# Safety in Mines Research Advisory Committee

MHSC

**Final Report**

# NIHL Prevention Programme:

# Track B – Noise Controls: New Technologies (Drilling)

**A. v. Z. Brink, G. Harper, Prof. N. Theron, H. Heukelman, J. Kok, H.J Ilgner, D. Johnson**

**Research agency** : **CSIR**

**Project number** : **SIM 05 05 01 Track B1.2**

**Date** : **07 March 2012**

# Executive summary

This project, SIM 050501 Track B1.2, follows from the original SIM 050501, *Project Scope for Low-Noise Drilling*, which concluded that ”technology is therefore a key element to the management of noise-induced hearing loss”. A number of new drill technologies were identified for development. Track B1.2 was proposed as a two-year project with the following primary outputs:

- Quantify the status of new technologies (plasma and high-frequency or ultrasonic drilling) with respect to their potential development as appropriate blasting and support-hole-making devices, including possible health effects
- Undertake a baseline technical study to establish the feasibility of alternative percussion-actuation techniques and frequency control
- Develop a business case detailing the viability of developing each of these new technologies.

Van Zyl Brink compiled this report which is based almost exclusively on the work done by CSIR, namely, Mike O’Brien, George Harper, Hartmut Ilgner and University of Pretoria, Prof. Nico Theron, Herman Heukelmal and Johan de Kok.

***Plasma drilling:*** William Moeny is co-founder and President of Tetra Corporation, a R/D company. He is the co-inventor in the development of the Focused Shock Drilling technology using pulsed electric discharges The status of ‘plasma’ drilling was ascertained during a visit to Tetra Corporation and Mr Moeny. Plasma drilling is achieved by generating plasma by means of a high-energy electrical discharge though a dielectric medium, typically through low conductive water. A shockwave is generated that may break the rock under compression. Subsequent development by Mr Moeny has allowed the plasma to be generated in the rock itself, resulting in heating and expansion behind the surface and therefore breaking of the rock in tension.

According to Mr Money, for hard quartz the amount of material removed is approximately 0,2 cc per pulse, with a potential pulse rate of 20–200 pulses per second, i.e. 40 cc per second. This extrapolation is could not be proven.

For a drilling rate of 0,5 m/min the energy required would be2–5 kW, as opposed to the 30 kW required for the previous electro hydraulic discharge (EHD) method. The specific energy needed for breaking with the newer method is therefore lower than that of conventional percussive drilling.

At present an oil-based fluid is used in the system to provide the requisite dielectric properties to coerce the streamer formation into the rock. Tetra acknowledges that this may not be practicable for South African applications and are confident that a water-based alternative can be produced.

Moeny’s expectation is that it should possible to hold a normal conversation within 1 m of the drilling device while it is operating, suggesting a sound pressure level substantially below 84 dBA. This would need to be confirmed once a system, which can produce multiple discharges on an ongoing basis, is manufactured and available for laboratory evaluation.

The technology presented recently by Tetra, i.e. discharge through rock, has been published by other research institutions many years earlier. There was no distinguishing fundamental difference between the known technologies and Tetra’s proposal.

***Ultrasonic rock drilling:*** The purpose of this study by Prof Nico Theron and Herman Heukelman from Univ. of Pretoria, was to investigate the use of ultrasonic rock drilling methods, aiming to implement such techniques in the mining industry, for the purpose of reducing or eliminating noise levels causing permanent bodily damage to miners. Two concepts were investigated: percussive drilling at ultrasonic frequencies and rock disintegration with focussed ultrasonic waves in the rock. Percussive drilling at ultrasonic frequencies with low noise in the audible frequency range was found to be possible but not viable yet, due to insufficient drilling efficiencies and high power requirements. This technique may be further investigated. The investigation into rock disintegration with focussed ultrasonic waves, which was done only superficially, showed that it is theoretically possible and promising. It is suggested that this concept may be further investigated.

***Ultrasonic rock breaking:*** The feasibility of ultrasonic rock breaking was investigated as an MSc project by Johan Kok under the guidance of Prof. Nico Theron at the University of Pretoria. The idea of using ultrasonic waves to accomplish this task was inspected, modelled, tested and evaluated. It was found necessary to focus these waves at a point (a volume of 1 $mm^3$ was chosen for this experiment). A 'focal bowl' was chosen to accomplish the task of focusing the ultrasonic waves. These focused waves will have to create enough energy to overcome the fracture energy of 17.5 $J/m^2$. For a focal bowl made of one of the highest-energy-creating ultrasonic ceramics, namely piezoelectric ceramic 4 (PZT 4), the radius needed is 135 km. This gives a projected surface area greater than Switzerland. It was therefore found that focused ultrasound with a piezoelectric ceramic cannot be used for drilling into rock.

***Feasibility of alternative percussion techniques:*** To break rock using percussive techniques requires a minimum of $2.10^4$ $J/m^2$ and an impact velocity of approximately 10 m/s. Work by Richards, Westcott and Jeyapalan (1997) on the prediction of impact noise indicates that if such energy levels are transferred to the rock via a drill steel, then the acceleration and ringing noise of the drill steel alone will produce noise in excess of 95 dBA. Therefore, regardless of the method of generating the percussion, noise levels during drilling will be in excess of 85 dBA. The only alternative is to seek ways of reducing the acceleration and ringing noise of the drill steel (e.g. by surface reactive damping) or by eliminating the drill steel itself (e.g. by using down-hole hammer drills).

The force causing tool movement and its penetration in the rock may be generated either as a large magnitude static force applied to the tool or via the kinetic energy of the tool as it is converted into work during the impact with the rock. The primary aim of rock breaking is to separate rock fragments with the largest volume possible with a minimal energy input. The generally accepted measure of rock-breaking effectiveness is the specific energy $E_\omega$.

$$E_\omega \propto \frac{E}{V} \qquad 1\text{-}1$$

where:
E = energy supplied to break the rock, J,
V = volume of broken rocks, $m^3$.

The specific energy given by (3-1) is the energy required to break a unit volume of rock. The lower the specific energy, the more effective is the rock-breaking process.

Potential mechanisms and technologies considered as a possible replacement for a hand-held rock drill include the following:

- Electro-Magnetic
    - Coil guns
    - Railgun
        - Classic
        - Augmented Railgun
        - Segmented Railgun
        - Helical Railgun
    - Mass Drivers
    - Superconducting Slingshots

    - Superconducting Quench Gun
    - Impulse Accelerators
    - Momentum Transformer
- Electric Discharge
- Ultrasonic / Piezo-Electric
- Magnetostriction
- Hydraulic Sonic Water-Hammer
- Thermal Laser impact (ablative drives)
- Thermal expansion
- Shape Memory Materials

Many of the technologies and mechanisms could be immediately discounted on the basis of general mining, environmental, safety and health constraints. When not discounted immediately a very basic preliminary analysis of the technologies was conducted as described in the report.

***Development of a business case:*** Neither plasma drilling nor ultrasonic drilling is seen as an alternative drilling technology ready for industrialisation in South Africa. The latter technology is simply not technically possible, but as far as plasma (or electric discharge) drilling is concerned, it is the researcher's view that the technology is not ready for large scale industrialisation..

Two potentially viable methods capable of replacing the current percussion mechanisms of pneumatic and hydraulic hand-held rock-drills are the coil gun approach and the Hydraulic Sonic Water-Hammer. It is recommended that both these technologies should be further investigated.

# Acknowledgements

The authors wish to thank the Mine Health and Safety Council for supporting this work.

# Table of Contents


**Executive summary** .... **2**

**Acknowledgements** .... **5**

**List of figures** .... **7**

**List of tables** .... **7**

**List of symbols** .... **8**

**1 Introduction** .... **9**

**2 Status of new technologies – Plasma hole-maker** .... **10**

2.1 Advances of electric rock breaking by other companies .... 10
2.2 Visit to Tetra Corporation .... 12
2.3 Critical review of Tetra's recent output .... 15

**3 Technical feasibility – Alternative Percussion systems for drilling** .... **16**

3.1 Introduction .... 16
3.2 Engineering Requirements .... 18
3.3 Noise Considerations .... 20
3.4 Potential Percussion Mechanisms .... 21
3.5 Summary .... 26

**4 Recommendations** .... **27**

**5 References** .... **29**

**Appendix A Rail Guns** .... **30**

**Appendix B Magnetostriction** .... **36**

| | | |
|---|---|---|
| **Ultrasonic** | **Rock Drilling** | **APPENDIX 1** |
| **Ultrasonic** | **Rock breaking with focussed ultrasonic waves** | **APPENDIX 2** |

# List of figures

Figure 1-1: Source of noise from a typical pneumatic rock drill (Scanlon and Harper, 1998) ..... 9

Figure 2-1: Plasma Blasting Technology (PBT) laboratory set up (Nantel, 2006).................... 10

Figure 2-2: Boulder broken with a 200 kJ PBT unit (Nantel, 2006) ........................................ 11

Figure 2-3: Electrode (3-inch) developed and constructed by Noranda (Nantel, 2006) ........... 11

Figure 2-4: Streamer formation............................................................................................ 12

Figure 2-5: Streamer formation within the rock ...................................................................... 13

Figure 2-6: Rock removal resulting from a single discharge.................................................... 13

Figure 2-7: Specific energy of rock breaking........................................................................... 14

Figure 4-1: Specific energy as a function of nominal fragment size for primary and secondary rock breaking methods in quartzite section (Cook NGW and Joughin NC, 1970)..................................................................................................... 18

Figure 4-2: The relationships between blow energy, frequency, impact velocity and the required actuator force for a 4kW device with a piston mass of 1 kg.................... 20

Figure 4-3: Typical rock drill emission sources ...................................................................... 20

Figure 4-4: Finite element analysis of single stage ................................................................ 23

Figure 4-5: Force-Displacement curve.................................................................................. 23

Figure 4-6: Constantineco's Water rill, 1913 .......................................................................... 25

Figure 5-1: EDD laboratory demonstrator .............................................................................. 27

# List of tables

Table 2-1: Measured dBA values for 100 mm diameter drilling .............................................. 14

Table 2-2: Calculated dBA values for 38mm diameter drilling ................................................ 15

# List of symbols

| | |
|---|---|
| A | Area |
| a | Acceleration |
| c | Speed of sound |
| $d_{33}$ | Moduli |
| $d_{tb}$ | Applied change in thickness |
| E | Young's Modulus |
| EDD | Electro discharge drilling |
| EHD | Electro hydraulic discharge |
| f | Frequency |
| $g_{33}$ | Pressure constant |
| $h_{33}$ | Piezoelectric deformation constant |
| I | Sound intensity |
| J | Joule |
| K | Wave number |
| P | Applied pressure |
| PZT | Lead zirconate titanate (piezoelectric material) |
| r | Radius |
| T | Time |
| t | Thickness |
| $V_t$ | Applied voltage |
| $V_{tau}$ | Voltage produced |
| v | Speed |
| W | Energy density |
| X | Focus depth |
| $\xi$ | Displacement |
| $\omega$ | Angular frequency |
| $\varphi$ | Phase difference |
| $\rho$ | Density |

# 1 Introduction

The drills used in the mining industry operate at high noise levels of above 80 dB. For example, the air-driven drill from Sulzer operates at levels of 100-106 dB at the machine itself. These noise levels cause damage to the operators' hearing, even though they wear ear mufflers to protect their ears. When a drill operator suffers hearing loss, the mine has to pay compensation and the humanitarian aspect has to be taken into account as well. If a way can be found to make an efficient drill that operates well under the sound level at which damage occurs, the mining industry would not need to pay compensation and the lower noise levels would result in a significantly better working environment for all mineworkers.

The Mine Health and Safety Council (MHSC) set two milestones for the reduction of the 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 deterioration in hearing of not greater than 10 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 source of noise from pneumatic rock drills was expanded upon by Scanlon and Harper (1998), who depicted these emissions diagrammatically as in Figure 1-1.

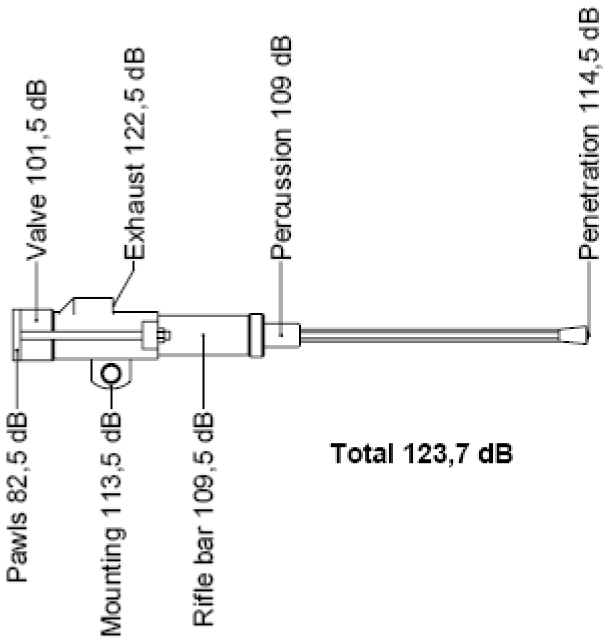



***Figure 1-1: Source of noise from a typical pneumatic rock drill (Scanlon and Harper, 1998)***

This report has the following objectives:

- Quantify the status of new technologies (plasma and high-frequency or ultrasonic drilling) with respect to their potential development as appropriate blasting and support-hole-making devices, including possible health effects
- Undertake a baseline technical study to establish the feasibility of alternative percussion-actuation techniques and frequency control

# 2 Status of new technologies – Plasma hole-maker

## 2.1 Advances of electric rock breaking by other companies

CSIR has recently been part of an international consortium on explosive-free-rock-breaking. During that work, the technological status and the capabilities of various companies regarding mechanical, electrical, microwave, thermal, and fluid-based rock breaking technologies were reviewed.

The fundamental principle of the plasma hole maker lies in creating a high energy discharge from an electrical storage device. Alternating current or direct current configurations have been used at various research laboratories around the world to create the discharge either through water or directly through the rock itself. An overview of the historical literature is provided by Ilgner (2006). This includes work by the German Forschungszentrum Karlsruhe, which published the potential energy savings when discharging through rock, instead of creating shockwaves form outside onto the rock (Edinger, 1995).

In Canada, Noranda Research Laboratories developed electric rock breaking technology, the so called "plasma blasting technology (PBT)", for industrial use. Extensive laboratory and field testing were conducted over many years. The laboratory set up is shown in Figure **2**-**1**.

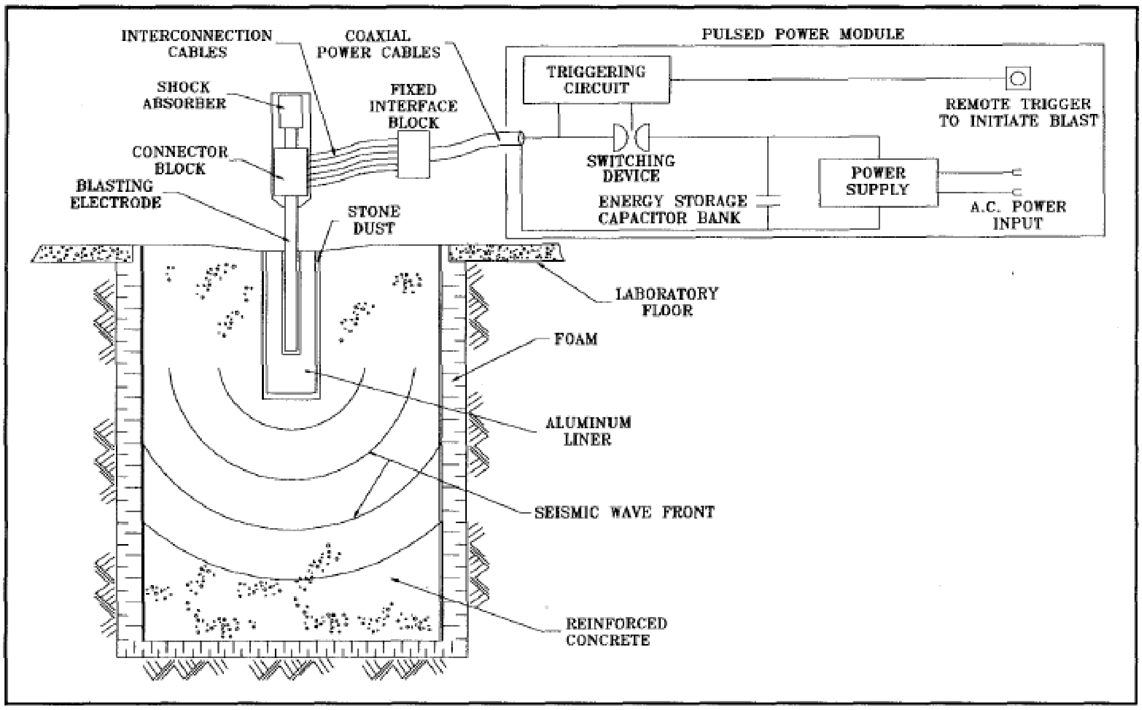



***Figure 2-1: Plasma Blasting Technology (PBT) laboratory set up (Nantel, 2006)***

It is interesting to note that there is a shock absorber on top of the blasting electrode. This indicates that the electrode will bounce away from the rock face during discharge. Therefore, discharge frequencies are expected to be low, as the electrode has to be repositioned near or on the rock face.

Trucks were used to transport the heavy electrical charging equipment during test work, and large boulders were broken in quarries. The largest boulder (18 tons) successfully broken is shown in Figure 2-2 below.

***Figure 2-2: Boulder broken with a 200 kJ PBT unit (Nantel, 2006)***

A very considerable amount of $ 15 Million was spent before the PBT was abandoned (Nantel, 2006). It is reported, that the weakest link in the system was the electrodes, which transfer the electrical energy into or onto the rock. The latest electrode design, shown in Figure 2-3 was lasting a mere 550 shots.

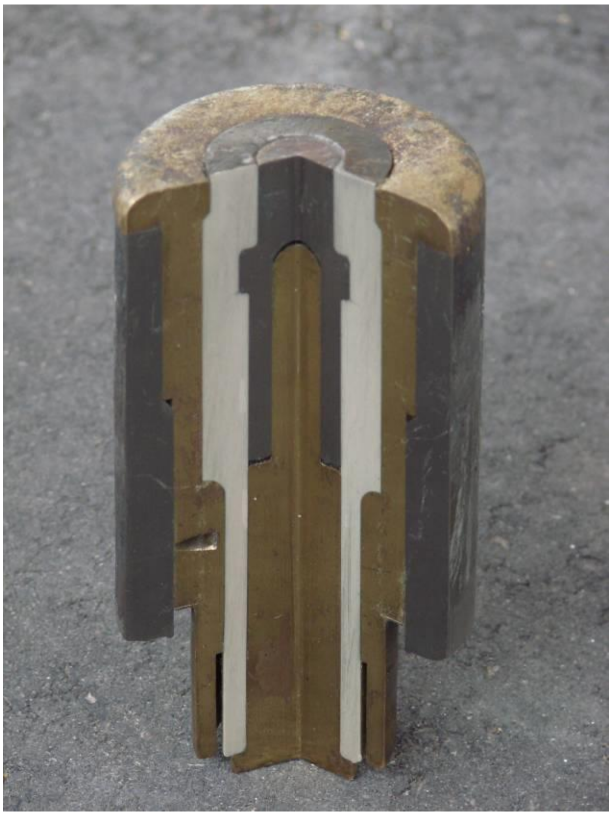


***Figure 2-3: Electrode (3-inch) developed and constructed by Noranda (Nantel, 2006)***

According to the schematic provided by Tetra, Figure 2-4, it is apparent that the Noranda design and the Tetra design are similar. Therefore, it is believed that the pulse rate of up to 200 Hz from Tetra would need to be confirmed during endurance test to ensure sufficient working life of the component.

## 2.2 Visit to Tetra Corporation

Discussions between Mr Harper and Dr Vogt of the CSIR and Mr W Moeny of Tetra Corporation have confirmed that the intellectual property produced under previous collaboration agreements with South African organisations has been superseded by new patents registered under the name of Tetra Corporation. The issues regarding intellectual property with regard to the plasma hole-maker have therefore been resolved.

During the technical visit to evaluate the new technology, Mr Moeney presented their latest developments in plasma drilling which has resulted from work they have conducted for application in the oil exploration drilling industry. The technology is substantially different from that investigated under previous collaboration agreements with South African organisations and forms the subject of two new patents (US 2005030178, *Pulsed Electric Rock Drilling Fracturing and Crushing Methods and Apparatus* and US 2006006502, *Portable Electro-Crushing Drill*) held by Tetra.

In previous applications of plasma technology to rock drilling a plasma was created in the water between the electrodes during each discharge, with rock being broken by the resultant shockwave. This method is now described by Tetra as electro hydraulic drilling (EHD) to differentiate it from their new technology, which they call electro discharge drilling (EDD).

In the new method a streamer is created **within the rock** (Figure 2-4 and Figure 2-5), which the plasma discharge then follows, resulting in the breakage of the rock (Figure 2-6).

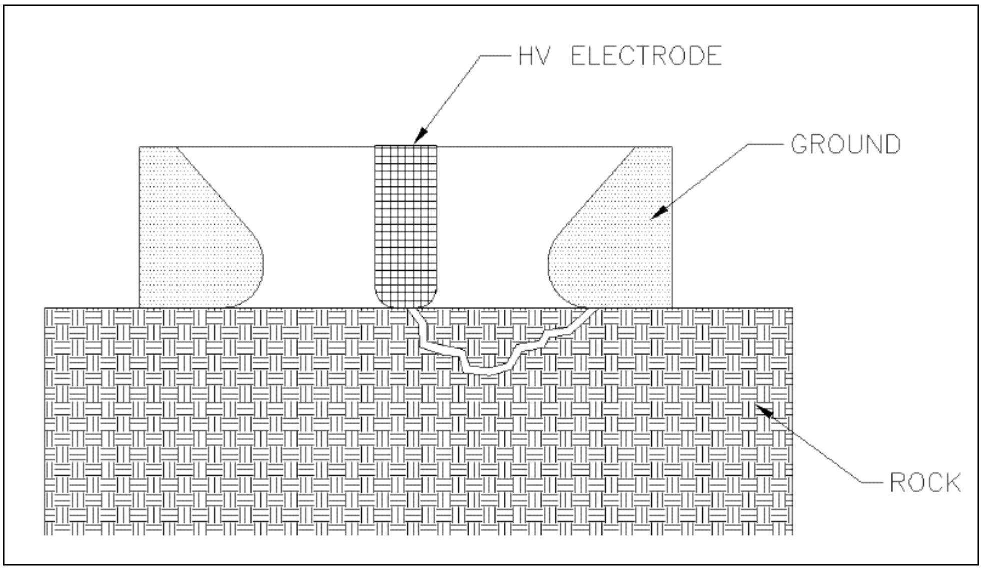



***Figure 2-4: Streamer formation***

***Figure 2-5: Streamer formation within the rock***

***Figure 2-6: Rock removal resulting from a single discharge***

For hard quartz the amount of material removed is approximately 0,2 cc per pulse, with a potential pulse rate of 20–200 pulses per second, i.e. 40 cc per second.

For a drilling rate of 0,5 m/min the new method would require 2–5 kW, as opposed to the 30 kW required for the previous EHD method. The specific energy needed for breaking with the new method is therefore lower than that of conventional percussive drilling, as shown in Figure 2-7 below.

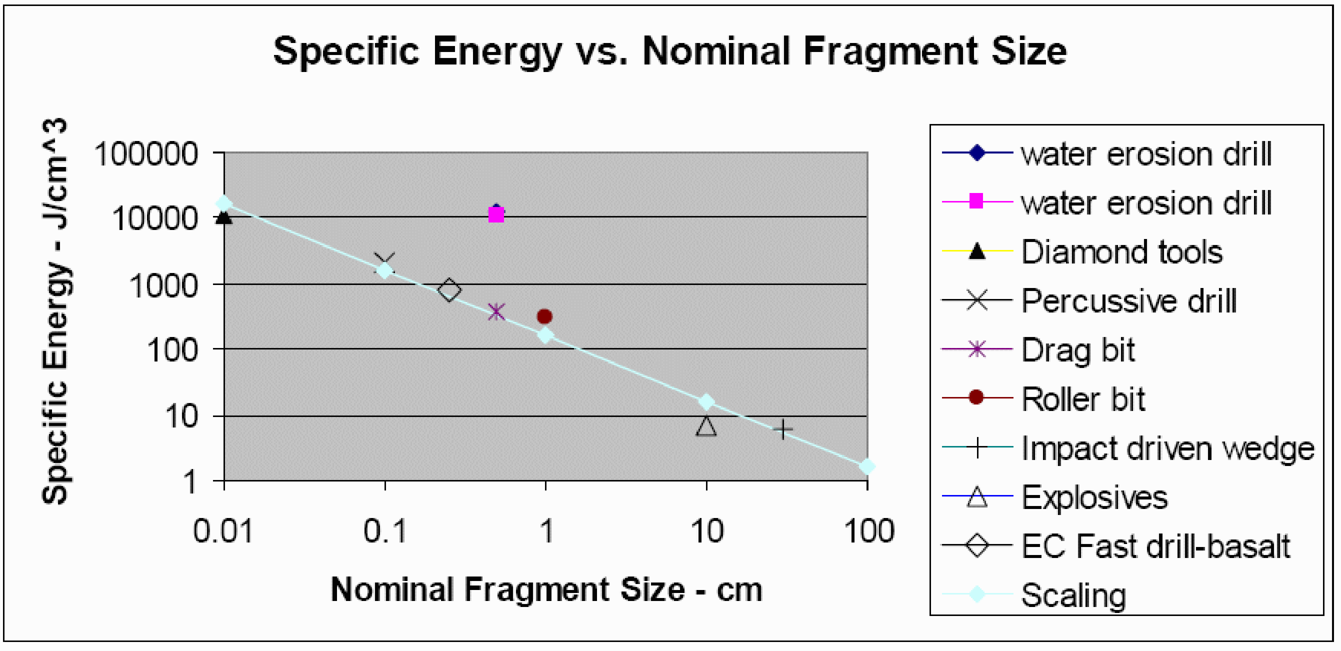



***Figure 2-7: Specific energy of rock breaking***

At present an oil-based fluid is used in the system to provide the requisite dielectric properties to coerce the streamer formation into the rock. Tetra acknowledges that this may not be practicable for South African applications and are confident that a water-based alternative can be produced.

There is anecdotal evidence that it is possible to hold a normal conversation within 1 m of the drilling device while it is in operation, suggesting a sound pressure level substantially below 84 dBA (see Table 2-1 for measured values for 100 mm diameter drilling. Table **2-2** displays calculated values for a 38 mm diameter drilling).

***Table 2-1: Measured dBA values for 100 mm diameter drilling***

| Location | dBa |
|---|---|
| 1 meter to the left side of the source | 79 |
| 1 meter to the front | 87 |
| 1 meter to the right side | 86 |
| About 1 meter above and slightly to the side. | 84 |
| ***Average*** | **84.9** |

***Table 2-2: Calculated dBA values for 38mm diameter drilling***

| Location | dBa |
|---|---|
| 1 meter to the left side of the source | 71 |
| 1 meter to the front | 79 |
| 1 meter to the right side | 78 |
| About 1 meter above and slightly to the side. | 76 |
| ***Average*** | **76.5** |

## 2.3 Critical review of Tetra's recent output

Figure 2-4 shows an idealised set up where the flat drilling head is in good mechanical contact with a flat rock face. This is necessary to create the discharge directly through the rock. However, as soon as an irregular chip is formed by a single discharge, this chip has to be removed from the face. This is conveniently done with circulating fluid, either water or oil. During the removal, the chippings will have to pass the ground electrode, which therefore has to be away from the rock face. After the removal of the chippings, the high-voltage and ground electrodes have to be repositioned to provide proper mechanical contact with the unbroken rock.

This cyclic forward and backward motion is limited by the inertia of accelerating the chippings and the drill head. Even if multiple ground contacts could be provided circumferentially at the drill head, pulsing frequencies of 200 shots per second seem to be very high.

Considering both the past experience by Noranda with plasma blasting technology and previously published concept for direct discharge, it is recommended that the recent proposal by Tetra does not warrant further perusal at this stage.

# 3 Technical feasibility – Alternative Percussion systems for drilling

The original sub-contractor has indicated that he is no longer able to complete the required work for this project within the necessary time frame. Alternate sub-contractors have been sought at the University of the Witwatersrand and the University of Cape Town without success, primarily because of a lack of the required expertise.

To facilitate the completion of the project it is proposed that the technical feasibility study of alternate percussion methods be undertaken by the CSIR. This work has been started but is still at a stage where it can be handed over to a sub-contractor if required.

To break rock using percussive techniques requires a minimum of $2.10^4$ J/m$^2$ and an impact velocity of approximately 10 m/s. For a hole with a diameter of 40 mm this equates to approximately 24 J, a value that is reasonably close to the impact energy of 26 J per blow of the Hilti electric drill. Furthermore, work by Richards, Westcott and Jeyapalan (1979) on the prediction of impact noise indicates that if such energy levels are transferred to the rock via a drill steel, then the acceleration and ringing noise of the drill steel alone will be in excess of 95 dBA. Therefore, regardless of the method of generating the percussion, noise levels during drilling will be in excess of 85 dBA. The only alternative is to seek ways of reducing the acceleration and ringing noise of the drill steel (e.g. by surface reactive damping) or by eliminating the drill steel itself.

Elimination of the drill steel can only be achieved by the use of down-hole hammer drill types. The minimum diameter of water-powered down-hole hammers is currently 55–60 mm and the technical problems associated with any further reduction in size are significant.

## 3.1 Introduction

The force causing tool movement and its penetration in the rock may be generated either as a large magnitude static force applied to the tool or via the kinetic energy of the tool as it is converted into work during the impact with the rock. The primary aim of rock breaking is to separate rock fragments with the largest volume possible with a minimal energy input. The generally accepted measure of rock-breaking effectiveness is the specific energy $E_\omega$.

$$E_\omega \propto \frac{E}{V} \qquad 3\text{-}1$$

where:

E = energy supplied to break the rock, J,

V = volume of broken rocks, m$^3$.

The specific energy given by (3-1) is the energy required to break a unit volume of rock. The lower the specific energy, the more effective is the rock-breaking process. However, applying specific energy as a measure of the process effectiveness requires caution.

In rock-breaking operations, the energy is used to destroy the rock structure and generate cracks and craters and it may be reasonably inferred that the energy E in any effective process should be proportional to the newly created surface area ($d^2$, where d denotes the linear dimension of the newly-formed rock fragment). Similarly the volume of the rock fragment V is proportional to the third power of its linear dimensions ($d^3$). Accordingly, we get:

$$E_{\omega} \propto \frac{1}{d} \qquad \text{3-2}$$

The specific energy of rock breaking is inversely proportional to the dimensions of the obtained rock fragments, i.e. the energy required to break unit volume of rock decreases with an increase of grain dimensions. This is the well-known Rittinger's hypothesis.

The assumption that the energy required for high-energy impact breaking is proportional to 1/d and that despite the increase of impact energy, the dimensions of rock fragments are the same (similar in shape) leads to some interesting conclusions. When $E = d^2$ and $V = d^3$, then:

$$V \propto E^{0.5} \qquad \text{3-3}$$

and

$$E_{\omega} \propto E^{0.5} \qquad \text{3-4}$$

An engineering interpretation of (1.3) is that a machine generating 20 impacts per minute with an impact energy of 10 kJ, may break 10 times more rock than a machine having the same power yet generating 2000 impacts per minute with an impact energy of 100 J. In reality however, the efficiency improvements arising from the application of high-energy tools are less significant since not all the impact energy E is expended in rock breaking or the forming new surfaces some portion of it is always absorbed as the kinetic energy of rock fragments and/or noise and heat energy. While experimental results reveal that the relationship between the specific energy and impact energy is not that straightforward and regular. It is generally accepted that:

$$V \propto E^{(1.2 \approx 1.5)} \qquad \text{3-5}$$

It can be clearly seen that the specific energy of rock breaking decreases with an increase of impact energy though this increase is less significant for greater values of the impact energy. This tendency may be explained by the presence of a so-called 'threshold' value which is dependent on rock strength parameters. When the threshold value is exceeded, the process of rock is initiated.

The specific energy of rock breaking was investigated by Cook and Joughin (Cook NGW and Joughin NC, 1970) with the results summarised in figure 1.

For mechanical methods of rock breaking such as drilling, the energy flux is limited by the mechanical strength and thermal resistance of the tool. With current technology, this limit appears to be about 5 kW per $cm^2$ of tool cross-section (Cook NGW and Joughin NC, 1970).

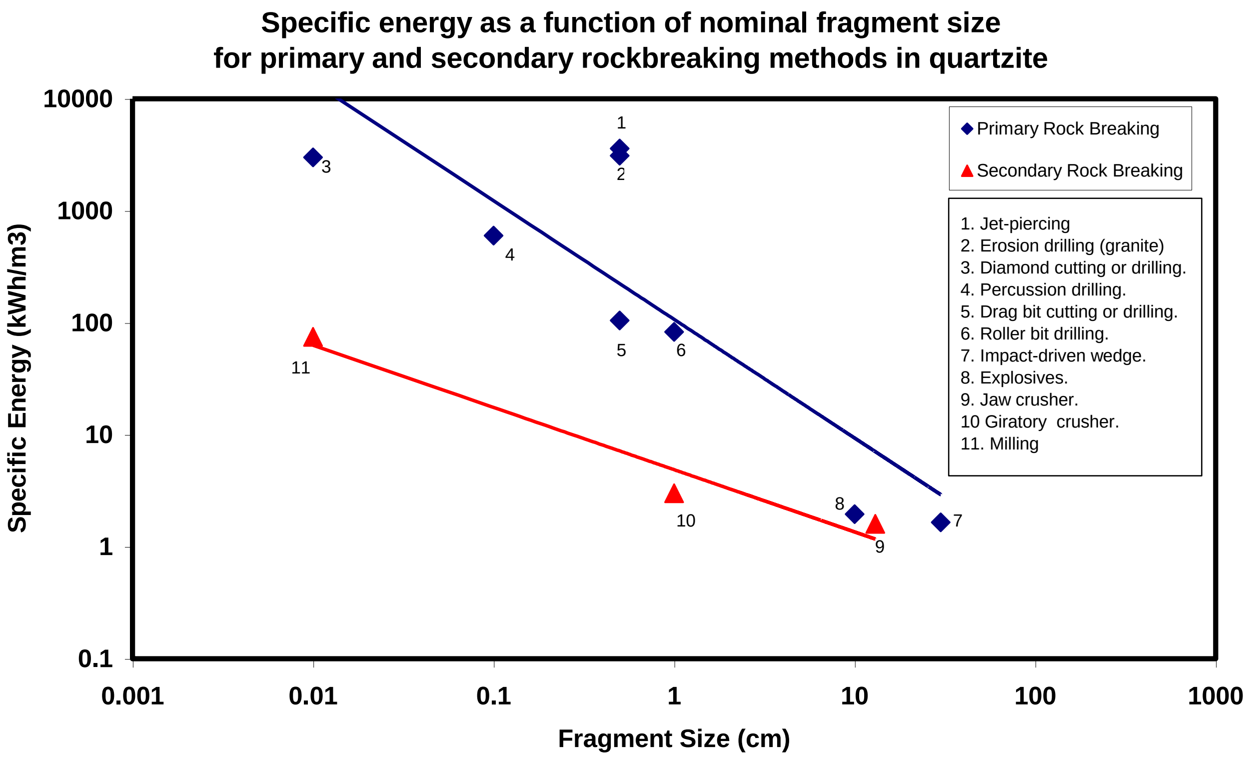



***Figure 3-1: Specific energy as a function of nominal fragment size for primary and secondary rock breaking methods in quartzite section (Cook NGW and Joughin NC, 1970).***

Fatigue considerations of both the tool and the operator of hand-held rock drills further limit the total percussive power to approximately 4 to 6 kW whilst an analysis of the performance of currently available hand-held rock drills indicates that the threshold energy level for percussive drilling of South African quartzite is approximately 2 Joules per $cm^2$ of hole cross-section.

## 3.2 Engineering Requirements

With the following identities:

F = actuator force (N) provided by whatever mechanism is selected

L = stroke (m)

M = mass of piston (kg)

The impact velocity, frequency, impact energy and drill power can be estimated as follows:-

**Impact velocity** v (m/s) is given by

$$v = \sqrt{\frac{2.l.F}{.m}} \qquad 3\text{-}6$$

Assuming the full actuator force operates over the full length of the stroke. Hustralid determined a generic equation for the piston velocity of pneumatic rock drills that includes a factor $B_0$ to compensate for these assumptions.

$$v = B_0 \sqrt{\frac{2.l.F}{.m}} \qquad 3\text{-}7$$

The value of $B_0$ for pneumatic machines is, according to Hustralid, 0.68

**Frequency** *f* (Hz) is given by *:*

$$f = 0.5 \sqrt{\frac{F}{2.l.m}} \qquad 3\text{-}8$$

(Assuming return stroke time is the same as the drive stroke and there is no dwell at reversal)

**Impact Energy** Ei (J) is given by:

$$\mathrm{E}_{\omega} \propto \frac{1}{\mathrm{d}} \qquad 3\text{-}9$$

**Drill Power** Pw is given by :

$$\mathrm{E}_{\omega} \propto \frac{1}{\mathrm{d}} \qquad 3\text{-}10$$

Assuming that the new percussive device should provide a drilling performance at least equivalent to existing pneumatic machines then we will require a device of at least 4kw percussive power (to accommodate the assumptions and simplifications) and a minimum blow energy of 25 joules for a hole diameter of 36 mm.

Figure 3-2 shows the relationships between blow energy, frequency, impact velocity and the required actuator force for a 4kW device with a piston mass of 1 kg.

It is important to note that most of the engineering restrictions result directly from the constraints of a hand-held rock drill and would be avoided by the use of a remote controlled drill rig.

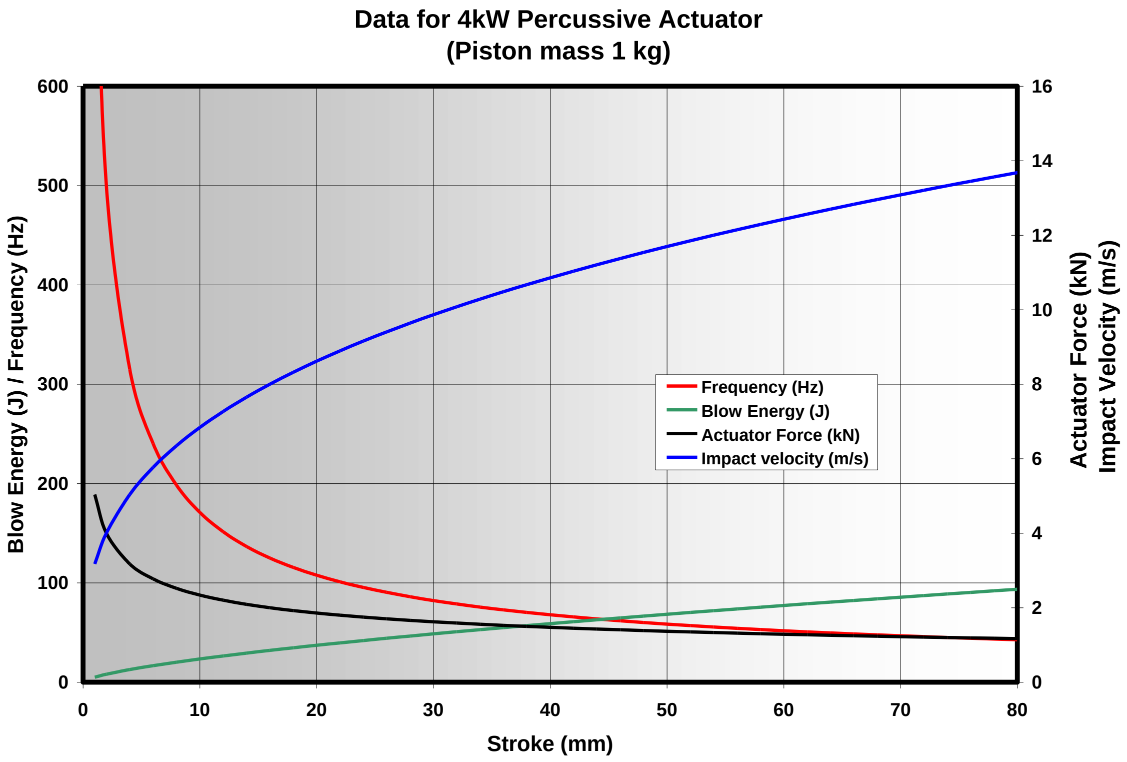



*Figure 3-2: The relationships between blow energy, frequency, impact velocity and the required actuator force for a 4kW device with a piston mass of 1 kg*

## 3.3 Noise Considerations

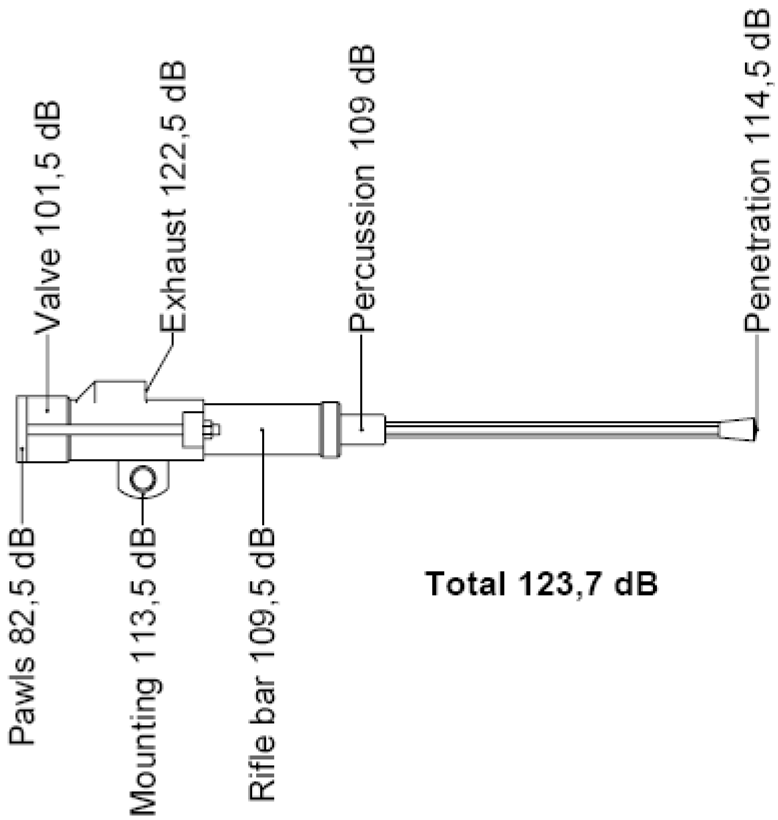



*Figure 3-3: Typical rock drill emission sources*

Figure 3.0 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. A noise source not specifically identified in figure 3.0 is the "Transmission" noise i.e. the noise emanating from the drill steel as the percussion energy is transmitted as a compressive wave along the steel.

The application of an alternate percussion mechanism in combination with an independent direct drive rotation mechanism could provide the opportunity to significantly reduce all of the noise sources identified in figure 3 with the exception of the percussion, transmission and penetration sources. 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 as a result of the dampening effect of the flushing water.

To effectively reduce the level of the remaining noise sources will require an isolation approach. This may be achieved either by the application of the shielding methods as described in SIM 05 05 01 "Project Scope for Low-Noise Drilling" [O'Brien et al 2006] or, if the new percussion mechanism is sufficiently compact, by applying the mechanism as a down-the-hole (DTH) drill configuration in which the noise can be attenuated by the flushing water within the hole.

As with the engineering requirements it is important to note that most of the noise engineering restrictions result directly from the constraints of a hand-held rock drill and would be avoided by the use of a remote controlled drill rig.

## 3.4 Potential Percussion Mechanisms

Potential mechanisms and technologies considered as a possible replacement for a hand-held rock drill include the following:

- Electro-Magnetic
    - Coil guns
    - Railgun
        - Classic
        - Augmented Railgun
        - Segmented Railgun
        - Helical Railgun
    - Mass Drivers
    - Superconducting Slingshots
    - Superconducting Quench Gun
    - Impulse Accelerators
    - Momentum Transformer
- Electric Discharge
- Ultrasonic / Piezo-Electric
- Magnetostriction
- Hydraulic Sonic Water-Hammer
- Thermal Laser impact (ablative drives)
- Thermal expansion
- Shape Memory Materials

Many of the technologies and mechanisms could be immediately discounted on the basis of general mining, environmental, safety and health constraints. When not discounted immediately a very basic preliminary analysis of the technologies was conducted as described in the following sections.

### 3.4.1 Rail Guns

Rail guns are accelerators using two, current conducting, parallel DC rails, short-circuited by a slide. This slide is accelerated by the Lorentz force of:-

$F = 2Bli$ Newton.

Accelerations of up to 20000m/s$^2$ on a mass of 1kg have been achieved at the Australian University of Canberra. As impressive as it may seem, rail guns have several drawbacks that renders them unusable as a percussive drill system.

- The slide is rapidly ablated during operation, which will render the device inoperable within a short period of time.
- The high currents in the rails heats- and distorts them rapidly, so continuous operation is not possible.
- The rails are subject to fast erosion.

A more detail description of rail guns is including in Appendix J for information

### 3.4.2 Superconductor methods

Both the Super-conducting Slingshot and the Super-conducting Quench gun are unsuitable for use in mines. All super-conductors require liquid Nitrogen to be super-conducting and amongst others, has the following drawbacks.

- Liquid nitrogen spills are dangerous and can have lethal consequences.
- Liquid nitrogen is an additional operational expense.
- Liquid nitrogen that is vented underground will dilute the available oxygen in the mine.

### 3.4.3 Coil guns

The coil gun, also called the inductive accelerator, is a quiet method to accelerate an impacting mass for the hammer drill. It consists of one or more coils and a ferromagnetic material, which is displaced from the coil(s).

Once a coil is excited, the magnetic field tends pull the projectile to the middle of the coil. In multiple coil arrays, these are switched sequentially in order to obtain higher speeds. Shown below in Figures 4.3 and 4.3a are simulation results for a single stage hammer (12.7mm diameter and 38mm long) and a dc coil carrying 10A. An accelerating force varies from 1 to 24N and back again.

This translates to a maximum accelerating force of over 60g's. This model can easily be scaled to a 1kg hammer, which can achieve the required 10m/s with a single stage. A spring or secondary coil return system can be employed to provide the return stroke.

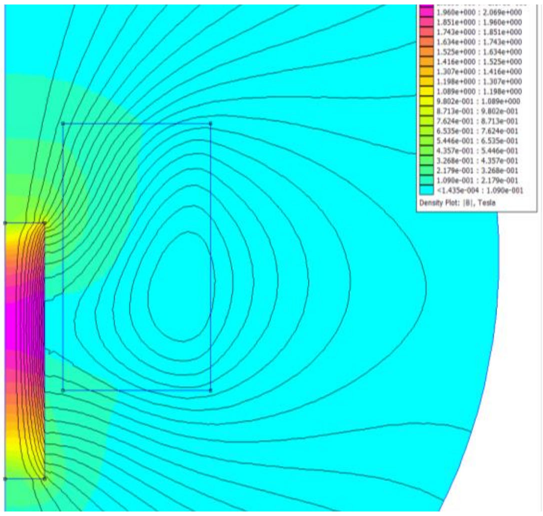


*Figure 3-4: Finite element analysis of single stage*

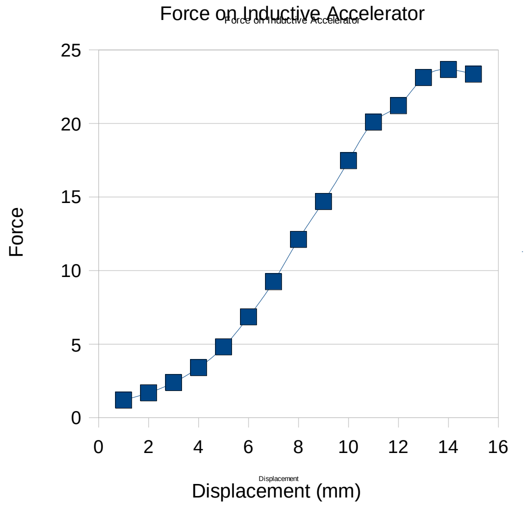



*Figure 3-5: Force-Displacement curve*

## 3.4.4 Electric Discharge

Electric discharge as a method for drilling has been discussed in section 2 of the main report. The use of an electric discharge to produce an impact was not considered further as it was considered that such a process for rock breaking would be significantly less efficient than the direct application of the discharge to the rock.

## 3.4.5 Ultrasonic / Piezo-Electric

The use of ultrasonic methods for direct rock breaking is discussed in section 3 of the main report. The use of ultrasonics as a method of producing a high frequency percussion is also discussed in section 3.1.1.1 USDC (Ultrasonic/Sonic Driller/Corer). E-mail correspondence with the American Jet Propulsion laboratory indicated that the method would not effectively scale to the size required for a blast-hole.

## 3.4.6 Magnetostriction

Magnetostriction is the changing of a material's physical dimensions in response to changing its magnetization. In other words, a magnetostrictive material will change shape when it is subjected to a magnetic field. Most ferromagnetic materials exhibit some measurable magnetostriction. Unfortunately even the most magnetostrictive materials produce only a very small strain ( approx 60 micro-strain) at room temperature and also require very high magnetic fields.

Further information on Magnetostriction is presented in Appendix K for information

## 3.4.7 Hydraulic Sonic Water-Hammer

In 1922, George Constantinesco published the Theory of Wave Transmission. This work was based on the transfer of power from a generator to a machine, using the compressibility of liquids e.g. water. Despite several machines, patents and achievements, such as the first interrupter mechanism for the allied forces in WW1, he was ridiculed as scientists at the time believed that liquids were incompressible.

Following is an example calculation of a generator, which would be used separately from the rock drill, connecting to it via a pipe filled with water.

The generator speed :

$a = \frac{2\pi n}{60}$, where a = speed in radians per second and n = speed in rpm

The maximum flow:

$I = ra\Omega$, where r = crank radius, a speed and $\Omega$ = Piston diameter

Capacity of reservoir is:

$C = \frac{V}{E}$, where C = capacity, V = volume and E = elasticity of the working fluid.

The effective resistance of the generator is:

$R = \frac{C + C_1}{aCC_1}$, where C & C1 are the capacities of the reservoirs.

The maximum work of the generator is:

$W = \frac{I^2 C_1}{4ac(C + C_1)}$,where I = effective current of the working fluid.

The hydro-motive force is:

$$H = \frac{I}{a(I + C_1)} \sqrt{I + \frac{C_1}{C} + \frac{1}{2}\left(\frac{C}{C}\right)^2}$$

To apply this mechanism in a rock drill can involve a system or a reciprocating power piston running at 3000rpm with a stroke of 8cm and an area of 5cm$^2$. The machine is connected to a free piston on the drill end and connected with a flexible metallic pipe. There is a 5000 cm$^3$ accumulator cm on the generator and a 2000cm$^3$ on the drill side. Using the above equations, the available work to the drill is calculated as follows.

| | | |
|---|---|---|
| Speed | 3000 | rpm |
| $a = \frac{2\pi n}{60}$ | 314.16 | |
| Stroke | 8 | cm |
| Max piston velocity | 1256.64 | cm/s |
| Piston section | 5 | cm$^2$ |
| $I = ra\Omega$ | 6283.19 | cm$^3$/sec |
| V | 5000 | cm$^3$ |
| $V_1$ | 2000 | cm$^3$ |
| Elasticity of water | 20000 | kg/ cm$^2$ |
| $C = \frac{V}{E}$ | 0.25 | |

| | | |
|---|---|---|
| $C = \dfrac{V_1}{E}$ | 0.1 | |
| $R = \dfrac{C + C_1}{aCC_1}$ | 0.04 | |
| $W = \dfrac{I^2 C_1}{4ac(C + C_1)})$ | 35903.92 | kg.cm |
| $W$ | 3.59 | kW |

This calculation shows that adequate power can be transferred to the drill rig by means of a 2.5cm diameter piston. Constantinesco built and demonstrated a rock drill in 1913. The drill was claimed to be much quieter than it’s pneumatic counterpart.

***Figure 3-6: Constantineco’s Water rill, 1913***

Unfortunately, much of Constantinesco’s work has never been published and an attempt in 1993 by the University of the Witwatersrand to replicate his sonic generator based on information in his patent was unsuccessful.

### 3.4.8 Thermal Laser impact (ablative* drives)

As with electrical discharge it is considered that the direct application of laser energy to break rock would be more efficient than the use of a laser to produce an ablative drive for a percussion system. It should be noted that previous work by the CSIR on the use of lasers to effect rock breaking by thermal spalling determined that the energy level of the available laser systems was insufficient for the process to be effective.

( **Ablation* means removal of material from the surface of an object by vaporization, chipping, or other erosive processes)

### 3.4.9 Thermal expansion

To produce the force over the stroke length required for a suitable percussion device precludes the thermal expansion of liquids and solids.  However, the thermal expansion of a gas can provide both the force and the stroke length required but the heating rate required to achieve the required frequency is that of an internal combustion engine. Whilst miniature combustion engines are available they are considered to be impractical for underground application on the basis of environmental heat load and the requirement to store flammable fuel.

### 3.4.10 Shape Memory Materials

Shape memory materials change shape when cycled through a temperature range. Such materials are capable of providing the force required and the necessary stroke length but have been discounted on the basis of the difficulties envisaged in producing the required thermal cycling at the necessary frequency.

## 3.5 Summary

It appears that there are only two potentially viable methods capable of replacing the current percussion mechanisms of pneumatic and hydraulic hand-held rock-drills and they are the coil gun approach and the Hydraulic Sonic Water-Hammer.

The coil gun appears to be technically feasible and has the following potential advantages:-

- Being electrically powered it lends itself to improved total energy efficiency over a pneumatic counterpart.
- Potentially could be small enough to fit a DTH configuration
- Small light and simple.
- Simple technology reasonably well understood.
- The rotation requirement can be met either with a small electric motor or by applying a second coil gun actuator to a rotation device such as that used in the water hydraulic rock drills.

The Hydraulic sonic hammer whilst technically feasible, as demonstrated by Constantinescu himself, would require significantly more development than the coil gun approach but could provide the following advantages:-

- Powered by an electrically driven generator, located in the gully, supplying 2-3 rockdrills the overall system efficiently would be much higher than a pneumatic version. .
- The system uses water but there is no water flow as such thereby obviated the need for a closed reticulation system.
- There are no moving parts within the rockdrill.
- The hydraulic sonic hammer forces may be high enough to permit the use of a very simple DTH arrangement
- The rotation requirement would be fulfilled by the used of an existing water hydraulic rock drill mechanism.

# 4 Recommendations

**Plasma hole-maker**

During the CSIR's visit to Tetra Corporation, it was suggested by Tetra that the following strategy be followed for developing the Blast Hole Drill:

- **Phase 1:** Fabricate a laboratory demonstrator to drill 38-mm holes in blocks of rock in the laboratory (**Error! Reference source not found.**). This demonstrator would be transported o the CSIR in South Africa, where the drilling rates and performance could be demonstrated in various types of rock from South African mines. It would be designed to propagate perhaps 0,5 to 1 m into the rock, utilising laboratory electrical power and water flow. It would not be designed to take underground because the electronics and control systems would not be fully packaged or hermetically sealed for underground use. Rather, it would be designed to demonstrate the drilling technology and drilling performance in different kinds of rock. After delivery of the demonstrator, a down-hole mining EDD Blast Hole Drill would be designed as part of Phase 1.
- **Phase 2:** The Prototype EDD Blast Hole Drill would be built, tested in the laboratory at Tetra Corporation, and then delivered to South Africa for underground testing in Phase 2. The underground testing is expected to reveal refinements that need to be made to the basic design for effective drilling of blast holes.
- **Phase 3:** These changes would be incorporated into a second prototype during Phase 3, to be delivered to the CSIR for further underground testing. At that point, the EDD Blast Hole Drill should be ready for initial commercial production.

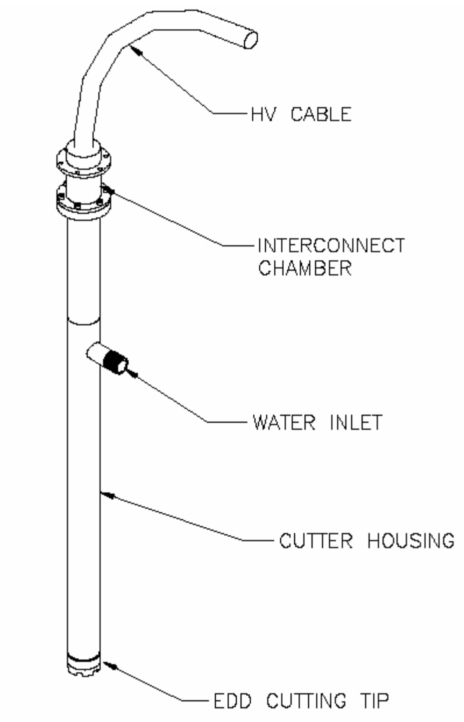



***Figure 4-1: EDD laboratory demonstrator***

According to Tetra, Phase 1 is expected to take about 8–9 months and cost about US$350k; this includes the delivery of a technology demonstrator and the design of an EDD Blast Hole Drill for application in South African mines.

Based on the critical review in Section 2.3, the research team concludes that the latest technology presented by Tetra does not seem to be novel in the field of electric rock breaking. Furthermore, any commercial agreement with Tetra Corporation would fall outside the scope or mandate of the CSIR, the MHSC and even the South African mining industry.

**Ultrasonic rock drill**

It was found that focused ultrasound with a piezoelectric ceramic cannot be used for drilling into rock and it is recommended that, for the purpose of rock drilling, no further research investment is made in this area.

**Feasibility of alternative percussion techniques**

Two potentially viable methods capable of replacing the current percussion mechanisms of pneumatic and hydraulic hand-held rock-drills are the coil gun approach and the Hydraulic Sonic Water-Hammer. It is recommended that both these technologies are further investigated.

# 5 References


**Ahrens, T. J. (Ed.) 1995.** Mechanical *Properties* and Failure Process of Fresh and Heated *Granite.* American Geophysical Union, Washington, DC.

**Alexande, M. 1999.** Engineer and Transport Properties of Interfacial Transition Zone in Cementitious Composites. RILEM (Reunion Internationale des Laboratoires et Experts des Materiaux, Systemes de Construction et Ouvrages (International Union of Laboratories and Experts in Construction Materials, Systems, and Structures).

**Andrew, C. and Baker, F. A. 1998.** Ultrasonics in Medicine. CRC Press, Boca Raton, Florida.

**Bao, X. Bar-Cohen, Y., Chang, Z., Dolgin, B. P., Sherrit, S., Pal, D. S., Du, S. and Peterson, T. 2003.** Modeling and computer simulation of the ultrasonic/sonic driller/corer (USDC). *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control,* 50: 1147-1160.

**Cook N.G.W., Joughin N.C,- 1970.** Rock Fragmentation by Mechanical ,Chemical and Thermal Methods, Proceedings of the International MiningCongress, Johannesburg, South Africa,.

**Department of Mines & Geology. 1999.** Rajasthan, India.

**Edinger, W., Neubert, V., Schultheiss, C., Strässner, H. and Wieczorek, H**., **1995** Process and device for electrodynamic fragmentation of solids – FRANKA, Forschungszentrum Karlsruhe, Germany

**Ilgner, H.J., 2006.** Electric rock breaking for South African ore bodies. Master of Science in Engineering dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg.

**Kundt, A. and Lehmann, O. 1874.** Longitudinal vibrations and acoustic figures in cylindrical columns of liquids. *Annalen der Physik und Chemie (Poggendorffs Annalen)* 153: 1.

**Nantel, J., 2006**. The status of plasma blasting technology. *A report to CAMIRO Mining Division. Ontario*

**Richards, E. J., Westcott, M. E. and Jeyapalan, R. K. 1979.** On the prediction of impact noise. I: Acceleration noise. *Journal of Sound and Vibration,* 62(4): 547-575

**Safety in Mines Research Advisory Council, 2005.** Invitation to submit project proposals (or the Gazette Package for 2005).

**Scanlon, T. and Harper, G. S. 1998.** Evaluation and further development of a 'quiet' non-atmospheric-polluting blast hole drilling system. SIMRAC report GEN 311.

**Sengpiel, E. 2004.** Personal communication. Berlin: Universität der Künste.

**Verwaal W. and Mulder, A. 1993.** Estimating rock strength with the equotip hardness tester. *Int. J Rock Mechanics, Mining Sciences & Geomechanical , Abstr.*, 30: 659-662.

**Wilson, O. B. 1988.** Introduction to Theoty and Design of Sonar Transdusors. Los Altos, California: Peninsula Publishing.

**Wright, M. E.** (undated). Riding Wave. (Retrieved 17 October 2007 from symmetrymagazine: http://www.symmetrymagazine.org/pdfs/200504/riding_wave.pdf)

# Appendix A Rail Guns

Following section has been extracted from:" *Overview of Electromagnetic Guns Electromagnetic Guns, Launchers And Reaction Engines" by Henry Kolm, Kevin Fine, Fred Williams and Peter Mongeau of the Massachusetts Institute of Technology Francis Bitter National Magnet Laboratory Cambridge, Massachusetts*.

**Electromagnetic Accelerator Concepts**

We are concerned here with linear motors which are capable of very high acceleration. This excludes at the outset the sizeable literature of linear motors[16] developed over the years for a variety of purposes, including traverse curtain rods, conveyor belts, solid waste separation, liquid metal pumps, high speed ground transportation, and even certain attempted launch devices. We shall characterize the features and limitations of our basic arsenal of accelerator concepts.

**The Classic Railgun**

The classic railgun is the simplest and also the highest perfected accelerator. It consists of two parallel rails connected to a source of dc current, the projectile consisting of a short-circuit slide propelled between the rails by the Lorentz force F = BLI/2 Newton, where B is the magnetic field intensity between the rails in tesla, L is the length of the current path through the slide, or the gap between rails in meters, and I is the current in amperes. The factor of 1/2 accounts for the fact that the field is B behind the slide and zero in front of it, the average being B/2.

The classic railgun has been studied extensively by Brast and Sawle of the MB Associates in the mid-sixties under NASA contract [17], and more recently by Marshall and Barber[10] using the world's largest homopolar generator at the Australian National University in Canberra; it is capable of storing 500 MJ.

Railguns can operate in two distinct modes. In the metallic conduction mode, current flows through the sliding projectile itself, and this mode has been demonstrated to a performance level of about 1 kg mass and 2,000 g (20,000 m/s2) acceleration by the switching gun used in the Canberra installation to feed the main gun. Marshall and Barber found that if the railgun is driven very hard, a plasma arc tends to bypass the projectile, leaving it behind. By using a non-conducting lexan (a polycarbonate resin) projectile and confining the arc behind it they were able to achieve a performance level of 16 gram accelerated at 250,000 g along a 5 m barrel to a final velocity of 5.9 km/s. As railguns are extrapolated to large projectile sizes, the distinction brush conduction mode and plasma mode is likely to vanish: brush conduction will be supplemented by arc conduction as the limit of brush current is exceeded.

The practical limit of railgun performance in regard to projectile size, acceleration, length and velocity will have to be explored by progressive refinement of material and engineering details, as in the case of any new technology. The Canberra work has provided sufficient information to justify the first attempt in this direction. Westinghouse[18], with support from DARPA, will construct a practical railgun system including the first pulse-rated homopolar generator designed with attention to overall weight. The objective is to demonstrate feasibility of accelerating a 0.33 kg (.73 pound) projectile to a velocity of 3 km/s (9.8 ft/s), corresponding to a muzzle energy of 1.5 MJ.

To a great extent, the practical limit of rail guns will depend on acceptable cost and service life. The problems relate to mechanical containment of the percussive expansion force that tends to blow the rails apart, the electromagnetic analogue of barrel pressure in a chemical gun, with the important difference that the railgun maintains more or less constant pressure throughout the acceleration. Instead of chemical corrosion, there is the destructive effect of high brush current density and the related metal vapour arc. The body of knowledge available from the study of brushes and circuit breakers does not extend to the current densities and velocities in question.

In addition to these limits, the classic railgun also faces certain fundamental limits which are not related to acceleration, but to maximum possible length or maximum muzzle velocity. As a railgun is lengthened, the resistance and inductance of the rails eventually absorb a dominant fraction of the energy. The effect is seen to begin at about five meters in the Canberra tests. Increasing velocity also causes an increasing back-emf. Current will continue to flow, even if this emf exceeds the output voltage of the homopolar generator, because the intermediate storage inductor acts as a current source. However, there is a practical limit to the voltage which can be stood off by the gap between rails, and this scales about linearly with size. Thus there are two fundamental effects which limit the amount of energy that can be transferred to the projectile, regardless of how much is available.

Another shortcoming of the railgun is its inherent inefficiency. An appreciable amount of energy is contained in the rail inductance at the instant the projectile leaves, and this energy must be absorbed by a muzzle blast suppressor. A fraction might conceivably be returned to the homopolar generator. There are several means for circumventing the limitations of the classic railgun.

**The Augmented Railgun**

The magnetic field between the rails can be augmented by supplementary current which does not flow through the sliding brushes. This current can be carried by separate conductors flanking the rails (which must be farther from the projectile), or it can be added to the rail current itself by simply terminating the rails with a load resistor or inductor at the muzzle to carry a fraction of the current. The rails themselves will obviously contribute more field than auxiliary rails located farther away, but the use of superconducting auxiliary rails might be expedient in some applications. It should be noted that railgun fields are much higher than the critical fields of superconductors. Augmentation has the obvious effect of reducing the amount of current flowing through the brushes and the projectile, and thereby the necessary conductor mass which must be accelerated.

It should also be noted that the augmenting field is twice as effective as the rail field itself. The augmenting field prevails in front of the projectile as well as behind it, thereby eliminating the factor of 1/2 in the Lorentz force expression. This fact is important inasmuch as it reduces to one half the rail bursting force which must be contained for a given acceleration.

Augmentation therefore ameliorates both the brush current density limitation and the bursting force containment limitation of classic railguns.

**The Segmented Railgun**

The length limitation imposed by rail resistance and rail inductance can be circumvented by simply subdividing a long railgun into short segments, each fed by an independent local energy source. This will of course involve certain commutation problems as the projectile transitions between segments, but will permit using part of the energy stored in each segment to energize the subsequent segment. The segmented railgun seems promising for launching large masses such as aircraft at low acceleration. In very long launchers, the use of multiple independent energy supplies will have other advantages as well.

**Mass Drivers**

As mentioned in the introduction, the mass driver is a direct adaptation of the linear synchronous motor first conceived and developed as the MIT Magneplane system in 1970-75[4], a high-speed magnetically levitated train. The mass driver can be planar or axial depending on requirements. The axial configuration permits higher efficiency and is therefore preferred for high acceleration, while the planar configuration will accommodate payloads which need not be cylindrical and may have any arbitrary shape.

In both cases, the payload is carried by a reusable vehicle, called the bucket, which is provided with two superconducting coils carrying a persistent current and guided without contact by repulsive eddy currents induced by the bucket motion in an aluminium guideway. The bucket is propelled by a series of drive coils which are pulsed in synchronism as the bucket passes by. The bucket operates like a surfboard riding the forward crest of a magnetic travelling wave, the wave being generated by the drive coils and synchronized by position sensors. Buckets can be launched at repetition rates of 10 per second. Each bucket releases its payload at a precise speed, is decelerated, and then returns to the starting point on a return track to be reloaded and relaunched.

Mass drivers can operate in the "push-only" mode as in the case of Mass Driver One, or in the pull-push mode of Mass Driver Two, now under construction, in which each drive coil undergoes a complete sinusoidal oscillation by being connected synchronously to a supply capacitor line. By tuning this cycle to the effective wavelength of the bucket it is possible to achieve energy transfer efficiencies, electric-to-mechanical, of better than 90 percent. We should add that the bucket-to-payload ratio is about unity, and that about half the bucket energy is recoverable by regenerative braking.

For all practical purposes, mass drivers have no velocity limit and no length limit. Acceleration has been limited thus far by the current and voltage capacity of the SCRs used for switching. Using shelf components, Mass Driver Two should achieve 500 to 1,000 g. If the SCR limitation is removed, by using ignitrons, spark gaps, or direct contact switching, performance will be limited by mechanical and thermal failure of the drive coils. Some preliminary calculations based on a four inch calibre mass driver using aluminium bucket coils and copper drive coils suggest an acceleration limit between 100,000 and 250,000 g. This is comparable to railgun performance, however, the failure mode of drive coils under fast pulse conditions is a very complex subject requiring experimental study.

All previous mass driver designs are based on a bucket coil current density of 25 kA/cm2 of cable, achieved in an operational model of the MIT magneplane. Superconductors should withstand up to four times this current density at the low field intensity and stored energy involved. It should also be pointed out that mass drivers do not necessarily require superconducting bucket coils. For periods of the order of 0.1 second it is actually possible to maintain higher current densities in normal conductors. Maximum performance mass drivers are therefore likely to utilize aluminium bucket coils, possibly precooled to liquid nitrogen temperature, fed by sliding brushes, and drive coils triggered by physical contact. Of course this would eliminate the non-contact advantages.

A unique feature of mass drivers bears emphasis: although they are energized by capacitors, the costliest, heaviest and bulkiest energy store known, each capacitor is used hundreds or thousands of times during each launch cycle by being connected to many drive coils through feeder lines. This permits the use of an efficient but slower intermediate energy store, such as a compulsator or MHD generator.

**The Helical Railgun**

The railgun is in essence a single-turn motor. A multi-turn railgun would reduce the rail current and the brush current by a factor equal to the number of turns. It therefore seems worth-while to study a "helical railgun". In this hybrid device, the two rails are surrounded by a simple helical barrel, and the projectile or re-useable carrier is also helical. The projectile is energized continuously by two brushes sliding along the rails, and two or more additional brushes on the projectile serve to energize and commute several windings of the helical barrel direction in front of and/or behind the projectile. The helical railgun is in fact a cross between the railgun and the mass driver.

## Superconducting Slingshots

Accelerators based on mechanical energy storage have not been used since the day of the bow and medieval catapult, with the exception of naval aircraft launching. Mechanical energy storage devices are bulky, heavy, and slow to release their energy. The advent of practical superconducting magnets provides a good mechanical storage mechanism, the magnetic slingshot.

Consider a short superconducting solenoid which is free to slide inside a long one. The travelling solenoid will be either attracted to or repelled from the centre of the long solenoid, depending on the direction of relative magnetization. Either configuration can serve as an electromagnetic slingshot.

In the attractive configuration, the travelling solenoid can serve as a payload-carrying shuttle bucket. Released at the breach end of the barrel coil, it will accelerate to the centre, where it will release its payload at maximum velocity, come to rest at the muzzle, and then return empty to a position short of its release point, from where it can be returned to the release point by mechanical force, possibly by a thermal cycle. This oscillation is inherently loss-less, except for possible eddy currents induced in nearby metal.

In the repulsive configuration, the travelling solenoid will be moved by mechanical force from the breach to a point just beyond the centre of the barrel. When released, it will be expelled from the muzzle as part of the projectile. Velocities up to several hundred m/s are attainable by slingshots.

## The Superconducting Quench Gun

By successively quenching a line of adjacent coaxial superconducting coils forming a gun barrel, it is possible to generate a wave of magnetic field gradient travelling at any desired speed. A travelling superconducting coil can be made to ride this wave like a surfboard. The device in fact represents a mass driver or linear synchronous motor in which the propulsion energy is stored directly in the drive coils.

## Impulse Accelerators

A brass washer placed on top of a vertically oriented pulsed field coil is driven upward, accelerated by eddy currents which tend to be 180 degrees out of phase with the inducing field pulse. The resulting impulse has been used commercially since 1962 for metal forming operations, for instance by swaging terminal fittings around aircraft control cables. The process has certain applications for acceleration. It can be made into a synchronous induction motor whose performance is limited by the thermal inertia of the sliding member.

## The Momentum Transformer

A novel concept described here for the first time is what we shall call the "momentum transformer". It makes use of a so-called "flux concentrator", first studied by Howland at MIT Lincoln Laboratory in 1960[19]. A flux concentrator is simply a conducting cylinder with a funnelled bore, and at least one radial slot extending from the inside to the outside surface. The cylinder is surrounded by a pulsed field winding, preferably imbedded in a helical groove to minimize hoop stresses. A fast pulsed current in the winding induces an opposite image current in the outer surface of the cylinder. Due to the radial slot, this induced current is forced to return along the inner perimeter of the cylinder, thereby generating a magnetic field in the funnelled bore. All of the magnetic flux which would have filled the pulsed field winding in the absence of the concentrator is thus compressed into the central bore, resulting in a field intensity which is higher than it would have been by about the outside-to-inside cross section ratio.

The device was used at MIT for high field research and also for industrial metal forming. In 1965, Chapman[20] used a flux concentrator with a tapered bore for accelerating milligram metal spheres to hypervelocities. Using a first stage explosive flux compressor, Chapman managed to reach peak fields in excess of 7 megagauss, starting with an initial field of only 40 kilogauss.

The momentum transformer proposed here uses a flux concentrator as the armature or sabot in a chemically driven conventional gun. The bore of this sabot is occupied by a much smaller projectile, for instance a rod-shaped armour penetrator. The muzzle end of the gun is a pulsed field winding imbedded in a helical groove, which is excited with a current pulse sufficiently slow to penetrate the barrel and fill the bore with magnetic flux. When the sabot enters this flux region so rapidly that the effective penetration depth of the field is small, it compresses the flux into its inner bore, decelerates drastically, and expels the projectile contained in its bore at a much higher velocity. The device should have very little recoil because the muzzle coil acts like a muzzle brake, transferring much of the sabot momentum to the barrel. The process can be multi-staged with a series of nesting sabots.

**References**


1. Albert F. Reidl III, "Preliminary Investigation of an Electromagnetic Gun", NWL Technical Not No. TN-E-10/72, July 1972, Naval Weapons Laboratory, Dahlgren VA, 22448.
2. R. D. Thornton, "Magnetic Levitation and Propulsion 1975", IEEE Trans. on Magnetics, Vol. MAG-11, No. 4, July 1975.
3. J. R. Powell and G. T. Danby, "The Linear Synchronous Motor and High Speed Ground Transport", 6th International Energy Conversion Engineering Conference, Boston MA, 1971.
4. H. H. Kolm and R. D. Thornton, "The Magneplane: Guided Electromagnetic Flight", Proc. 1972 Applied Superconductivity conf., Annopolis IN.
5. G. K. O'Neill, "The Colonization of Space", Physics Today, Vol. 27 No. 9, Sep 1974, pp. 32-40.
6. AC. Clarke, "Electromagnetic Launching as a Major Contribution to Space Flight", JBIS, Vol. 9 No. 6, Nov 1950.
7. The 1976 NASA-AMES OAST Summer Study on Space Manufacturing with non-terrestrial Materials, published by AIAA as Progress in Astronautics and Aeronautics, Space-Based Manufacturing from Non-Terrestrial Materials, Series Vol. 57, editor: M. Summerfield.
8. W. Arnold, S. Bowen, S. Cohen, K. Fine, D. Kaplan, H. Kolm, M. Kolm, J. Newman, G. K. O'Neill and W. Snow, "Mass Drivers", parts I, II and III, Proc. of the 1977 NASA-AMES Summer Study: "Space Resources and Space Settlements" NASA, SP-428, 1979, U. S. Govt. Printing Office.
9. G. K. O'Neill and H. H. Kolm, "Mass Driver for Lunar Transport and as a Reaction Engine", Jour. of the Astron. Sciences, Vol. 1`5 No. 4, Jan-Mar 1976.
10. G. K. O'Neill, "High Frontier", Astron. and Aeron. Mar 1978, special issue on space industrialization.

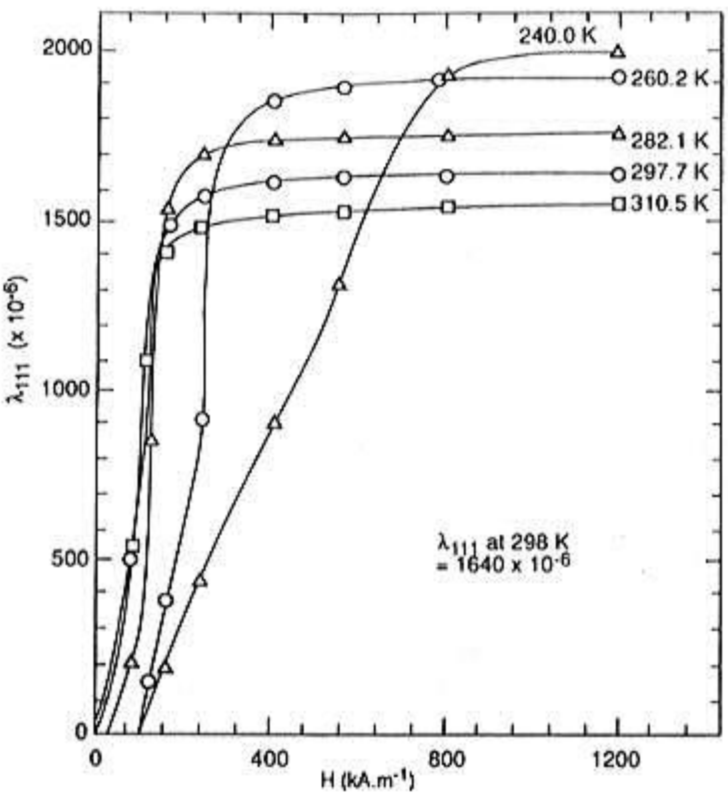
11. H. H. Kolm, "Basic Mass Driver Reference Design", K. Fine "Basic M D Construction and Testing", G. K. O'Neill, "M D Reaction engine as Shuttle Upper Stage", F. Chilton, "MD Theory and History", Proc. of the Third Princeton-AIAA Symp. on Space Manufacturing, 1977, published by the AIAA.
12. H. Kolm, K. Fine, P. Moneau, F. Williams, W. Snow, G. K. O'Neill: three papers on Mass Driver Two to appear in the Proceedings of the 4th Princeton AIAA Symposium on Space Manufacturing, 1979, to be published by the AIAA in late 1979.
13. S. C. Rashleigh and R. A. Marshall, "Electromagnetic Acceleration of Macroparticles and a Hypervelocity Accelerator", dissertation 1972, Dept. Engr. Phys. Australian Natl. Univ., Canberra.
14. W. F. Weldon et al, "The Design, Fabrication and Testing of a 5 MJ Homopolar Motor-Generator", International. Conf. on Energy Storage, Compression and Switching, Torino, Italy, Nov 1974.
15. M. D. Driga et al, "Fundamental Limitations and Topological Considerations for Fast Discharging Homopolar Machines", IEEE Trans. on Plasma Science, Dec 1975.
16. W. L. Gagnon et al, editors, "Compensated Pulsed Alternator", Lawrence Livermore Lab., July 1976.
17. MIT Francis Bitter Natl. Magnet Lab, "Annual Report July 1977 - June 1978", Cambridge MA, 02139; see also various technical reports.
18. J. D. Lindsay and D. M. Wedon, "Loss Measurements in Superconducting Magnetic Energy Storage Coils", Report LA-6790-MS, Los Alamos Science. Lab, Los Alomos NM, May 1977.
19. M. Cowan et al, "Pulsar - a Flux Compression Stage for Coal-Fired Power Plants", Proc. 6th Internatl. Cryogenic Engr. conf., Grenoble, France, May 76, Published by IPC Science and Technology Press Ltd. Guildford, surrey, England.
20. S. A. Nasar and I. Bolea, "Linear Motion Electric Machines", Wiley, NY, 1976.
21. D. E. Brast and D. R. Sawle, "Feasibility Study for Development of a Hypervelocity Gun", Final Report NASA Contract NAS 8-11204, May 1965.
22. John Mole, Westinghouse Research Lab., Pittsburgh PA 15235, personal communication.
23. B. Howland and S. Foner, "Flux Concentrators", High Magnetic Fields, H. Kolm, editor, Wiley NY, 1962.
24. R. I. Chapman, "Field Compression Accelerators", Proc. Conf. on Megagauss Field Generation by Explosives, Frascati, Italy, Sep 1965 (Euratom).
25. Dr. Chul Park, NASA-AMES research Center, Moffett Field, CA, 94035; personal communication.

# Appendix B Magnetostriction

**Magnetostriction and Magnetostrictive Materials**

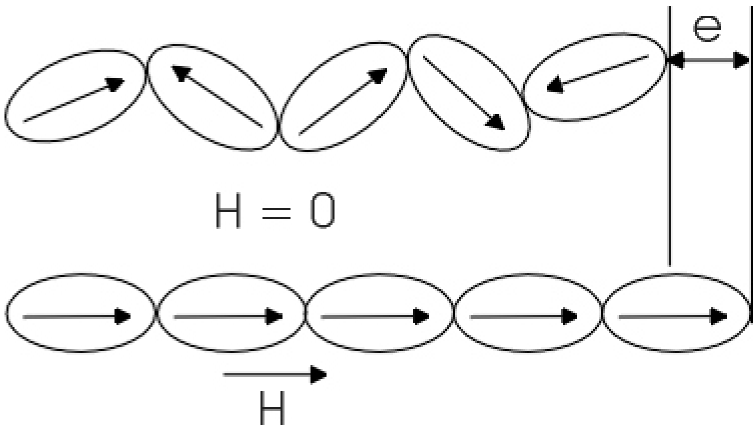
**(**from Clark, A. E. Ferromagnetic Materials, vol 1, ed Wolfhart, E.P. (Amsterdam: North-Holland) pp. 531)

Magnetostriction is the changing of a material's physical dimensions in response to changing its magnetization. In other words, a magnetostrictive material will change shape when it is subjected to a magnetic field. Most ferromagnetic materials exhibit some measurable magnetostriction. The highest room temperature magnetostriction of a pure element is that of Co which saturates at 60 microstrain. Fortunately, by alloying elements one can achieve "giant" magnetostriction under relatively small fields. The highest known magnetostriction are those of cubic laves phase iron alloys containing the rare earth elements Dysprosium, Dy, or Terbium, Tb; DyFe2, and TbFe2. However, these materials have tremendous magnetic anisotropy which necessitates a very large magnetic field to drive the magnetostriction. Noting that these materials have anisotropies in opposite directions, Clark(1) and his co-workers at NSWC-Carderock, prepared alloys containing Fe, Dy, and Tb. These alloys are generally stochiometric, of the form TbxDy1-xFe2 and have been coined Terfenol-D. Terfenol-D, operated under a mechanical-bias, strains to about 2000 microstrain in a field of 2 kOe at room temperatures. For typical transducer and actuator applications, Terfenol-D is the most commonly used engineering magnetostrictive material.

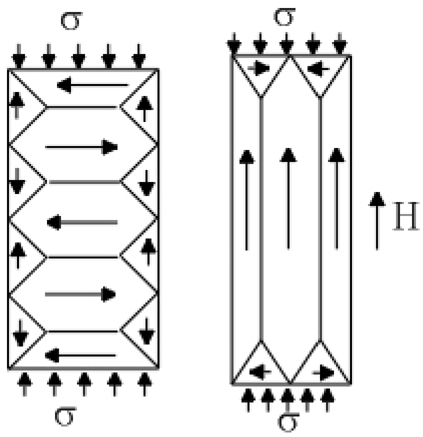



Terfenol-D response around room temperature, from Clark1

The mechanism of magnetostriction at an atomic level is relatively complex subject matter but on a macroscopic level may be segregated into two distinct processes. The first process is dominated by the migration of domain walls within the material in response to external magnetic fields. Second, is the rotation of the domains. These two mechanisms allow the material to change the domain orientation which in turn causes a dimensional change. Since the deformation is isochoric there is an opposite dimensional change in the orthogonal direction. Although there may be many mechanisms to the reorientation of the domains, the basic idea, represented in the figure, remains that the rotation and movement of magnetic domains causes a physical length change in the material.




Magnetostrictive materials are typically mechanically biased in normal operation. A compressive load is applied to the material, which, due to the magneto-elastic coupling, forces the domain structure to orient perpendicular to the applied force. Then, as a magnetic field is introduced, the domain structure rotates producing the maximum possible strain in the material. A tensile preload should orient the domain structure parallel to the applied force though this has not yet been observed due to the brittleness of the material in tension.




Clark, A. E. Ferromagnetic Materials, vol 1, ed Wolfhart, E.P. (Amsterdam: North-Holland) pp. 531