise/Time Exposure** (sub set of technology?)

D. **Apply technologies** (causal?)

E. **Apply standards** (effect?)

**Apply Technologies**

With limited time available there was some “unpacking” of this function, further work will obviously be appropriate.

- Develop current mechanised
- Design new mechanised
- Standards
- Prototype
- Commercial funding
- Benchmarks
- Association (Supplier)
- I.P.
### The Workshop concluded at 16:10

### Issues / Concerns – Results to Achieve cross reference Matrix

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Issues / Concerns</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. R100m/Year x 10 Compensation details</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. 110 dB Max</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Legislation (Current &amp; in Pipeline)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. (Quantify) Measuring the milestones</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Definitions – (Clarification required)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Current driller culture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Percussion noise</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Costs of drilling 38c/Ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Million blast holes every day</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Operator level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Drilling ergonomics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. Acting driller</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13. Appreciation of consequences of N.I.H.L.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14. Disincentive to protect (pension top up)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. Hearing protection devices</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16. Ergonomics of protection devices</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. Discipline (Apply protection)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18. Noise exposure time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19. Drilling penetration rates</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20. Production incentive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21. Lack of co-ordinated approach to problem</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22. Make holes without hearing loss</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23. Drill bit noise</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24. Noise sources</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25. Technologies (Drilling holes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26. Admin control (Moving people around)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27. Remote control drilling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28. General ignorance into N.I.H.L.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29. Conservative mine management</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30. Safety is paramount in a mine (walk talk)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31. Production pressures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32. Maintenance (e.g. Air pressure)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33. Technology transfer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34. R C Factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35. Development costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36. Funding mechanisms (R &amp; D)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37. Enforcement - inspectorate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38. Implementation strategy (Buy-In)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39. What &amp; where are the incentives</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40. A “Buying on price” syndrome</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41. Industry common goal &amp; understanding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42. Other noise sources blast hole=70% noise</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43. I.P. Rights</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44. Standardisation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45. Aids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Value Management/Value Engineering

A brief introduction to the VM /VE methodology:

**Value Management/ Value Engineering is a decision-making methodology (not a cost cutting exercise)**

A systematic process focusing the collective wisdom of multi disciplinary groups, Value Management/Value Engineering defines a common objective, functionally prioritises what needs to be done & then creatively identifies how best to achieve the targeted results.

Applications of Value Management/Value Engineering are many & varied, & include; Strategic Decision Making - Cost Improvement - Project Management - Product /Process design & Improvement - Customer/Supply Chain Interacts - Industry Forums - Team Building (with strategic focus/alignment)

**Why Value Management/ Value Engineering?**

- To enhance cost effective decision making
- Reduce delays in projects
- Reduce cost without sacrificing requirements

**Basic Principles of Value Management/Value Engineering:**

Value as used in Value Management / Value Engineering can be defined as: The lowest cost to reliably provide the required functions or service at the desired time & place & with the essential quality.”

\[
\text{Value} = \frac{\text{Function} (+ \text{quality})}{\text{Cost} \ (\text{incl. Life Cycle Cost})}
\]

The lower the cost for optimum function, the better the value.

**Benefits of Value Management/ Value Engineering:**

Cost Optimisation: Value Management (VM) or Value Engineering (VE) measures results by measuring Value, i.e. the end result of doing something functionally correct for the least cost.

Alignment: VE / VM incorporate the principles of aligning diverse opinions normally expressed in a real decision making scenario.

**Outputs of Value Management/ Value Engineering:**

1. We get Correct & Cost Effective Solutions to the problems we encounter, as we ensure Functional Correctness before deciding on the solution to be implemented.

2. Through participation in a VM / VE study / workshop we obtain Buy-in and achieve Alignment of the people who have to implement & run with the solution.
We trust you benefited from the outcome of your Workshop.
And thank you for your input.
Appendix 3  Conditions pertaining to the use of this report

1. This report is the property of the sponsor and may be published by him provided that:
   (a) The CSIR is acknowledged in the publication
   (b) It is published in full, or where only extracts there from or a summary or an abridgment thereof is published, the CSIR’s prior written approval of the relevant extracts, summary or abridged report be obtained.
   (c) The CSIR be indemnified against any claim for damages that may result from publication.

2. The CSIR will not publish this report or the detailed results without the sponsor's prior consent. However, the CSIR is entitled to use technical information obtained from this investigation but undertakes not to identify the sponsor or the subject of this investigation in doing so.

3. The sponsor will not make reference to the investigation or the report in any advertisement or promotional medium without the CSIR’s written approval of the text of such advertisement or reference.

4. While care is taken to ensure the accuracy of any work performed by the CSIR under this Contract, the CSIR does not guarantee or warrant the accuracy of the work or the merchantability or commercial viability of the research results. Any claim for damages, whether direct or indirect, including consequential damages, against the CSIR arising from this Contract, shall be limited to an amount equal to the Contract Price or amount actually paid by the Client to the CSIR in respect of the work done in terms of this Contract, whichever is the smaller.