MINIMOLE: DEVELOPMENT AND FIELD TESTING OF A NARROW-VEIN HARD ROCK MECHANICAL MINING MACHINE

Eric Jackson - Cellula Robotics Ltd., New Westminster, BC

Don Clarke - Cellula Robotics Ltd., New Westminster, BC

Abstract

This paper describes highlights of the Placer Dome MiniMole project - the development and testing of a robotic machine for mining narrow ore veins. A prototype hydraulically controlled robotic machine was built and tested. The machine provided a platform for testing numerous cutters in the field. Other cutters, e.g. undercutting devices, were tested in the lab. Extensive analyses were done on specific energies and cutter penetration. Three sets of quarry trials were done, then the machine was tested in an underground mine. Rock UCS values varied from 180 MPa to 230 MPa. The paper includes lessons learned and recommendations based on the project findings.

MiniMole Program Objectives

The MiniMole program objectives were multiple:

- to provide a continuous mining system
- to remove miners from the ore face
- to allow economic exploitation of narrow ore deposits.

The latter goal was the primary economic driver - MiniMole was conceived as the “Solution to Dilution” - a machine that was able to mine narrow ore veins while leaving the remaining host rock in place.

An early risk analysis on the overall program identified in situ identification of ore veins as the highest risk project element. Therefore, the program was focussed on the excavation issues. As opposed to finding and following ore veins, the excavators would be directed by geologists to mine specific structures.

Initial Technologies Considered

A number of excavation technologies were considered initially, e.g:

- concentrated Plasma blasting
- Undercutting discs
- conventional raise drill and tunnel boring machine cutting technologies, e.g. button cutters, disc cutters

Experiments were performed in all of these technology areas.

Rock types were determined by the requirements of candidate mines, i.e. the Campbell and South Deep mines.

Machine Description

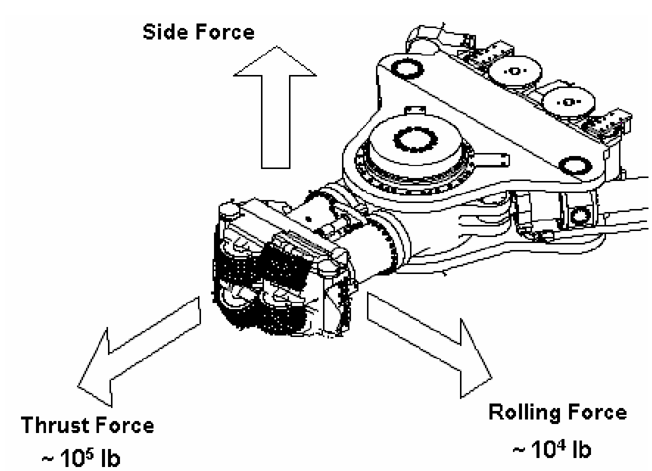

Figure 1 MiniMole Layout and cutting forces

The MiniMole, shown without a rear housing in Figure 1, consists of a main frame, a set of hydraulic grippers, and the cutting mechanisms. The main frame consists of two roughly triangular thick iron plates spaced about 700 mm apart, joined by a rear plate. These circular plates of 0.7m diameter are located in the centre of the main frame. A set of four rear grippers mounted on the back of the frame adjust and hold the MiniMole alignment.

The MiniMole secures itself within a pre-cut slot with a set of opposing hydraulically actuated grippers, which are pressed against opposite walls of the slot with forces of almost 200,000 lbs.

The main frame supports a rotation housing, which is rotated about the main gripper cylinder by two pivoting swing cylinders. These are offset for maximum travel. Two parallel thrust cylinders are mounted to the rotating housing. These cylinders are capable of a combined output of around 350,000 lbs. Finally, attached to the end of the thrust cylinders is the cutter head which contains an array of rolling cutters, a set of grippers, and scrapers for cuttings removal.

Located behind the rear grippers is a housing for the hydraulic manifolds, control valves and the on-board computer. The rear housing also contains the lifting pins and terminus for the hydraulic and telemetry umbilical.

The MiniMole is powered hydraulically by a 250 hp remote hydraulic pressure unit (HPU). This is connected to the MiniMole by a flexible umbilical, containing hydraulic circuits of 5000 and 1500 psi. The umbilical also contains the telemetry cable which connects the onboard computer to the operator's console, and air and water lines for cuttings removal.

Machine Operation

The MiniMole is operated remotely from an operators console. Some of the operating sequences are fully automated.

The MiniMole uses a walking procedure to position itself at the cutting face. With the thrust cylinders fully extended, cutterhead grippers are engaged and then the main frame grippers were disengaged. This allows the MiniMole to travel along the thrust cylinders. Once the thrust cylinders are fully retracted, the main frame grippers are re-engaged, the cutter head grippers are disengaged, the thrust cylinders are extended, and the cycle is repeated. Alignment of the main frame is achieved by engaging the cutter head grippers, disengaging the rear grippers, and then adjusting the swing cylinders. With adjustable main and rear gripper positioning, the MiniMole position can be adjusted in all six degrees of freedom.

Once in position and aligned, the main frame grippers are securely engaged, and the cutters are swung side-to-side, with an available arc length of just over 180 degrees. At the beginning of each swing, the thrust cylinders are extended a pre-set amount. This continues until the thrust cylinders reach their full extent, at which point the walking and realignment is repeated.

Test Descriptions

Tests were performed at three locations: at the Earth Mechanics Institute of the Colorado School of Mines (CSM), at a granite quarry in Squamish, British Columbia, and at the Campbell Mine in Ontario.

A range of cutter types were tested throughout the program on a Linear Cutting Machine (LCM) at the CSM. Among those tested were

- various roller button cutters
- conventional minidiscs
- undercutting minidiscs

Rock samples on which the cutters were tested included barre granite, grano-diorite from the Squamish quarry, and samples taken from Campbell mine.

Three sets of quarry trials were performed. In the first set, a series of roller button cutters was tested with the MiniMole advancing horizontally into a horizontal slot cut into a rock face. In the second set, the horizontal mode was again tested with a series of button, multi-disc and minidisc cutters. The second half of the second set of trials was performed in a vertical slot, with the MiniMole advancing downward. The slot was open to the edge of a face so that cuttings could be swept out at each pass. Here another set of minidisc, roller button and multi-roller cutters were tested.

The focus of the third set of tests at the quarry was the MiniMole deployment system which was to be used at the Campbell mine trials. Overall, a slot of about 1m by 6m wide by 10m deep was excavated during the vertical quarry trials. This slot can be seen in Figure 2 and Figure 3.

Finally, at the Campbell mine, minidisc and roller button cutters were tested in a quasi-vertical (~80 degree) slot. The slot was positioned beside a pre-drilled shaft from a lower drift into which cuttings were swept.

At each of the MiniMole trials, the main parameters varied were the penetration depth and the swing rate.

Figure 2 Lowering into position

Figure 3 Cutting at quarry

Measurements and Automation

The MiniMole was equipped with a thorough suite of sensors. The position and pressure of each hydraulic cylinder except for the two at the cutter head were measured and logged at 10 and 1000 Hz. Pitch and roll along with pitch, roll and yaw rates were recorded. An accelerometer mounted on the main frame measured machine vibrations. A set of cameras were positioned on the MiniMole and at the slot entrance.

High-level commands such as penetration setpoints and walk commands sent from the control console were handled by an on-board machine interface computer. Continuous swing sequences, cylinder position/force setpoints and machine state transitions were controlled here. These commands were processed by another software module which generated swing trajectories and servoed the cylinder positions at 1 kHz.

Cutter Testing Results

Roller and Disc Cutters

Two cutter types had the durability to last long enough for substantial data collection. These were a button roller set made by the Robbins company, and an 8” minidisc array made by Excavation Engineering Associates. These were tested in the vertical quarry and in the mine trials. The horizontal trials did not produce sufficiently “clean” data, as difficulties in removing material from the cutting face resulted in regrind and thus higher forces.

The three orthogonal components of force used to describe the reaction at the cutter head are the rolling (drag) force, the thrust (normal) force, and the side force, which are shown in Figure 1. The rolling and thrust forces were measured through the hydraulic actuator pressures. The side forces were not measured. To make comparison of these forces with those of other rock cutting devices or with single discs possible, the cutter forces are presented as force per unit of width of cut. The width (dimension parallel to the side force direction) of the cutterheads we used (and thus the excavated slot) was 880 mm.

An example of the sheer volume of data collected is shown in Figure 4. The different colored points correspond to different swing rates. It was found that the swing rate did not contribute significantly to the average cutter forces. However, the variance of the data increased with decreasing swing rate. This may be attributed to machine stalling, as the forces spiked as the controller tried to follow the setpoints.

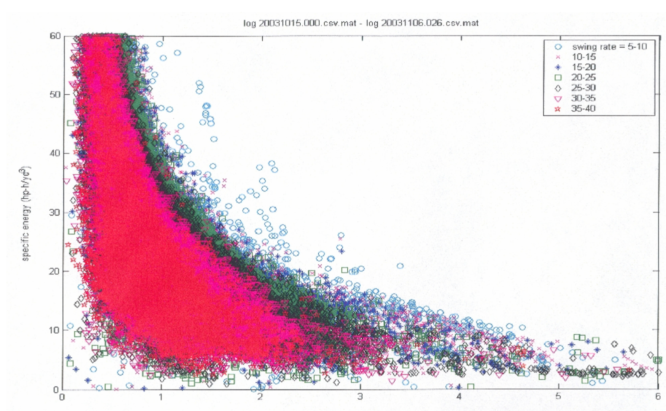

Figure 4 Specific energy vs. depth of cut data points for roller button cutters at quarry

Figure 5 shows the rolling force per unit of cut width for both cutter types in the mine and quarry. In the range of zero to three mm penetration, which was the operating envelope of the MiniMole in the rock types encountered, the rolling force appeared to have a fairly linear dependence on the penetration. The rolling force was relatively insensitive to both the cutter type and the rock type.

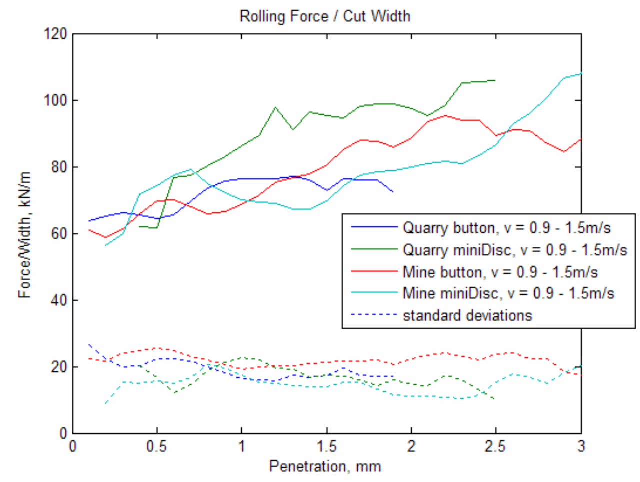

Figure 5 Rolling Force

It should be noticed that for both the rolling and thrust forces, the data for some cutters begins to level off or decrease at higher penetrations, especially for the button cutters at the mine trials (shown in red in Figure 5 and Figure 6). With limited visibility at the face, only the position and force data could be used in trying to determine when the cutters were in full contact with the rock. The total forces encountered during partial cutter contact are lower. Thus, at deeper penetrations the data contains higher instances of partial contact, and should therefore be ignored. It is included here to demonstrate the difficulties of gathering cutting force data in the field as opposed to the lab.

The thrust force was much more sensitive to the rock type than was the rolling force. The mine and quarry rock compressive strengths were approximately 180MPa and 130MPa, respectively. The thrust forces were considerably lower in the mine rock, though the UCS is higher here. Figure 6 shows the thrust forces for the minidisc and button cutters at both the mine and the quarry.

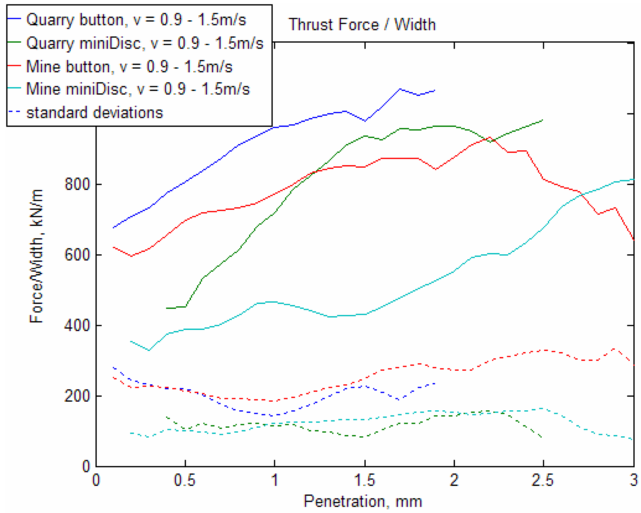

Figure 6 Thrust Force

It can easily be shown that specific energy has units of pressure. The pressure is evaluated as the quotient of the rolling force and the cross-sectional area of cut at one instant. The rolling force vector is perpendicular to this area. This geometry is illustrated in Figure 7.

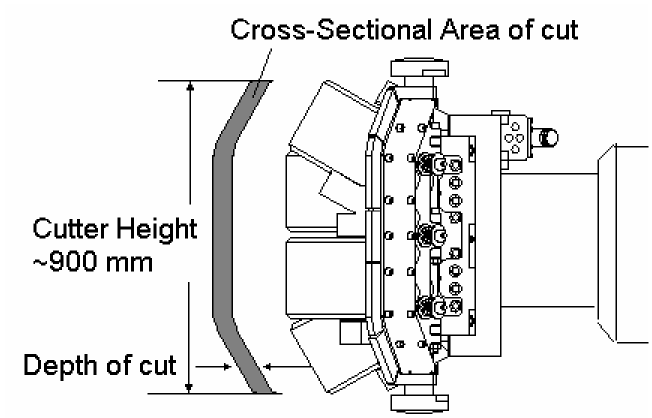

Figure 7 Cutting Geometry (swinging into page)

As such, it is possible to compare the specific energy in pressure units to the rock strength properties. Figures 7 and 8 show the specific energies calculated from the mine and quarry data. Two rock strength values are also included in these plots, the UCS and BTS. For reference, Fifty MPa is equivalent to 50 MJ/m^3, or 14.8 $hp\text{-}h/yd^3$.

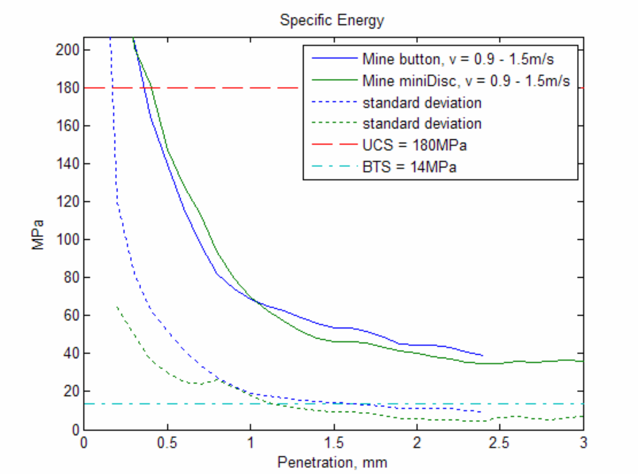

Figure 8 Mine specific energies

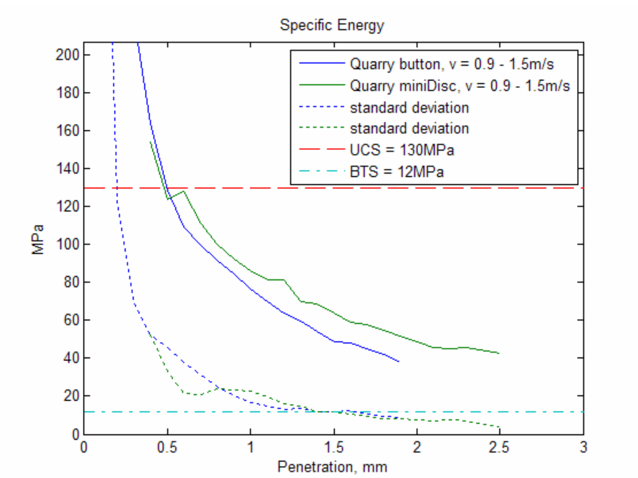

Figure 9 Quarry specific energies

For both these trials, the specific energy appears to approach a minimum value near the tensile strength.

Trials were performed on the CSM linear cutting machine using minidiscs on samples of rocks taken from Campbell mine. Single discs were passed over the rock in parallel passes of fixed spacing to mimic a multi-disc array. The forces acting on the disc were logged. Figure 10 shows rolling forces from this data superimposed on the MiniMole mine trial minidisc rolling forces. In the case of the CSM data, where individual discs were tested, the cut width is the spacing between the individual passes. The penetrations tested at the lab exceeded the MiniMole capabilities, but the trends appear to agree. The dashed blue line corrects for the MiniMole cutter penetration since, due to the cutter angles, the average penetration of the individual minidiscs on the cutter head is lower than the advance of the cutterhead.

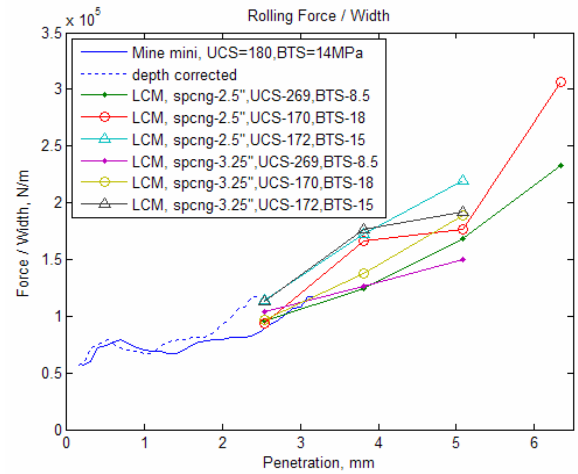

Figure 10 LCM and field rolling force measurements

Undercutting Discs

A method of undercutting using a tilted 8” minidisc was tested at the Colorado School of Mines. The disc was tilted about the direction of motion and about the horizontal normal to this direction. Figure 11 shows the cutter configuration. Using the Linear Cutting Machine at the Earth Mechanics Institute, the disc penetrated slabs of granite taken from the quarry where the MiniMole was tested. The components of force were recorded for various trials in which the pass spacing, penetration, and tilt angles were varied.

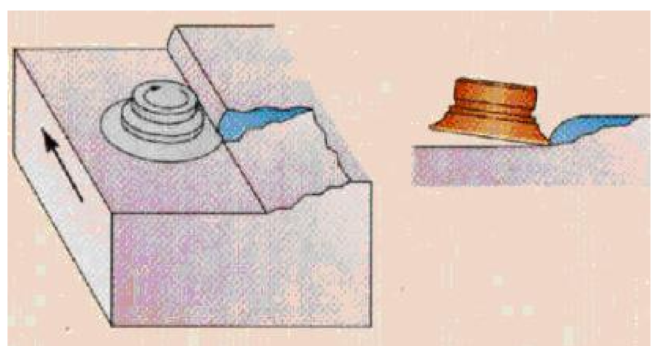

Figure 11 Undercutting using discs

The cutting specific energies for undercutting measured on the LCM are shown in Figure 13. These energies should be compared with those of conventional cutting in similar rock, shown Figure 14. Both these tests were performed in the same rock type, but for the conventional mode, the specific energy is less than 12 hp-h/yd^3 even for depths of up to 0.25”, whereas it is greater than 20 hp-h/yd^3 in undercutting. In addition, the total transverse (normal and side) loading on the undercutting discs was found to be greater than the normal loading on a conventional disc.

Figure 12 Undercutting with 8" disc on LCM

The discs used in the undercutting lab trials showed heavy wear after only a few tests. This high wear rate, combined with the high loading and specific energies, led us to discard undercutting as an option of further interest.

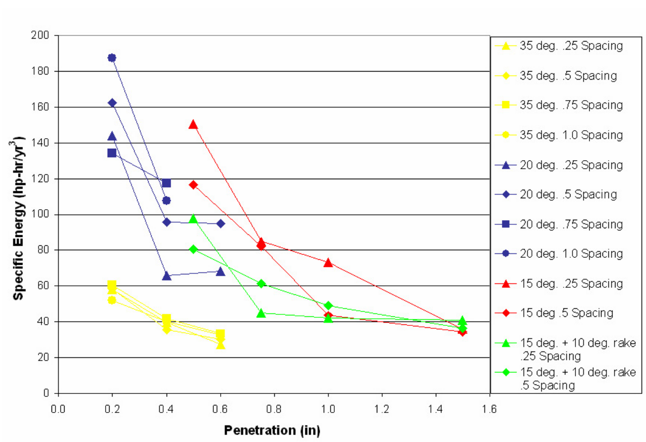

Figure 13 SE of 8" discs in undercutting on LCM

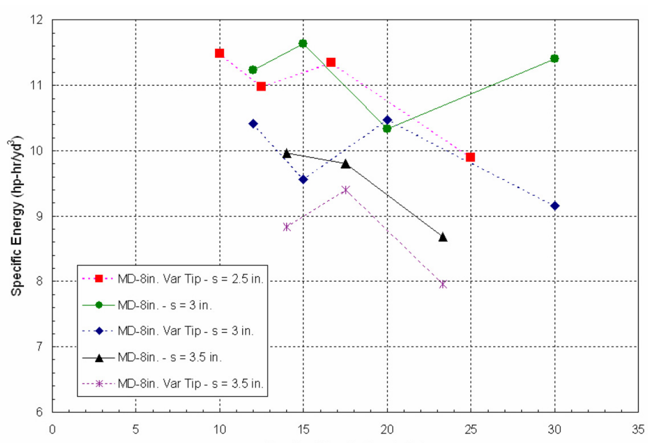

Figure 14 SE of 8" discs in conventional cutting on LCM

Underground Trials

Overview

The main objectives of the underground mining trials were to test and demonstrate the MiniMole's narrow vein mining capability and ease of integration with the infrastructure of an operating mine. The process of deploying the MiniMole in a narrow vein 1200 m below the surface involved the following steps:

- site preparation
- assembly
- deployment
- operation

Site Preparation and Assembly

The site required an initial slot into which the MiniMole could be placed, locations for assembly and maintenance, and the console enclosure and HPU. The excavated room was equipped with concrete floors, a crane, and a rail bed for transporting the MiniMole to and from the stope.

The initial launching slot measured approximately 0.9m X 7m long X 4.5 m deep, and was positioned adjacent to a 1.5m vertical shaft extending to the next sublevel, a distance of 13m. This was tilted at an angle of about 10° from vertical.

The MiniMole was broken down into components small enough for mine transportation and reassembled at the underground site.

Deployment

The assembled MiniMole was lifted onto a deployment rail-truck equipped with two winches for lifting the MiniMole to and from the cutting face. With the truck straddling the slot, the MiniMole was lowered into the stope. Using a combination of winch and gripper walking, with the visuals provided by on-board and remote cameras, the MiniMole was brought into cutting position.

Operation

Excavation in a vertical stope required two phases: downward advancing and horizontal collaring. The second was necessary to start a new extension at the top of the stope, from which the MiniMole could resume downward cutting.

In downward advancing, it was necessary to leave a sufficient portion of the cutting swing extending over the previous cut. Otherwise, a "bathtub" would be formed by the cut, as shown in Figure 15, into which cuttings would gather, clogging the cutters and causing stalling. Thick rubber squeegee-like scrapers on either side of the cutterhead were unable to remove all of the cuttings if the bathtub became too deep.

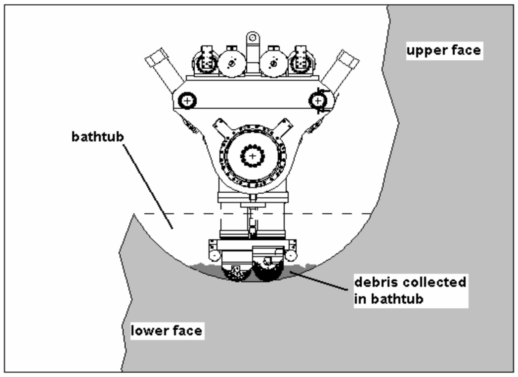

Figure 15 Collection of cuttings in "bathtub"

Results

In all, the MiniMole excavated approximately 750 tonnes of rock from the Campbell mine, over a period of three months. The final dimensions of the excavated void were 51 ft long by 43 ft high. The stope was initially cut at 3 ft width; however as time elapsed, the stope walls deteriorated and the final width was over 6 ft for much of the stope by the end of the trials.

The gripping forces contributed to wall collapse. High gripping forces were required to achieve the required normal cutting forces. These high forces led to short grippers during the design phase. Longer grippers (i.e. with more extension) would have been useful at times during the trials.

Of the two cutter types, the minidiscs generated the "best" size of cuttings for handling underground. However, the roller button cutters were more robust.

Steady increases were achieved in machine availability and production rate. By the end of the trials the machine was producing over 3 tonnes/hr. We estimate that the existing machine could be fine-tuned to achieve up to 5 tonnes/hr.

A "moderate sized" seismic event occurred during the trials, which was attributed to the MiniMole trials activities. A slender pillar was formed during cutting, which led to a rock-burst, which relieved the stress loading. No damage or injuries occurred as a result.

Recommendations and Lessons Learned

1. The MiniMole program demonstrated that mechanical excavation is feasible for narrow vein underground mining.
2. Smaller machines would be more practical and less expensive for underground use. They could be used in smaller drives and would be easier to transport and set up. They would also be more maneuverable in stopes.
3. The size of the machine is a direct consequence of the cutting forces required. Lower cutting forces would enable the development of smaller machines and would also allow for lower gripping forces and longer grippers.
4. Lower cutting forces are achievable by having fewer cutters in the rock at any one time. An attractive option is a rotating drum cutter with discs (e.g. rather than picks). Rather than pushing, say, 16 discs into the rock at one, the 16 discs could be distributed around a drum. As the drum rotates, all 16 of the discs will cut into the rock, but only about a quarter of them will cut the rock at any time. The net normal force is far less than when all of the cutters are cutting the rock at once.
5. Benefits analyses performed later in the program showed that the use of mechanical excavation techniques for making access drives would be of even more potential benefit than narrow-vein mining machines. Even if the operating costs were to significantly exceed those for conventional techniques, such systems would have benefit as long as access to underground ore bodies could be achieved faster than at present.
6. A recommended activity would be to look at the development of a small drive excavation machine based on the lessons learned in the MiniMole program.