Ultrasonic Rock Drilling

Report prepared for

CSIR Natural Resources and the Environment

by

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October 2007
Executive Summary

The purpose of this study is 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. Currently in South African mines blasting holes in rock are created with percussive drilling, using pneumatics, hydraulics or electricity as energy source. These techniques cause sound levels so high that permanent hearing loss is induced in 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 be further investigated.
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<th>Symbol</th>
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<td>$A$</td>
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<tr>
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1. Introduction

1.1. Problem Statement
Currently in South African mines blasting holes in rock are created with percussive drilling, using pneumatics, hydraulics or electricity as energy source. During mining operations of this nature, the operator is exposed to extremely high noise levels. This causes damage to his hearing ability and can result in permanent deafness.

Business Enterprises at the University of Pretoria was commissioned to perform an investigation into the possible use of ultrasonic methods for the disintegration of solid material such as rock as a substitute for conventional rock drilling techniques, with the aim of substantially reducing or eliminating damaging noise.

1.2. Objective
This study had the objective to find a manner of creating holes or cavities in rock typically found in South African mines, employing ultrasonic pressure waves, that is economically viable and that does not cause noise levels leading to injury.

1.3. Execution
This report essentially reflects the execution of the project. A literature review was done and the background on mining operations and ultrasonics were investigated. The literature review led to the investigation of two ultrasonic drilling concepts: percussive drilling at ultrasonic frequencies and rock disintegration with focussed ultrasonic waves in the rock. The former was investigated to the point that experiments were conducted and small holes were drilled in a number of rock samples. The results were compared to actual industry standards and conclusions were drawn on the feasibility of this method. The second method, that of rock disintegration by focussed ultrasonic waves, was investigated only superficially. The report concludes with recommendations.
2. Literature Review

2.1. Mining Techniques

All mining operations consist mainly of the excavation of various types of rock. (Teale, 1965). When this rock is still intact in the earth’s crust, only one face is revealed and excavation takes place by breaking off fragments from the rock face. The drilling of a shot hole reveals a bigger surface and excavation can take place on a larger scale by blasting the rock into fragments.

The pneumatic rock drill is the most common drill used in mines and is powered by a high-pressure air supply, in the region of four bar. The air is channelled by valves around a piston that causes it to oscillate at a frequency of about 40 Hz. A rotational movement is also produced by the oscillation, improving the drill rate. The piston drives the drill steel onto which the drill bit is attached and with an axial force of about 750 N, produced by the air leg and the operator, a hole is drilled into the rock face (Roberts 2007). Looking at the mechanics involved when the hole is drilled, it can be described as percussive indentation. The only way for the drill bit to penetrate the rock is by breaking off small rock fragments from the surface, and the rock is essentially crushed continuously on one spot to produce a hole (Teale, 1965).

A main cause of the high noise levels generated by a pneumatic rock drill is the air escaping from the exhaust ports and flowing through parts like the chuck. The compressed air undergoes expansion in the exhaust port and this contributes significantly to the high noise levels (Du Plessis, et al., 1988). Other sources of noise include the drill steel and the drill body that vibrate in the region of 5 kHz, producing additional noise.

Both hydraulic and electric percussive drilling are used in South African mines as alternatives to pneumatic drilling. Noise data recorded by Heyns and Windell (2006) shows that the noise levels associated with these alternative drilling methods are not significantly lower than that caused by pneumatic drills. There also is some opinion that the drill steel and the rock face into which is being drilled with percussive techniques generate significantly high levels of noise, regardless of the method of powering the drilling. All of this support efforts like the current project to find alternative crushed drilling techniques that would generally operate at lower noise levels.

Numerous possibilities are available to develop better mining methods although very few concepts ever make it into the industry. It is interesting to note that in his book Underground Practise in Mining 1938, Bernard Beringer stated: “Undoubtedly hand drilling is a thing of the past.” as he predicted that machine stoping will completely replace hand drilling. He further described the miner as one of the most conservative people in the world, which can be one of the reasons why hand drilling is still an essential part of mining today. An inventive idea and compatible method is thus needed in order to really have an effect on the mining industry.

The field of ultrasound is still a relative unexplored option for mining purposes and conducting this study will indicate whether it is viable. Looking at the mining procedures
of today, there are great opportunities for improvement and ultrasonic methods may hold the key for a better mining future.

2.2. Ultrasound

Ultrasound can be described as pressure fluctuations at frequencies above the human spectrum of audible sounds, and ranges from 20 kHz to 5 MHz in gasses and MHz in solids or liquids, although the upper limit of ultrasonic frequency is not clearly defined (Li, Sanderson and Hurndall, 2004). The human ear is capable of hearing sound in the frequency range from 20 Hz to 20 kHz, called the acoustic range (Fig 2.1).

![Figure 2.1 Sound frequencies (Wikipedia.com)](Image)

Sound waves progress through a substance, be it a solid, a fluid or a gas, by movement of the particles in a direction parallel to the direction in which the wave is travelling and are called longitudinal waves. Longitudinal waves are associated with alternating compression and rarefaction (or extension) and are also called compression waves. The elasticity of the material, in the case of solids, or the drive to equalize pressure in the case of fluids and gasses, causes the particle to return to its original position in an oscillatory manner, with, in the case of a short duration disturbance, a continued reduction in the amplitude due to damping caused by internal friction in the substance.

Ultrasound can be divided into two areas. The first called low power or high frequency ultrasound consists of high frequency and low amplitude waves and is used for medical scanning, chemical analysis and the testing of materials for flaws. The second area called power ultrasound ranges in the low frequencies of 20 kHz to 100 kHz and can cause permanent changes within the medium. These high amplitude waves are used for cleaning, drilling, plastic welding and effecting chemical reactivity (Mason and Lorimer, 1989). This study will mainly focus on power ultrasonics.

2.3. Power Ultrasound

High energy ultrasonic waves are defined as those for which there is no longer a linear relationship between the applied stress and the resultant strain (Blitz, 1967). There will be an effect on the medium through which these waves pass. One example of this is the forming of cavitation in a liquid through which high energy ultrasonic waves are irradiated. Cavitation is a common phenomenon in boiling water, hydraulic pumps and also near the rotating propeller of a ship. It is caused by the rapid alternating pressures in the liquid. Any bubbles present will then contract and expand and given a certain critical radius of the bubble, it will then collapse under the pressure. This sudden collapse is known as cavitation and a relative large amount of
energy is released in a short period of time. As a result of this energy release, cavitation is often associated with erosion of solids that may be immersed in the fluid in the vicinity of the cavitation. It can clearly be seen how the sound wave propagating through the liquid will cause a negative pressure for the first half of the wave and a positive pressure during the second half, thus creating this alternating pressure and causing cavitation.

The amount of energy released depends on the ratio of the critical radius to the maximum radius of the bubble as well as the surface tension and the vapour pressure. This amount can be determined by the loss in weight due to erosion of a solid, placed in the liquid. The minimum pressure wave amplitude required for cavitation is called the threshold of cavitation and varies with frequency and the amount of gas or air inside the liquid. Generally the threshold intensity will decrease with an increase in temperature and a decrease in pressure. It will also decrease with an increase in time exposure to the sound, because of the time delay between the excitation and the commencement of cavitation.

In ultrasonic cleaning, cavitation as well as the agitation of the wave is used. Frequencies ranging from 20 kHz to 40 kHz are applied in most cleaning purposes, where cavitation effects are responsible for the majority of the cleaning work. However, for items that may sustain damage due to cavitation, higher frequencies from 100 kHz to 1 MHz are used and the cleaning process is performed fully by agitation.

Other current uses of power ultrasound are in the medical field where kidney stones are disintegrated when high amplitude waves are focused on the specific location of the stone. The ultrasonic waves propagate through the human body (consisting mainly of water) and create a focal point at the kidney stone where the resulting cavitation causes it to break up.

Zhang, et al. (2007) conducted a study on the ultrasonic treatment of biological sludge in order to determine the effect on the solid content and biological activity. The results revealed a disintegration of the sludge and slowed the biological activity. The effect increased as the energy of the ultrasound was increased. Here the waves propagated through the water-based substance as in the case of the kidney stone disintegrator. Replicating such a mechanism for the breaking of rocks will perhaps also require water as the application medium.
2.4. **Ultrasonic/Sonic Driller/Corer**

Recently Cohen et al. (2001) developed an Ultrasonic/Sonic Driller/Corer (USDC) for in-situ sampling as part of the NASA planetary exploration program. The USDC uses a novel driving mechanism, based on a piezoelectric actuator oscillating at ultrasonic frequencies that causes a free mass to resonate, at sonic frequencies, but with a bigger amplitude. The free mass oscillates against a drill bit where the impact creates a stress impulse at the drill tip where the rock interface is, causing it to break (Figure 2.2).

![Figure 2.2 A USDC drilling through sandstone (Chang et al., 2004)](image)

A schematic illustration of the USDC is shown in Figure 2.3. The USDC is a lightweight compact device that requires minimum operating force as can be seen in Figure 2.2. This is ideal to attach to the sojourner rover and can drill through basalt, granite, diorite and limestone. The acoustic horn that was used resonates at an optimum frequency of 21.5 kHz, and serves as an amplifier for the oscillation.

The free mass resonates at a frequency of 1000 Hz between the top of the drill stem and the tip of the horn. The impact on the drill stem is transferred to the rock face where the rock is excited past its ultimate strain and fractures. The USDC is therefore essentially a percussive drill operating in the audible frequency range.
Low power (12W) is required for the drill and 200V AC current generates a maximum tip velocity of about 1.4 m/s for the horn with no loading. The displacement of the tip can reach a maximum of 10 µm and it is this displacement that forms one of the crucial aspects in the drilling process.

The test results from the USDC showed a drilling rate between 1 and 5x10^{-4} cm^3/s for rocks of moderate hardness such as basalt. For a 2.85mm diameter drill bit, it is equivalent to about 15 mm in 10 minutes. Harder rocks such as quartz or granite were not drilled and will most likely give slower drilling rates.

Clearly, it can be seen that the USDC is not a fast drilling device, but the focus is on the efficiency and compactness of the drill. Although the excitation frequency is ultrasonic, the drilling frequency is well into the acoustic range, and will be audible by an operator. It needs to be noted, though, that minimizing drilling noise was never a goal for the researchers who developed the USDC. Unfortunately, no report could be found of the level of noise generated by this drill during operation.
2.5. **Ultrasonic drilling**

The main use of ultrasonic drills today is in the lapidary field where artisans drill holes in precious stones in the process of making jewellery. Companies such as GemTek and Cutting Edge Solutions manufacture these drills for jewellers around the world. A big advantage of the ultrasonic drill is that there are no rotating parts. This allows for much smaller drill bits that can be used, as well as holes that can be drilled in any shape, such as a square or oval.

The main idea, on which all of the percussion drills work, is based on the concept of applying sufficient force or energy to induce stresses in the rock that exceeds the rock strength. According to Maurer (1966), rock failure occurs when the minimal principal stress exceeds the tensile strength of the rock, or when the shear stress of the rock is exceeded. These stresses are created as the drill bit is impacting at ultrasonic frequencies on the rock surface. An abrasive, in the form of a silicon carbide powder, is added to the drilling area and circulated through the system with the help of water. With its high hardness, it contributes in the process of disintegrating the rock surface under the drill bit. Without the abrasive, it will not be possible to drill a hole in the hard stones, or it will take painstakingly long.

Ultrasonic drilling is a highly specialised field, and its uses have not yet been fully explored. It forms an integral part of the jewel manufacturing industry and provides opportunities that would not have been available without it.

Conducting a study to investigate the advantages that ultrasonic drilling may hold for the mining industry is very important. Kravcenko (1957) investigated the ultrasonic drilling principle based on abrasion and cavitation, but found that a lot more energy is needed, compared to other drilling methods. However, in the past fifty years, the technology has progressed exponentially and many new techniques have been implemented in all areas of the industry.
3. Ultrasonic resonator for percussive drilling

By modifying an ultrasonic resonator supplied by the CSIR in Pretoria, a drill was created to use in an experimental investigation. The characteristics of the ultrasonic drilling device had to be determined. Displacement measurements were done with the resonator being excited at the optimum frequency.

3.1. Background information

The ultrasonic resonator works on the simple principle of exciting axial vibration in an elongated object at a frequency such that a specific standing wave is generated inside the body, leading to a high vibration amplitude at a specific point, for example a free end. Another way of looking at this is that the body is excited at a natural mode of axial vibration, hence the term resonator. Standing waves occur when integer multiples of half-wavelengths fits in over the length structure.

Piezoelectric actuators are typically used to excite the resonator, but the amplitude of oscillation achievable by this type of actuator is often too small for the purpose. An acoustic horn is then used to amplify the oscillation as the axial sound wave is progressing through the length of the device. There are a number of different shapes and sizes of acoustic horns being used. Figure 3.1 illustrates the basic types and their characteristics.

The stepped horn has by far, the best magnification characteristics, as the gain is equal to the quadratic ratio of the diameters. There is however, a problem with high stress values when large amplifications are implemented. The axial vibration structure is designed that, to get most benefit from the amplification cause by the horn, the standing wave, in terms of displacement, has a node at the step. The axial strain and hence the axial stress are at local maxima at the displacement nodes, leading to possible high stress values. The horn is then strengthened by making use of fillets or flanges, although some of the amplification will be lost.

Figure 3.1 Displacement magnification of horns (Belford, 2001)
A characteristic that plays a major role in the design of a resonance device is the **Q** value of the material. The mechanical **Q** represents the ratio of energy stored to energy dissipated per cycle (Belford, 2001). It is largely dependent on the type of material from which the resonator is made, but can also change for various geometrical configurations and modes of vibration. A high value for **Q** is needed in these applications to ensure the wave will propagate through the device without major losses in energy. This is especially important for the piezoelectric crystal to ensure good resonance. A PZT-8 or PZT-4 stack is an example of a piezoelectric transducer that may be used in these applications.

Initially it was planned to build an ultrasonic resonator, consisting of piezoelectric transducers and an acoustic horn. The biggest challenge was finding a piezoelectric actuator, such as the PZT-8 and PZT-4 stacks. Three international companies were identified that produce these actuators. Only one of these was able to manufacture the specific shape and size needed, but had a 20 week waiting period.

A later visit to the CSIR in Pretoria revealed the availability of a suitable ultrasonic resonator. The CSIR previously used this resonator to create sound waves in air, and was prepared to lend this to the University. Figure 3.2 illustrates the dimensions and components of the device with a mass of 1.75 kg. It can be seen that the two piezoelectric actuators, on either side of the handle flange, work against each other, creating the displacement nodal point at the handle. The resonator is made of steel, for which the wavelength of a 20 kHz sound wave is about 254 mm. A half wave length at this frequency fits in between the handle and the diameter step which forms the root of the acoustic horn. This means that a standing wave with a displacement node at the handle will have a similar node at the diameter step. The small diameter horn has a length of a quarter wavelength, and with a displacement node at its root this results in a maximum displacement amplitude at its free end. The total length of the resonator corresponds to one wavelength. The bolt is used to pretension the actuators and to provide support by fixing the backing onto the device.

Realistic and credible experiments could be conducted with the CSIR resonator and the study was continued with it. It was transformed into a drill by manufacturing two drill bits that fit onto the tip of the horn.
3.2. Measurement set-up

Figure 3.3 shows a picture of the resonator with a transformer that is attached to the input terminals of the device to double the voltage signal that is sent to the resonator.

An HP 8904A Multifunction Synthesizer produced the necessary AC signal. This signal generator allows for precise frequency and amplitude input to the system. These input parameters could be adjusted digitally. The signal generator is capable of producing a maximum output signal of amplitude of 10V.
The amplifier used is an A-303 high voltage piezo driver from AA Lab Systems. It produces a maximum 200 V amplitude, 200 mA signal, implying, with a ten volt input, a twenty-fold gain. Its frequency range stretches from DC to 450 kHz, making it ideal for this experiment. The combination of the signal generator, amplifier and transformer produced a signal of maximum 400 V amplitude to the resonator.

In order to verify the amplification produced by the amplifier and transformer, a two-channel oscilloscope and a scope probe with a factor ten attenuation was used to measure the signal at the different positions in the system. It was also used to measure the output signal from the laser vibrometer that was used to measure the velocity of the drill tip.

A Polytec PDV 100 laser vibrometer measured the tip velocity of the drill. The velocity signal was integrated in the frequency domain to produce a displacement time trace.

The experimental set-up for measuring the tip velocity of the resonator is shown in figures 3.4 and 3.5.
In the measuring procedure, the value of the oscillation amplitude was determined as well as a relationship between the oscillation amplitude and the applied voltage. This was done by increasing the voltage input amplitude incrementally from a minimum to the maximum. The results of the measurements will be discussed and the analysis procedure explained.

The procedure was started with a 20 kHz sinusoidal input from the signal generator at a 1 Volt amplitude. This signal was amplified to approximately 22 V by the amplifier and then doubled to 44 V by the transformer. This indicates that the amplifier has a gain of slightly higher than 20. Referring to Figure 3.6, a screen capture of the oscilloscope, the purple trace indicates the input signal to the drill, before it was doubled by the transformer. The peak-to-peak value of the signal is displayed at 4.38 V. This is a factor of ten times less than the actual value at 43.8 V, as the signal was measured using the scope probe.

Figure 3.5 Schematic representation of measurement set-up

3.3. Measurement procedure and analysis
Figure 3.6 Oscilloscope screen capture: resonator input (purple) and output signals

The laser was directed to the tip of the drill (Figure 3.7), and the velocity was measured and sent to the oscilloscope as a voltage signal. The yellow trace in Figure 3.6 represents the velocity of the tip in terms of voltage. The yellow box, pertaining to the yellow signal, indicates vertical and horizontal axis scaling of 0.5 V and 50 µs per division, respectively. Thus, an amplitude of 0.78V was measured on the yellow trace.

Figure 3.7 Laser measurement at tip

A calibration factor of 0.025 m/s/V needs applied to the voltage signal, in order to convert it to velocity. For an input amplitude of 44 V to the resonator, a tip velocity amplitude of 0.02 m/s is therefore achieved, as also shown in figure 3.8. It is clearly
shown that the sine wave that was applied to the resonator is also retrieved as a velocity at the tip, at the same frequency of 20 kHz, as expected.

**Figure 3.8 Resonator tip velocity for a 44V amplitude input signal**

Using a Fast Fourier Transform (FFT) in Matlab, the velocity signal was integrated in the frequency domain to determine the displacement. The maximum amplitude was found to be 0.15 µm (Figure 3.9).
The same method was applied to obtain the tip displacement for a maximum input signal of 440 V amplitude. This resulted in a tip displacement amplitude of 1.55 µm.

The amplitude of displacement for the incremental voltage inputs between 44 and 440V is shown in figure 3.10. The increasing slope of the graph towards higher input voltages indicates that even higher displacements may be achieved with input voltages exceeding 450 V. This was not possible with the amplifier that was available, but it warrants further investigation, as the resonator never heated up during the experiment and should be able to handle higher input levels.
Figure 3.10  Relationship between tip displacement and voltage
4. Experimental drilling procedure: ultrasonic percussive drilling

4.1. Experimental set-up
The components used in the drilling experiment were the signal generator, the piezo amplifier and the ultrasonic drill with its attached transformer. The oscilloscope was used to verify that that the input signal to the drill remained constant throughout the drilling process and does not weaken the moment the drill makes contact to the rock or when the amplifier started to heat up. The set-up is illustrated schematically in Figure 4.1.

![Figure 4.1 Schematic representation of drilling experiment](image)

A stop watch with a count down alarm indicated the time periods in which the drilling took place and a vernier calliper measured the diameter and depth of each hole. Great care was taken not to touch two different poles on the drill, as the AC current was conducted through the whole device. The current is not hazardous at 100 mA but the 440 V did produce a sharp sting and burn when a finger slipped from the safe position on the handle. Rubber gloves were used to prevent any major injuries.

Silicon carbide was added to the drilling area as the abrasive. The powder was purchased at a gem store and is the typical abrasive that jewellers use with their ultrasonic drills. It is mixed with water to form a grinding paste, and then circulated through the drilling area.

Two drill tips were manufactured from mild steel. A solid tip with a diameter of 5 mm and a corer tip with a 6 mm and 10 mm, inner and outer diameter respectively.
In figure 4.2 the drilling procedure is shown where a hole is being drilled with the solid tip without adding abrasive. The powder of the brick is seen, as it forms in the air around the tip.

Various types of rock and stone were drilled in order to give a wide spectrum of results. This included brick, concrete, shale, granite, quartzite and spotted anorthosite. Granite and quartzite is typically the extremely hard rock that is drilled in gold and platinum mines with pneumatic rock drills, and was drilled with success. However, it was not possible to drill into these hard stones without adding the abrasive and the drill rate was not as high as expected.

These rock specimens were obtained directly from the mines and cut at the University of Pretoria to produce a smooth surface from where accurate hole measurements could be made.

4.2. Experimental procedure

The drilling procedure consisted of 5 to 10 minute periods and was conducted with the help of an assistant to add the abrasive and ensure a stable set-up. The following steps summarises the procedure.

- The rock specimen is placed on a paper towel, to catch the water and abrasive mixture. It is then ensured that the rock is standing firmly to prevent tip-over.
- The signal generator is switched on and set to produce a 20 kHz, 10 V AC sine wave signal. The amplifier is also switched on and a sine wave with an amplitude of 440 V is received by the drill.
- The drill is then picked up and the drill tip placed on the rock specimen.
- Abrasive is added to the drilling area throughout the process, by means of a spout, to ensure that the bit is exposed to new particles.
• The drill is turned and twisted to improve the circulation of the abrasive.
• At the end of the time period the drill is removed from the hole, the signal
turned off and the hole diameter and depth measured.

All the data is then recorded on paper and comments are added on the different
aspects of the specific drill procedure.

During the drilling process, some resonance of the drill could be heard as an irritating
screech. This resonance was at frequencies below 20 kHz and was also felt through
the drill handle, as the nodal point of zero amplitude was no longer at the handle like it
is in the case of a 20 kHz vibration. This noise was dependent on the type of rock that
was drilled and the pressure applied to the drill. Granite produced the most noise but
could be controlled by applying a little pressure. Drilling into the brick and shale only
produced noise when the abrasive was added, and although a faster drilling rate was
achieved with the abrasive, a completely silent hole could be made without it.

Connecting the drill to the signal at full power of 440V, a high pitched tone can be
heard when a young person place his or her ear close to the device. This however, is
not valid to all younger people as some could not hear any difference with the drill on
or off.. All the older people exposed to the drill at full power could not hear anything.
This can be ascribed to the fact that humans lose their hearing ability in the high
frequency range as they get older. It is most likely that a person who is exposed to
this sound regularly, will loose the very fine hair in their ears quicker than normally. It
is these hairs that enable them to hear such a high frequencies like 20 kHz. Losing
these hairs will however not affect their ability to hear any other sound or method of
communication, which we experience daily. It should be remembered that the
frequency at which the experimental drilling was conducted was determined by the
available resonator on loan from the CSIR. For a newly designed resonator drill the
excitation frequency may very well be shifted upwards, further away from the human
audible range, to further reduce the possibility of injury.

4.3. Results
A summary of the results will be given in tables for each rock type, with applicable
graphs where necessary. The values did not vary significantly for different drilling
attempts, as the same drilling rate was achieved when new holes were drilled. All of
the holes were drilled with the solid drill bit. The corer bit did not produce any hole
with or without abrasive. In all the cases, except were it is stated otherwise, the thrust
applied is equal to the weight of the drill which is 17 N. With additional pressure the
thrust is equal to 40 N. In Figure 4.3 some of the holes that were drilled are shown.
Figure 4.3 An example of the drilled holes

The brick was the most stable and easy specimen to drill, and delivered a good spectrum of results, depending on parameters being changed. In Table 4.1 the results are depicted with an average drilling rate after each time period. These holes were drilled without additional pressure and by adding abrasive. Figure 4.4 indicates the reduction in drilling rate, which declines steeply as the hole depth increases.

Table 4.1 Brick drilling results

<table>
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<tr>
<th>Drilling time (min)</th>
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<th>Depth (mm)</th>
<th>Drill rate (mm³/min)</th>
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<td>10.623</td>
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<tr>
<td>10</td>
<td>5.2</td>
<td>3.8</td>
<td>8.070</td>
</tr>
<tr>
<td>20</td>
<td>5.2</td>
<td>5.5</td>
<td>5.840</td>
</tr>
</tbody>
</table>
Further tests were carried out to determine what difference additional force will make on the drilling rate, as well as the effect of the abrasive. From Table 4.2 it is clear that the additional force did improve the drilling rate slightly. The abrasive had a much greater effect and showed an improvement of nearly double the drilling rate, compared to the case when no abrasive was added.

Table 4.2 Brick drilling comparative results

<table>
<thead>
<tr>
<th></th>
<th>Drilling time (min)</th>
<th>Diameter (mm)</th>
<th>Depth (mm)</th>
<th>Drill rate (mm³/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No force</td>
<td>5</td>
<td>5.1</td>
<td>2.6</td>
<td>10.623</td>
</tr>
<tr>
<td>Added force</td>
<td>5</td>
<td>5.1</td>
<td>3.2</td>
<td>13.074</td>
</tr>
</tbody>
</table>

(Abrasive was used in the above two cases.)

<table>
<thead>
<tr>
<th></th>
<th>Drilling time (min)</th>
<th>Diameter (mm)</th>
<th>Depth (mm)</th>
<th>Drill rate (mm³/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No abrasive</td>
<td>10</td>
<td>5.4</td>
<td>2.1</td>
<td>4.809</td>
</tr>
<tr>
<td>Abrasive added</td>
<td>10</td>
<td>5.2</td>
<td>3.8</td>
<td>8.070</td>
</tr>
</tbody>
</table>

Two types of concrete, with different water-cement ratios were drilled. The concrete proved very tough in comparison with its compression strength, but the drill rate did correspond to the different strengths (Table 4.3).
Table 4.3 Concrete drilling results

<table>
<thead>
<tr>
<th>Compression strength</th>
<th>Drilling time (min)</th>
<th>Diameter (mm)</th>
<th>Depth (mm)</th>
<th>Drill rate (mm³/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44MPa</td>
<td>10</td>
<td>5.1</td>
<td>1.35</td>
<td>2.758</td>
</tr>
<tr>
<td>46MPa</td>
<td>10</td>
<td>4.9</td>
<td>1.1</td>
<td>2.074</td>
</tr>
</tbody>
</table>

Of the three hard rock types the quartzite proved to be the easiest to drill. It also produced the best drill rates. To start a hole in the granite was very difficult, as the drill tip kept on sliding around. Table 4.4 to 4.6 summarises the results of the three hard rock specimens.

Table 4.4 Quartzite drilling results

<table>
<thead>
<tr>
<th>Drilling time (min)</th>
<th>Diameter (mm)</th>
<th>Depth (mm)</th>
<th>Drill rate (mm³/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4.8</td>
<td>0.75</td>
<td>2.714</td>
</tr>
<tr>
<td>10</td>
<td>4.8</td>
<td>1.45</td>
<td>2.624</td>
</tr>
<tr>
<td>20</td>
<td>5.1</td>
<td>2.1</td>
<td>2.145</td>
</tr>
</tbody>
</table>

Table 4.5 Granite drilling results

<table>
<thead>
<tr>
<th>Drilling time (min)</th>
<th>Diameter (mm)</th>
<th>Depth (mm)</th>
<th>Drill rate (mm³/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4.6</td>
<td>0.45</td>
<td>1.496</td>
</tr>
<tr>
<td>10</td>
<td>4.7</td>
<td>0.8</td>
<td>1.388</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>1.7</td>
<td>1.669</td>
</tr>
</tbody>
</table>

Table 4.6 Spotted anorthosite drilling results

<table>
<thead>
<tr>
<th>Drilling time (min)</th>
<th>Diameter (mm)</th>
<th>Depth (mm)</th>
<th>Drill rate (mm³/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.7</td>
<td>1.35</td>
<td>2.342</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>1.95</td>
<td>1.914</td>
</tr>
</tbody>
</table>

From Figure 4.5 a comparison between the three rock types can be seen. For both the quartzite and spotted anorthosite, the drill rates decreased with depth as expected. The granite shows an increase with depth and this can be due to the difficulty in starting the hole.
For all three of the cases, abrasive was needed to drill a hole. Without it, the drill tip only bounced on the rock surface without any effect. Additional pressure had no effect on the drill rates, although an increase was expected. In one case the granite formed a crack and broke open during drilling. This indicated the porosity of the rock, and may be an area in which further research should be carried out.
5. Analysis of results: ultrasonic percussive drilling

In analysing mechanical drilling or breaking of rock, one of the rock properties that needs to be considered is the specific energy $E$ (J/m$^3$), which gives the amount of the energy that is needed to remove one cubic meter of rock. If the specific energy of a certain rock, and the power consumed in breaking the rock, $P$, is known, the drilling rate $R_t$ can be calculated as (Bao, et al., 2003)

$$R_t = \frac{P}{E} \quad (5.1)$$

The energy used to break the rock is in general less than the energy available in the drill or even the energy transferred to the rock. The developers of the USDC found that in the case of drilling with the USDC in hard rock only a small percentage of the energy is used in the end, to break the rock. They pointed out (ibid.) that only that part of the energy transferred into the rock while the stress is higher than the strength of the rock, contributes to breaking the rock. One may modify the above equation, to provide for a drilling efficiency $\eta$, as follows:

$$R_a = \frac{\eta P}{E} \quad (5.2)$$

Teale (1965) observed a correlation between the crushing strength of the rock and the specific energy. This is illustrated by data produced by Maurer, as quoted by Bao, et al. (2003) and given in table 5.1. In addition to this, for 250 MPa granite, the specific energy is calculated with data supplied by Boart Longyear (Roberts, 2007) and a value of 380 J/cm$^3$ is found, correlating well with Table 5.1.

**Table 5.1 Specific energy and compression strength of rocks. (Bao et. al., 2003)**

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Compression strength (MPa)</th>
<th>Specific energy (J/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft</td>
<td>&lt;50</td>
<td>30</td>
</tr>
<tr>
<td>Medium</td>
<td>50-100</td>
<td>50</td>
</tr>
<tr>
<td>Hard</td>
<td>100-200</td>
<td>260</td>
</tr>
<tr>
<td>Very hard</td>
<td>&gt;200</td>
<td>390</td>
</tr>
</tbody>
</table>

During the experiments described in chapter 4, the power input to the drill tip was unfortunately not determined. If some estimation was available, the theoretical drilling rate could have been calculated with equation (5.2) and by comparison with the actually measured drilling rate, the drilling efficiency could have been calculated.

It is useful at this point to consider the performance of rock drills currently in use in South African mines. A pneumatic rock drill is capable of drilling a 32 mm diameter hole in 250 MPa granite, at a rate of 400 mm/min (Roberts 2007). In comparison to the ultrasonic drill, it is a drill rate of 321 700 mm$^3$/min $= 5.362 \times 10^{-6}$ m$^3$/s, a factor of 200 000 times faster than the ultrasonic drill (see table 4.5). The power output at the drill tip is in the region of 2000 W. Operating at a frequency of 40 Hz, this means
that 50 J of energy is available at the drill tip for each blow. It also means that, according to equation (5.2), the drilling efficiency of this drill calculates to a value slightly higher than 1. This is of course not possible, and it probably means that some of the data used in the calculation is not entirely accurate. It can be taken, though, that the drilling efficiency of the currently used pneumatic drills are very high.

If one looks at the performance of the USDC, reported by Bao, et al. (2003), drilling rates between 6 and 30 mm³/min were measured in soft and medium hardness rock, at a peak power input of 24 W or 12 W average on a 50% duty cycle. This power included circuit losses in the driving electronics, accounting for 30% of the power. If one therefore calculate the drilling efficiency of the drill based on a medium rock specific energy of 50 J/cm³ (table 5.1), a drilling rate of 30 mm³/min and a power input of 8.4 W, a value of 0.0030 is obtained, which is very low. One should also keep in mind that, even though the piezoactuator in this case was operated at just above 20 kHz, the percussion frequency on the drill bit was in the region of 1 kHz.

An upper limit for the power input to the CSIR resonator during the measurements reported in chapter 4 can be estimated, based on the maximum voltage and current output from the amplifier used, of 220 V and 100 mA. If these are assumed to be rms values (rather than peak-values), the maximum power that can be delivered to the transformer and resonator is 22 W, assuming the power factor is 1. (If the above voltage and current values were taken as peak values, the power level would be 11 W at a power factor of 1.) Since the piezoelectric actuator is a high capacitance element, it is expected that the power factor may actually be small. One can say that the power delivered to the resonator and the drilling rates measured are of the same order of magnitude as in the case of the USDC described above, and thus conclude that the drilling efficiency attained during the experiment was similarly poor.

One can take the comparison between the three drilling concepts one step further. The efficient pneumatic drill delivers 50 J per blow at a relatively low frequency of 40 Hz. The USDC delivers percussive blows at 1 kHz, at a frequency 25 times higher than the pneumatic drill. The CSIR resonator delivers percussive blows, if one can call it that, at a frequency 20 times higher than the USDC and 500 times higher than the pneumatic drill. If an ultrasonic drill operating at 20 kHz is to be made with the same power consumption as the pneumatic drill, of 2000 W, it will necessarily deliver only 0.1 J per blow, compared to the 50 J of the pneumatic drill. Based purely on this argument the ultrasonic drill is not feasible in production mining.

In free conditions the resonator delivered a maximum displacement amplitude of 1.55 μm (figure 3.10). This amplitude is expected to reduce once the resonator-drill is brought in contact with the rock, due to the structural dynamics of the rock. One can argue that at this low value, the indentation that can be caused on the rock face, given the drill tip diameter of 5 mm, is too small to cause stress levels sufficient to break hard rock. This argument is supported by observations during the experiment. Even though the resonator could drill a hole in brick and softer rock, it could not do so in the case of harder rock without the aid of an abrasive. One effect that the abrasive may have is to concentrate the indentation over a much smaller area, in effect causing a stress concentration and thus raising the induced stress to levels where breaking can occur. This is however speculative. The reason why the low amplitude high
frequency oscillation was able to drill softer but not harder rock, may be further investigated, perhaps through numerical analysis. Such an investigation may perhaps also be seen as an investigation into the poor drilling efficiency of the ultrasonic drill and may suggest ways of improving this efficiency. If significantly higher power consumption, compared to that of the pneumatic drill, were to be acceptable, ultrasonic drilling in production mining would be brought in focus again, but then still the drilling efficiencies (really, the transfer of power from the drill tip into the rock, at stress levels where rock breaking would occur) will have to be significantly improved.

The idea of higher power consumption in itself should not be rejected right away, because with significantly improved drilling efficiencies, this higher power consumption will result in significantly improved drilling rates. This may be thought of as using fewer drills that drill faster, while the overall energy consumption may remain the same.

Another observation that was made during the experiments is that of a decrease in drill rate, with an increase in depth. The reason for this occurrence is most likely a build up of rock powder in the hole, which dampens the impact of the drill bit. This was also observed by Bao, et al. (2003.) in the case of the USDC.

A variation in diameters at shallow depths was also observed. This was caused by the drill bit becoming blunt (i.e., the circular edge rounded) during the drilling experiments. Evidently, the abrasive was wearing down the rock as well as the drill tip, but it is understandable, as the tip is made out of mild steel. A harder tip made from titanium or a high carbon steel, will show a much longer lifespan, although having a softer tip with the abrasive may also be beneficial, while the tip is not blunt. This was not investigated experimentally, though. The importance of having a sharp edged tip during drilling of this kind is highlighted by Bao, et al. (2003.)

It should also be noted that the CSIR resonator delivered higher drill rates in granite, using an abrasive, than predicted for the USDC in Bao, et al. (2003). (Boa et al. did not do any measurements on hard rock like granite at the time of writing their paper.) Yet all the results reported on the USDC were obtained without any abrasive.
6. Rock disintegration by focussed ultrasonic waves

The fact that kidney stones can be destroyed by ultrasonic waves focussed from an exciter outside of the human body naturally raises the question as to whether the same technique cannot be used to fragment rock directly with focussed ultrasonic waves. The idea of having this disintegration happening inside the rock, that is, some distance behind the rock face, has some appeal, because if possible the blasting hole can then be drilled from a depth towards the rock face, containing the fragments and dust until the completion of the hole. It would also allow the hole to be drilled with varying diameter along its length, which may be beneficial in the blasting operation.

The mechanism by which kidney stones are disintegrated with ultrasound is the creation of cavitation in the watery fluid surrounding the kidney stone or contained inside the kidney stone due to its porosity. To the extent that significant amounts of water are present inside the rock that needs to be mined, this technique may be used in mining also. It is expected that insufficient water is contained inside rock like granite to make this technique generally viable, although this aspect has not been researched and is a topic for further investigation.

A further question that is raised is whether focussed ultrasound can cause the rock to disintegrate in a direct manner, rather than indirectly, as in the case of cavitation in nearby fluid. Conceptually this is possible, if the pressure wave, be it at ultrasonic frequencies or in the audible range, causes the stress in the rock to rise above the ultimate strength of the rock. This means that for granite with tensile strength in the region of 20 MPa, a sound pressure level of \(20 \log_{10} \frac{20 \times 10^6}{(2 \times 10^{-5})} = 240\) dB needs to be generated at the point where this disintegration needs to take place. This is an extremely loud noise!

The concept of rock disintegration with focussed ultrasound has not been investigated in depth. What follows is merely some first calculations to see whether it is possible in terms of sound power and sound pressure levels. To consider a case where sound waves are focused at a point, it is expedient to think of a spherical sound wave front in an infinite medium. With respect to an elastic solid medium, this problem is addressed by Timoshenko and Goodier (1970, p. 508). They indicate a general solution that consists of an outward-moving spherical wave, often associated with an explosion, and an inward moving spherical wave, often associated with an implosion. It is this latter wave that is of interest for the disintegration of the rock at the focal point, at the centre of the sphere. The velocity of the spherical wave is slightly larger than that of a planar wave in the same medium, and can be calculated (ibid., equation 277) as 4750 m/s in granite with modulus of elasticity of 53 GN/m², Poisson’s ratio of 0.236 and density of 2750 kg/m³. The reference by these authors to waves associated with explosions and implosions is actually somewhat enlightening in the context of this report: in conventional mining as currently used, holes are drilled in rock and then filled with explosives. The resulting explosion can actually be considered as the creation a sound wave in the rock, probably a single pulse or otherwise a small number of waves, with associated pressure so high that the rock is fragmented. The idea of disintegrating the rock with ultrasound is thus not that much different from the explosive methods already used. It differs in the sense that not a few but a continuous train of
pulses at high frequency is suggested and that the disintegration of the rock is perhaps spatially more controlled.

The mathematical analysis of the outward moving and inward moving spherical waves are quite similar. Nelson and Elliot (1992) describes the solutions of the three-dimensional wave equation (ibid., p. 24) and point sources of spherical radiation (ibid., p. 26). The latter analysis may be repeated for a spherical point sink, which represents the problem of the inward-moving sound wave. The solution presented indicates that the pressure is a hyperbolic function of the radial coordinate \( r \) (ibid., equation 1.11.8), where the origin is at the centre of the spherical wave. This means that the pressure goes to infinity as one approaches the origin. Let the sink be thought of as a sphere of diameter \( 2a = 1 \) mm, with its centre at the origin, such that the pressure amplitude reaches a value of 20 MPa, close to the ultimate tensile strength of the granite, when the inward moving spherical wave reaches the source at \( r = a \). From the pressure expression (ibid. equation 1.12.1) the pressure amplitude coefficient can then be calculated as \( A = (20 \times 10^5)(0.005) = 10000 \) Pa m. Using this result, the sound power absorbed by the sink is calculated as 48 W (ibid. Equation 1.13.6), where the above rock density and the speed of the spherical sound wave in rock have been used. This means that to have a spherical volume of diameter 1 mm, within which the maximum pressure rises to above 20 MPa under radiation from a spherical sound wave, the power absorbed inside the 1 mm sphere should be at least 48 W. Of course this also means that a spherical rock surface of larger diameter should be excited with 48 W of acoustical power, to create the inward moving spherical wave.

In practical terms one would not use excitation along a complete sphere but rather on a spherical surface that covers an area smaller than a half-sphere. For such a case the analysis above is not accurate, but the analysis was done merely to get an idea of the power involved.

The acoustic power of 48 W may not seem very much, but this translates to a sound power level of 137 dB, which is comparable with that of a large orchestra or an aircraft engine. To generate this on a rock face may not pose an impossible task, but it was, at first at least, not believed to be practical yet. An installation able to deliver ultrasonic waves at this kind of acoustical power levels will be quite sizeable. Furthermore, a single sphere of 1 mm in diameter right in the middle of a large rock is not very useful from a miner’s perspective. To be practical the sink sphere needs to traverse a certain volume inside the rock, in order to disintegrate a volume that would resemble a blast hole. This renders a serious practical problem, because whatever exciter is used, it needs to be fixed to the spherical outer rock area without any air gaps, and especially with sound at ultrasonic frequencies, there should be no borders or cracks between the exciter and the small spherical sink, as any such borders or cracks will simply reflect the ultrasonic waves, and any air gaps will attenuate the sound. Having a spherical area onto which the exciter is fixed in itself would require significant preparation work on the rock. A further problem is possible non-uniformities in the rock, which may adversely affect the focus or destroy the spherical nature of the wave.

The concept of fragmenting rock with focussed ultrasonic waves as explained above was discussed with Prof Arthur Every of the School of Physics of the University of the Witwatersrand. Prof Every is an expert on ultrasonics. This discussion took place
on 29 November 2007. Prof Every pointed out that the idea of having a focal sphere of 1 mm diameter is not practical, for two reasons:

- Granite and many other rock types are granular solids, and the focal sphere should be larger than the typical granule, otherwise the waves may simply bounce (reflect) off the granule boundaries. It is expected that the typical granule size is larger than 1 mm, calling for larger focal spheres.

- The focal sphere cannot be smaller than one wavelength. With the speed of the spherical wave at 4750 m/s in granite, as calculated above, a wavelength of 1 mm corresponds to a frequency of 4.8 MHz, which is extremely high. If the focal sphere is enlarged to a 10 mm diameter, the frequency would be brought down to 480 kHz, which is more reasonable, but still quite high.

Prof Every also pointed out that it is not necessary to have a spherical rock face on which the ultrasonic exciters are mounted in order to create a spherical wave front in the rock. A spherical wave font may be created from an arbitrary shaped rock face — provided the rock surface geometry is known — with a phased array of exciters. This means that a computer can control the pulsing of the exciters in such a way that a spherical wave front is created. This removes one of the stumbling blocks, mentioned above, to the practical implementation of the concept of focussed ultrasonic waves to disintegrate rock. Computer control of the phased array exciters also will enable the focal sphere to traverse a larger volume inside the rock in order to create a blasting hole.

If the focal sphere is increased in diameter by a factor 10, from 1 mm to 10 mm, as suggested above, the required power to ensure that the pressure reaches the ultimate strength of the rock of 20 MPa at the outer edge of the focal sphere, increases with a factor of 100 to 4.8 kW, translating to a sound power level of 157 dB. This is comparable to the sound power level associated with a jet aircraft. It would be quite formidable task to pump so much sound energy into a rock with a phased array of ultrasonic exciters, but it is not considered impossible. Since the acoustical pressure of the spherical wave is inversely proportional to the radius of the spherical wave front, one can easily calculate the pressure in the rock at any radial distance from the centre of the sphere. For instance, at a radial distance of 500 mm (i.e., 495 mm outside the edge of the focal sphere) the required pressure is 200 kPa, which translates to a sound pressure level of 200 dB. If the phased array exciters are mounted at a distance of about 500 mm from the location where the 10 mm diameter cavity is to be formed, the exciters will be required to generate a stress of 200 kPa at their interface with the rock, which does not sound impossible.

The sound pressure and sound power levels roughly calculated above also need to be viewed in terms of what is acceptable from a human exposure point of view. Studies have been done to investigate the effect of ultrasound on the human body. A worthwhile example is that of Lawton (2001). Even though this report has not been studied in any depth, some graphs included (op cit., figures 10.1 and 10.2) indicate that the ultrasonic sound pressure and power levels calculated above are too high for human tolerance, even for relative short durations. This means that the implementation of focused ultrasonic waves to disintegrate rock will have to be executed in some or
other automated mode, without the presence of humans close to the action. This may not necessarily disqualify the concept, since the phased array exciters in any case need computer control. Implementation of this concept may however imply a paradigm shift in the way miners think of mining. This author is of opinion that it is worthwhile to further investigate this concept.

The investigation presented above is based on the theory of elasticity as applied to sound or pressure waves in a solid medium. On the other hand, the earlier part of this report focussed on exploiting resonance. This does raise the question as to whether there may be some wave that can be used to cause resonance on a molecular scale in order to disintegrate solid material, and whether focusing such waves may not be used to create blasting holes from inside a rock, with the associated benefits. Microwaves come to mind, i.e., a form of electromagnetical wave. This should also be further investigated.
7. Conclusion and Recommendation

7.1. Conclusion
An ultrasonic drill was created from an ultrasonic resonance device. The drill tip velocity during free operation was measured with a laser vibrometer.

The resonator was used to drill a number of holes in various rock types. The actual drilling rates were determined. These values indicated very poor drilling efficiencies. Nonetheless, it was proved that the rock typically found in South African mines can be drilled ultrasonically with significantly reduced noise levels. Audible noise only occurred in some of the cases and could be controlled with the thrust applied to the drill.

With the low drilling efficiencies and/or the high power consumption, it has been shown that it will not be feasible to implement this drilling concept in the mining industry. However, if the drilling efficiency can be improved significantly, this concept of rock drilling may become feasible. In that case very high power will be required, but very high drill rates should result. In such a scenario the possible adverse effect of high power ultrasonic waves on the human body — on the hearing system or otherwise — should be investigated.

Rock disintegration with focussed ultrasonic waves was investigated superficially and found to be theoretically possible and worth of further investigation.

7.2. Recommendations
Firstly, the drilling efficiency of ultrasonic rock drilling needs to be improved, and numerical and laboratory experiments should be carried out to find methods that will enhance this value.

• Using a smaller diameter drill bit is a method of concentrating the energy to a smaller area on the rock.
• Other methods, such as adding abrasives should be explored.
• The steady force applied to the drill may play a role in improving the drilling efficiency. This was seen with the brick, where the drill rate increased by applying additional force.
• During the experiment the drill was powered by piezoelectric actuators which rendered very small displacements. A more optimally designed resonator should be investigated.
• The possibility of using a magnetostrictive vibration actuator should be considered. These actuators work on the principle that an oscillating magnetic force is induced by an alternating current that flows through coils and can produce a bigger displacement than piezoelectric actuators.
Additionally, the following need attention:

- The residual noise experienced during the ultrasonic drilling experiment should be investigated with the aim of eliminating this.
- No attention was yet given to possible adverse effects of ultrasonics, especially at high power levels, to human health. This should be investigated.

Since the investigation into rock disintegration with focussed ultrasonic waves was done only superficially, a more thorough investigation is recommended. It is also recommended that rock disintegration through resonance at the molecular level with focussed waves, of a kind other than sound, be investigated.
8. References


Lawton, B.W., 2001, *Damage to human hearing by airborne sound of very high frequency or ultrasonic frequency*, contract research report 343/2001 prepared for Health and Safety Executive of the British Government by The Institute of Sound and Vibration Research of the University of Southampton, ISBN 0 7176 2019 0.


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