Waterjet Scaling for Reducing Injuries in Underground Mining

Final Report

by
Mark Kuchta,
Hugh Miller, and
Erik Poeck

December 15, 2008

PI: Mark Kuchta
Mining Engineering Department
Colorado School of Mines
1500 Illinois Street
Golden, CO 80401
phone: 303 273 3306
email: mkuchta@mines.edu

Institution Award Made To:
Colorado School of Mines
1500 Illinois Street
Golden, CO 80401

Project Sponsor: NIOSH

Grant Number: 5 R01 OH 008709 – 03

Project Period: August 1, 2005 through July 31, 2008

Abstract

Scaling is the activity of removing loose and unstable rock from underground mine openings, and is a fundamental activity necessary to promote employee safety and minimize the inherent risk associated with ground falls in underground metal/nonmetal mining operations. Unfortunately, a significant number of accidents occur while scaling. While mechanized scalers are common in most large operations, manual scaling is still the standard throughout the U.S. underground hardrock industry.

A job safety analysis (JSA) study performed as part of this research identified three major areas of risk associated with hand scaling: 1) The immediate proximity of the miners to the working face and unstable/unsupported ground, 2) Working on uneven and irregular floors/surfaces, and 3) Physical fatigue caused by the strenuous nature of manual scaling. The most logical conclusion to mitigate and/or eliminate these potential hazards involve automating the process and removing the miner from the operating environment through the use of an alternative technology or technique.

This report summarizes research performed at the Colorado School of Mines, Edgar Experimental Mine with the primary goal of evaluating the effectiveness of using waterjet scaling as part of a mechanized scaling system. It is believed that proper implementation of waterjet scaling could significantly reduce the number of accidents and injuries that result as a consequence of scaling.

A prototype waterjet scaling system was built and used for the tests conducted in this project. A pump configured to operate at 24 MPa (3500 psi) and a flow rate of 0.11 m3/min (30 gpm) was used to provide high pressure water for scaling. A donated shotcrete truck served as the carrier vehicle. The hydraulically actuated boom of the vehicle was used to sweep the waterjet nozzle across the area to be scaled. An electronic hydraulic valve bank was installed on the rig that allowed for remote tethered operation, thus allowing miners to operate the rig at a safe distance away from the area being scaled.

As part of this research, five different nozzle designs were evaluated: a single orifice continuous jet, a dual orifice self-rotating jet, an acoustically pulsed, single orifice jet, and two types of mechanically oscillated single orifice jets. All of the nozzles tested performed well. However, based upon empiric results and observations made during testing, a preferred nozzle design was selected. The researchers chose the hydraulically powered, mechanically oscillated, single orifice jet for a variety of reasons. The design of the oscillating unit is a device similar to those commonly used to provide nozzle rotation in conventional shotcrete applications. Using the rotational unit with the single orifice continuous jet meant the power and performance of the single orifice jet could be maintained, while maximizing surface area coverage. The simplicity, low cost, and robust design of this unit proved to be a definite advantage in the harsh working environments often encountered in underground mining.

An unplanned additional benefit of this research was to evaluate the effects of smoothwall blasting on the amount of material scaled. With smoothwall blasting, scaling times were shorter, and the total amount of material scaled was on average about one-third the volume of when perimeter holes were fully charged with ANFO.

This research demonstrated that the safety advantages of waterjet scaling were pronounced and it represents a viable alternative to conventional scaling techniques. Furthermore, there appears to be tremendous potential benefits that could dramatically improve miner safety as a consequence of integrating waterjet scaling with other advanced underground excavation practices, including precision drilling, engineered round design, smoothwall blasting, and the utilization of new techniques and products related to shotcrete and rock support systems.

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1. Highlights/Significant Findings

Scaling is a fundamental activity necessary for the safe operation of underground mines and involves the removal of loose and unstable rock from mine openings. Unfortunately, a significant number of accidents in underground mining occur during the actual process of scaling. While some underground mines employ mechanized scaling machines, manual scaling with a hand-held metal or fiberglass bars is still the most common method of scaling in US underground hard rock mines.

A job safety analysis (JSA) study performed as part of this research identified three major areas of risk associated with hand scaling: 1) The immediate proximity of the miners to the working face and unstable/unsupported ground, 2) Working on uneven and irregular floors/surfaces, and 3) Physical fatigue caused by the strenuous nature of manual scaling. While select controls were identified for each of the hazards identified during the JSA on manual scaling, the most logical conclusion to mitigate and/or eliminate these potential hazards involve automating the process and removing the miner from the operating environment through the use of an alternative technology or technique.

The primary goal of this research was to evaluate the effectiveness of using waterjet scaling as part of a remote scaling system. Experimental results indicate that waterjet scaling is a viable alternative to both manual and current mechanical scaling systems.

A prototype waterjet scaling system was built and tested at the Colorado School of Mines, Edgar Experimental Mine located in Idaho Springs, Colorado. A pump configured to operate at 24 MPa (3500 psi) and a flow rate of 0.11 m3/min (30 gpm) was used to provide high pressure water for scaling. An shotcrete rig donated to the project by a local mining company served as the carrier vehicle. The hydraulically actuated boom of the vehicle was used to sweep the waterjet nozzle across the area to be scaled. An electronic hydraulic valve bank was installed on the rig that allowed for remote tethered operation, thus allowing a miner to operate the rig at a safe distance from the area being scaled.

A total of sixteen experiments were conducted to evaluate the effectiveness of five different nozzle designs that included: a single orifice continuous jet, a dual orifice self-rotating jet, an acoustically pulsed, single orifice jet, and two types of mechanically oscillated single orifice jets. A total of ten waterjet experiments were initially conducted (two experiments for each nozzle type). The remaining six waterjet experiments utilized a preferred nozzle design selected as a consequence of the initial testing.

All of the nozzles tested performed well. Based on experimental results and observations made while scaling with each system, the design preferred by the researchers was a hydraulically powered, mechanically oscillated, single orifice jet. Although this hydraulically powered rotational unit was custom designed for this project, the design is based on similar devices commonly used to provide nozzle rotation in mechanical shotcrete applications. Using the rotational unit with the single orifice continuous jet meant the power and performance of the single jet was obtained, while good surface coverage was also assured. Another advantage of the unit was the ability to easily turn off the rotation, allowing the operator to focus the jet at specific cracks or problem areas. The simplicity, low cost, and robust design of this system is a definite advantage in the harsh working environments often encountered in underground mining.

Initially, it was believed that the pulsed nozzle would give superior performance. Although the nozzle performed well in comparison to the other nozzles tested, a performance advantage that would justify the high cost of the pulsed nozzle could not be clearly demonstrated. Pulsed nozzles have been shown to be dramatically more effective than continuous jets in a wide range of industrial cleaning and cutting applications. A more robust parametric evaluation than could be conducted in this study might yield clearer results in favor of the pulsed jet.

Prior to testing, it was also believed that a rotating nozzle would provide more efficient surface coverage than a continuous jet and thus, better scaling results. Consequently, several variations of rotating nozzle assemblies were tested, including a self-rotating jet and two types of mechanically rotated jets. Although the results gathered did not show a definitive difference between continuous and the rotating nozzles in terms of scaling performance for the rock type tested, it was the consensus of the researchers based upon the test observations that the use of rotating jets was in fact a preferred method due to the high rate of surface coverage that could be achieved during scaling.

Two waterjet experiments were conducted in reverse order, where hand scaling was performed first followed by waterjet scaling. With the reverse order tests, the area was first thoroughly scaled by hand and deemed safe by experienced mine personnel. The fact that in both tests the subsequent waterjet scaling brought down nearly as much material as the previous hand scaling indicates that significant improvements in worker safety with waterjet scaling would likely be realized over hand scaling due to the ability of the waterjet to remove loose that can not be easily detected by hand scaling.

An unplanned additional benefit of this research was to evaluate the effects of smoothwall blasting on the amount of material scaled. The first five waterjet experiments consisted of perimeter holes fully loaded with ANFO, where two different smoothwall blasting methods were employed in the remaining eleven waterjet experiments. The effects of smoothwall blasting were very positive. With smoothwall blasting, scaling times proved to be significantly shorter, and the total amount of material scaled was on average about one third the amount scaled where the perimeter holes were fully charged with ANFO.

A scaled material size analysis showed a substantially larger portion of fine material obtained with waterjet scaling as compared with hand scaling. This seems to indicate the ability of waterjets to thoroughly clean rock surfaces of fine material. Previous research has indicated that waterjet scaling has the additional benefit of improving the adhesion characteristics of shotcrete applied as a support membrane.

2. Translation of Findings

This project has demonstrated that waterjet scaling is a viable remote scaling alternative to both mechanical and hand scaling. It is believed that proper implementation of waterjet scaling could significantly reduce the number of accidents that occur while scaling. The equipment required to implement waterjet scaling is quite simple. Optimal implementation would depend on the mining cycle at each mine, but the equipment is simple enough that it could be installed on a mechanized roof bolter or shotcrete rig as an alternative to having a dedicated waterjet scaling rig. Waterjet scaling could be integrated as part of a modern and safe system for underground excavation that would include precision drilling for accurate hole placement, smoothwall blasting to minimize wall rock damage, and advanced engineering approaches towards shotcrete and ground support installation. The potential benefits of such a system are substantial and could be quantified through improved worker safety compared to processes and techniques commonly used today. Although financial considerations were not a motive for this research, it is believed that waterjet scaling systems will be significantly more cost effective than the conventional scaling methods currently being used in most underground mines.

One of the keys to the acceptance of this technology by industry will be the ability to observe demonstrations of the waterjet scaling system first-hand. A demonstration of the CSM waterjet scaling system is being planned in conjunction with the Society of Mining, Metallurgical, and Exploration (SME) Annual Meeting that will take place in Denver, CO from February 22-25, 2008. A large percentage of the engineers within the U.S. mining industry will attend this meeting. Invitations will be sent out to companies who operate underground mines that may be interested in participating in an on-site demonstration of the technology. One or more demonstrations will be conducted before, during, or after the meeting. Additionally, the researchers involved in this waterjet scaling project will present a paper at the meeting titled "Potential Benefits of Waterjet Scaling in Rapid Tunneling Systems".

Plans are also being made by engineers at the NIOSH Spokane Mining Research Laboratory to perform a series of demonstrations at the Colorado School of Mines Edgar Experimental Mine as part of the ongoing project called "Controlled Blasting for Improved Ground Control". The ultimate objective of this research is to reduce accidents that result from loose or damaged ground and other blast-related hazards. While the emphasis of this research is on precision blasting, the overall goal of reducing injuries caused by fall of ground are the same as those for the waterjet scaling project discussed in this report. Three drift rounds are planned with the goal of demonstrating the advantages of a drift excavation system that uses precision drilling for accurate blast-hole placement, smoothwall blasting to minimize wall rock damage, waterjet scaling, and shotcrete application. These demonstrations are being coordinated by NIOSH and will provide an excellent opportunity to demonstrate the waterjet scaling system to representatives of mining industry.

3. Outcomes/Relevance/Impact

The major outcome of this research was to demonstrate that waterjet scaling is a viable alternative to both manual and mechanical scaling.

The relevance of the research is that accidents associated with scaling activities could be significantly reduced by utilizing waterjet scaling.

The key to realizing the potential impact of this new technology is to implement it in underground mines that currently rely heavily on manual scaling methods.

4. Project Background

The scaling of loose rock from the back and ribs of workings is a fundamental activity integral to the safe execution of nearly every unit operation in underground hardrock mining. Geologic structure, rock deformation, physical/chemical degradation, and blast damage are but a few of the many factors that weaken the structural integrity of rocks comprising the exposed surfaces of underground excavations. These processes, usually compounded by irregular surfaces and geologic factors, often result in ground failures and rock falls. The act of scaling involves the systematic removal of this loose and unstable rock from the roof and walls of underground workings in order to reduce the potential hazards to mine employees and equipment.

While most operators emphasize the importance of scaling in their mine safety training programs and rock/roof control plans as specified by federal and state regulations, rock falls still account for a significant portion of the total fatalities and lost-time accidents incurred in underground mines (CDC NIOSH 2000). According to a recent publication (O'Neil, 2001), a review of Mine Safety and Health Administration (MSHA) accident and fatality reports for underground metal/nonmetal mines showed that nearly one-quarter of all fatalities at such mines were related to rock falls. About one-third of these fatalities involved scaling. In addition, employee injuries associated with the actual process of scaling are quite common. Pauppas and Prosser, 2003, discuss recent accidents that have occurred while scaling in underground stone mines. These occupational hazards only increase as back heights get higher and spans between pillars get larger, as is often the case in room & pillar and bulk mining systems.

The equipment and techniques used in scaling have remained essentially unchanged in the last twenty years. While mechanized scalers utilizing hydraulic hammers mounted on mobile diesel carriages are common in most large operations, manual scaling bars are still the standard throughout the hardrock industry. Mechanized scalers are notorious for digging into soft materials and often create and/or propagate fractures adjacent to the impact area. Furthermore, these scalers are confined by the specific operating envelope for which they are designed and are limited by height, access, and floor conditions. In stopes possessing high cut/back heights, man-lifts are widely employed. In these situations, miners often work twenty or more feet off the ground to manually bar down loose material. Such activities are extremely labor intensive and expose the miner to variety of hazardous conditions. Even in circumstances where manual scaling is performed on ground level, there are significant hazards associated with the close proximity to unstable rock conditions, working off of muck piles, and the limited ability for rapid egress.

The high frequency and severity of accidents associated with current scaling practices have led to a number of research activities that attempt to minimize or eliminate the risk-exposure of miners to rock falls and slabbing through the use of innovative technology and support systems. Of the techniques and equipment designs investigated, waterjet technology presents one of the most promising venues for developing a safe, low cost scaling system that can be operated remotely in a wide range of mining environments.

Waterjet scaling systems possess a number of potential advantages over conventional scaling methods, including:

- No direct mechanical contact between the scaling apparatus and the rock,
- Ability to focus tremendous amounts of force over long distances,

- Very low reactive forces,
- Highly amenable to remote control and operation,
- Omni-directional (jets can operate in any direction without appreciable power losses),
- Highly selective, where jet impingement can precisely target specific areas without damaging neighboring rocks and rock structures,
- Can effectively scarify and clean rock surfaces prior to and during shotcrete placement,
- Environmentally safe, emitting no hazardous dust, fumes, or high velocity rock debris/chips, and
- Operating parameters can be dynamically adjusted for different rock types and scaling conditions by changing fluid pressure, flow rate, and traverse motion/velocity.

While the research in waterjet scaling performed in this project is extremely pertinent and directly applicable to current mining practices, it also represents a necessary incremental step towards the continued development of automated mining systems for high-risk operating environments.

5. Specific Aims

A large number of accidents in underground mining are caused by rock falls and ground failure. Of these accidents, a significant percentage of injuries occur while attempting to scale loose and fragmented rock from the periphery of underground workings. Many of these accidents could be eliminated through the smart implementation of integrated concepts that relate ground control issues with technical innovations in drill and blast drifting and tunneling. Such systems would utilize:

1. Controlled blasting practices to reduce collateral rock damage and minimize the fracture envelope created around underground excavations,
2. Remote scaling technologies to efficiently remove loose and unstable rock created during blasting,
3. Advanced roof support technologies and installation practices, including rock bolts, shotcrete, and thin-membrane liners,
4. Monitoring methodologies to detect ground loading and remotely identify the presence of loose and unstable rock.

The objective of this project was to evaluate one component of this overall strategy by testing the effectiveness of using high-pressure waterjet technology as part of a mechanized scaling system to safely remove loose and unstable rock from underground mine openings. The project builds upon previous research in waterjet scaling performed at the Colorado School of Mines (CSM) Experimental Mine, where an existing prototype waterjet scaling rig and high-pressure pump was available for use. The relative effectiveness of various nozzles designs, including continuous, oscillating, and two types of pulsed jets, was examined. Pulsed jets have been shown to be dramatically more effective than continuous waterjets in a wide range of industrial cutting and cleaning applications. It is believed that the utilization of a properly designed pulsed jet system will provide significant improvements in employee safety over that of conventional manual or mechanized scaling methods by removing miners from high-risk areas and reducing their potential exposure to rock falls. Additional benefits stem from the increased efficiency of high velocity fluid to scour and displace damaged rock and substantive improvements in the performance and adhesion characteristics of shotcrete as a ground support membrane.

Focal to this research was efforts to empirically quantify the critical operating variables associated with hydraulic scaling and to assess the performance and efficiency of these systems relative to conventional scaling methods in terms of employee health and safety.

Although financial considerations are not a primary motive for this research, it is believed that waterjet scaling systems will be significantly more cost effective than existing scaling methods. Additional economic savings could be realized through a reduction of overall cycle times and increased efficiency by equipping a roof-bolter or shotcrete rig with waterjet scaling equipment. In conjunction with improved worker safety, these economic incentives may serve as a motivating factor to encouraging operating mines to adopt this new technology.

The four specific aims of this research were:

1. To empirically quantify the critical variables unique to the impingement of high velocity continuous and pulsed waterjets in order to optimize rock scaling for a given set of operating

assumptions,

2. To evaluate the effectiveness of various nozzle types, including pulsed, oscillating, and continuous nozzles, as a viable alternative to manual and mechanized scaling for the removal of loose and unstable rocks in underground mine openings,

3. To perform a detailed safety analysis that examines the potential hazards and exposures associated with the utilization of waterjet systems in rock scaling applications and provide a comparative safety analysis of current scaling practices,

4. To perform a series of field trials at an operating underground mine to assess issues that could potentially impede the introduction of this technology from a laboratory setting to a production environment.

Due to the difficulty of finding an operating mine where field trials would not interfere with ongoing production, point 4 was later modified to conduct the field trials and demonstrations at the CSM Edgar Mine.

6. Related Previous Work

The use of high pressure waterjet scaling has been tested in Sweden at LKAB's Kiruna mine as an alternative to mechanical scaling, (Malmgren and Svenson, 1999). A prototype rig was built which used a water pressure of 20 MPa (2900 psi) and a flow rate of 0.21 m3/min (55 gal) per minute. The main support system at the mine consists of untensioned fully grouted dowels and shotcrete layer with an average thickness of 4 cm (1.6 in). Test were performed to evaluate the adhesion strength of shotcrete applied to rock surfaces cleaned with low pressure and by of high pressure waterjet scaling. The test results showed an increase in the adhesion strength by a factor of three on the waterjet scaled rock surfaces as compared to surfaces cleaned with low pressure water.

Waterjet scaling was evaluated by the Swedish construction company Skanska, (Lundmark and Nilsson, 1999). The tests were performed at the tunneling project in Halandsås, Sweden. The authors recommended that a pressure of 30 MPa (4350 psi) at 0.220 m^3/min (58 gal/min) through a 4.5 mm (0.177 in) nozzle be used for scaling. The tests indicated that waterjet scaling requires less total time than mechanical scaling, especially when the number of blast rounds with underbreak is minimized. Although verifying that waterjet scaling is less harmful to the rock than mechanical scaling was more difficult, it could be visually observed that waterjet scaling caused less damage to the rock than a hydraulic hammer. The tests also indicated that the bond strength increases on surfaces that have been waterjet scaled compared with ones that have not. The spread within the samples was so wide that this result is difficult to verify conclusively. It was also found that at times large blocks that were judged to be unsafe could not be scaled down by the waterjet equipment, but instead were scaled using the hydraulic hammer. The authors concluded that waterjets could not completely replace mechanical scaling in all cases, but was a good complement to mechanical scaling.

The company Falconbridge Limited at the Sudbury Operations, Ontario conducted a project to evaluate a water based liner material called TekFlex as a replacement for wire mesh, (Swan and Henderson, 1999). High-pressure water scaling was tested as a potential method of preparing the rock surface before applying a thin layer of TekFlex liner. Equipment was built using a 24.8 MPa (3600 psi) water pump delivering 0.057 m3/min (15 gpm) through a nozzle assembly that was attached to the spray boom used for applying the TekFlex. Results clearly demonstrated the efficacy of water scaling for the removal of small-scale loose, (<500 kg, (1,100 lb)). It was concluded that mechanical scalers are not considered mandatory with liners but should be used in much the same way as they are presently used with wire mesh, which is for the removal of large-scale loose in very blocky conditions.

A division of MIRARCO known as The Centre for Mining Technology, located in Sudbury, Ontario, has recently conducted investigations into the applicability of high pressure waterjet scaling for underground hard rock drift development, (Dunn and Whitmore, 2005). The ultimate aim of the project is to increase drift development rates. The project was sponsored by Placer Dome Canada, Inco Limited, Western Mining Corporation (Australia) and Falconbridge Limited. The work involved field testing of a high performance waterjet scaler in combination with various spray-on supports. A 10 MPa (1450 psi) jet running at approximately 0.23 m3/min (60 gpm) was used. Scaling was done by positioning the nozzle in the center of the drift and rotating 180 degrees from rib to rib, which resulted in average standoff distances between 2 and 3 meters. Scaling performance was tested through a subsequent manual check, whereby a failure was defined as rock material that fell from the back after vigorous striking with a 3.6 m (12 ft). scaling bar. The material that was removed during the waterjet scaling experiments was collected on tarps. The estimated material weights removed during scaling ranged from 500 to 3000 kg (1100 to 6600 lb), and the largest single rock removed weighed approximately 500 kg (1100 lb). A majority of the scaling experiments were completed in 2 - 6 minutes, and shotcrete was applied to the back and ribs when the experiment was over. Operators noticed a reduction in shotcrete spraying time due to a reduction in shotcrete re-work, reduction in rock fall during operation, and increased adhesion of the shotcrete to the rock surface.

In research conducted at CSM, (Kuchta, 2002), experimental testing showed an increase in adhesion strength of shotcrete by a factor of four applied to a concrete test wall cleaned with water at 21 MPa (3000 psi) as compared to a surface on the same test wall cleaned at 0.7 MPa (100 psi). Tests at 41.4 MPa (6000 psi) showed no additional surface cleaning and revealed that competent rock and concrete on the test panels were being scarified by the water stream. Based on these results and observations, it was decided that a working pressure of 21 MPa (3000 psi) would serve as the basis for further research in waterjet scaling.

Numerical simulations were performed using the Universal Distinct Element Code (UDEC) software for the purpose of evaluating the shotcrete thickness-interface strength relationship, (Kuchta, Hustrulid, and Lorig, 2004). A simple drift model containing a triangular wedge in the crown was used. It was found that the shotcrete thickness required to support a rock wedge increases rapidly with decreasing interface strength. The authors conclude that although poor interface strength conditions can be overcome by the application of greater shotcrete thickness, this is a poor economic solution, and that greater efforts should be focused on thoroughly cleaning the rock surface in order to remove contaminants, such as loose pieces of rock, dust, dirt, and oil, prior to the application of shotcrete. Waterjet scaling was deemed to be a promising alternative to conventional scaling, with the added benefit of substantially improving the cleaning of the rock surface.

A prototype waterjet scaling system was developed and tested in order to help quantify the performance of a waterjet versus a manual scaling process, (Kuchta, Hustrulid, and Lorig, 2004). The carrier vehicle was a refurbished shotcrete truck donated to CSM by Climax Molybdenum's Henderson Mine. This vehicle was then fitted with high-pressure hoses and a nozzle assembly at the tip of the hydraulically actuated, retractable boom. Five experiments were performed by first drilling and blasting a standard drift round with dimensions of approximately 3 m by 3 m (10 ft by 10 ft). Each advance was about 1.8 m (6 ft). The diameter of the drill holes was 41 mm (1-5/8 in), and smooth wall blasting was performed along the ribs and back. After each blast, the majority of the broken rock was removed from the drift. The floor was then covered with a large tarp in order to collect any rock scaled from the back. In four of the five experiments, scaling was first done with the high-pressure waterjet. The scaled material was collected, weighed, and screened. As a control, hand scaling was also performed after the waterjet scaling. The material scaled by hand was also collected, weighed, and screened. The results of the first four experiments are shown in Fig. 6.1. The scaling system operated at pressure of 17.2 MPa (2500 psi) and a flow rate of approximately 0.046 m3/min (12 gpm). In each case, the amount of rock removed by the waterjet exceeded the amount removed by manual scaling. However, it must be noted that the amount of material removed by subsequent hand scaling was not zero.

As an additional control, one experiment was performed in reverse order (Fig. 6.2). Scaling was first performed by hand, followed by waterjet scaling, and finally by a second hand scaling. After the first hand scaling the area appeared to be properly scaled. A significant amount of material, however, was subsequently removed by waterjet scaling. Surprisingly, nearly as much material was removed again by the second hand scaling. This experiment also illustrates the dilemma with trying to quantify the effectiveness of different scaling operations. Even though deemed safe by an experienced and competent professional, additional material can still be scaled from any rock surface given enough time and effort.

By observing the six waterjet scaling experiments, it was apparent that the overall effectiveness of the scaling operation could be improved by rapidly moving the jet across the rock face. Observing loose rocks falling immediately after a jet had passed a given area reinforced this supposition.

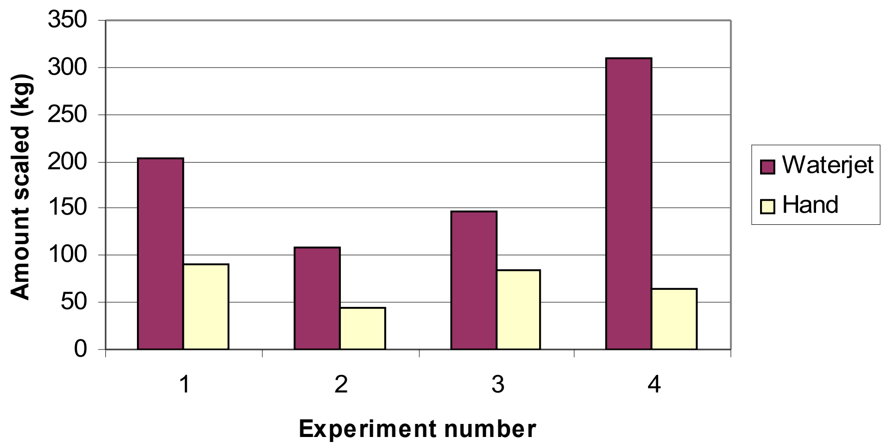

Fig. 6.1. Material removed in four experiments, (Kuchta, et. al. 2004).

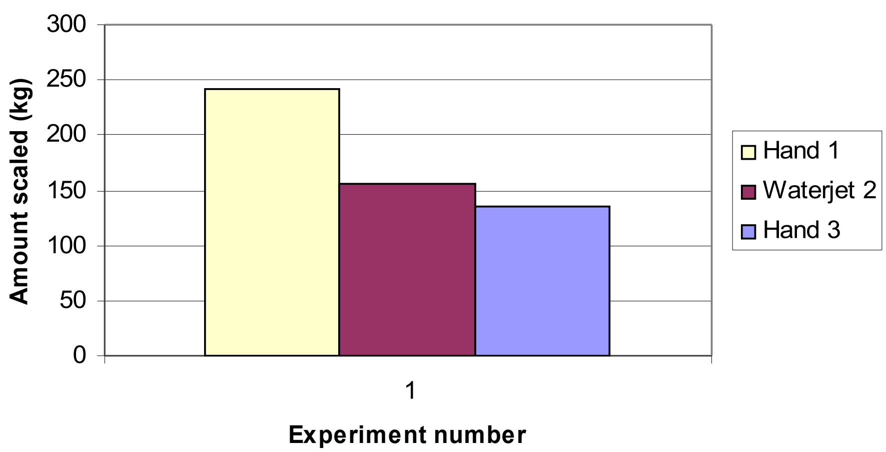

Fig. 6.2. Material removed in reverse order experiment, (Kuchta, et. al. 2004).

7. The CSM Waterjet Scaling System

A waterjet scaling system consists of the following major components:

- Power source,
- Water source,
- High pressure pump,
- High pressure hoses, fittings, and flow controls,
- Carrier vehicle and motion system, and
- Nozzle assembly.

This section describes the major components of the CSM waterjet scaling system used for this research.

Power was provided through the 480 V three phase mine electrical system. The electrical power source was chosen over diesel due to ventilation considerations, and that a 480 V mine power system would most likely be available in mines where waterjet scaling might be used.

To provide water, three 5.8 m^3 (1500 gal) plastic tanks were installed underground, and small electric pump transferred water from the tanks to the mine water-piping network at a pressure of 0.7 MPa (100 psi) with a maximum flow rate of 0.38 m^3/min (100 gpm), (Fig 7.1). This pressure and flow rate was sufficient to prime the high-pressure pump. No filtration systems were installed.

An overhauled Wheatley Quintuplex model 5P-323, (Fig 7.2) was used to supply high-pressure water at a discharge pressure of approximately 24 MPa (3500 psi) and a flow rate of 0.11 m^3/min (30 gpm). The pump was mounted on skids, together with a rebuilt 480-volt, 100 HP electric motor. A pressure gauge, a 3-way flow bypass valve, and a 34.4 MPa (5000 psi) rupture disc were installed at the pump outlet, (Fig 7.3). Pressure and flow rate testing as a function of the nozzle orifice size was performed to develop the actual pump curves shown in Fig. 7.4 and Fig. 7.5.

Water was conveyed to the nozzle by 30 m (100 ft) of heavy-duty high-pressure flexible hose with an internal diameter of 19 mm (3/4 in). As scaling progressed away from the pump, a second 30 m (100 ft) section of flexible hose was added. The total rated hose pressure drop was 0.02 MPa/m (1.0 psi/ft). An additional 6 m (20 ft) length of high-pressure hose was also mounted to the boom of the carrier vehicle.

The carrier rig used (Fig. 7.6), was donated to CSM by Climax Molybdenum's Henderson Mine located in Empire, Colorado. The Eimco truck had been reconfigured for use as a shotcrete rig, and as such, provided an extendable 4.6 m (15 ft) hydraulically actuated boom that was used to orient the waterjet nozzle assembly, (Fig. 7.7).

The extendable boom could be operated manually by a series of five hydraulic valves and levers or remotely with a 12-volt electric joystick control box (Fig. 7.8) installed specifically for this research by Shotcrete Technologies of Idaho Springs, Colorado. The electronic valve bank and tether provided a degree of control and operator safety that was a significant improvement over the manually operated boom controls. Functions included tilt, swing, and extension of the main boom, as well as tilt and rotation of the nozzle.

Fig 7.1. Low pressure pump and plastic storage tank that provide water to the high pressure pump.

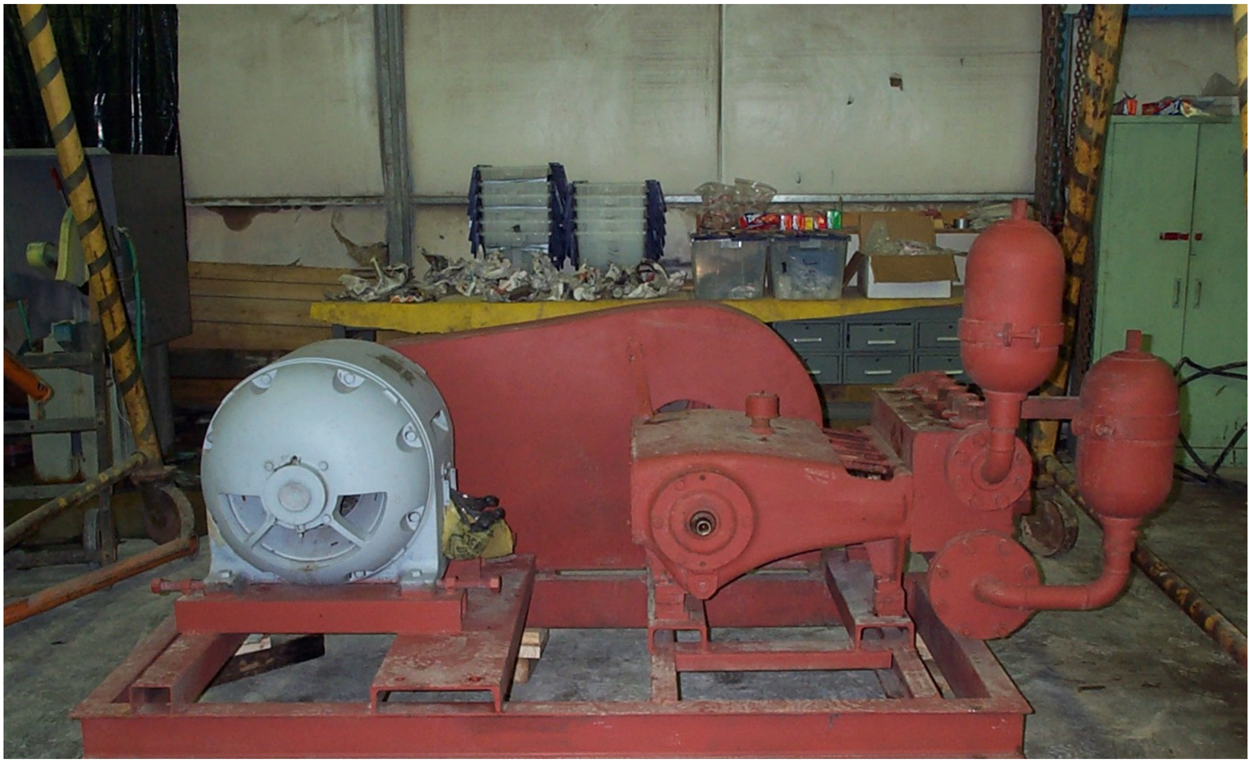

Fig 7.2. The Wheatly Quinteplex pump used to provide high pressure water to the scaling system.

Fig 7.3. The pressure gage, flow control valve, and rupture disc assembly mounted on the Wheatly Quinteplex pump.

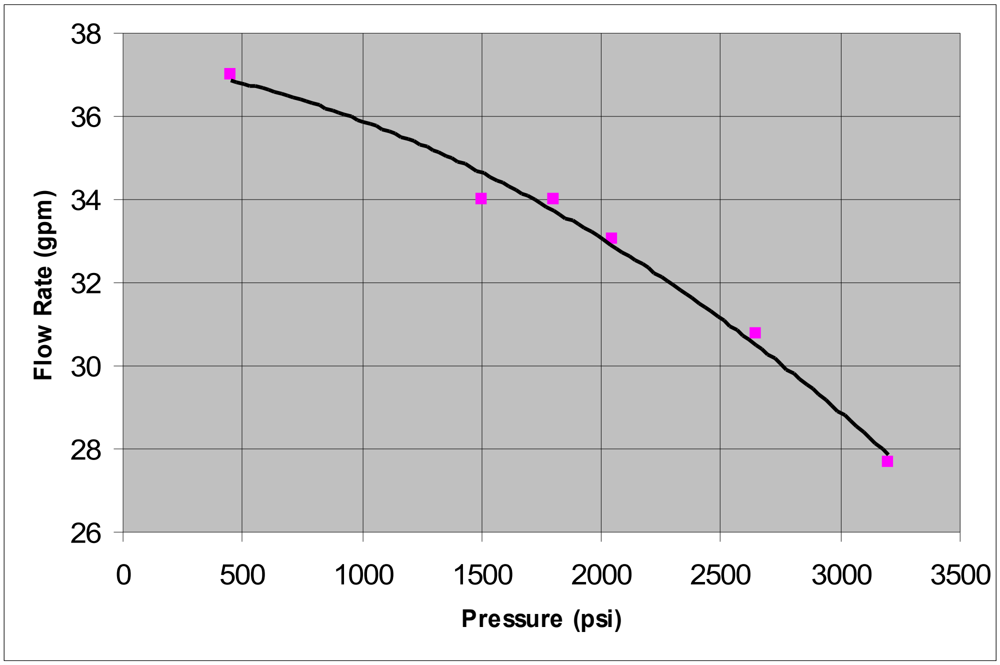

Fig. 7.4. Flow rate vs. pressure curve for the Wheatly Quinteplex pump.

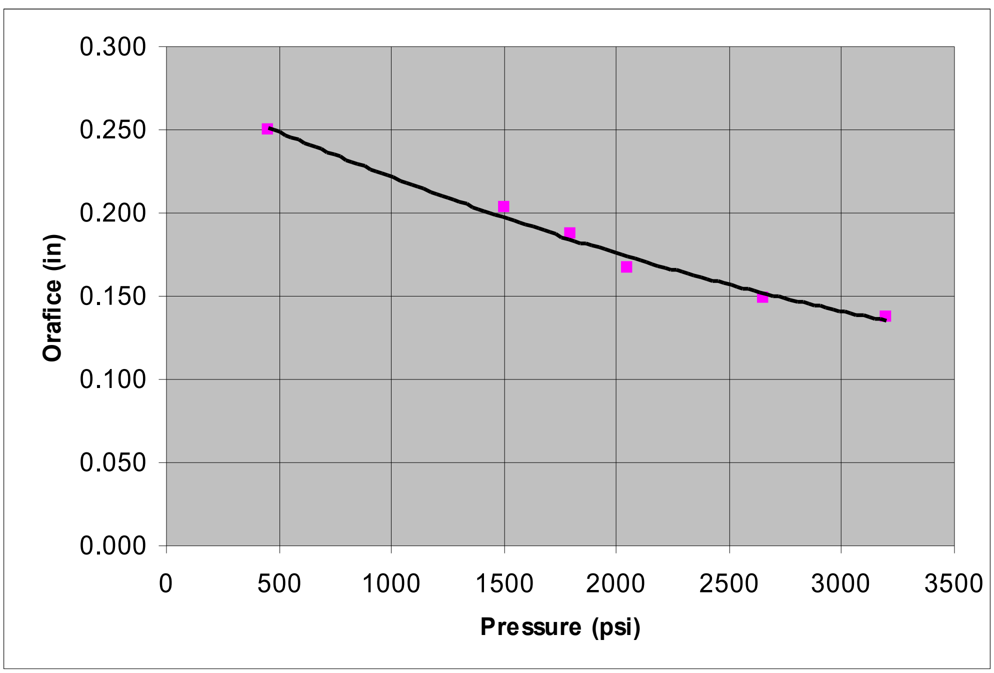

Fig. 7.5. Nozzle orifice size vs. pressure curve for the Wheatly Quinteplex pump.

Fig. 7.6. The CSM waterjet scaling carrier vehicle.

Fig. 7.7. The end of the hydraulic boom showing nozzle assembly mounting on the CSM waterjet scaling carrier vehicle.

Fig. 7.8. The 12-volt electric joystick control box for controlling the motion of the hydraulic boom on the CSM waterjet scaling rig.

8. Nozzles Tested

The types of nozzles tested in this research included:

- a single orifice continuous jet,
- a dual orifice self-rotating jet,
- an acoustically pulsed, single orifice jet, and
- two types of mechanically oscillated single orifice jets.

This section describes the characteristics of each nozzle.

8.1. Single orifice continuous jet

The single orifice nozzle assembly, (Fig 8.1), consists of a machined carbide 3.56 mm (0.140 in) diameter orifice held in place by a steel outer protective holder. In turn, this assembly was attached to a 250 mm (10 in) long, 19 mm (¾ in) diameter straight section of steel pipe. The assembly was purchased from Stoneage Waterjet Tools Inc. of Durango, Colorado. This nozzle assembly was operated at a pressure of approximately 22 MPa (3200 psi) and a flow rate of approximately 0.106 m^3/min (28 gpm).

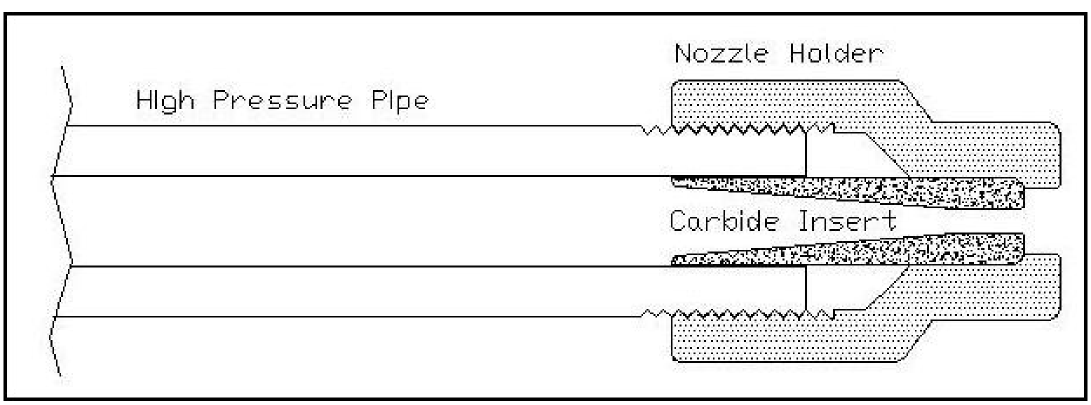

Fig 8.1. Single orifice continuous nozzle with holder.

8.2. Dual orifice self rotating jet

The second nozzle tested consisted of dual orifice inserts mounted to a fluid-damped, rotating head, (Fig. 8.2). The nozzle was designed and manufactured by Stoneage Waterjet Tools Inc. of Durango, Colorado for use in pipe and sewer cleaning applications. The galvanized steel jacket covering the main body was designed to prevent contact between the nozzle and internal pipe surfaces and to keep the nozzle assembly centered and stable while in operation. The two replaceable nozzle inserts were angled in opposing directions to provide rotation for the nozzle head. A viscous fluid governor in the main body of the unit provides control over the speed of rotation while operating at a specific flow rate. The operating pressure of the dual orifice jet was 20.7 MPa (3000 psi), and each of the inserts had a 1.65 mm (0.065 in) orifice that emitted 0.0545 m^3/min (14.4 gpm).

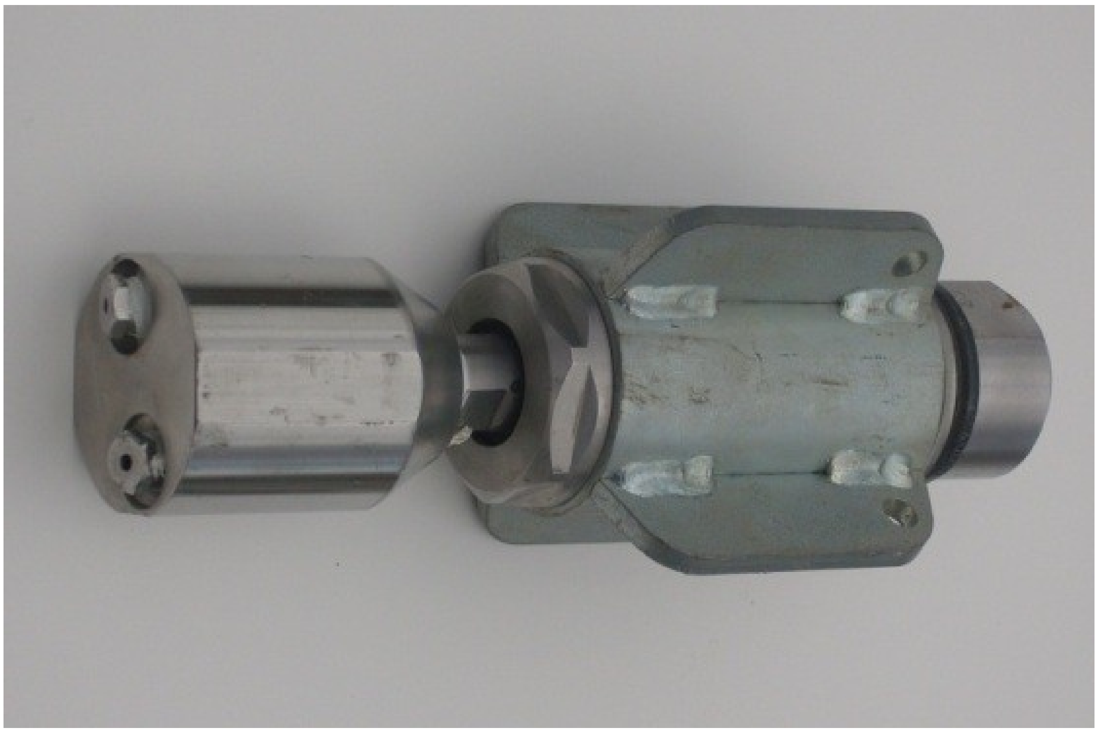

Fig. 8.2. Dual orifice, self-rotating, continuous nozzle.

8.3. Acoustically pulsed single orifice jet

The third nozzle tested consisted of an acoustic pulsed nozzle capable of generating high frequency pulses in the jet's free-stream over a specific range of operating pressures and flow rates, (Fig. 8.3). Sometimes referred to an organ-pipe nozzle, the assembly was designed and manufactured by Dynaflow Inc. of Jessup, Maryland. There are numerous types of pulsed jets that have been developed, where each possesses unique physical and impingement characteristics. The system selected for this research is dependent upon the creation of flow perturbations that form nondiscrete fluid slugs inside the jet's free-stream. The internal surface of the nozzle is machined in such a way that the flow of water at a designed pressure and flow rate generates a standing wave. The wave propagates at high frequency through the fluid, and as it leaves the nozzle orifice, bunching occurs as a consequence of differences in fluid velocity. As a result, the jet is comprised of a series of high-frequency fluid slugs that possess dynamic impingement characteristics far superior than continuous waterjets over specific standoff distances.

The various components visible in the Fig. 8.3 are all required to produce and accommodate the standing wave. The barrel at center contains the precisely machined surface where the standing wave is initiated, and the extra fitting between the barrel and the orifice dictates the exact distance required to produce resonation in the water stream. The orifice was 3.43 mm (0.135 in) in diameter, and the jet operated at 23.4 MPa (3400 psi) and 0.101 m^3/min (26.6 gpm). The acoustic nozzle was significantly more expensive than the other waterjet nozzles used. Since the exact distance between fittings and shape of the interior surface are crucial to the development of the standing wave, the barrel and orifice assembly must be replaced as a whole should either piece become worn or damaged.

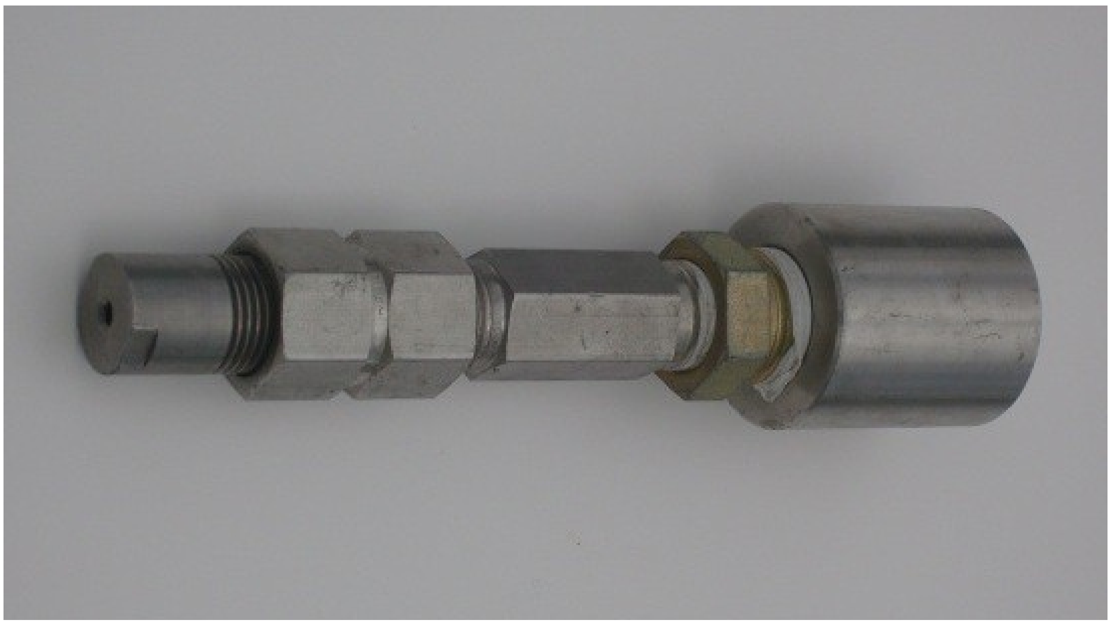

Fig. 8.3. Single orifice continuous acoustic pulsed nozzle.

8.4. Compressed air powered mechanically oscillated single orifice jet

The fourth nozzle type, (the first of two mechanical oscillation systems tested), was comprised of a single orifice, continuous waterjet attached to a pneumatic mechanical oscillator. The concept was similar to the self-rotating nozzle, however, the design utilized an external power source to rotate a single orifice nozzle. The unit, (Fig. 8.4), manufactured by Stoneage Waterjet Tools Inc., of Durango, Colorado, incorporates a pneumatic motor using a 0.76 MPa (110 psi) compressed air source to drive the rotation of a short, bent pipe with a replaceable nozzle insert. The air motor and gearbox were designed as a universal waterjet oscillation unit and the head is capable of accommodating dual orifices. Since the purpose of testing the unit was to use a single orifice, the inactive nozzle was plugged and braced to the active nozzle for rotational balance and greater durability. The orifice size was 3.56 mm (0.140 in) in diameter, and the nozzle operated at 22 MPa (3200 psi) and a flow rate of 0.106 m^3/min (28 gpm).

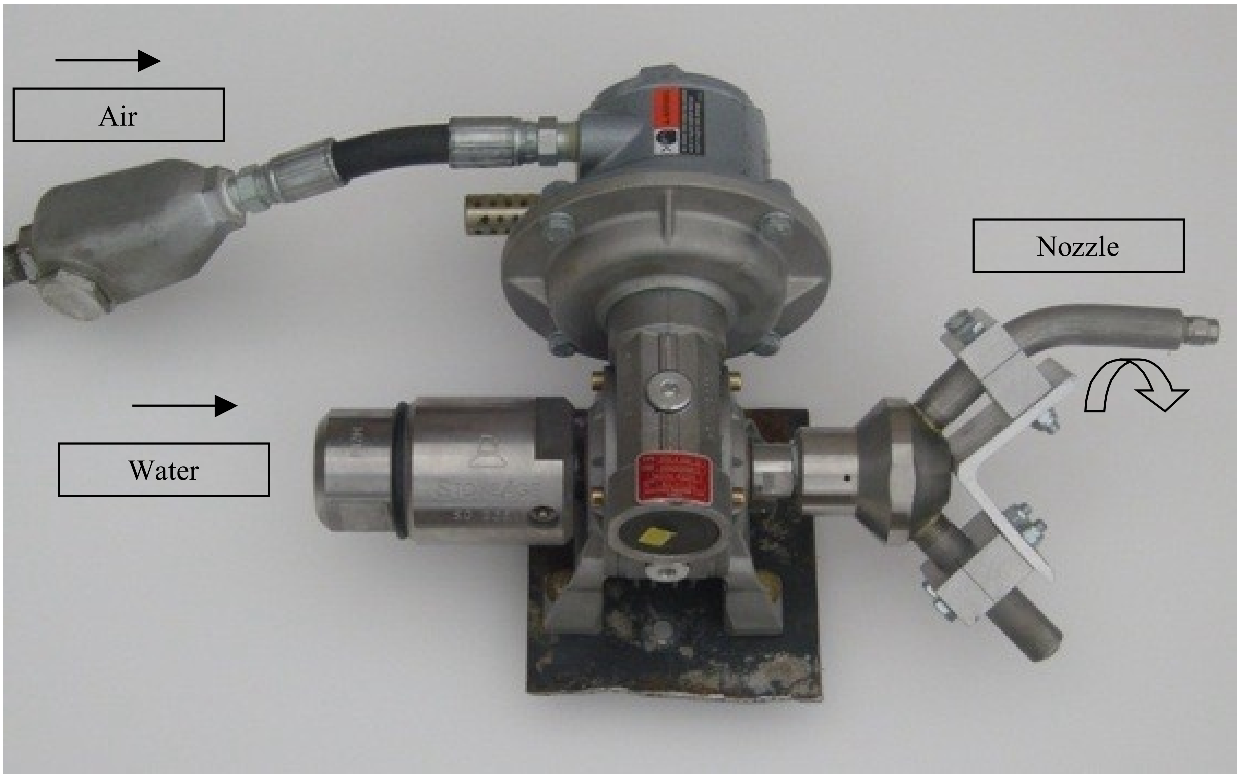

Fig. 8.4. Compressed air powered mechanical oscillating system.

8.5. Hydraulically powered mechanically oscillated single orifice jet

The fifth nozzle design tested was a mechanically oscillated, single orifice jet, which uses a small hydraulic motor at the boom/nozzle interface to provide rotation, (Fig. 8.5). The system was designed by Shotcrete Technologies Inc. of Idaho Springs, Colorado and built by CMC Machine Shop of Idaho Springs, Colorado. The assembly is based on similar units used by the company in mechanical shotcrete applications. Some degree of control of the rotation action can be achieved. Pivoting about two axes is accommodated by the universal joint at the rear of the frame resulting in a cone-shaped path of rotation. The radius of rotation generated by the hydraulic motor can be adjusted with the bolt and slot shown in the photograph. Moving the bolt away from the hydraulic motor's axis of rotation will result in a larger circle. A graphic representation of the con-shaped nozzle path is shown in Fig. 8.6. While it would normally be desirable to power the motion assembly directly from the main hydraulic system of the carrier vehicle, the prototype rig did not possess the necessary capability. To overcome this, a separate hydraulic pump and reservoir were mounted to the main body of the scaling vehicle. The speed of oscillation was controlled by a hand-operated valve located near the pump/reservoir and could adjusted between 0 and approximately 90 rpm. The main power switch was also located in the proximity of the pump/reservoir, making it easy to turn the unit on and off. The clamp interface on the oscillating unit allows for the attachment of many different types of nozzle assemblies. For the tests conducted in this research, the single orifice nozzle discussed at the beginning of this section was used.

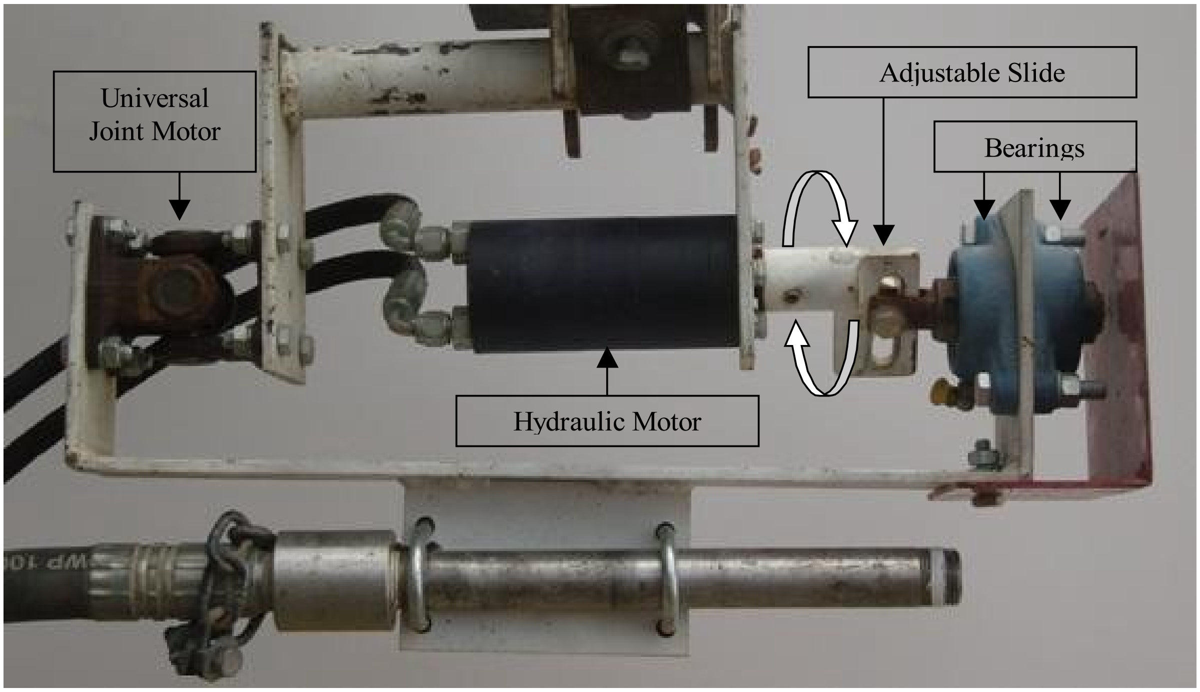

Fig. 8.5. Hydraulically powered mechanical oscillating system.

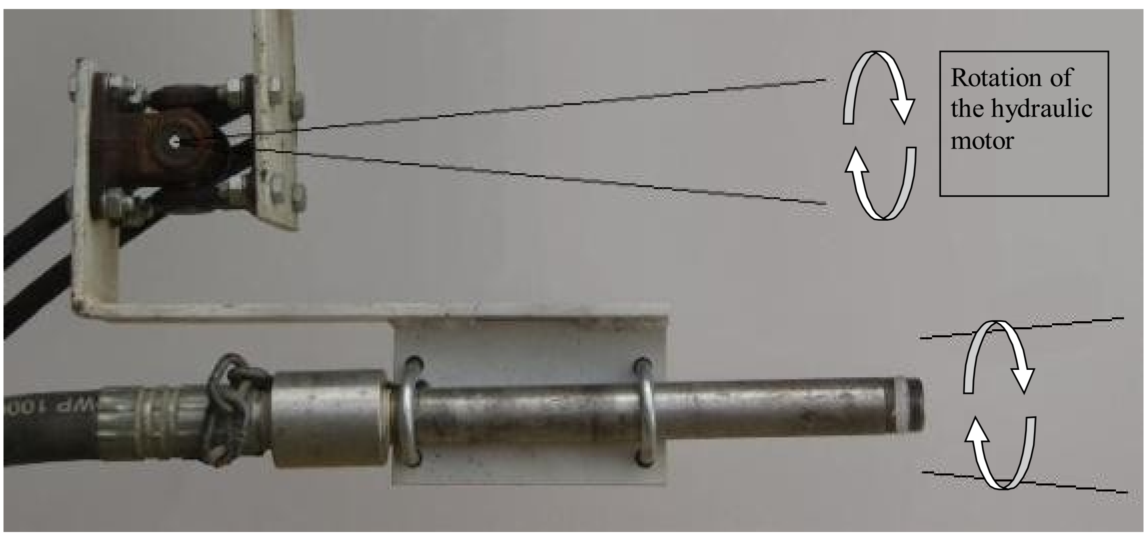

Fig. 8.6. Cone shaped jet path achieved with the hydraulically powered mechanical oscillating system.

9. Test Location and Procedures

This research was conducted at the Colorado School of Mines Edgar Experimental Mine, located in Idaho Springs, Colorado. The mine lies within the Precambrian Idaho Springs Formation made up of highly altered gneiss, pegmatite intrusions, schist, and granite, (Anonymous, 1984). The rock type is known to vary significantly within a matter of feet throughout the region and, thus, a general geologic description does not accurately reflect the conditions met during any particular experiment. Significant weathering has occurred within 40 - 60 feet of the surface throughout the region, and some of the effects of weathering extend deeper through veins and minor faults. Clay-filled joints appear and disappear abruptly and discontinuities intersecting the mine openings occasionally run with water during wet seasons. The intact rock strength of the Idaho Springs Gneiss is moderate to high.

A total of nineteen experiments were conducted. The experiments were conducted by scaling a freshly blasted rock surface that was produced by slashing an existing 2.4 m by 2.4 m (8 ft by 8 ft) drift to approximately 3.7 m by 3.7 m (12 ft by 12 ft). The slash rounds were drilled using between twenty five to thirty 48 mm (1 7/8 in) diameter holes that averaged approximately 3 m (10 ft) in length. Holes were drilled using a single boom Atlas Copco Jumbo rock drill. Fig. 9.2 shows a plan view of the CSM Experimental Mine, and Fig 9.1 shows the location of the first ten waterjet scaling experiments conducted.

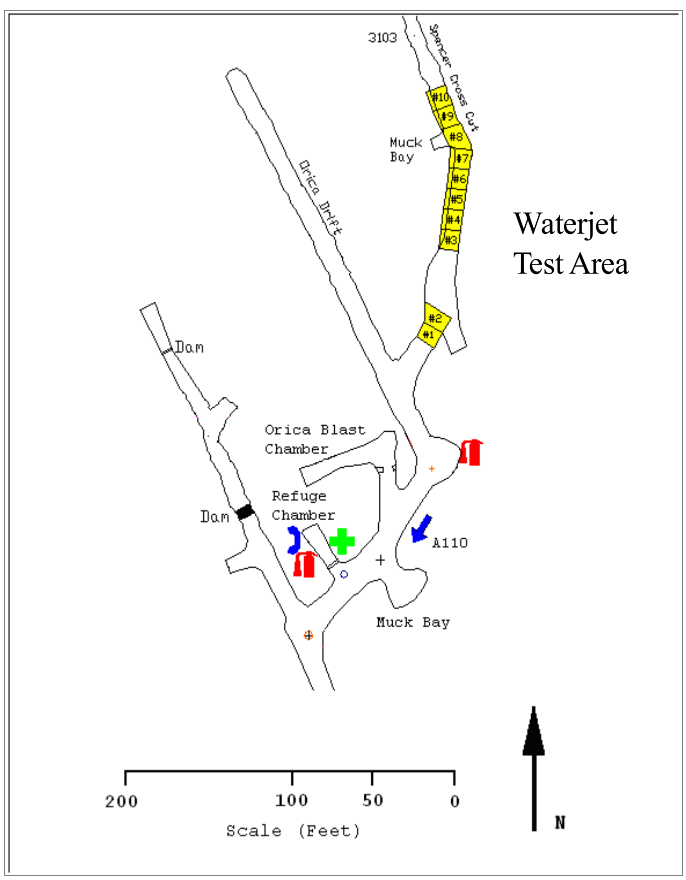

Fig. 9.1. Location within the CSM Edgar Experimental Mine of the first ten waterjet scaling experiments performed.

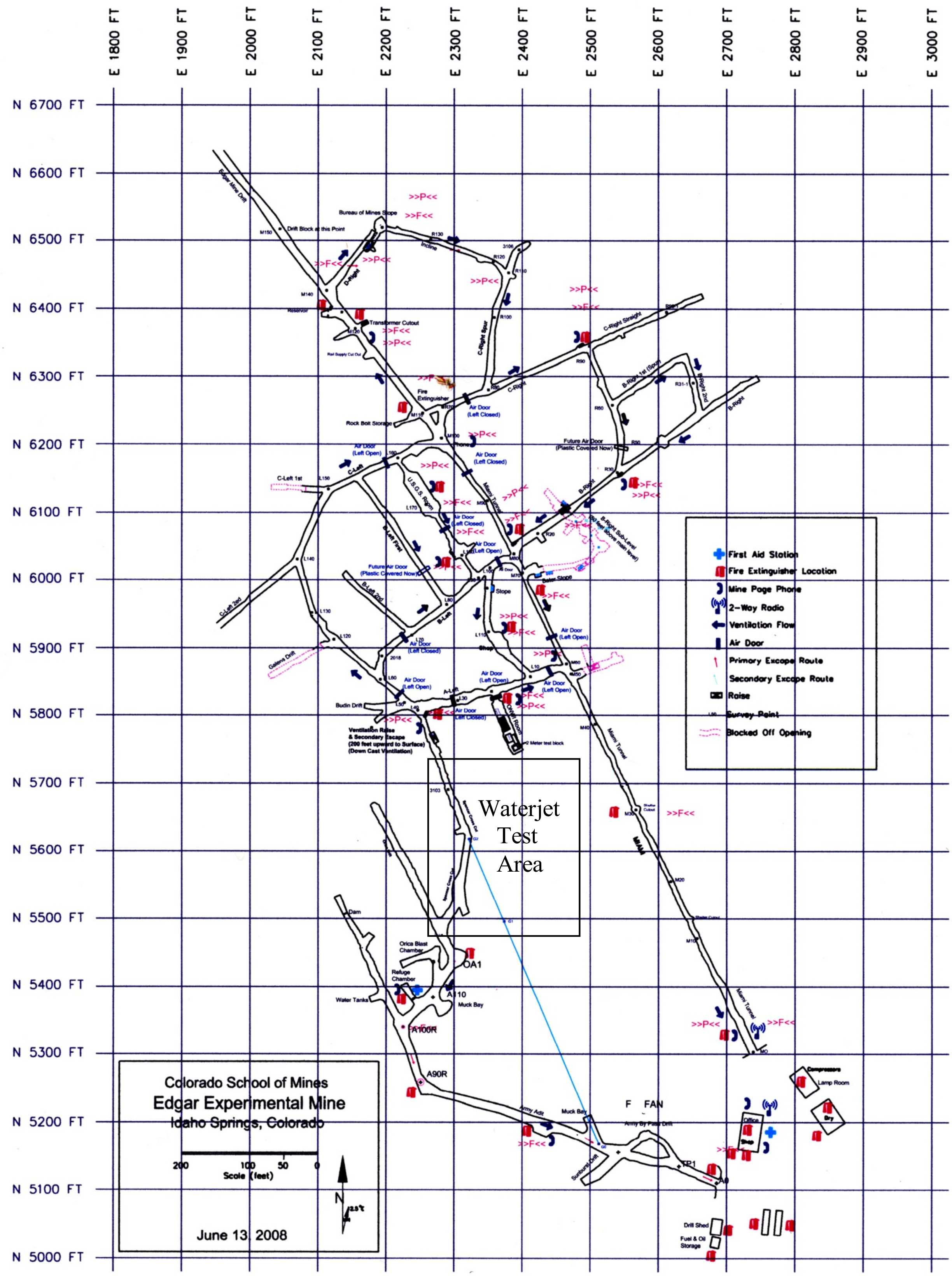

Fig. 9.2. Location within the CSM Edgar Experimental Mine of the ten scaling experiments performed.

The first three experiments were performed using hand scaling only. The location of these tests was on consecutive slash rounds located immediately to the south of the waterjet scaled round labeled #1 in Fig 9.1. Next, ten waterjet scaling experiments were conducted using the five different types of waterjet nozzles discussed in the previous chapter. These rounds are labeled #1 through #10 in Fig. 9.1. Finally, six additional waterjet experiments were conducted in slash rounds located consecutively immediately to the north of the round labeled #10 in Fig. 9.1.

9.1. Test Procedure

The normal procedure followed for each waterjet scaling experiment was to drill the round, charge, blast, ventilate, and then level the muck pile in preparation for scaling. A large tarp was then placed on the ground beneath the area to be scaled. The waterjet rig was positioned and the back scaled. After this, a second tarp was placed over the area and the back was scaled again using a hand-held scaling bar. Hand scaling served as a control the effectiveness of individual nozzles, as well as waterjet scaling in general. Upon completion of the hand scaling, the material from both hand and waterjet scaling was each collected separately using five gallon buckets and weighed. Rocks and boulders too large to weigh were given estimated weights. Material from the first five waterjet experiments was screened in order to determine the particle size distribution. With two of the first ten waterjet experiments, the sequence was reversed and the area was first scaled manually, followed by waterjet scaling.

9.2. Blasting Procedures

As part of the research methodology, three types of blasting methods used. The slash rounds for the first three hand scaling and the first five waterjet scaling experiments were charged exclusively with ANFO and stick emulsion, (normal blasting). For the waterjet scaling experiments six through sixteen, two different smooth wall blasting techniques were used. Fig. 9.3 shows a typical drill hole pattern used for the rounds that employed normal blasting and Fig. 9.4 shows a typical drill hole pattern used for the rounds that employed smoothwall blasting.

The drill pattern for normal blasting was similar in design to those used in smoothwall blasting, however, the perimeter holes were spaced farther apart. With both blasting procedures, the holes were primed with a NONEL blasting cap inserted into a 305 mm (12 in) long stick of packaged emulsion. With normal blasting, this primer assembly was pushed to the back of the hole, and the hole was then loaded to within about 305 mm (1 ft) of the hole collar with ANFO.

Waterjet rounds number six through ten employed a smoothwall blasting technique whereby the perimeter holes were charged primarily with 200 grain detonation-cord (det-cord). With this smoothwall blasting technique, an approximately 3 m (10 ft) length of 200-grain det-cord was inserted into the emulsion cartridge (Fig. 9.5). This primer assembly was pushed to the back of the hole and the hole was then loaded with about 305 mm (1 ft) of ANFO. The purpose of the ANFO was mainly to hold the primer in the hole. The 200-grain det-cord extended along the length of the hole, and a plastic plug was inserted in the hole collar. It is believed that the plastic plug helped to contain the gas presure created during detonation within the hole as long as possible.

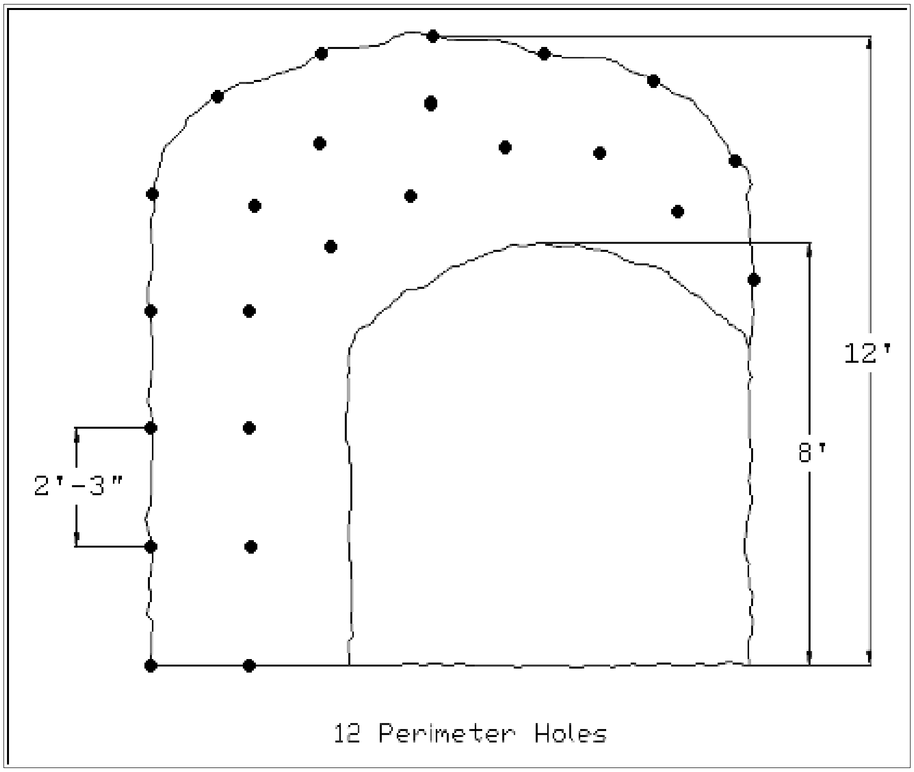

Fig. 9.3 A typical normal blast pattern used for the first five waterjet experiments.

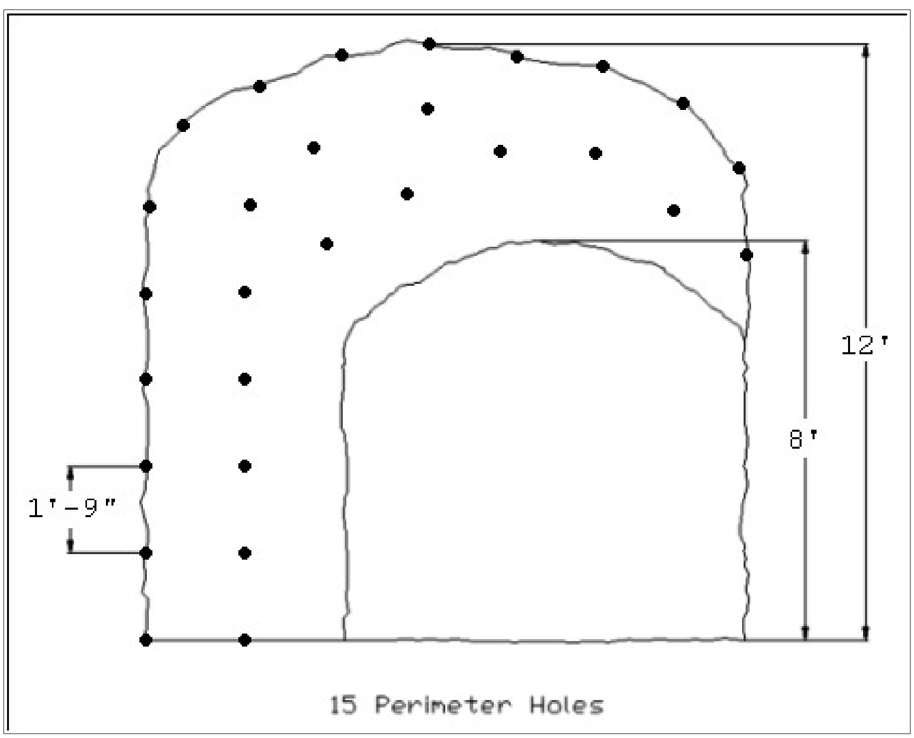

Fig. 9.4. A typical smoothwall blast pattern used for the last eleven waterjet experiments.

Fig. 9.5. A typical smoothwall blast primer showing 200 grain det-cord (thick orange) inserted into a stick of packaged emulsion explosive.

Waterjet rounds number eleven through sixteen employed a smoothwall blasting technique on the perimeter holes called air-decking. The holes were primed with a NONEL blasting cap inserted into a 305 mm (12 in) long stick of packaged emulsion. This primer assembly was pushed to the back of the hole, and the bottom of the hole was then loaded with about 0.9 m (3 ft) of ANFO. Two red-hat plugs were then inserted into the hole about 18 inches from the hole collar. Approximately 1 ft of ANFO was then blown into the hole to form a plug. The ANFO plug does not detonate. The purpose of the plug is to hold the gases formed during the detonation of the bottom charge with the hope that significant amounts of the gases will enter cracks in the perimeter rock and then break the rock to the desired smooth contour. The air-decking technique is considered easier to implement since it does not require any additional explosives other than those used to charge the remaining holes in the round.

With both smoothwall techniques employed, all of the perimeter holes were usually detonated with the same blasting cap delay.

The smoothwall blasting techniques worked very well. Due to fractures in the rock mass, however, "collar boots" (sections of the blasted hole that did not break) were observed in several of the rounds. The smoothwall blasting was conducted in order to demonstrate the correlation between controlled blasting, rock mass damage, and the amount of scaling required. These factors are the key to the integrated approach towards underground safety mentioned in the introduction of this report.

For each of the nozzle types, one experiment each was conducted with normal and smoothwall blasting. Usually, waterjet scaling was followed by hand scaling. The fifth and tenth experiments were conducted in reverse order, with hand scaling performed first followed by waterjet scaling. This was done in order to gain additional insight into the effectiveness of waterjet scaling as compared to hand scaling. Fig. 9.6 shows a summary of the first ten waterjet experiments performed. Experiments eleven through sixteen were all conducted using the simple single orifice continuous nozzle together with the hydraulically powered mechanical oscillating system, (nozzle 5).

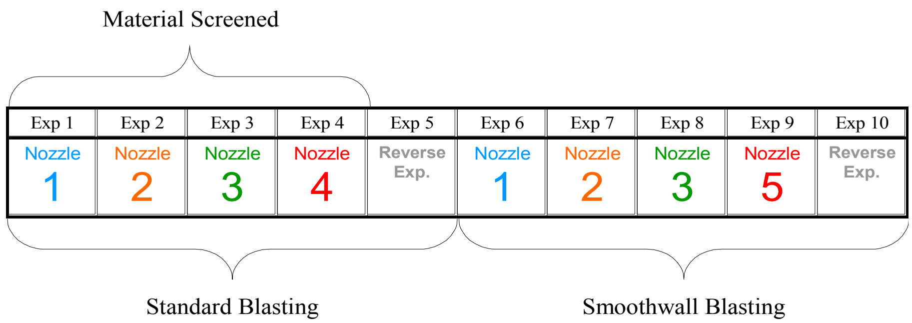

Fig. 9.6. Summary of first ten waterjet experiments performed.

10. Nozzle Performance Experimental Results

This section describes in detail the results of the waterjet scaling experiments where the performance of the various nozzle designs was tested. The material presented is taken from Poeck, 2008.

10.1 Experiment #1, Single Orifice, Continuous Nozzle

Experiment #1 took place on Monday, January 22, 2007 at the top of the ramp between the newly connected Army and Miami drifts of the Edgar Mine (Fig. 10.1). Standard blasting methods were utilized in the round that consisted of 37 holes in three rows along the existing back. No holes were drilled in the ribs.

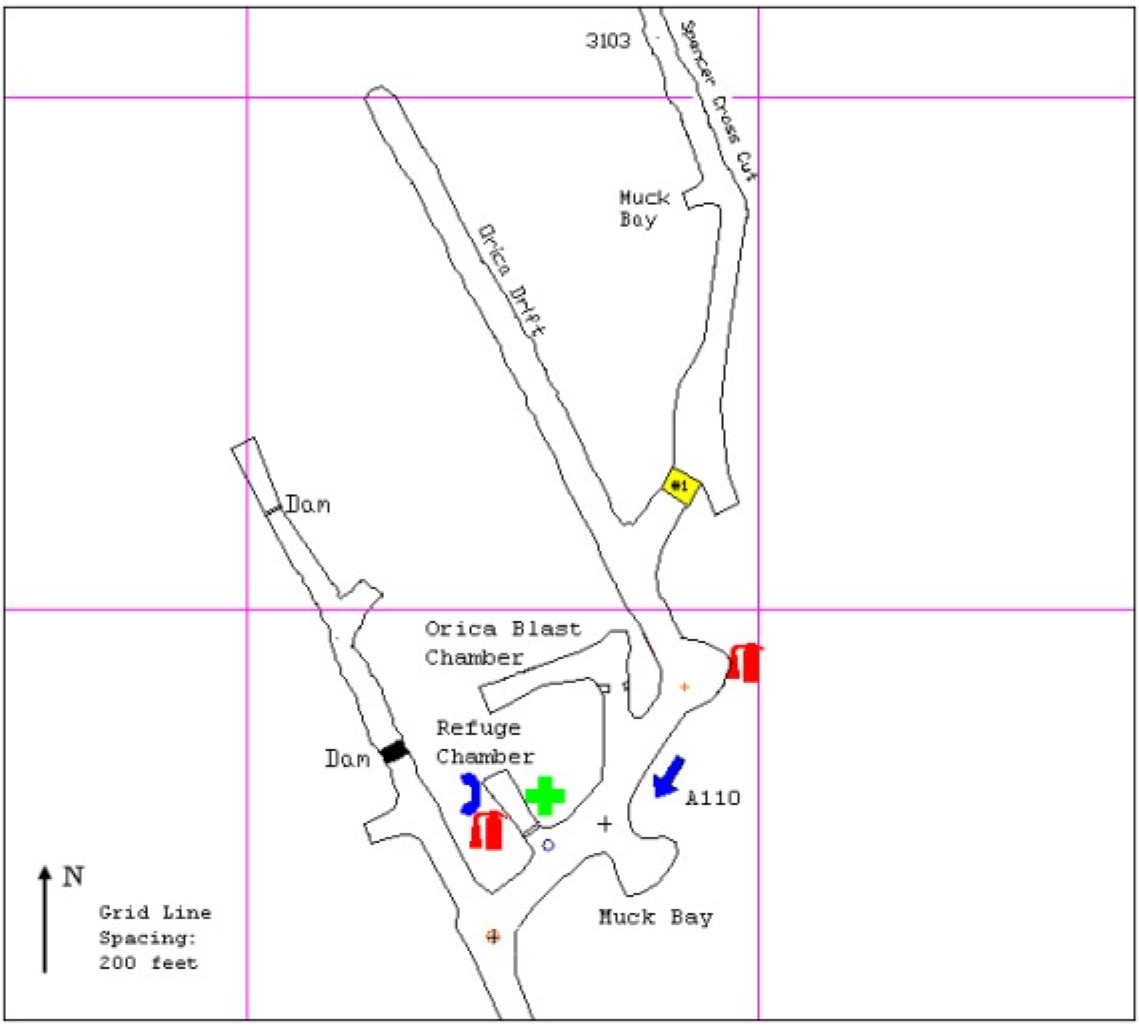

Fig. 10.1 Location of Experiment #1

10.1.1 Rock Conditions
The rock present in Experiment #1 consisted of highly altered gneiss with extensive layering of granite, biotite, and pegmatite. The random and irregular rock surface left by the blast indicated that the areas

of contact between various geologic compositions did not serve as points of weakness or failure during blasting. Rather, the abundance of random jagged edges and lack of significant discontinuities suggests that the rock mass was fairly competent before the blast.

A Rock Mass Rating (RMR) evaluation of the area after scaling revealed few significant features other than a set of near-vertical discontinuities. One peculiar individual feature was a near-vertical discontinuity with a 20 mm gap between faces. While a series of such discontinuities would spell disaster for ground support, a lack of similar, parallel joints limited its impact on the overall condition of the rock mass. Refer to Appendix A for the RMR analysis, which includes a birds-eye sketch of the rock surface and map of prominent discontinuities.

Photographs taken before and after the scaling experiment under the same lighting conditions and from the same physical location illustrate the cleaning effect offered by the waterjet (Figs. 10.2 and 10.3). Also notable in the photograph taken before the experiment is the presence of moisture along the left rib. Although this area was noted for being wet year-round and containing exceptionally soft and weathered material, the formation did not intersect the scaling area. It did, however, indicating the type of groundwater activity present in the rock mass and the effect it has on the materials in contact.

Overall, there were no geologic features or blast damage that would significantly skew the results of the scaling experiment with respect to the other experiments performed.

Fig. 10.2 Before Experiment #1

Fig. 10.3 After waterjet scaling, Experiment #1

10.1.2 <u>Results</u>

Waterjet scaling was performed for a period of 25 minutes with the high pressure pump set to 3050 psi. Hand scaling followed for a period of approximately 20 minutes. The largest single rock scaled by the waterjet weighed approximately 80 lbs, and the largest rock removed by manual scaling weighed 29 lbs. The amount of material removed by each method is illustrated in Fig. 10.4.

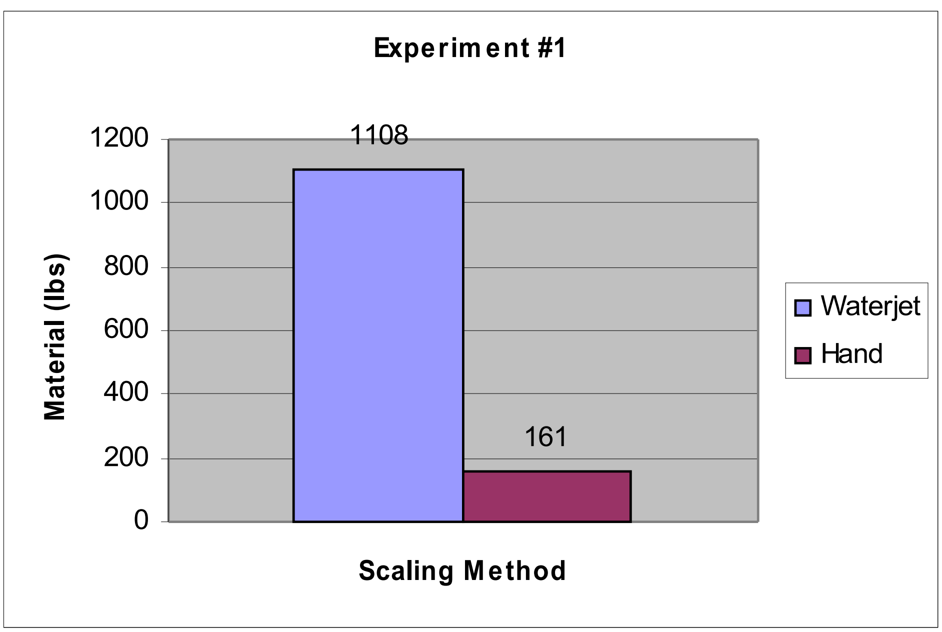

Fig. 10.4 Results of Experiment #1

All of the material removed in Experiment #1 was placed on tarps in a nearby drift for screening, as shown in Fig. 10.5.

Fig. 10.5 Waterjet and Manual scaling results

The screening results for Experiment #1 are shown in Table 10.1 and Fig. 10.6.

Table 10.1 Experiment #1 screen analysis results

Screen Size	Waterjet		Manual	
6.000	Weight Retained	% Passed	Weight Retained	% Passed
4.250	252.0	77%	119.0	26%
3.000	79.0	70%	25.0	10%
2.000	177.0	54%	11.0	4%
1.500	126.0	43%	1.00	3%
1.000	101.0	34%	2.10	2%
0.742	140.3	21%	1.27	1%
0.500	62.2	15.4%	0.56	0.5%
0.371	36.4	12.1%	0.28	0.3%
0.263	30.9	9.3%	0.10	0.2%
0.185	28.1	6.8%	0.07	0.2%
	17.2	5.2%	0.03	0.2%
<0.185	58.1	0.0%	0.27	0.0%

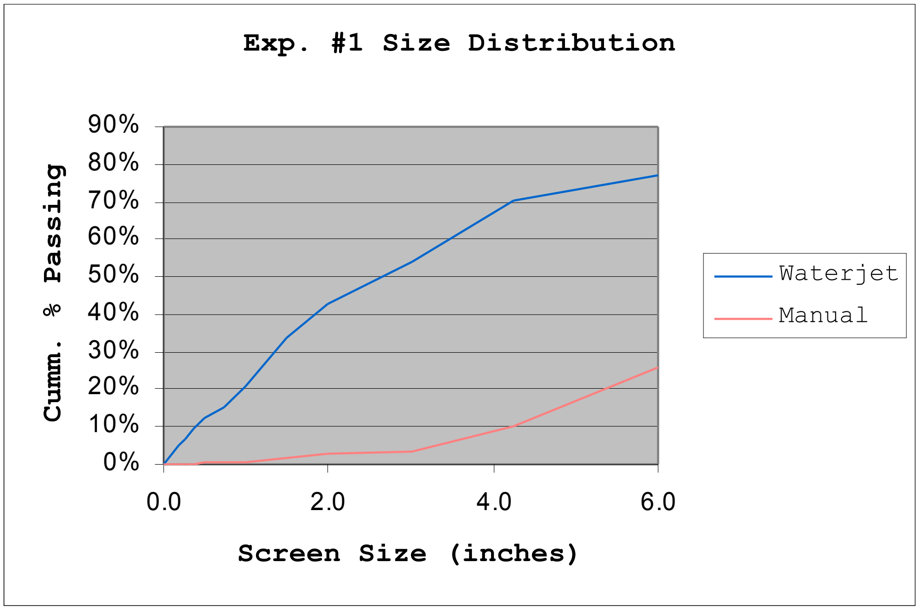

Fig. 10.6 Experiment #1 particle size distribution

The screen analysis illustrates several points of interest. Only about 22% of the material removed by the waterjet was larger than six inches, and about 45% of the material was below two inches. These numbers help illustrate the cleaning effect offered by waterjet scaling. The increase in adhesion strength of shotcrete applied after waterjet scaling (Kuchta, 2002) can be attributed to the removal of dust and other small, unconsolidated particles. On a contrary note, approximately 75% of the material removed manually (after the waterjet test) was larger than six inches. This statistic suggests that a waterjet is less effective against larger sized blocks of rock.

10.1.3 Notes

Overall, the results of Experiment #1 were as expected. The difference in the quantities of material removed by each scaling method seemed consistent with the results of the preliminary experiments.

Most of the material that came down during the subsequent hand scaling was located in a raised portion of the back that was not visible from the distance at which the waterjet operator stood. It was believed at the time of the experiment that a rotating waterjet nozzle of some type would have helped cover the areas that were misjudged through poor visibility.

During the manual scaling process, a student employee of the mine sustained a minor injury due to rock fall. The employee was standing at the lower end of a steep gradient in the muck pile, atop which two other employees were scaling. Although the by standing employee was watching carefully and obeying general rules of safety, a rock approximately 2 inches in diameter bounced several times off the side of the muck pile and struck the employee's face. Bleeding and swelling occurred, but no immediate medical attention was required. The incident served as an example of the dangers involved with manual scaling, even for those not directly involved.

10.2 Experiment #2, Dual Orifice, Self Rotating Nozzle

Experiment #2 took place on Wednesday, February 7, 2007 at the breakthrough point of the Army-Miami connection. Standard blasting techniques were used for the round, which consisted of 19 holes in one row across the back and two to three columns along the left rib. The intent of the blast was to smooth the difference in elevation between the Army and Miami drifts and widen the connection for LHD and jumbo drill access. The specific location of the experiment is shown in Fig. 10.7.

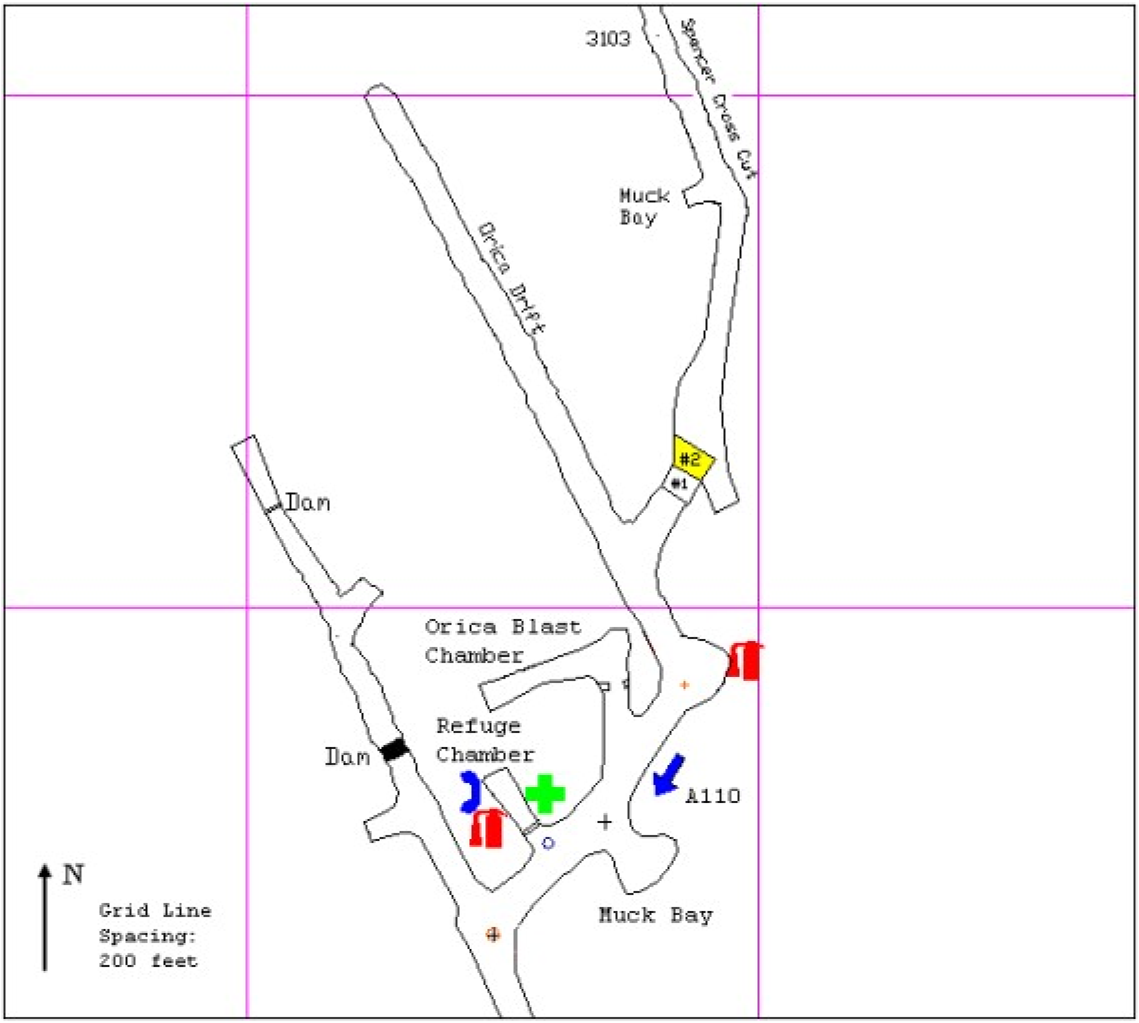

Fig. 10.7 Location of Experiment #2

10.2.1 <u>Rock Conditions</u>

The rock mass in Experiment #2 shared many features with that of Experiment #1. The first feature was the presence of the highly weathered, soft orange material on the left rib. Although the material was not in the scaling zone, similar colored residue was noted in many of the surrounding discontinuities, which suggests some previous movement of water and weathering through the area. Additionally, as more time was spent in the area during later waterjet experiments, droplets of water were known to fall from the back through the wetter seasons of the year. A photograph taken before the start of the experiment is shown in Fig. 10.8.

Fig. 10.8 Photograph taken before Experiment #2

The most significant feature in the rock mass was the presence of several near-vertical, parallel discontinuities. Some of them had 2-3 mm gaps, and some of them were intersected by perpendicular discontinuities creating conditions favorable for large rock fall. Before the start of the waterjet test, a photograph was taken of the discontinuities that posed the greatest danger. The photograph is shown in Fig. 10.9 with an arrow to indicate the trend of the joint set.

Fig. 10.9 Troubling discontinuities noted before Experiment #2

Another significant feature noted in the scaling area was a large, nearly horizontal surface that most likely formed the top half of a discontinuity before the blasting of the drift. Though difficult to distinguish in Fig. 10.8, the surface was angled 20-30 degrees from horizontal and sloped up into the rock mass above Experiment #2. The presence of such a discontinuity plane at a nearly horizontal orientation further diminished confidence in the integrity of the rock mass.

Aside from these major features, the scaling area was predominantly rough and irregular as a result of the blast. The geologic composition was very similar to that in Experiment #1.

10.2.2 Results

The 41 minute duration of this waterjet scaling test was longer than any other experiment. It was agreed upon by all parties involved that the priority of each waterjet test was to remove all loose and unsafe material from the back before entering the area for manual scaling or the collection of data. The known condition of the rock mass and the amount of material seen falling to the tarp justified the extra scaling time. The results of Experiment #2 are shown in Fig. 10.10.

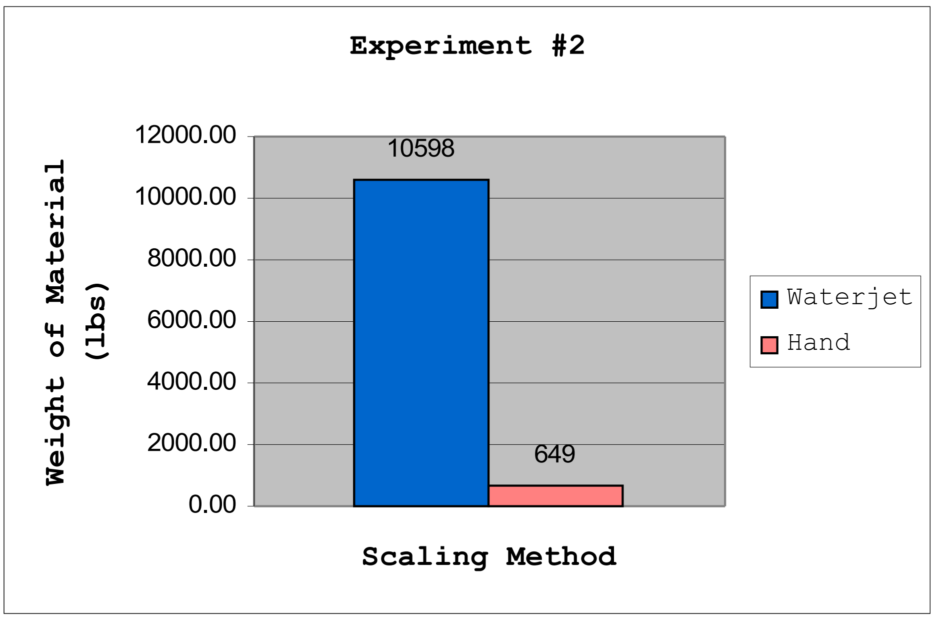

Fig. 10.10 Results of Experiment #2

While the quantity of material scaled by waterjet in Fig. 10.10 seems impressive at nearly 11,000 lbs, Experiment #2 was made unique and memorable by the sudden collapse of approximately 8,000 lbs of intact rock. There was no evidence to suggest that the dual orifice nozzle offered any necessary advantage in the removal of the slabs, but the incident was considered a justification of remotely controlled waterjets in terms of safety. The largest rock removed by manual scaling weighed 73 lbs.

The massive rock that fell during the waterjet experiment was bound by the discontinuities pictured previously in Fig. 10.9. Based upon the photographs taken before and after the experiment, it was believed that much of the material fell as a whole and broke into several pieces when it hit the ground. Most of the rocks were still too large to be moved by hand, and thus the total weight of material removed in Experiment #2 is an estimate based on the rough dimensions of each block. The slab of rock is shown in Fig. 10.11 with the waterjet operator positioned above for scale. All of the rock in the immediate foreground fell at once.

Fig. 10.11 Slab of rock that skewed results for Experiment #2

The raw screen analysis for the material collected in Experiment #2 is of little value. With nearly 9,000 lbs of rock greater than six inches, the percentages of waterjet-scaled material passing lower screen sizes seems nominal. The results of the analysis are shown in Table 10.2 and Fig. 10.12.

Table 10.2 Experiment #2 screen analysis results

Screen Size	Waterjet		Manual	
6.000	Weight Retained	% Passed	Weight Retained	% Passed
4.250	8921.0	16%	293.0	55%
3.000	391.0	12%	117.0	37%
2.000	337.0	9%	104.0	21%
1.500	307.0	6%	63.0	11%
1.000	117.0	5%	23.0	8%
0.742	148.0	4%	18.0	5%
0.500	62.0	3.0%	10.0	3.3%
0.371	72.3	2.3%	7.5	2.1%
0.263	43.8	1.9%	3.5	1.6%
0.185	45.0	1.5%	3.1	1.1%
	30.4	1.2%	1.7	0.8%
<0.185	124.0	0.0%	5.4	0.0%

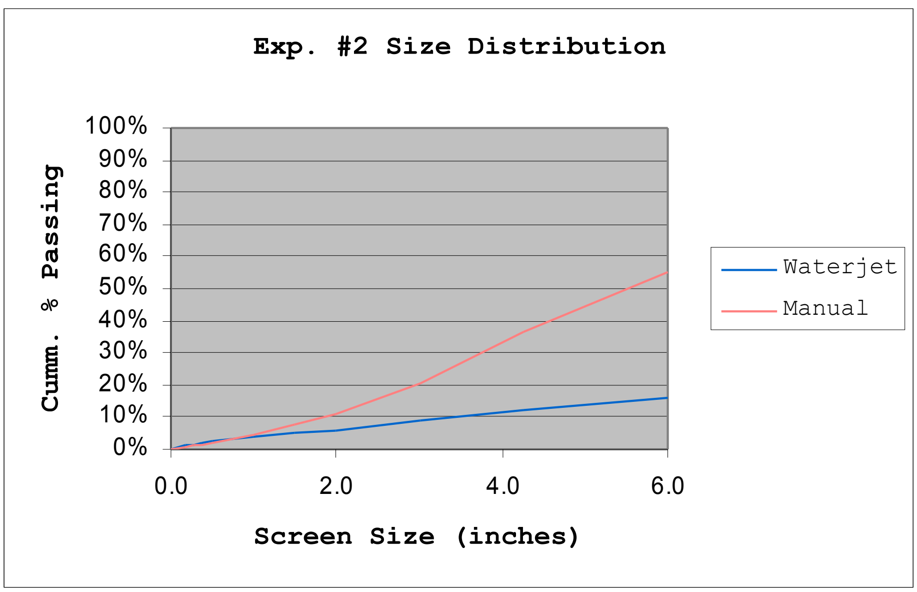

Fig. 10.12 Experiment #2 particle size distribution

10.2.3 <u>Notes</u>

If the data is corrected by removing the estimated weight of the fallen slabs, the results of Experiment #2 seem more consistent with other experiments. The proportions of material removed by each scaling method become more consistent with other experiments, and the particle size distribution adjusts to represent a well graded assortment of material. The corrected data can be seen in Fig. 10.13 and Fig. 10.14 as well as Table 10.3,.

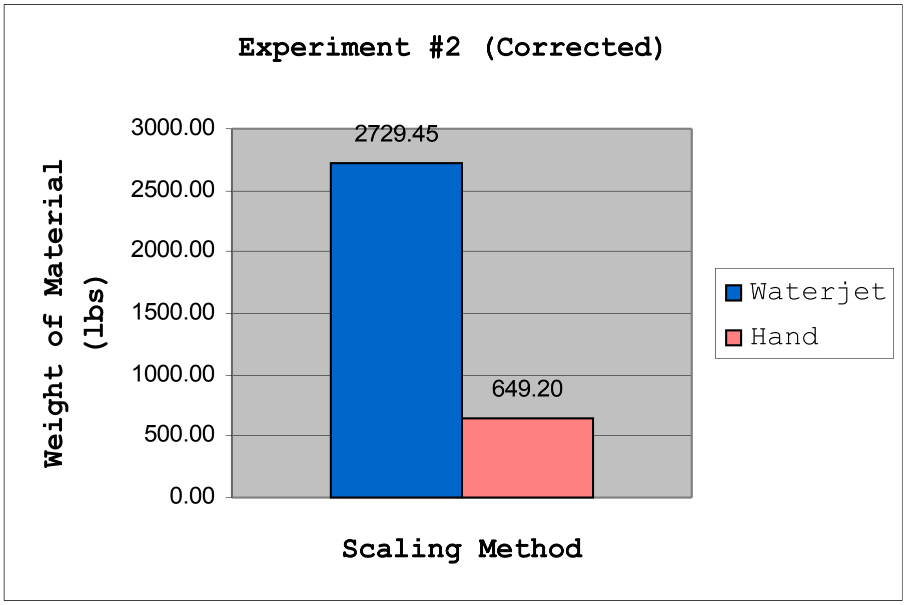

Fig. 10.13 Corrected results for Experiment #2

Table 10.3 Corrected data for Experiment #2 screen analysis

Screen Size		Waterjet			Manual	
6.000		Weight Retained	% Passed		Weight Retained	% Passed
4.250		1086.0	61%		293.0	55%
3.000		391.0	47%		117.0	37%
2.000		337.0	35%		104.0	21%
1.500		307.0	24%		63.0	11%
1.000		117.0	19%		23.0	8%
0.742		148.0	14%		18.0	5%
0.500		62.0	11.6%		10.0	3.3%
0.371		72.3	8.9%		7.5	2.1%
0.263		43.8	7.3%		3.5	1.6%
0.185		45.0	5.7%		3.1	1.1%
		30.4	4.5%		1.7	0.8%
<0.185		124.0	0.0%		5.4	0.0%

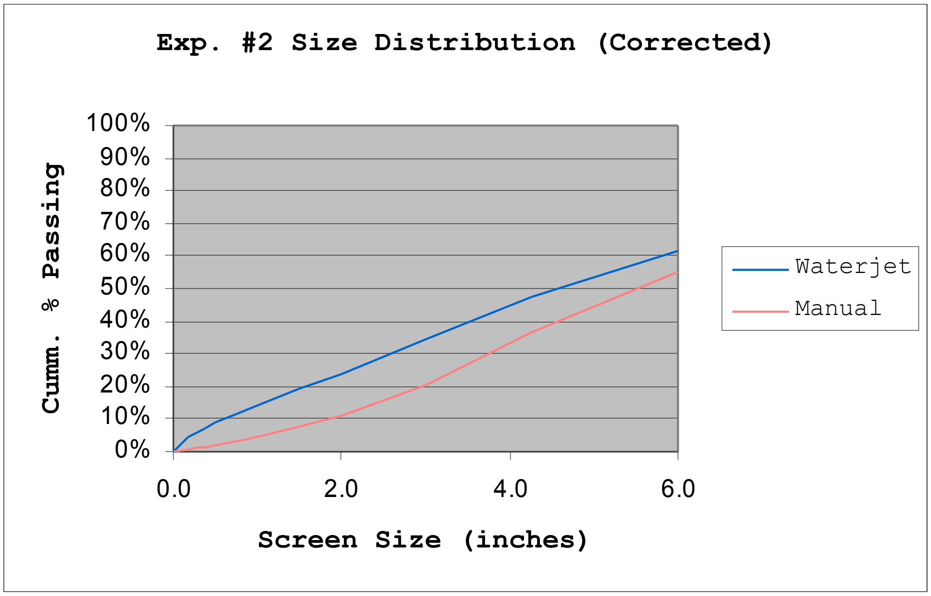

Fig. 10.14 Corrected particle size distribution, Experiment #2

The corrected particle size distribution indicates that a moderate 55 - 60% of the material removed by each scaling method was larger than six inches. The data also suggests that the dual orifice, self rotating waterjet was more successful than the single orifice nozzle in Experiment #1 in removing blocks larger than 6 inches. Of course, a single experiment is not statistically meaningful and the rock mass will always have an effect on the results of the test.

10.3 Experiment #3, Pulsed Single Orifice Nozzle

Experiment #3 took place on Wednesday, March 7, 2007 in the Spencer Crosscut on the north side of the Army-Miami connection. Experiment #3 was considered the first true slash round, which consisted of 16 holes in one to two rows along the back and one to two columns along the left rib. Standard blasting techniques were used. The exact location of the experiment is shown in Fig. 10.15.

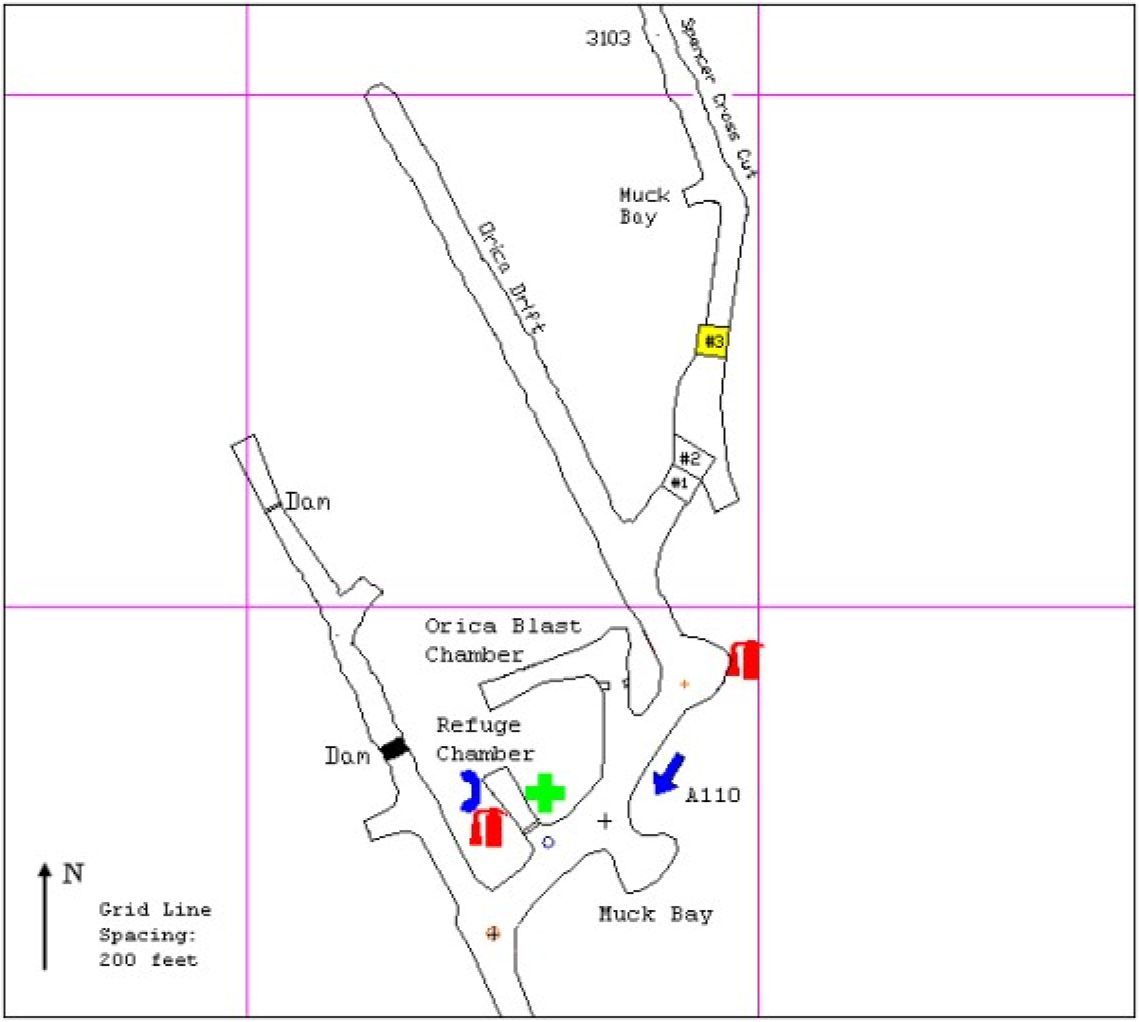

Fig. 10.15 Location of Experiment #3

10.3.1 <u>Rock Conditions</u>

The rock present in Experiment #3 was slightly different than that of the previous two experiments. Most of the back was fairly competent biotite and pegmatite with very few discontinuities. The RMR analysis, available in Appendix A, revealed several minor joints along the left edge of the back, though none of them seemed to belong to a set. The surface left by the blast included several orange-stained planes similar to those in previous experiments. Additionally, a couple of the discontinuities on the right rib contained a thin clay filling. Although these features were most likely affected by moisture at some point in the past, the area appeared to be completely dry since the development of the Spencer Crosscut several months before.

The most significant feature in the rock mass was a small shear zone running diagonally over the south-east corner of the back. The rock in the shear zone was lighter in color, consisting of moderately weathered pegmatitic feldspar. It was highly fractured and contained clay filling which gave way to crumbling. The shear zone also continued into the rock mass just south of Experiment #3, causing concern over small scale rock fall while working in the area. A graphic representation of the shear zone trend through the drift is shown in Fig. 10.16.

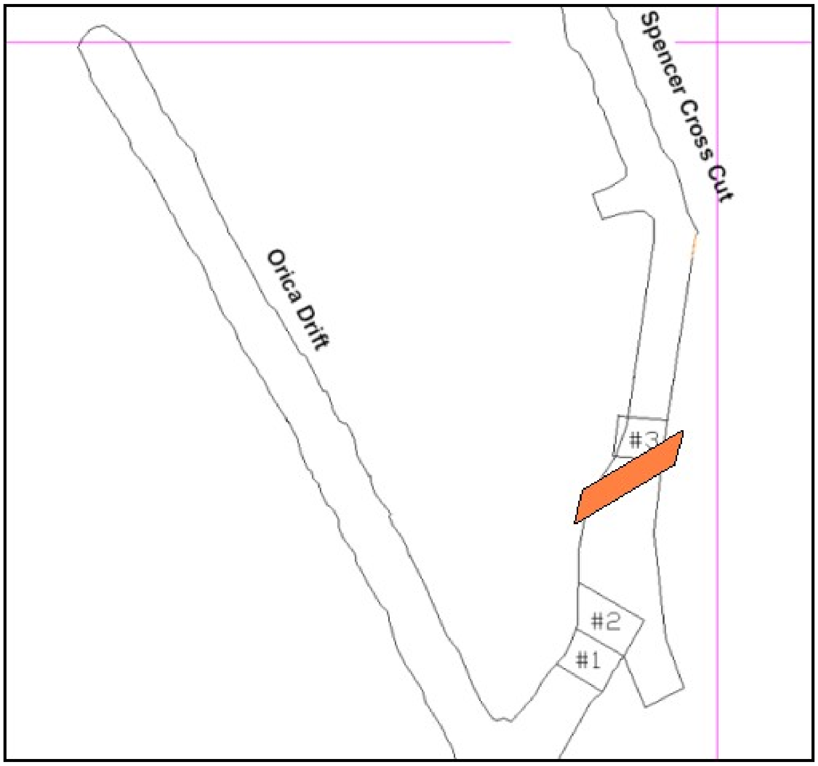

Fig. 10.16 Orientation of small shear zone in Experiment #3

10.3.2 Results

The proportion of material removed by each method in Experiment #3 was similar to that of Experiment #1 and the corrected results of Experiment #2. The quantities of material removed are shown in Fig. 10.17.

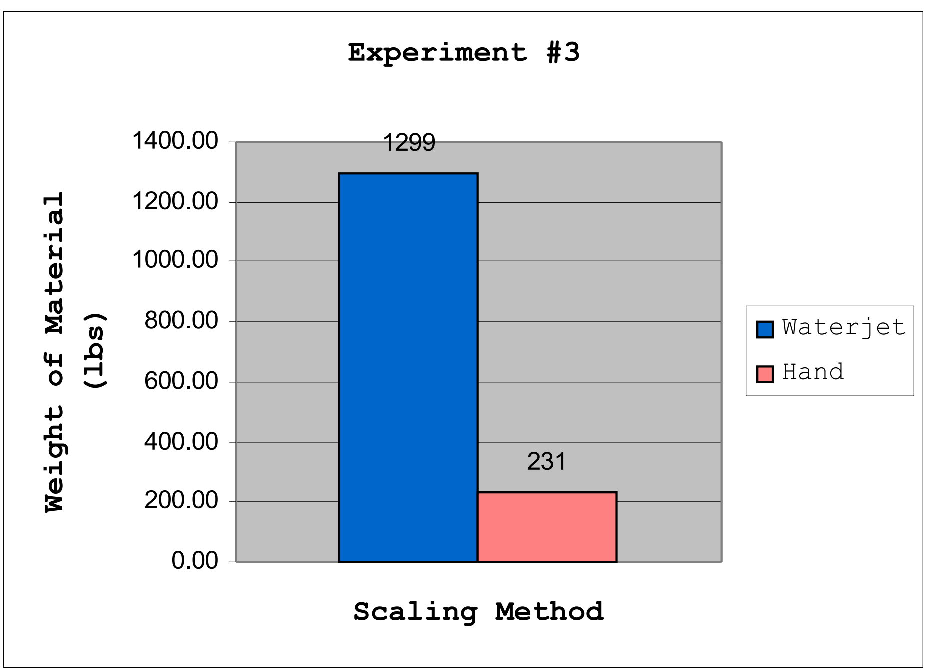

Fig. 10.17 Results of Experiment #3

The largest single rock scaled by the waterjet weighed approximately 80 lbs, and the largest rock removed manually weighed 25 lbs. Given the relatively good condition of the rock mass over 90% of the back, the amount of material that fell to the tarp would have been lower if not for the shear zone. Photographs taken before and after the experiment make the location of the shear zone fairly evident. The southeast corner of tarp is inundated with lightly colored, highly fractured rock with a general northeast – southwest trend. See Figs. 10.18 and 10.19. The results of the screen analysis for Experiment #3 are shown in Table 10.4 and Fig. 10.20.

Fig. 10.18 Photograph taken before Experiment #3

Fig. 10.19 Photograph taken after Experiment #3

Table 10.4 Experiment #3 screen analysis results

Screen Size	Waterjet		Manual	
6.000	Weight Retained	% Passed	Weight Retained	% Passed
4.250	209.0	84%	58.0	75%
3.000	73.0	78%	66.0	46%
2.000	134.0	68%	20.0	38%
1.500	173.0	55%	33.0	24%
1.000	100.0	47%	12.0	18%
0.742	134.0	37%	15.0	12%
0.500	89.2	29.8%	6.4	9.1%
0.371	83.7	23.3%	7.2	6.0%
0.263	59.8	18.7%	3.8	4.3%
0.185	51.0	14.8%	2.8	3.1%
	35.1	12.1%	1.8	2.3%
<0.185	157.0	0.0%	5.4	0.0%

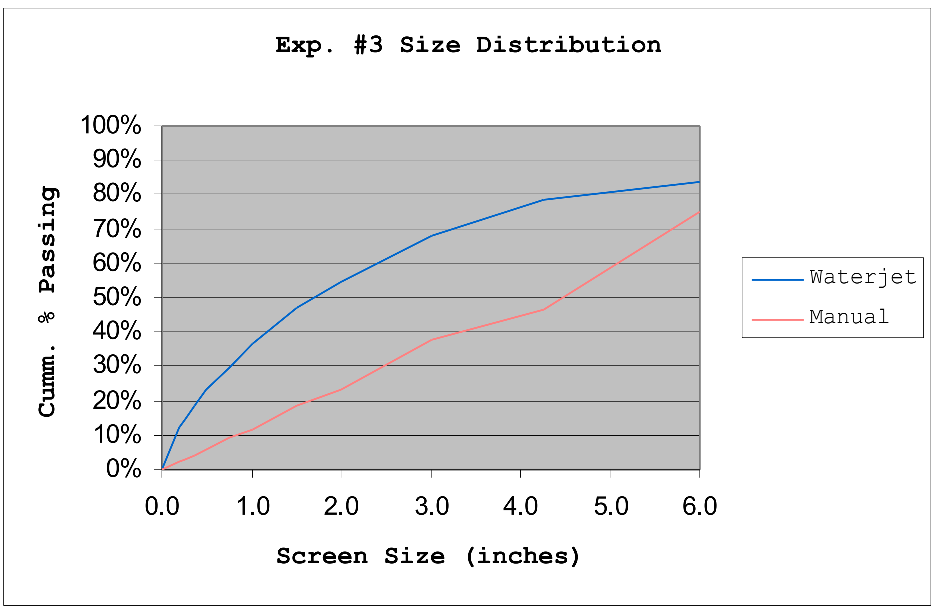

Fig. 10.20 Experiment #3 particle size distribution

The particle size distribution illustrates that only 15% of the waterjet-scaled material and 25% of the manually scaled material was larger than six inches. These statistics, along with visual evidence in the photographs, suggest that there was a general scarcity of large blocks to be scaled. The curve also indicates that nearly 55% of the material scaled by waterjet is two inches or smaller in size. Though such evidence is encouraging for the cleaning effect of waterjets, the highly fractured shear zone undoubtedly contributed to the statistics for small sized particles. It is difficult to determine whether the pulsed single orifice nozzle had any necessary effect on the results.

10.3.3 Notes
Statistically, the results of Experiment #3 speak of neither excellence nor mediocrity in regards to the performance of the acoustically pulsed single orifice nozzle. The only information worth considering is in the experienced gained by the waterjet operator, wherein the cloud of mist generated by the pulsed nozzle was unrelenting in its obstruction of vision. Though a high pressure, pulsed stream was accomplishing work at the core of the cloud, it was difficult to utilize it to its fullest potential without knowing where it was in relation to the rock surface. Other nozzles generated mist when held at certain orientations to the rock surface, but shorter standoff distances usually resulted in less mist and increased visibility. The acoustically pulsed nozzle was difficult to use regardless of its position and orientation.

10.4 Experiment #4, Air-Powered Mechanical Oscillator

Experiment #4 took place on Wednesday, March 28, 2007 immediately north of Experiment #3. The exact location is shown in Fig. 10.21. Standard blasting techniques were used in the slash round that consisted of 15 holes in one to two rows along the back and one column along the left rib.

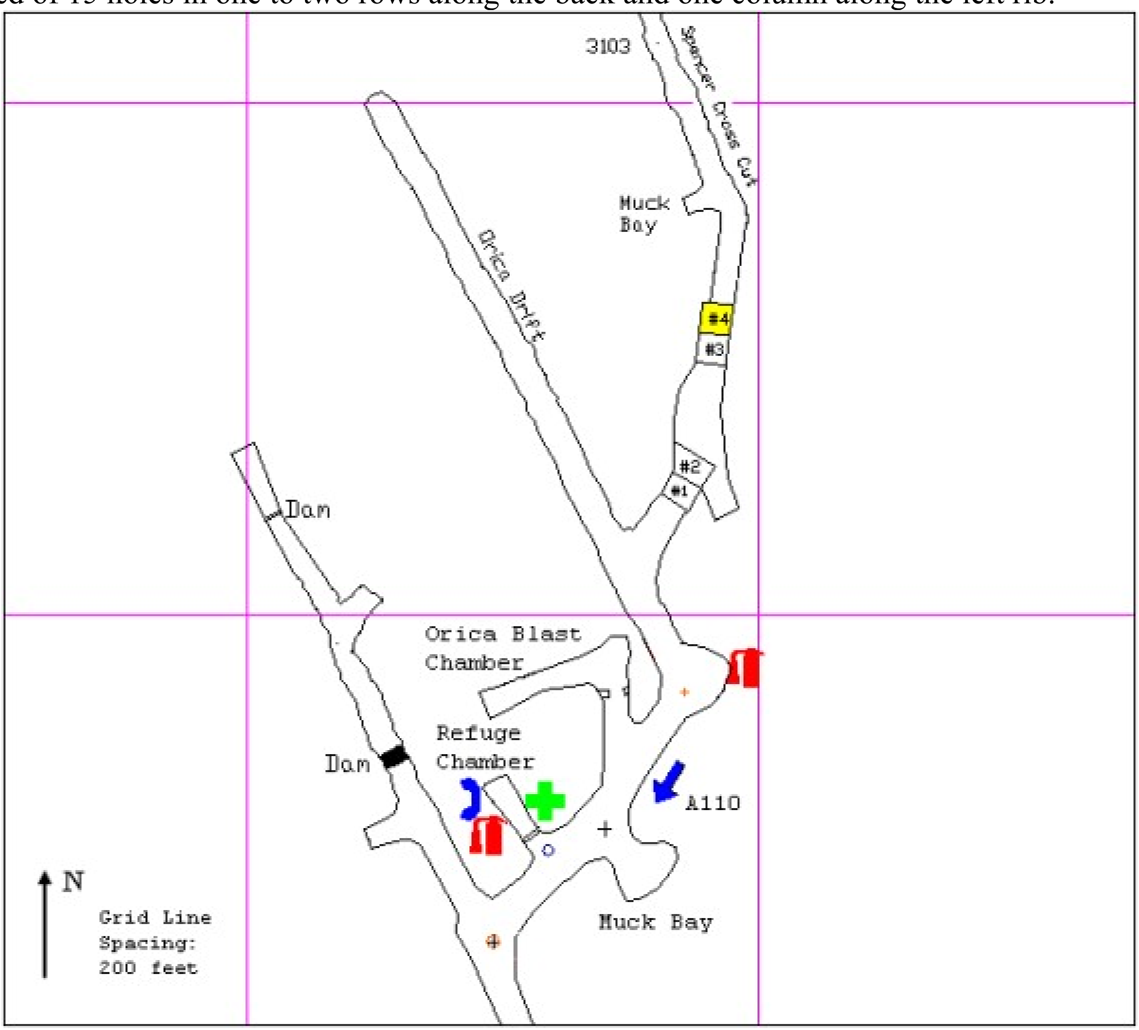

Fig. 10.21 Location of Experiment #4

10.4.1 Rock Conditions

The RMR analysis conducted in the drift where Experiment #4 took place did not reveal any significant hazards or features that would skew the results of the nozzle test. Smooth wall blasting techniques were not utilized for Experiment #4, but the back was left in moderately good condition with an admirable arched shape. There was a long, jagged edge on the left rib indicating the presence of a weak discontinuity, but it seemed to terminate near the back and had no effect on the area to be scaled. Several minor discontinuities were noted in the back, but none caused concern.

10.4.2 Results

The results of Experiment #4 were not a convincing testimony to the effectiveness of waterjets for scaling. The largest single rock removed by the waterjet weighed 39 lbs, and the largest rock removed manually weighed 52 lbs. As shown in Fig. 10.22, the total amount of material, being approximately 1500 lbs, was close to that of Experiment #3, but a large portion of the material was removed by manual scaling.

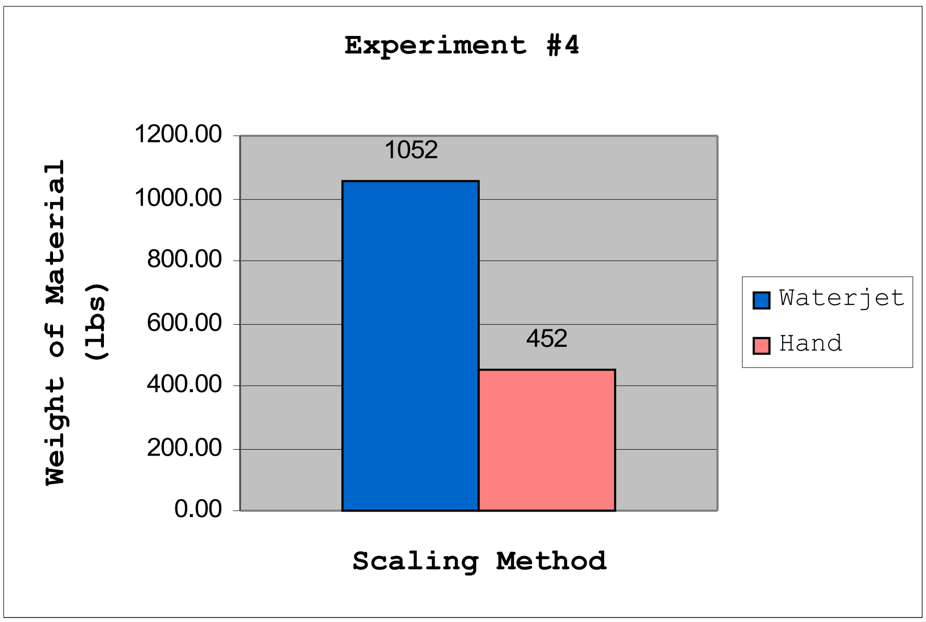

Fig. 10.22 Results of Experiment #4

The results of the screen analysis were similar to Experiment #1 in terms of contrast between the particle size distributions generated by each scaling method. Only 10% of the waterjet-scaled material was larger than six inches compared to 60% of that scaled by hand, and 55% of the waterjet-scaled material was below two inches. These statistics further illustrate the cleaning effect of waterjets and their lack of force against larger blocks of rock. The results of the screen analysis by weight and the particle size distribution graph can be found in Table 10.5 and Fig. 10.23.

Table 10.5 Experiment #4 screen analysis results

Screen Size		Waterjet			Manual	
6.000		Weight Retained	% Passed		Weight Retained	% Passed
4.250		91.0	91%		278.0	39%
3.000		120.0	80%		67.0	24%
2.000		134.0	67%		43.0	14%
1.500		133.0	55%		34.0	7%
1.000		76.0	47%		11.0	4%
0.742		112.0	37%		7.0	3%
0.500		70.4	30.0%		2.8	2.1%
0.371		71.6	23.2%		3.5	1.3%
0.263		42.0	19.2%		1.6	1.0%
0.185		41.4	15.3%		1.3	0.7%
		28.4	12.6%		0.7	0.5%
<0.185		132.1	0.0%		2.3	0.0%

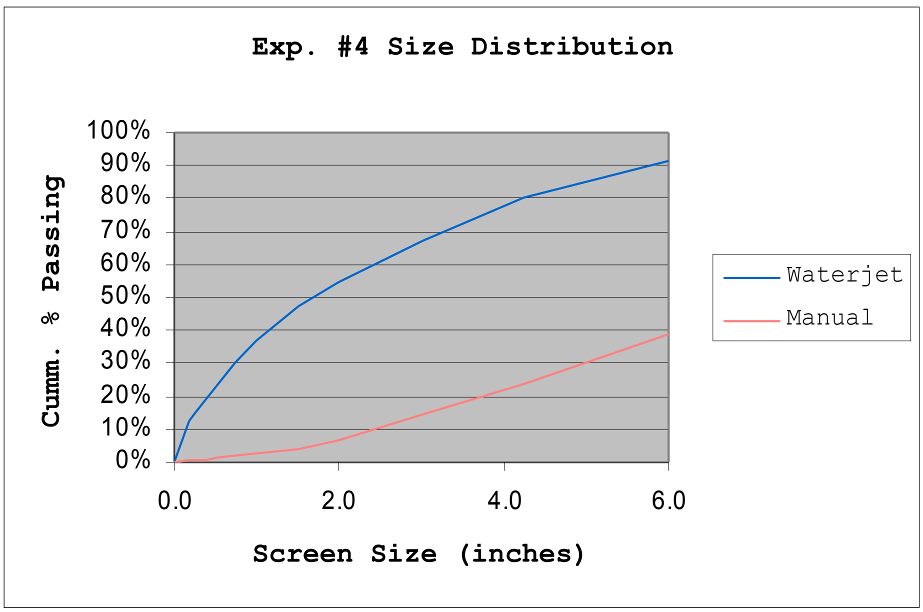

Fig. 10.23 Experiment #4 particle size distribution

10.4.3 Notes

The waterjet operator experienced difficulty with the air-powered mechanical oscillator. The weight of the unit, at approximately 40 lbs, caused severe bouncing when the scaling boom was extended. For that reason, the extension of the boom was kept at a shorter distance than usual, perhaps jeopardizing the competency of the scaling job toward the far end of the drift. Additionally, the hydraulic cylinders responsible for manipulating the nozzle at the end of the boom were barely strong enough to support the air-powered oscillator, making it difficult to aim the jet. The standoff distance also had to be maintained at a greater distance than normal to avoid collision between the bouncing nozzle and the rock.

The large portion of material removed by hand is the strongest indicator of the difficulty experienced with the air-powered oscillator. The bouncing effect of the boom combined with the inherent delicacy of the protruding nozzle tip made for an uneasy feeling on the part of the waterjet operator and a sub-par scaling test.

10.5 Experiment #5, Single Orifice, Continuous Nozzle

Experiment #5 took place on Tuesday, April 17, 2007 in the Spencer Crosscut. It was a reverse-order scaling test in which manual scaling was performed first and the subsequent waterjet scaling was done with the single orifice, continuous jet. Standard blasting techniques were utilized in the slash round, which consisted of 22 holes in two rows along the back and left rib. The location of the experiment is shown in Fig. 10.24.

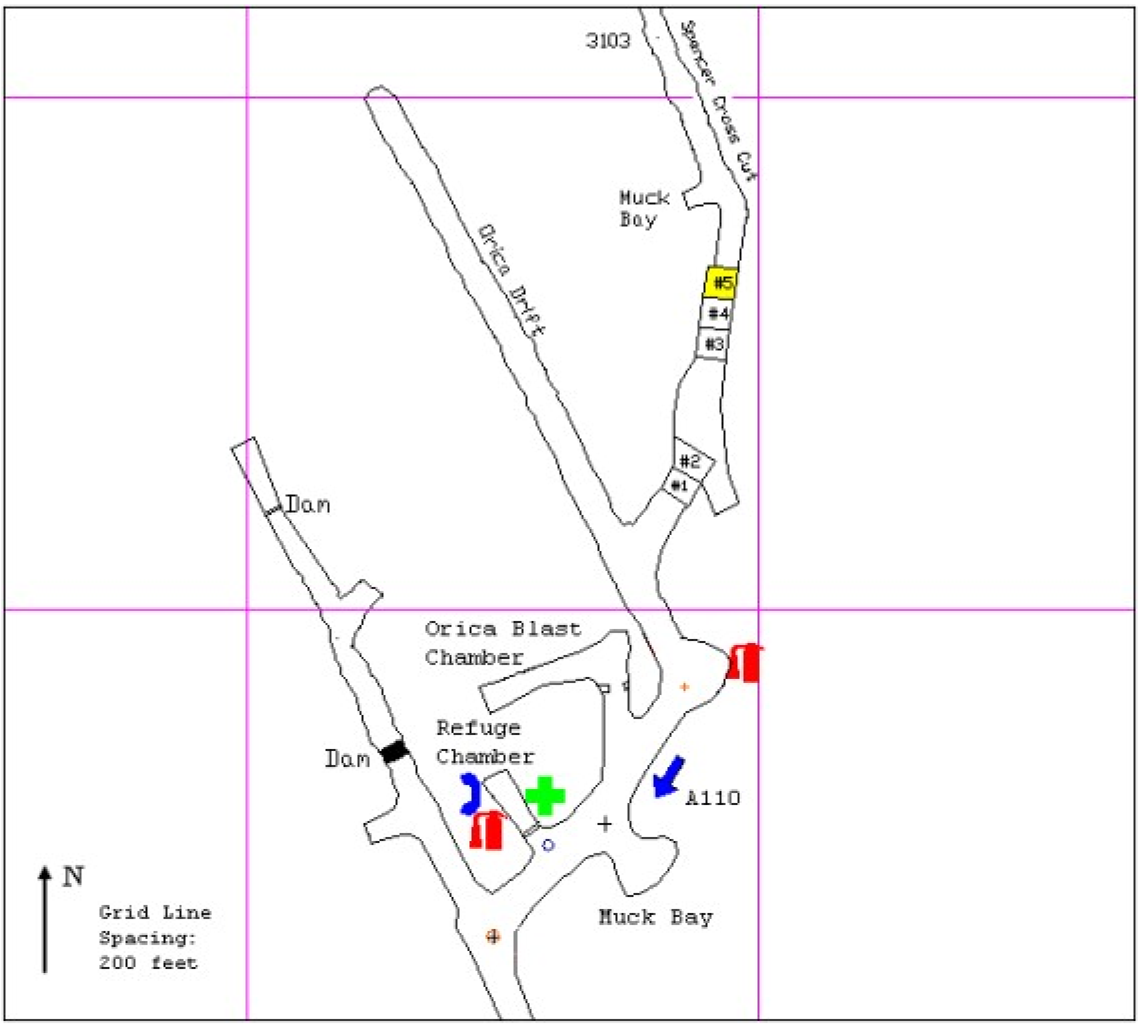

Fig. 10.24 Location of Experiment #5

10.5.1 <u>Rock Conditions</u>
The surface to be scaled was rough and irregular but contained no major geological hazards. The most notable feature of the area was the abundance of small, random discontinuities that could most likely be classified as blast damage. The fractured surfaces appeared to be rough and were not weathered to any

extent. There was one long, straight discontinuity that ran diagonally from northeast to southwest across the back and down the left rib. Though it was a notable feature, it had little effect on the rock mass other than serving as a plane of weakness. One other discontinuity worth noting was oriented at 40 degrees from horizontal and dipped almost directly south. It was characterized by thick pyrite filling and several millimeters gap in places. It was difficult to determine how far the discontinuity continued into the rock mass.

10.5.2 Results

The largest single rock scaled manually weighed 105 lbs. The largest single rock removed during the subsequent waterjet scaling weighed 43 lbs. The total quantity of material removed by each method is illustrated in Fig. 10.25.

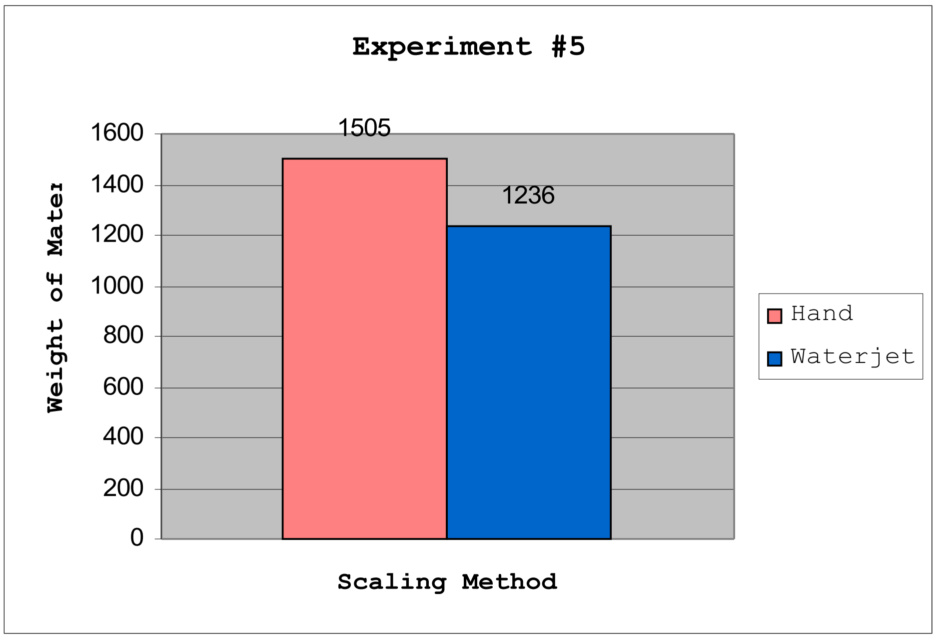

Fig. 10.25 Results of Experiment #5

The task of manual scaling was completed by a combination of 3 mine employees and 5 U.S. Army Rescue trainees and took place for roughly 75 minutes. The duration of the waterjet test, at 35 minutes, was also abnormally long because of U.S. Army participation in the control of the joysticks. The material that fell during the process of manual scaling was simultaneously collected and weighed while the experiment was in progress, and therefore, there is no photograph of the results. The results of the waterjet scaling can be seen in the before and after photographs shown in Figs. 10.26 and 10.27.

Fig. 10.26 Photograph taken before Experiment #5 waterjet test

Fig. 10.27 Photograph taken after Experiment #5 waterjet test

10.5.3 Notes

The amount of material that fell during the waterjet test was surprising because of the time and effort that went into the manual scaling. The back was considered thoroughly scaled after the rotation of eight different laborers, all of whom had different perspectives on the rock surface.

A screen analysis was not performed on the results of Experiment #5, nor any of the subsequent scaling experiments.

10.6 Experiment #6, Single Orifice, Continuous Nozzle

Experiment #6 was conducted on Tuesday, May 22, 2007 and was the first experiment in which smooth wall blasting techniques were utilized on the perimeter holes of the drift. The smooth wall blasting technique was incorporated as a means of improving long term condition of the drift and reducing the risk of injury by rock fall. The blast consisted of 24 holes in two rows along the back and left rib.

Experiment #6 took place in the Spencer Crosscut immediately north of Experiment #5, as shown in Fig. 10.28.

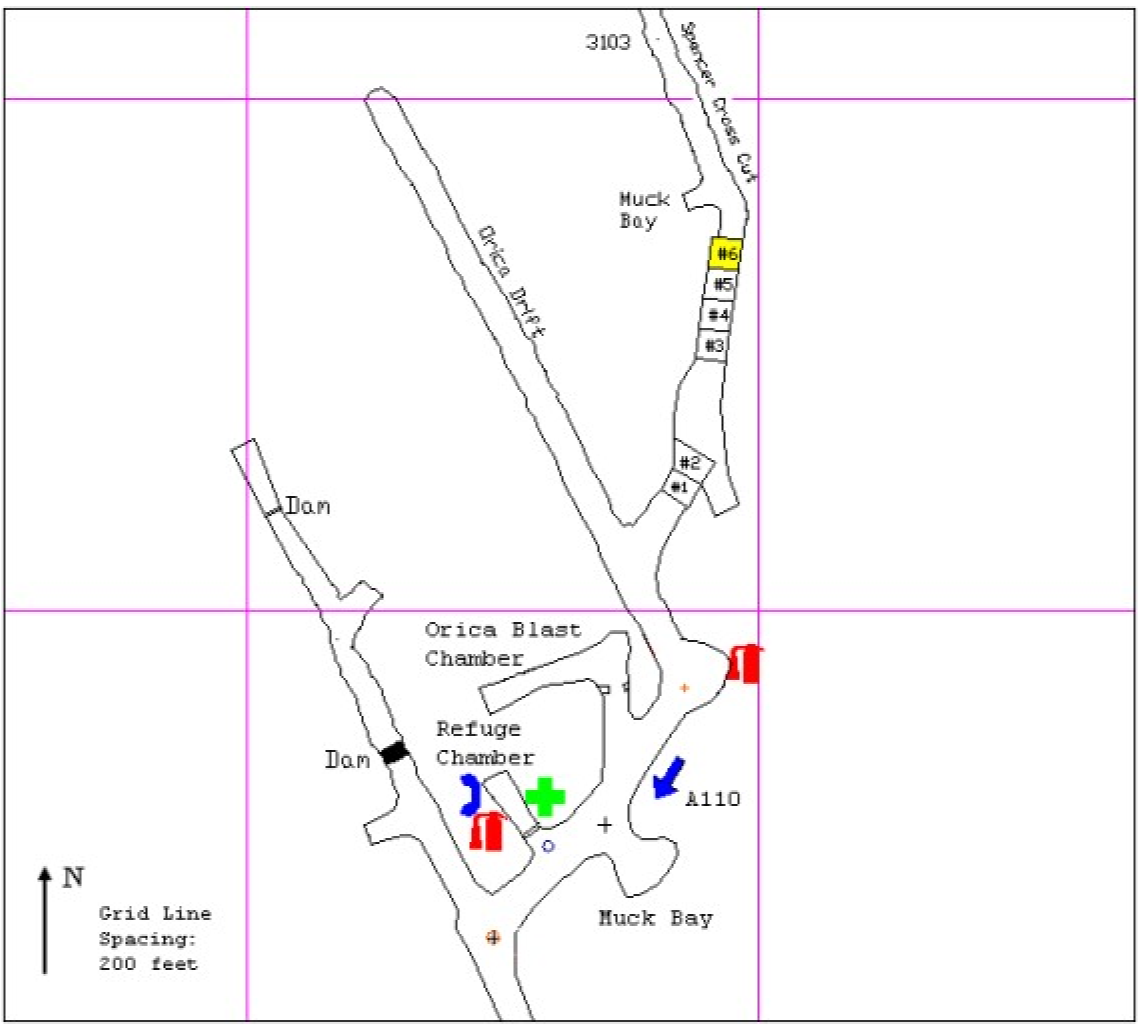

Fig. 10.28 Location of Experiment #6

10.6.1 Rock Conditions

The surfaces of the back and left rib formed an ideal arch as a result of the precision perimeter blasting. The success of the blast was also made evident by several half-cast drill holes, plainly visible upon first glance through the drift. Fig. 10.29 shows a photograph of the left rib immediately after blasting.

The area to be scaled contained no issues of major concern. The only features noted were two parallel discontinuities running diagonally across the north east corner of the back. There was no separation in the joints and they did not appear to be weathered to any extent. The one area that did not seem to benefit from the smooth wall blasting technique was on the opposite side of the outer most discontinuity, suggesting that the joints may have absorbed or deflected the shock wave. The north east corner of the back, consisting of biotite and pegmatite layering, was left slightly rough and irregular.

Fig. 10.29 Half-cast drill holes visible after blast

10.6.2 Results

Smooth wall blasting had a significant effect on the amount of scaling that needed to be done and the amount of material that was removed. The duration of the waterjet test was only 16 minutes and it was evident while the jet was in operation that not much material was falling. Manual scaling lasted for 15 minutes, and the total amount of material removed in all of Experiment #6 was less than 500 lbs. The largest single rock removed by each of the scaling methods was not recorded, as no single rock likely weighed more than 10 lbs. Figs. 10.30 and 10.31 show a graphic representation of the results and a photograph of the tarp taken after the waterjet test.

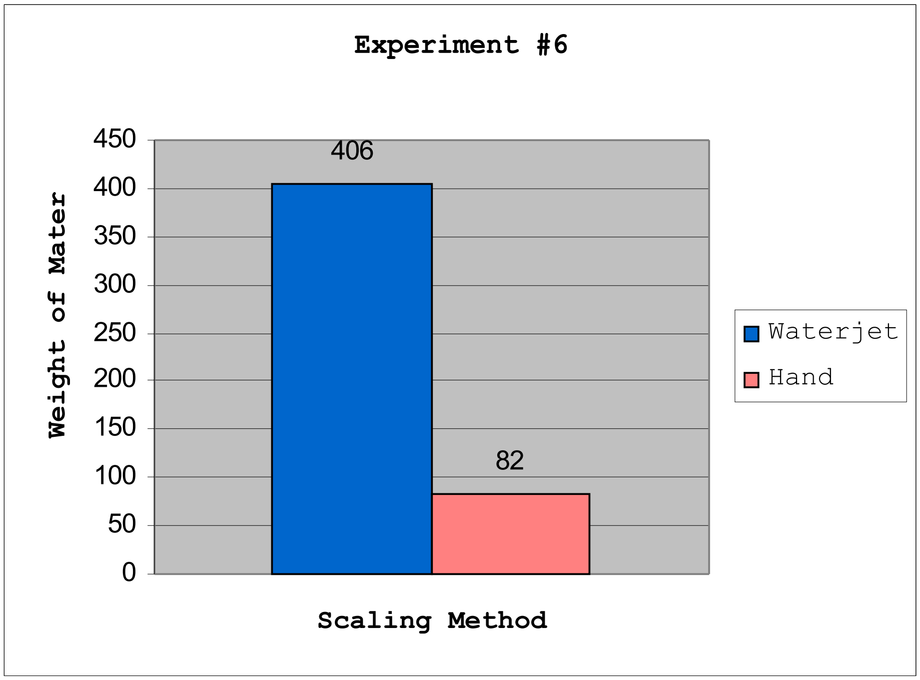

Fig. 10.30 Results of Experiment #6

Fig. 10.31 Material removed in Experiment #6 waterjet test

10.6.3 Notes

The photograph in Fig. 10.31 illustrates that the tarp contained very little rock after scaling with the waterjet. It's also evident in the picture that most of the fallen material came from the far side of the blast round, where the drill holes ended and the drift reduced back to an eight foot square profile. The transitional surface at the far end of the blast did not benefit from the smooth wall techniques and therefore required more scaling.

10.7 Experiment #7, Dual Orifice, Self Rotating Nozzle

Experiment #7 took place on Wednesday, June 6, 2007 in the Spencer Crosscut, just south of an intersection with a muck storage bay. The exact location of the experiment is shown in Fig. 10.32. Smooth wall blasting was utilized in the slash round, which consisted of 17 holes arranged in one to two rows along the back and left rib.

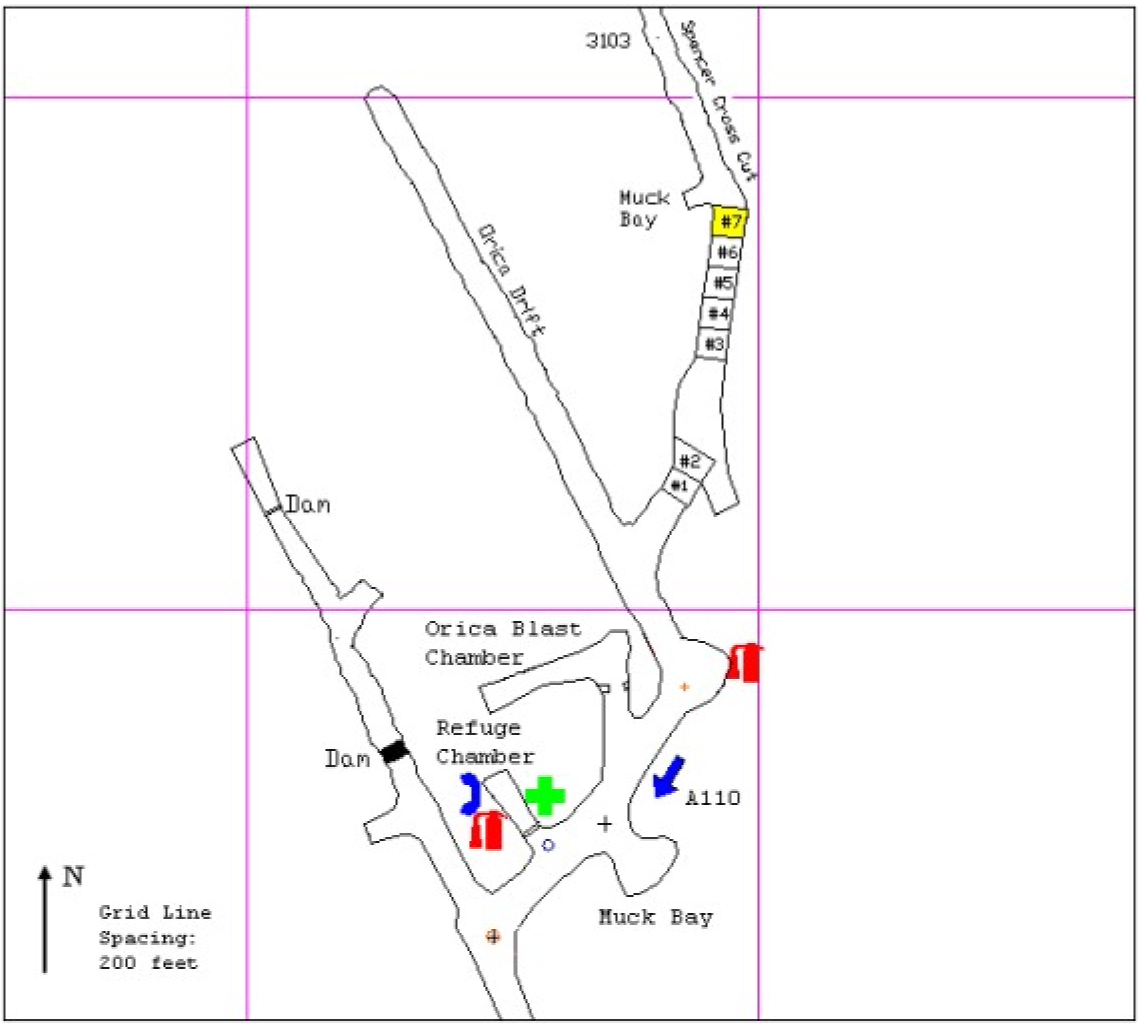

Fig. 10.32 Location of Experiment #7

10.7.1 Rock Conditions

An RMR analysis of the back, available in Appendix A, revealed that the rock in the area was fairly competent, with only a few notable discontinuities in the area to be scaled. Several instances of a near vertical (82, 225 dip/dip direction) set of joints were noted running diagonally through the area, though none of them seemed to have a significant effect on the stability of the rock or the results of the scaling experiment. It's worth noting that several days after the experiment, a wedge of rock approximately 70 lbs in weight fell from the right side of the back while employees were installing roof bolts. There were no significant features or discontinuities noted in the immediate surroundings.

Most of the back was characterized by half-cast drill holes typical of a successful smooth wall blast. The normal gneissic composition of biotite and pegmatite layering was interrupted by a two to three feet wide band made up almost entirely of light colored pegmatite running perpendicularly through the center of the drift. Though minor fractures seemed to exist, the pegmatite was very competent and broke ideally under the smooth wall blasting technique.

The exact physical location of Experiment #7 resulted in several abnormalities in the rock at the north end of the round. The rock mass immediately to the north was characterized as a weak zone with extensive fracturing and weathering, and some mineralization. The core of the weak zone ran coincidentally with the orientation of the muck storage bay and was equal in width at about ten feet. The effects of fracturing and weathering were apparent for an additional two or three feet on either side of the weak core and therefore the transition zone from new drift height in Experiment #7 to old drift height suffered from poor fragmentation. It was by pure coincidence that the dual orifice, self rotating nozzle was being tested once again with expectations of large rock fall.

The nose at the south west corner of the intersection was highly damaged by the blast and manual scaling had to be performed on the rib before it was considered safe to enter the area for setup of the waterjet test. The area that bordered Experiment #7 to the north was littered with remnants of ground support that was damaged but not removed by the blast. See Figs. 10.33 and 10.34 for photographs of the area taken before the waterjet test.

Fig. 10.33 Photograph taken before Experiment #7

Fig. 10.34 Fractured material in north east corner

10.7.2 Results

The waterjet scaling test commenced for 19 minutes, and surprisingly none of the large blocks of fractured rock noted beforehand fell to the tarp. The block pictured in Fig. 10.34 was targeted for several minutes, and though high pressure water aimed at the back side of the rock was seen shooting out the front side of the large fracture, the rock proved to be more stable than first estimated. A photograph of the material removed during waterjet scaling is shown in Fig. 10.35.

Fig. 10.35 Material removed in Experiment #7 waterjet test

As evident in the photograph, the smooth wall blasting technique once again resulted in a relatively low overall quantity of scaled material. The largest single rock scaled by the waterjet weighed approximately 90 lbs, and the largest single rock removed manually weighed approximately 120 lbs. The graphical results of the experiment are shown in Fig. 10.36.

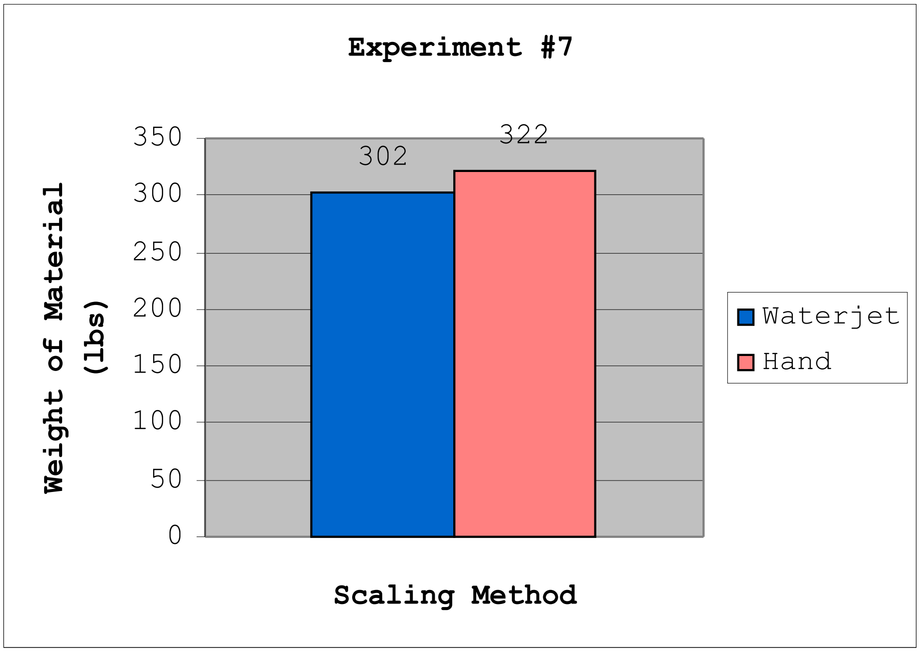

Fig. 10.36 Results of Experiment #7

Only slightly more than 600 lbs of rock was removed in Experiment #7, but nearly half of it was accounted for by the hazardous blocks at the north end that had to be removed manually. There was very little material left to scale otherwise.

10.7.3 Notes

Considering the results of Experiment #2, the dual orifice, self rotating jet was put under ideal conditions to prove or disprove its effectiveness against large blocks of rock. Given the manual scaling that was required afterwards, it appears that it failed. However, when put into a different perspective, the ratio of material that fell from all other areas of the back during the waterjet and manual scaling processes was probably eight to one respectively, making it a highly effective scaling tool under normal, smooth wall blasted conditions.

10.8 Experiment #8, Pulsed Single Orifice Nozzle

Experiment #8 took place on Thursday, June 21, 2007 at the intersection of the Spencer Crosscut and the muck storage bay. The exact location is shown in Fig. 10.37. Smooth wall blasting techniques were utilized in the back only, as the left rib was open to the muck bay.

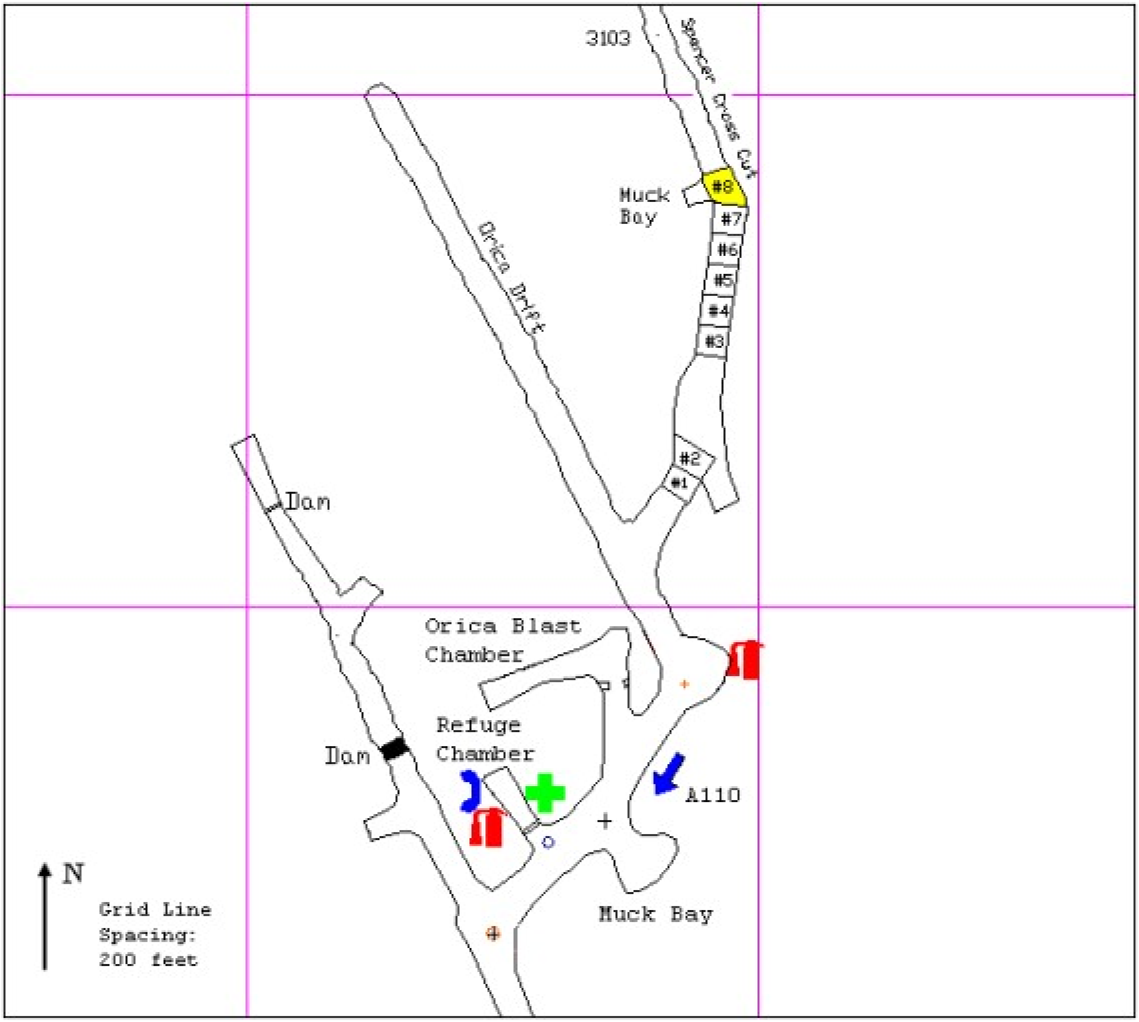

Fig. 10.37 Location of Experiment #8

10.8.1 <u>Rock Conditions</u>

The rock mass present in Experiment #8 was highly fractured and highly weathered with oxidized staining in nearly every discontinuity and evidence of mineralization in areas. Fig. 10.38 shows a photograph of the area taken before the experiment.

Fig. 10.38 Fractured and weathered weak zone in Experiment #8

There was very little similarity to the rock seen in previous experiments. After the blast, there were extremely large and unstable slabs on the north west rib of the intersection. Some were bound by clay-filled discontinuities and others by open fractures. Fig. 10.39 shows a photograph of one of the slabs taken after the experiment was complete and rock bolts were installed.

Fig. 10.39 Large slab bound by open discontinuities

The magnitude of unsafe ground and high risk of personal injury required the use of an excavator bucket to scour the ribs and back of the muck storage bay before work could continue in the intersection. Given the hazards present, the scaling experiment was not allowed to commence immediately after the blast. Air slacking and moderate rock fall was noted by mine employees between night and morning.

The profuse orange staining on nearly every visible surface made it difficult to determine exactly what rock types were present in the zone. See Fig. 10.40 for a closer view of the rock mass.

Fig. 10.40 Closer view of rock mass in Experiment #8

The rock seemed to consist of nearly everything known to the area, including granite, feldspar, biotite, pegmatite, and weathered schist, with bands of mineralization including quartzite and pyrite. It would be extremely difficult to map or describe individual geologic features in the area, but extensive fracturing was noted in the north east corner of the back and clay filled discontinuities were common all along the north edge of the zone.

10.8.2 Results

Waterjet scaling lasted for 21 minutes, and hand scaling followed for approximately 40 minutes. The largest single rock removed by the waterjet weighed approximately 40 lbs, and the largest single rock removed manually also weighed approximately 40 lbs. The total amount of material removed by the pulsed waterjet was less than that of Experiments 1 - 4, suggesting that the smooth wall blasting still had some effect on the rock mass, but a nearly equivalent amount of material was removed manually as well. Given the abnormally large amount of material removed by hand, the total amount of material removed in Experiment #8 was the third highest of all the experiments performed thus far, at just over 1,600 lbs. The results of Experiment #8 are shown in Fig. 10.41.

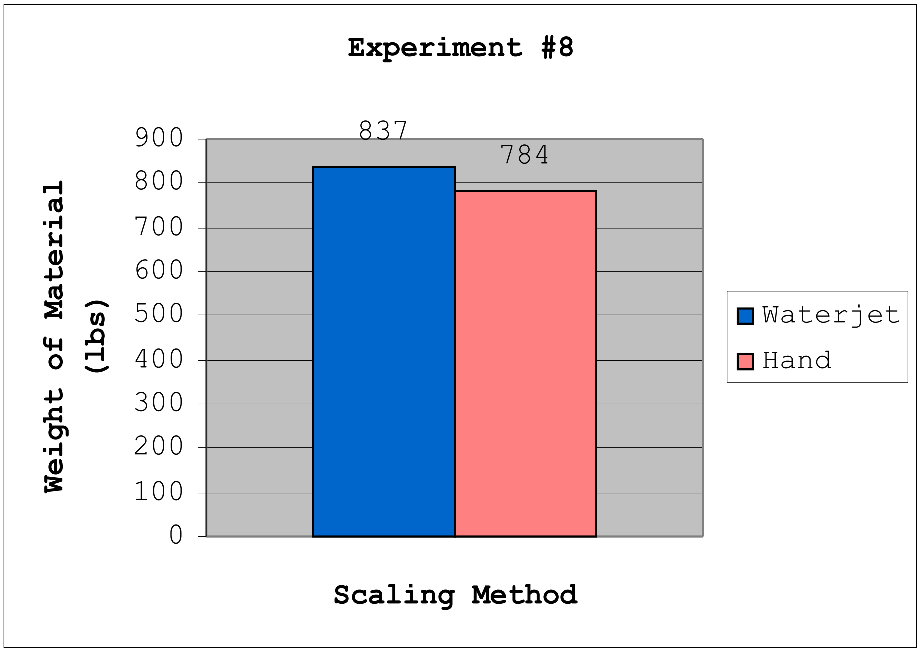

Fig. 10.41 Results of Experiment #8

10.8.3 <u>Notes</u>
As noted by mine employees before the experiment took place, the rock within the weak zone reacted relatively quickly with fresh air and moisture, transitioning from a matrix of tightly oriented blocks to a zone of loose material in a matter of hours. It is believed that the waterjet may have accelerated the penetration of moisture through the network of cracks and supplied the discontinuity surfaces with the lubrication needed to pry the blocks manually. There was a time period of several hours between the first application of high pressure water and the end of the manual scaling procedure, offering plenty of time for such a reaction to take place.

10.9 Experiment #9, Custom Mechanical Oscillator

Experiment #9 took place on Thursday, June 28, 2007 in the Spencer Crosscut, just north of the intersection with the muck bay. The exact location is shown in Fig. 10.42. Smooth wall blasting was utilized for the slash round, which consisted of 24 holes arranged in two rows along the back and two columns along the left rib.

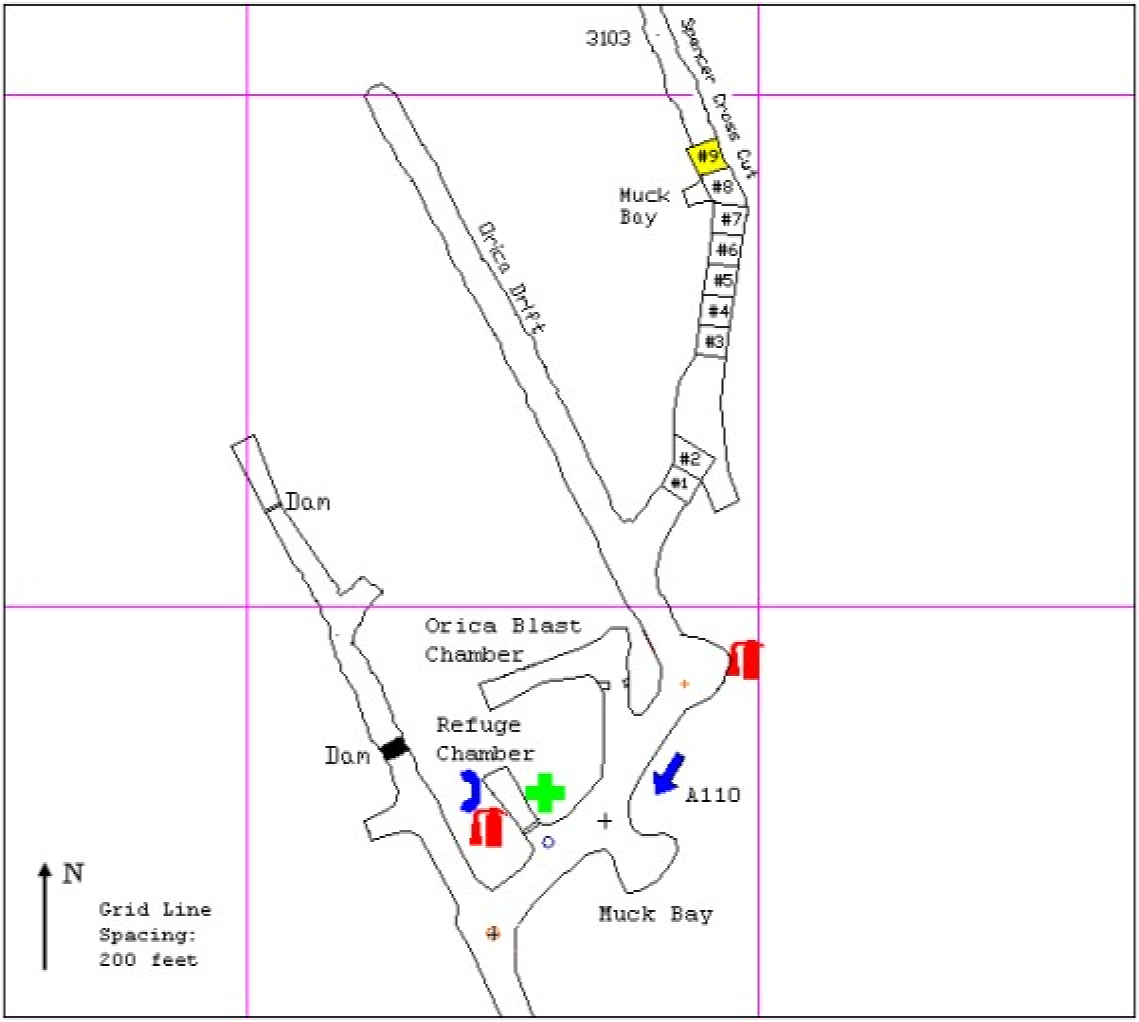

Fig. 10.42 Location of Experiment #9

10.9.1 <u>Rock Conditions</u>

The rock in Experiment #9 was fairly competent at the north end, consisting of typical biotite and pegmatite layering. The middle of the scaling area contained a few discontinuities with a thin clay filling, and the south end, bordering the massive weak zone, was characterized by extensive fracturing and weathered fill material. Fig. 10.43 shows a photograph of the back taken after waterjet scaling.

Fig. 10.43 Variation of rock type in Experiment #8

For scale, the yellow spray-painted lines mark the southern end of the round, and the white and black surface at lower left is the transition to the old drift height. The length between the two features is approximately ten feet. Though difficult to distinguish because of the bright lighting, the area between the yellow lines and the darkly colored rock to the left is actually a cavity 0.5 to 1.5 feet deep. The photograph in Fig. 10.44 illustrates the presence of the void.

Fig. 10.44 Void created by waterjet during Experiment #8

10.9.2 Results

Waterjet scaling took place for 38 minutes with the custom built mechanical oscillator. The duration of the waterjet test was prolonged by the extra scaling required at the south end of the drift. Hand scaling followed for a period of 48 minutes and also required special attention at the south end. The largest single rock removed by the waterjet weighed approximately 70 lbs, while the largest rock removed manually weighed approximately 130 lbs.

The amount of material removed during Experiment #9 was surprisingly high. As indicated by the previous photographs, the first two feet of the drift coincided with the most weathered and fractured area of the troublesome weak zone. A significant amount of material was removed from the southern end of the drift, part of which had already been scaled in Experiment #8. The waterjet removed more than 2,500 lbs of rock, and the manual scaling process removed more than 1,100 lbs afterward. The results are shown in Fig. 10.45.

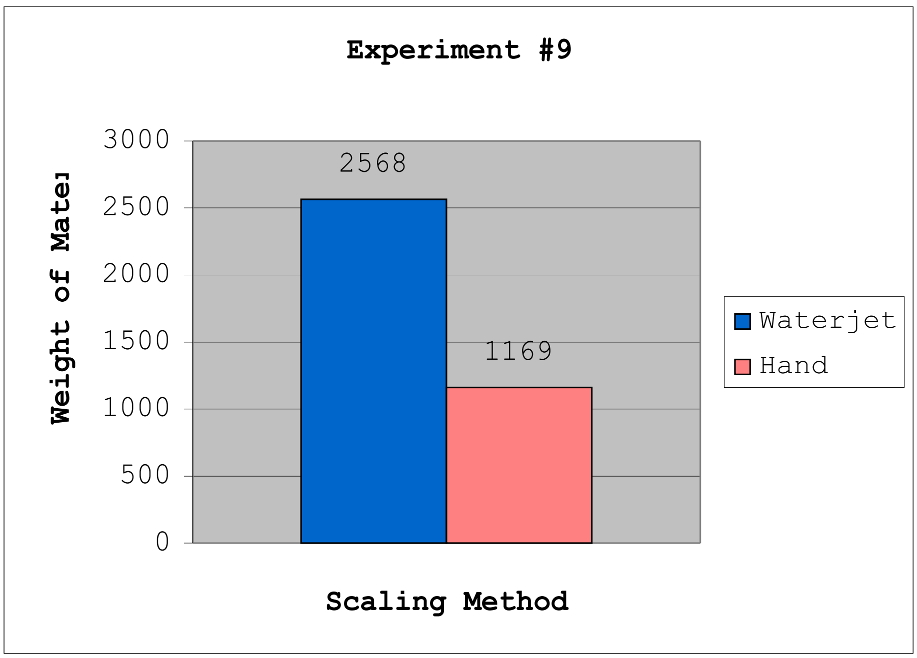

Fig. 10.45 Results of Experiment #9

Based on the experience of the waterjet operator, the custom built oscillator was deemed to be a huge advantage in Experiment #9. The effectiveness of the system was verified several times by keeping the boom still and watching new material fall to the tarp after several rotations of the nozzle. It was felt that a more thorough coverage of the back was achieved than with any other nozzle, and the durability of the design was proven by repeated collisions with outlying rock surfaces. At the end of the waterjet test, the oscillation unit was turned sideways and had lost much of its paint, but it continued to perform until the high pressure pump was turned off.

10.9.3 Notes

The high quantity of material removed during Experiment #9 was puzzling considering the much lower quantities removed in Experiment #8, where all scaling took place in the weak zone. Several unique circumstances most likely accounted for the substantial difference in quantities of material removed, including the 7 days of air slacking that were allowed in the weak zone between experiments and the shock wave that rattled the material during the Experiment #9 blast. Also worth considering is the oscillation provided to the nozzle in Experiment #9, though it's unlikely that the motion of the waterjet alone could account for such a large difference in results.

Similar to Experiment #7, the results of this experiment were dominated by the activity in the weak zone at one end of the drift. Very little scaling took place in the competent, darker colored rock at the north end of the drift. The proportion of material that came from the weak zone is illustrated by the photograph in Fig. 10.46, where the north end of the tarp is seemingly bare.

Fig. 10.46 Manual scaling during Experiment #9

10.10 Experiment #10, Single Orifice, Continuous Nozzle

Experiment #10 was a reverse order experiment conducted on Friday, August 10, 2007 in the Spencer Crosscut. It took place just north of Experiment #9, as shown in Fig. 10.47. Smooth wall blasting techniques were utilized in the slash round that consisted of 15 holes, arranged in two rows along the back and one column along the left rib.

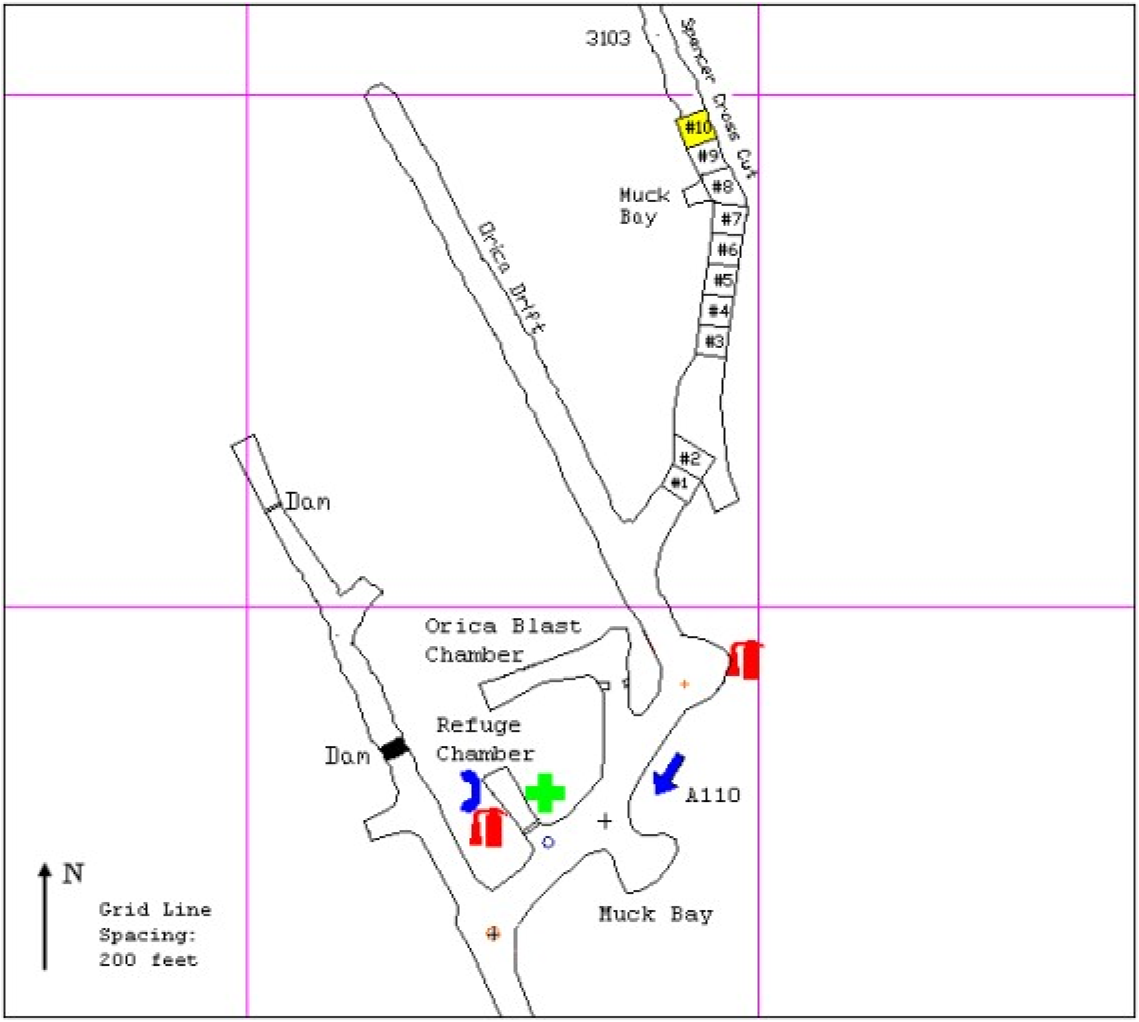

Fig. 10.47 Location of Experiment #10

10.10.1 <u>Rock Conditions</u>

The rock in Experiment #10 was fairly competent, consisting of typically layered biotite and pegmatite. The discontinuities that ran through the back and ribs contained a very thin white filling and did not appear to serve as weaknesses during the blast. There was no separation in the joints and the slightly rough surfaces followed irregular paths. Fig. 10.48 shows a photograph of the right rib after cleaning with the waterjet.

Fig. 10.48 Right rib of Experiment #10 drift

The drill holes visible in Fig. 10.48 are spaced approximately 2 feet from each other, and as illustrated by the photograph, most of the rock broke extremely well during the blast. The first two to three feet of the back and left rib, however, suffered from extremely poor fragmentation. There were approximately two tons of slabs that had to be barred down manually before setup and preparation of the experiment could begin. The RMR analysis, available in Appendix A, did not reveal any geologic features that would likely influence the blast in such a way. Most of the material that had to be removed was already fractured along the perimeter of the intended new drift profile, suggesting that a last-second malfunction of the hole plugs allowed the force of the explosion to escape from the end of the drill hole rather than push the fractured rock outward. Such a malfunction is usually referred to as a collar boot.

10.10.2 Results

Manual scaling was conducted for a period of 45 minutes and resulted in 297 lbs of material. The waterjet test lasted for 19 minutes and only 154 lbs of rock were removed. The results are shown in Fig. 10.49.

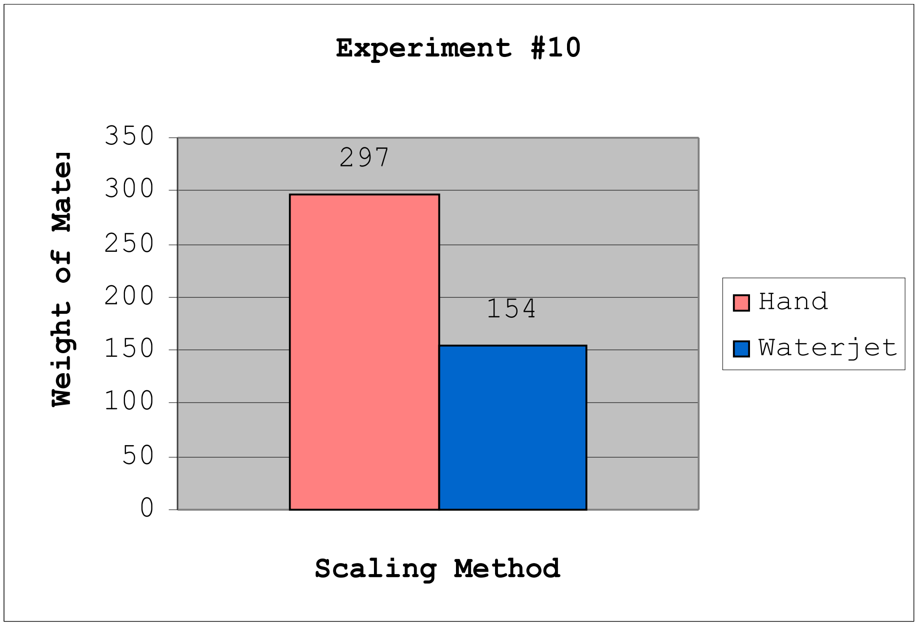

Fig. 10.49 Results of Experiment #9

The total amount of material weighed in Experiment #10, at less than 450 lbs, was the lowest of any experiment. The scaling that had to be completed before the start of the experiment, however, makes it difficult to determine whether the quantity of rock weighed accurately reflects the quality of the blast. Regardless, the purpose of the experiment was to prove the efficiency of the waterjet over a thorough manual scaling job, and this was achieved.

11. Summary of Experimental Results

11.1 Manual (Hand) Scaling

The first three experiments were performed using manual scaling only. This was done since the high pressure pump was being rebuilt and was not available at the start of the project period and because the experimental area required that several irregular slash rounds be conducted in order to prepare the area for the subsequent waterjet scaling experiments. The material scaled in these first three experiments was not collected and weighed. The hand scaling was observed with the purpose of obtaining insight into the risks associated with hand scaling. In each case the slash round blast consisted of a series of 3 m (10 ft) long holes, with smooth-wall blasting used on the perimeter holes. A hand held scaling bar was used to remove loose rocks, as is the standard practice in many underground mines. Each of the hand scaling tests took about 45 minutes to complete. The scaling tests were filmed using a digital camera, and detailed notes were taken. Results of these hand scaling tests were used in the Employee Safety and Occupational Health analysis given in Chapter 12 of this report.

The preliminary hand scaling tests captured a number of the inherent safety hazards and health concerns common to conventional hand scaling:

- The hand scaling was performed by an experienced miner in excellent physical condition in his early twenties. The extreme physical exertion required by hand scaling resulted in substantial fatigue and exhaustion after just a few minutes.

- At one point, a fist sized rock slid down the scaling bar and struck the scaler in the forearm. Similar incidents with falling rock are known to be a significant cause of scaling accidents.

- The scaler was working off broken and blasted rock. Several times he had problems with the unstable footing.

All of the sources responsible for worker injury described above could be eliminated by high pressure waterjet scaling. Fig. 11.1 shows a comparison of a mine worker performing hand scaling and operating the waterjet scaling rig. With hand scaling, the miner must work in the freshly blasted area and is thus directly exposed to the hazards of loose and falling rock as well as tripping hazards associated with scaling from a muck pile. Significant physical exertion is also required. With waterjet scaling the miner can easily operate the scaling rig from a safe distance using the tethered controls, and thus is never directly exposed to the dangers of loose and falling rock from the blast area. Physical exertion is minimal.

(a) *(b)*

Fig. 11.1. A mine worker performing hand scaling (a) and operating the waterjet scaling rig (b).

11.2 Cumulative Nozzle Analysis

In all cases, the various waterjet nozzles performed quite well. Proving the relative effectiveness of the different nozzle configurations, blasting methods, and scaling techniques was difficult due to variations in geology and the limited number of experiments. Some rounds were conducted in areas of relatively competent rock, while the results of other tests were affected by the presence of fractures and clay fillings. Due to geological variations, a sample size larger than ten rounds would be necessary to make any definitive conclusions regarding nozzle performance. In addition, no effort was made to optimize the system parameters (e.g., flow rate, pressure, traverse velocity, rotation speed, standoff distance). Unfortunately, time and cost considerations prohibited additional experiments being performed. Nevertheless, a comparison of the weight of the material scaled and observations during scaling were quite useful in making some general conclusions regarding the nozzles tested.

The nozzle tested in waterjet experiments one and six was the single orifice continuous jet, (Fig 11.2). The stream of water exiting the nozzle was fairly coherent, which in turn means the standoff distance to the rock can vary somewhat without noticeable loss in scaling productivity. The advantages of this nozzle were its simplicity and low cost. Additionally, during scaling, the operator can easily point the stream of water at a crack or an area of weakness. A disadvantage is the potential lack of surface coverage since the operator must use the hydraulic boom controls to provide motion to the nozzle. Overall, the nozzle preformed well and the simple design and low cost make it a strong candidate.

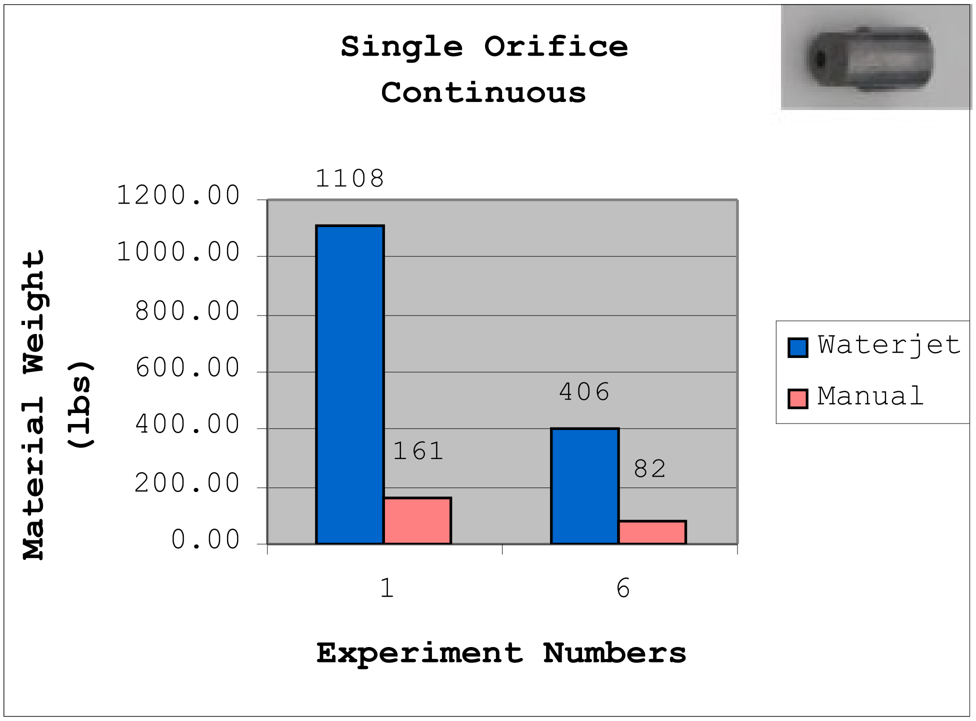

Fig. 11.2. Results of Waterjet Experiment Numbers 1 and 6, Single Orifice, Continuous Nozzle.

The nozzle tested in waterjet experiments two and seven was the duel orifice self-rotating jet (Fig 11.3). The major advantage to the self-rotating nozzle is the increased surface coverage due to the rotational action as compared to a single orifice nozzle. Due to the geometry of the twin jets, the surface area covered can be somewhat controlled by varying the standoff distance. Another advantage is the low cost of the replaceable inserts. The primary disadvantage of a dual orifice nozzle is the 50% decrease in flow rate through each of the orifices as compared to a single orifice design. Although there are essentially two nozzles in operation, the amount of energy applied to the target surface by either orifice at any given time is less than half of the single orifice nozzle operating at the same overall pressure and flow rate. This, in turn, may reduce the nozzles effectiveness due to insufficient threshold pressure during impingement (not enough energy to scale materials), higher frictional losses within the nozzle, and reductions in standoff distance. Another disadvantage was the inability to aim the waterjet in a specific direction when attempting to target a feature of special interest. While the path of the two rotating orifices can be directed in a general direction, precise targeting of obvious weaknesses and discontinuities in the rock mass proved difficult.

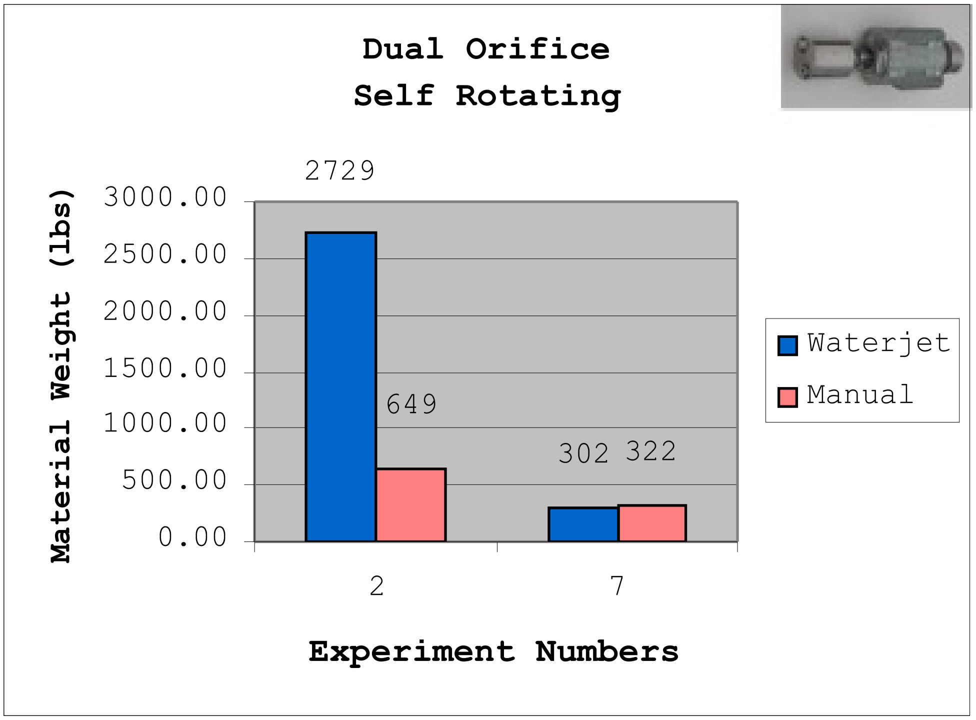

Fig. 11.3. Results of Waterjet Experiments 2 and 7 with Dual Orifice, Self Rotating Nozzle.

The nozzle tested in waterjet experiments three and eight was the single orifice acoustically pulsed jet, (Fig. 11.4). The nozzle design has the same advantages as those associated with a single orifice nozzle. The pulsed stream, however, adds another dimension to the destructive force of the jet. In theory, the dynamic loading of the individual slugs could result in the loosening and removal of more material during scaling due to impingement dynamics and material fatigue. However, the two tests performed were not sufficient to verify this. A distinct disadvantage was the relatively large cloud of mist that resulted from aerodynamic drag on the pulsed stream, making it very difficult for the operator to see the position of the nozzle relative to the rock. The pulsed stream requires a minimal distance to fully develop once it leaves the nozzle, and without proper visibility, it can be quite difficult for an operator to assure optimal standoff distance during use. Based on the two tests conducted, it became obviously that to obtain the performance advantages associated with this nozzle it would required some extensive testing to achieve the optimal flow conditions. Given the nozzle's sensitivity to system flow parameters and standoff distance, problems with visibility, and its relatively high cost, this type of pulsed jet would require substantial research and development prior to successful utilization in most scaling applications.

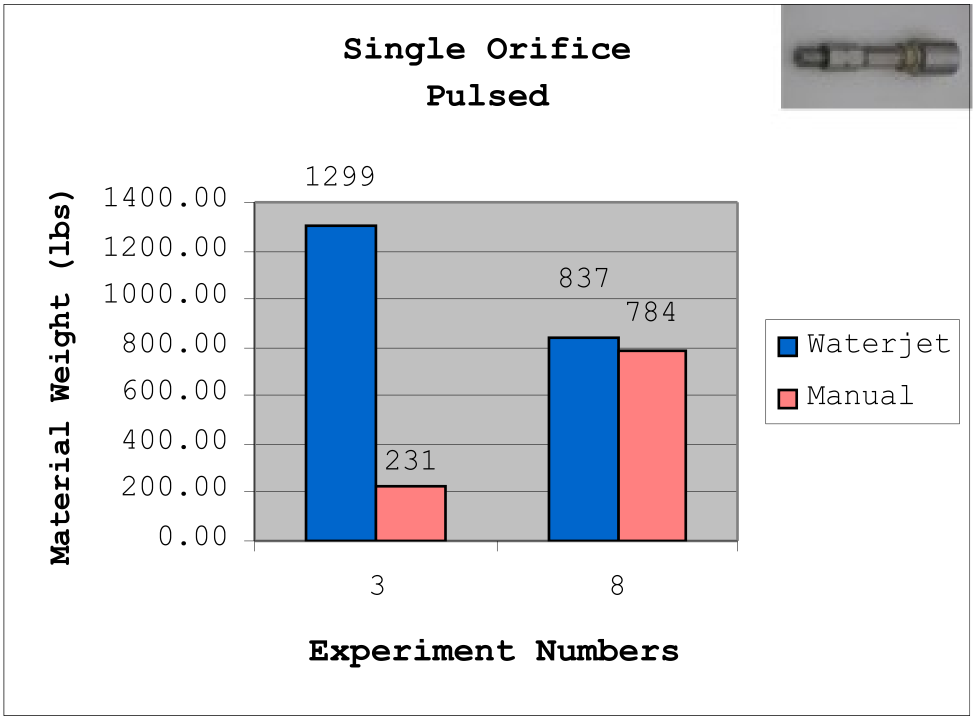

Fig. 11.4. Results of Waterjet Experiments 3 and 8 with Single Orifice, Pulsed Nozzle.

The nozzle tested in waterjet experiment four was the compressed air powered mechanically oscillated single orifice jet, (Fig. 11.5). This nozzle was only tested once. The stream of water exiting the nozzle traveled nearly parallel to the axis of rotation, due to the angle at which the short pipe holding the nozzle had been designed. This feature results in a relatively cylindrical jet profile, which resulted in the surface area covered by the jet remaining constant regardless of standoff distance. The major advantage is that the relative power of a single orifice nozzle is maintained, while the surface coverage is greatly improved due to the rotational action similar to a dual orifice self rotating nozzle that is achieved. However, this configuration proved problematic for the experimental setup being used. The main disadvantage was the extra weight due to the compressed air motor that had to be mounted at the end of the boom of the waterjet rig. The extra weight seemed to be more than the boom could handle and there was constant concern that the boom would break. The additional weight would not necessarily be a problem with a new robust hydraulic manipulating boom.

The nozzle tested in waterjet experiment nine was the hydraulically powered, mechanically oscillated single orifice jet, (Fig. 11.5). This nozzle was also used for the waterjet scaling following the hand scaling in experiment ten. The design of this nozzle configuration stemmed from the challenges that arose while testing the pneumatic oscillator. This unit was custom made with the design based on similar devices used to provide nozzle rotation in mechanical shotcrete rigs. As with the compressed air powered mechanically oscillated system, the major advantage of this design is that the relative power of a single orifice nozzle is maintained, while the surface coverage was greatly improved due to the rotational action achieved. The diameter of the rotational cone (area of coverage) at the target surface could be varied by mechanical adjustments, and by increasing or decreasing the standoff distance. For this test, the single orifice continuous jet used in experiments one and six was attached. The combination performed very well as was judged by the experimental team to be the preferred design of the systems tested. The rotational action was smooth and capable of good surface coverage.

Using the rotational unit with the single orifice continuous jet meant the power and performance of the single jet was obtained. Another advantage of the unit was the ability to easily turn off the rotation, thus allowing the operator to point the jet at cracks or problem areas. While the initial cost of the system was high, its robust design should provide many hours of use. The nozzle replacement cost is also the lowest of all systems tested. For these reasons this nozzle was used for waterjet experiments 11 through 16, and will also be implemented as the standard scaling technique for the CSM Edgar Experimental Mine.

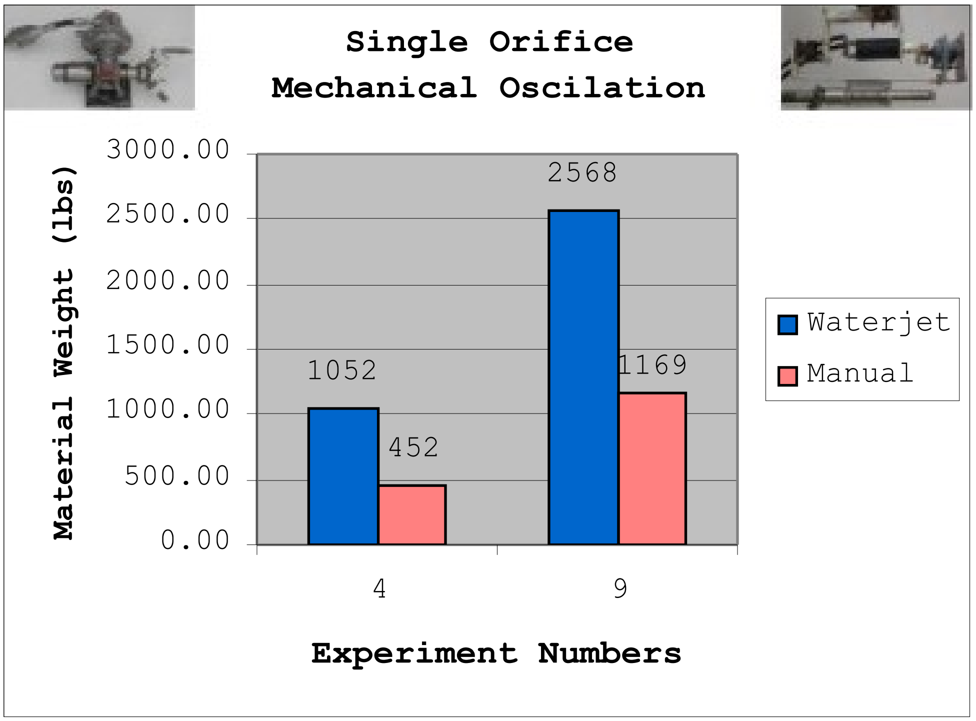

Fig. 11.5. Results of Waterjet Experiments 4 and 9 with Single Orifice, Mechanically Oscillated Nozzles.

The amount of material removed in the reverse order waterjet experiments five and ten is given in Fig. 11.6. For these experiments, the round was first scaled by hand. The hand scaling was supervised by a trained miner with approximately 30 years underground mining experience. When the supervisor and miner were sure that there was no material left to be scaled, the area was again scaled by the waterjet. It is significant that the waterjet scaling removed almost as much as the hand scaling even though the area was deemed to be thoroughly scaled. The fact that the waterjet is able to remove a significant amount of additional material not visible to the miner scaling by hand is a very positive result pointing to the increased safety that can result by using waterjet scaling.

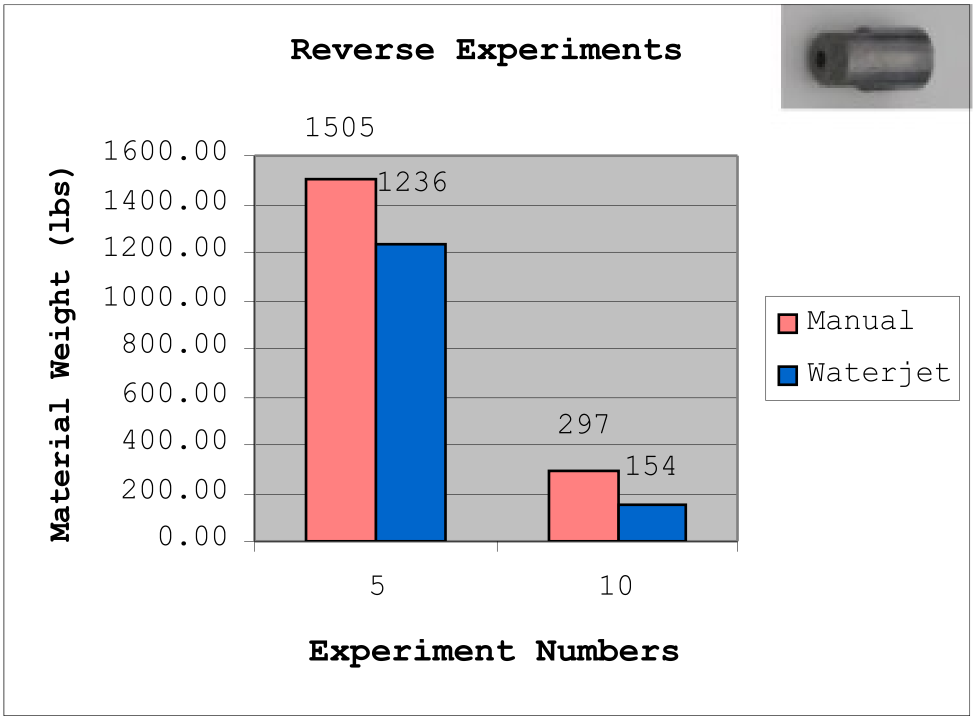

Fig. 11.5. Results of Reverse Order Waterjet Experiments 5 and 10.

11.3 Cumulative Waterjet Scaling Results

Fig. 11.2 shows a summary of the weight of material collected during each test and Fig. 11.3 shows the percentages of material scaled by each method and test. The percentages were calculated using the weight of material removed by each scaling method, divided by the total weight per experiment. With all nozzle designs tested, scaling was accomplished by systematically sweeping the nozzle across the area to be scaled using the joystick controlled hydraulic manipulator arm on the scaling rig while trying to maintain a standoff distance of about 0.3 m (1 ft). Scaling times varied between 15 to 48 minutes. The primary objective with each part of the scaling tests was to scale until the area was deemed thoroughly scaled and safe, and as such, scaling times were allowed to vary.

With the reverse order tests performed in experiments five and ten, the area was first thoroughly scaled by hand and deemed safe by experienced mine personnel. The fact that subsequent waterjet scaling brought down nearly as much material as the previous hand scaling indicates that a waterjet is very effective in removing material that can easily go undetected when scaling by hand. Significant improvements in worker safety with waterjet scaling would likely be realized.

Geologic conditions encountered in experiments two and nine were unfavorable which resulted in large amounts of material being scaled. Results are more pronounced if these two experiments are not included in the analysis.

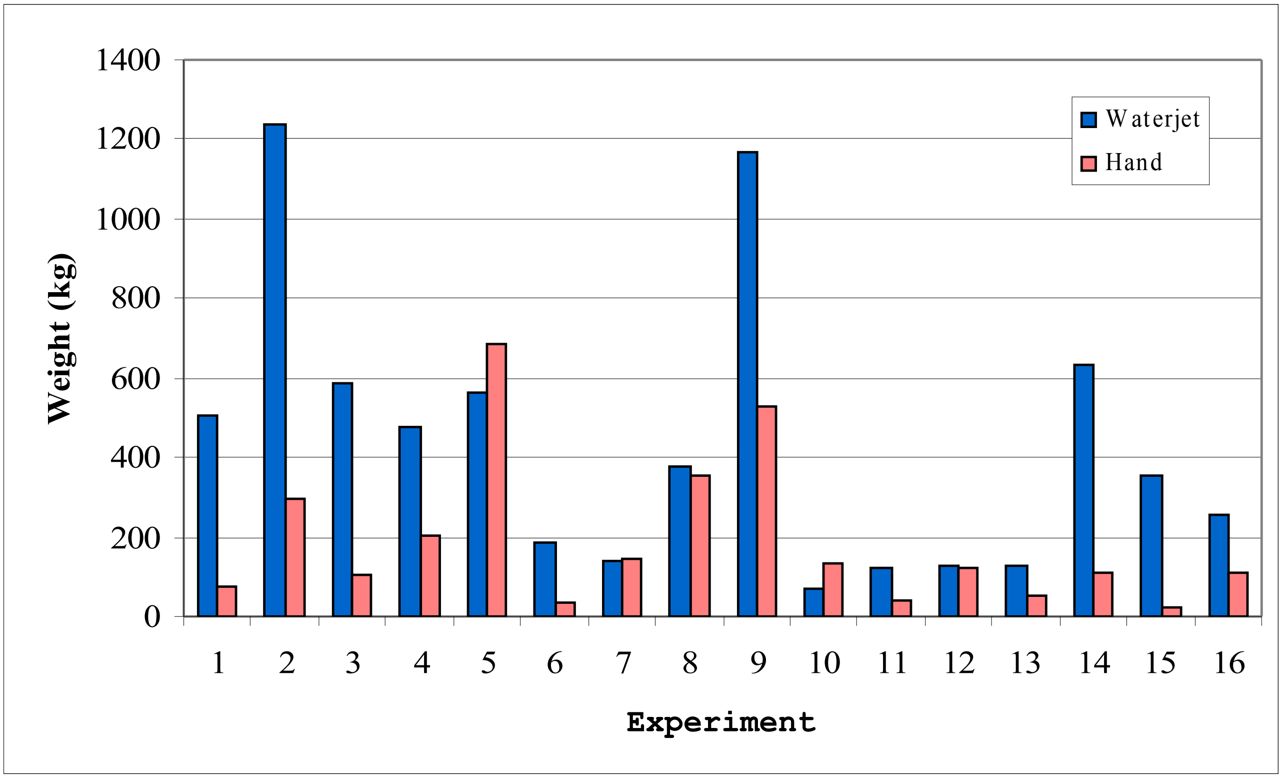

Fig. 11.2. Weight of material scaled by waterjet and by hand for the sixteen waterjet experiments.

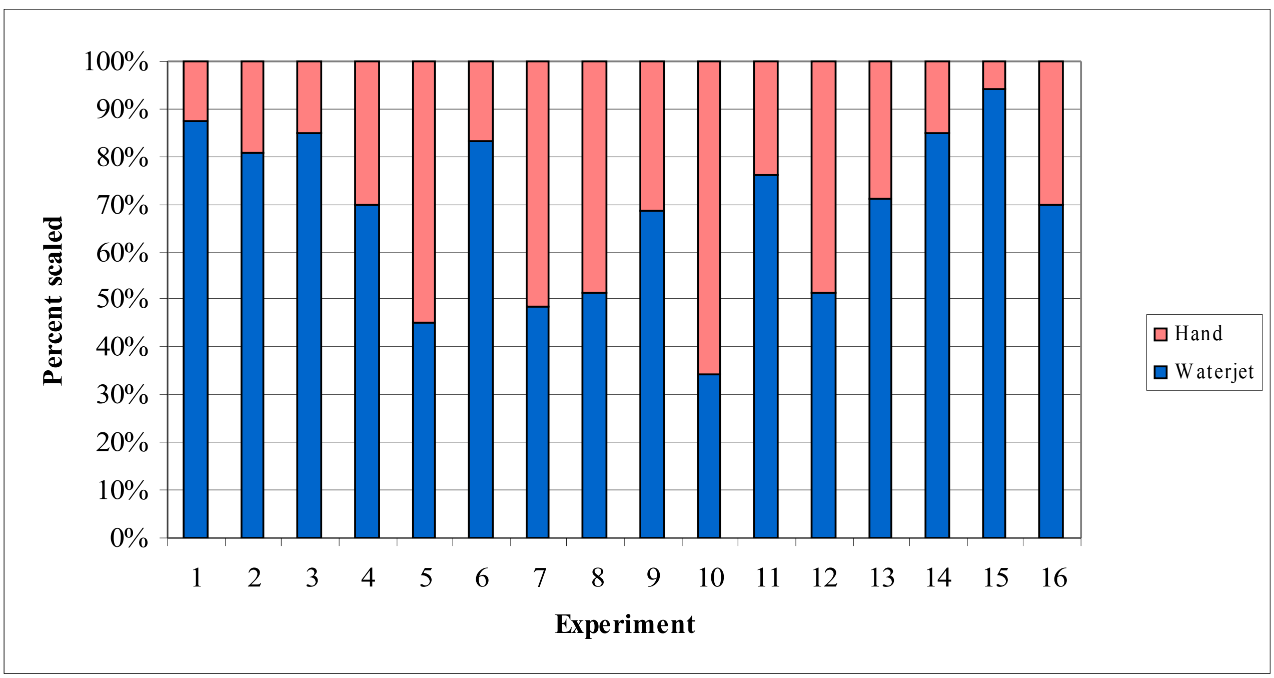

Fig. 11.3. Percentage of material scaled by waterjet and by hand for the sixteen waterjet experiments.

The results of experiment two were made unique and memorable by the sudden collapse of approximately 3600 kg (8000 lb) of intact rock during the waterjet scaling portion of the experiment. The slab came down in one large piece and broke in to several smaller pieces when it hit the ground (Fig. 11.4). The large slab appeared to have been "keyed" in and came down shortly after a smaller slab at its left corner was removed by the waterjet. In terms of safety, the incident validated the research motivation behind developing a remotely controlled scaling system. Scaling such large slabs with a hand-held scaling bar inherently exposes the miner to considerable risk of injury. The weight of this large slab greatly skewed the data, and as such, was removed from the analysis (Fig. 11.2 and Fig. 11.3).

Fig. 11.4. The approximately four-ton slab scaled by the waterjet during experiment two.

In a few cases, the material that was removed by subsequent manual scaling was quite loose and it appeared that the waterjet might have simply missed this material. In general, the hand scaled material was quite well wedged in and required considerable amount of work to remove. In operations where shotcrete is to be applied, such material could probably be safely left in place. It is, however, troubling that the various waterjets did not remove 100% of the loose material, and as such, in areas where shotcrete is not to be applied, waterjet scaled areas should be rechecked with either a hand-held scaling bar or a mechanical scaler.

A Rock Mass Rating (RMR) analysis was conducted in the zones covered by experiments 1 through 10 (Appendix 1). The results varied from a low value of 56 to a high of 87, with the average rating of 75. Interestingly, there did not appear to be a correlation between RMR and the amount of material scaled. RQD values were generally between 70% and 80%.

11.4 Smoothwall Blasting Effects

The charging details for the two different smoothwall blasting technique employed are given in Chapter 9. The perimeter holes in experiments 6-10 were charged using the det-cord smoothwall technique and the perimeter holes in experiments 11-16 were charged with the air-decking smoothwall technique.

The smoothwall blasting methods used worked well and both charging techniques produced a relatively smooth arched drift contour. Half casts from the blast holes were clearly visible (Fig. 11.5), which is typical of successful smoothwall blasting.

Fig. 11.5. Half-cast drill holes visible after a smoothwall blasting in experiment six.

The effects of smoothwall blasting can readily be seen in the experimental results (Fig. 11.2 and Fig. 11.3) showing the amounts of material scaled. The most noticeable effect is that the total amount scaled per blast in experiments 1 through 5 greatly exceeded the total amount scaled per blast in experiments 6 through 10 and experiments 11 through 16. In Fig. 11.6 the total amount of material scaled per blasting method and scaling technique is summarized and the fact that significantly less material was scaled when smoothwall blasting was employed can more easily be seen. Fig. 11.7 shows the total average amount of material scaled for normal blasting and smoothwall blasting. Again, it can readily be seen that the amount of material scaled when smoothwall blasting is employed is significantly less than the amount scaled when normal blasting is used.

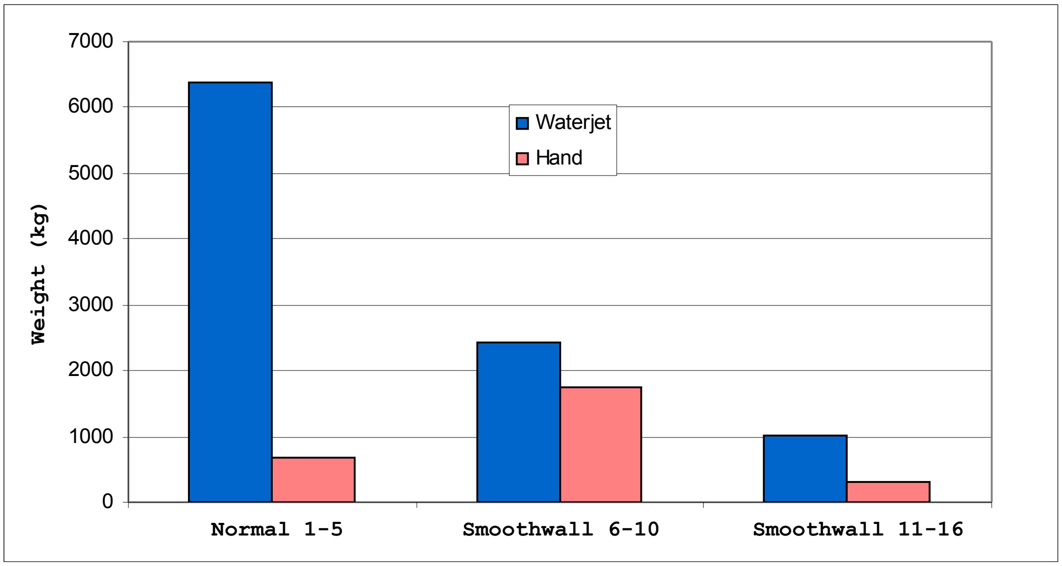

Fig. 11.6. Amount of material removed by scaling method in experiments 1-5 (normal blasting), experiments 6-10 (smoothwall blasting with det-cord), and experiments 11-16 (smoothwall blasting by air-decking.

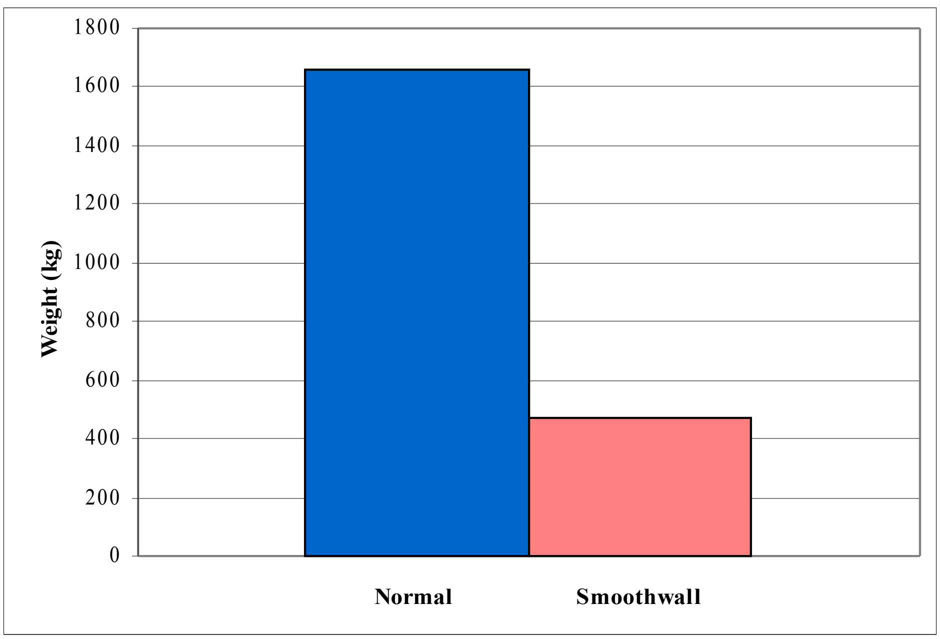

Fig. 11.7. Average total weight of material scaled by blasting method.

It is well documented that smoothwall blasting techniques inflict less damage to the wall rock than conventional blasting processes. To see this effect realized in the amount of material generated by scaling was quite interesting. Since smoothwall blasting results in less wall rock damage, it is reasonable to conclude that the amount of ground support required (e.g., bolts and shotcrete) should also be less than that necessary when conventional blasting is used. Furthermore, it is clearly evident from this research that the amount of time devoted to scaling should also be substantially less.

Although an economic analysis has not been performed in association with this study, it would appear that the cost savings incurred as a result of reduced scaling, ground support requirements, and production cycle times would more than offset the time and cost of implementing precision perimeter blasting techniques.

11.5 Scaled material size analysis

In additional to obtaining the total weight scaled, material from the first four experiments was also screened and the individual material fractions weighed. Fig. 11.8 shows the results of the screening analysis for the material scaled by waterjet and a hand-held scaling bar, which is consistent with similar screening results (Kuchta, Hustrulid, and Lorig, 2004). As an example, with waterjet scaling, 50% of the material scaled would be less than approximately 10.5 cm (3 in), while only about 20% of the hand scaled material would be less than this size.

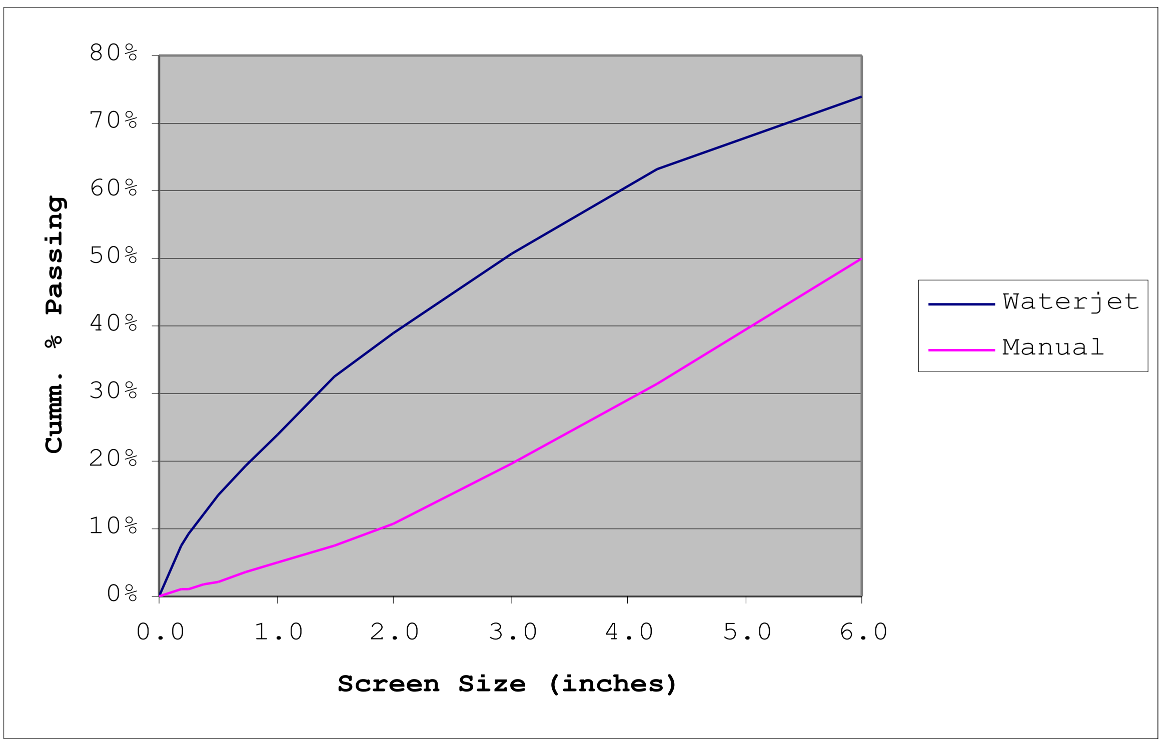

Fig. 11.8. Size distribution for the material scaled by waterjet and by hand in experiments 1 through 4.

Photographs typical of the material scaled by hand and waterjet are shown in Fig. 11.9. The relatively large amount of fine material removed by the waterjet was likely due to the ability to scour the rock surface and remove material that would otherwise be difficult or impossible to remove with a hand-held scaling bar. Based upon previous research, the ability to thoroughly clean the rock surface will result in substantial improvements in the adhesion strength of shotcrete if it were applied [8 & 4]. It is important to note, approximately 50% of the material scaled by manual methods after being scaled by waterjets was greater than 15 cm (6.0 in). Although this analysis is not conclusive, it would tend to support the observation that the waterjet is less effective in removing large rocks.

Further evidence of the ability of the waterjet to clean a rock surface can be seen in Fig. 11.10. This photograph was taken at the completion of the waterjet scaling part of experiment ten. Compare the relatively clean and dust free surface to that of Fig. 11.5, which was taken shortly after blasting the round for experiment six. The half-cast from smoothwall blasting are also clearly visible.

Fig. 11..9. Typical size distribution of material scaled by waterjet (upper) and a hand held scaling bar (lower).

Fig. 11.10. Photograph of the right rib of the drift after waterjet scaling in experiment ten.

12. Employee Safety and Occupational Health

In support of the research effort to quantify the effectiveness of waterjet scaling as a viable alternative to conventional (manual) techniques in underground mining, a preliminary assessment of the potential health and safety hazards of using waterjet technology was believed to be an important element of this process. As such, a comparative analysis was performed to isolate the hazards and risk potential to miners for each scaling method in a conventional 4.0 m x 3.0 m drift. This assessment was comprised of two distinct components; a modified job safety analysis and a health surveillance and worker monitoring study. Both components were conducted by trained, experienced safety and health professionals using data collected during empiric testing at the CSM Edgar Experimental Mine. The report from this study is given in Appendix B.

A job safety analysis (JSA) is an integral part of any safety management program and is widely employed in mining operations where new equipment, technology, and processes are being introduced. Often referred to as a Job Hazard Analysis, the intent of this study is to identify the safety hazards associated with each step comprising the scaling process, characterize the nature and situational aspects of these identified hazards, and then develop control measures to eliminate or mitigate each hazard. In addition, a qualitative risk assessment matrix was also constructed that examined the probability of occurrence and likely severity of each of these identified hazards should they occur. Through this process, it became possible to establish a qualitative comparison of the level of risk associated with each of the two scaling methods, as well as identify areas of interest from which the health exposure assessment study could focus.

Using a conventional methodology, the JSA of manual scaling included 5 task elements and 17 sub-elements as constructed by 3 experienced individuals possessing different professional backgrounds and using standardized safety and task training procedures common to underground metal mines. The participating individuals included an experienced miner, an operations supervisor, and an engineer/safety professional. For each of these task elements and sub-elements, hazards and appropriate controls were identified and the risks assessed. As expected, this analysis showed that three primary conditions contributed to the greatest hazard potential for miners engaged in manual scaling. They include:

1. *The immediate proximity of the miners to the working face and unstable/unsupported ground.* Based upon accident narratives and statistics, couple with empiric observations and experience, falling rock associated with scaling activities represents a significant safety hazard possessing a moderate to high risk potential for injury depending upon the specific rock conditions and drift characteristics. In addition, this environment often impairs rapid egress from the work area in the event of an unexpected problem or hazardous situation (e.g. rock fall). The close proximity of the working face also places miners in a position to be injured by ejected debris (i.e., rock chips from scaling bar contact and falling rock).

2. *Working on uneven and irregular floors/surfaces.*
Trips and falls are common during manual scaling as a consequence of working off of muck piles, broken rock, and uneven surfaces. While these rarely translate to fatalities, they do have a high frequency of occurrence with injuries normally classified as being low to medium in severity. It is important to note that manual scaling off of elevated platforms, ladders, or mobile equipment were not considered in this analysis. Similarly, manual scaling over open-holes, pockets, or raises were

also not considered. In situations where these conditions are present, the inherent risk and hazards of falls and the diminished ability to rapidly egress a work area become significant.

3. *Physical fatigue caused by the strenuous nature of manual scaling.*
The process of manual scaling is physically taxing and represents a hazard that often facilitates poor worker judgment and behavioral issues like failing to properly scale areas as thoroughly and often as prescribed or as deemed necessary. This situation is further compounded in poor rock conditions (more scaling required) and when back heights get higher (longer scaling bars).

While select controls were identified for each of the hazards identified during the JSA on manual scaling, the most logical conclusion to mitigate and/or eliminate these potential hazards involve automating the process and removing the miner from the operating environment through the use of an alternative technology or technique. Ironically, this is precisely one of the intended objectives of this research. The use of waterjet technology in conjunction with a mechanized support system (shotcrete rig and boom) allows miners to remotely scale a drift heading from a safe location under supported ground through joysticks and tele-robotic control. A JSA performed on the current configuration of the waterjet scaling system showed outcomes very similar to other types of rubber-tired mobile equipment used in underground metal mining, with the exception of the potential risks associated with operating high-pressure fluids and the reduction of visibility caused by water aerosols/rebounded spray. Among other things, the hazards common to underground powered haulage and mobile equipment included accidents related to collisions, workers being struck by equipment, and workers being penned or crushed by a piece of equipment or between equipment and rock surfaces. Equipment mechanical failures, poor operating practices, fire, diesel exhaust exposure, and employee training were other major issues identified in this analysis. Of those hazards unique to waterjet scaling systems, working with high-pressure fluid represents the greatest concern. That said, the risk associated with human exposure to high energy fluid as a consequence of mechanical failure (hoses, pumps, fittings, flow controls) or errant misdirection of the nozzle assembly were assessed to be extremely low in terms of probability of occurrence with a potential severity rating ranging from medium to high if it did in fact occur. Fortunately, numerous controls were identified to further minimize the potential risk of these hazards. These controls will be directly integrated into the standard operating procedures, training protocols, and equipment maintenance guidelines to be constructed prior to the implementation of this equipment in an operating environment. This aspect of the analysis was based on the equipment configuration and fluid pressures/flow rates currently being used in the CSM scaling experiments, accident statistics derived from the waterjet petro-chemical plant cleaning industry(1), and the recommended operating procedures adopted by the WaterJet Technology Association(2), and equipment manufacturers.

During empiric testing of the waterjet scaling system, visibility of the work area often became problematic due to the spray coming from the free-stream of the waterjet as a consequence of aerodynamic drag and stream incoherency, as well as water rebounding off of rock surfaces. Through the experiments, different nozzle designs produced varying amounts of spray. As such, the spray produced by a given nozzle configuration became an assessment criteria nearly as important as the apparent productivity and performance of the jet. Over long stand-off distances, one of the major advantages for using a single orifice, mechanically oscillated nozzle was that visibility was far superior to other nozzle configurations due to the coherency of the jet. A number of other additional controls were identified that could potentially further improve visibility during waterjet scaling, they included adjustments in the nozzle orifice and the rake angle of motion, the use of short-chain polymers in the fluid, and potentially the use of some type of vision system.

From the JSA performed for both manual and waterjet scaling, it became apparent that the potential health hazards associated with dust and noise exposure needed to be assessed. A sub-contract was issued to researchers from the University of Arizona, Mel and Enid Zuckerman College of Public Health in order to help quantify differences in noise and dust exposures between the different scaling methods and to determine if the levels warranted additional analysis and/or control measures. The research component was conducted over a 4 day period, where personal monitoring data was collected over a series of scaling experiments that utilized both manual and waterjet methods. As expected, the waterjet system proved to produce significantly more noise than manual scaling as a consequence of the shotcrete rig's diesel power plant, the operation of the electric high-pressure pump, the hydraulic system used to actuate the boom, and the jet emanating from the nozzle orifice. That said, the noise generated by the waterjet system was barely high enough to invoke the MSHA TWA action level of 85 dBA that would necessitate the establishment of a hearing conservation program. Through engineering controls, it is thought that the TWA could be reduced significantly by using sound absorption materials, equipment enclosures, and sound barriers. With regards to respirable dust, the measured exposure for both scaling methods proved to be substantially below regulatory limits for insoluble or poorly soluble inhalable dust. While this proved to be encouraging, additional sampling with longer duration periods is required prior to making quantitative assertions regarding silica exposure.

Predicated upon this analysis, it is possible to conclude that on aggregate, the waterjet scaling method being utilized in this research possesses substantial safety and health benefits over conventional (manual) scaling techniques for the application reviewed. While these results reflect a preliminary assessment, waterjet systems appear to eliminate most of the dominate hazards indicative of manual scaling. Furthermore, waterjet scaling possesses few intrinsic hazards of moderate risk, where even these hazards can likely be readily mitigated through engineering and administrative controls. The combination of these factors greatly enhances the attractiveness of waterjet scaling as a safe and viable alternative to existing manual methods.

13. Summary and Conclusions

A large number of accidents in underground mining are caused by rock falls. Scaling is a proactive means of mitigating the risk associated with falling ground and encompasses activities intended to remove loose and unstable rock from exposed underground mine openings. Ironically, the actual process of scaling is often hazardous and is responsible for a significant number of accidents and employee injuries. While mechanized scalers utilizing hydraulic hammers mounted on mobile diesel carriages are common in most large operations, manual scaling bars are still the standard throughout the underground hardrock industry.

This report summarizes research performed at the Colorado School of Mines Edgar Experimental Mine with the primary goal of evaluating the effectiveness of using waterjet scaling as part of a mechanized scaling system. It is believed that proper implementation of waterjet scaling could significantly reduce the number of accidents that occur while scaling.

A job safety analysis (JSA) study performed as part of this research identified three major areas of risk with hand scaling: 1) The immediate proximity of the miners to the working face and unstable/unsupported ground, 2) Working on uneven and irregular floors/surfaces, and 3) Physical fatigue caused by the strenuous nature of manual scaling. While select controls were identified for each of the hazards identified during the JSA on manual scaling, the most logical conclusion to mitigate and/or eliminate these potential hazards involve automating the process and removing the miner from the operating environment through the use of an alternative technology or technique.

Before starting with the waterjet scaling experiments, three experiments were conducted with hand scaling only. The preliminary hand scaling tests captured a number of the inherent safety hazards and health concerns common to conventional hand scaling. Fatigue and exhaustion of the miner conducting the scaling was quite obvious. At one point, a fist sized rock slid down the scaling bar and struck the miner in the forearm. Similar incidents with falling rock are known to be a significant cause of scaling accidents. Several times, the miner had problems with the unstable footing caused by the need to work off broken and blasted rock while scaling. All of the sources of worker injury described above can be eliminated by correctly implementing a waterjet scaling system.

A prototype waterjet scaling system was built and and used for the tests conducted in this project. A pump configured to operate at 24 MPa (3500 psi) and a flow rate of 0.11 m^3/min (30 gpm) was used to provide high pressure water for scaling. An old shotcrete truck served as the carrier vehicle. The hydraulically actuated boom of the vehicle was used to sweep the waterjet nozzle across the area to be scaled. An electronic hydraulic valve bank was installed on the rig that allowed for remote tethered operation of the rig, thus allowing the scaler to operate the rig from a safe distance away from the area to be scaled.

A total of sixteen experiments were conducted with waterjet scaling. Five different nozzle designs were evaluated:

- a single orifice continuous jet,
- a dual orifice self-rotating jet,
- an acoustically pulsed, single orifice jet, and
- two types of mechanically oscillated single orifice jets.

A total of ten waterjet experiments that included two experiments for each nozzle type were conducted first. The remaining six waterjet experiments were conducted with the preferred nozzle design.

Evaluating the relative performance of the various scaling techniques proved to be difficult. The evaluation procedure used was to collect the material scaled by the waterjet on a tarp for subsequent weighing, after which the area was hand scaled as a control and the material again collected and weighed. In all cases significantly more material was scaled by the waterjet than subsequent hand scaling. In a few cases, the material that was removed by subsequent hand scaling was quite loose and it appeared that the waterjet might simply have simply missed this material. In general the material removed by subsequent hand scaled was quite well wedged in place and required considerable amount of work to remove. In operations where shotcrete is to be applied, such material could probably be safely left in place. It is, however, troubling that the various waterjets tested did not remove 100% of the loose material, and as such, in areas where shotcrete is not to be applied, waterjet scaled areas should be rechecked with either a hand-held scaling bar or a mechanical scaler. The hand scaling also showed that the waterjet is not generally effective in removing large and/or securely wedged in rock.

Initially it was believed that the pulsed nozzle would give superior performance. Although the nozzle performed well in comparison to the other nozzles tested, a performance advantage that would justify the high cost of the pulsed nozzle could not be clearly demonstrated. Pulsed nozzles have been shown to be dramatically more effective than continuous jets in a wide range of industrial cutting and cleaning applications. A more robust parametric evaluation than could be conducted in this study might yield clearer results in favor of the pulsed jet.

It is also believed that a rotating nozzle would provide better surface coverage and thus better scaling results than a continuous jet. A self rotating jet and two types of mechanically rotated jets were tested. Although the results gathered did not show a definitive superior performance with rotating jets it was the observations of the researchers that rotating jets are preferred due to the ease in which the surface area to be scaled can be covered.

All of the nozzles tested performed well. However, based on experimental results and observations made while scaling with each system, the design preferred by the researchers involved in this study was the hydraulically powered mechanically oscillated single orifice jet. Although the hydraulically powered rotational unit used was custom designed for this project, the design is based on similar devises commonly used to provide nozzle rotation with mechanical shotcrete application. Using the rotational unit with the single orifice continuous jet meant the power and performance of the single jet was obtained, while good surface coverage was also assured. Another advantage of the unit was the ability to easily turn off the rotation, thus allowing the operator to point the jet at cracks or problem areas. The simplicity, low cost, and robust design was a definite advantage in the harsh working environments that are often encountered in underground mining.

Two waterjet experiments were conducted in reverse order where hand scaling was performed first followed by waterjet scaling. With the reverse order tests, the area was first thoroughly scaled by hand and deemed safe by experienced mine personnel. The fact that in both tests the subsequent waterjet scaling brought down nearly as much material as the previous hand scaling indicates that significant improvements in worker safety with waterjet scaling would likely be realized over hand scaling due to the ability of the waterjet to remove loose that can not be easily detected by hand scaling..

An unplanned additional benefit of this research was to evaluate the effects of smoothwall blasting on the amount of material scaled. The first five waterjet experiments consisted of perimeter holes fully loaded with ANFO, and two different smoothwall blasting methods was employed in the remaining eleven waterjet experiments. The effects of smoothwall blasting were very positive. With smoothwall blasting, scaling times were shorter, and the total amount of material scaled was on average about one third the weight scaled when the perimeter holes were fully charged with ANFO.

A scaled material size analysis showed a substantially larger portion of fine material obtained with waterjet scaling compared with hand scaling indicating the waterjets ability to thoroughly clean the rock surface of fine material. Previous research has indicated that waterjet scaling has the additional benefit of improving the adhesion characteristics of shotcrete applied as a support membrane. Waterjet scaling could be part of a modern and safe system for underground excavation that would include precision drilling for accurate hole placement, smoothwall blasting to minimize wall rock damage, waterjet scaling, shotcrete application, and final roof bolting as required. The potential benefit of such a system would be improved worker safety compared to systems commonly used today. Although financial considerations were not a motive for this research, it is believed that waterjet scaling systems will be significantly more cost effective than scaling methods currently used in underground mining.

The research was motivated by the desire to develop a remote scaling technique as a method of reducing accidents and injuries associated with rock scaling. The results obtained clearly show that waterjet scaling is a viable alternative to both manual (hand) and mechanical scaling, and it is believed that by implementing a waterjet scaling system, accidents associated with scaling could be reduced. It is recommended that future projects should be dedicated to demonstrate the advantages of waterjet scaling technology to the mining industry with the hope that the technology would be adopted and used in active underground mines.

14. Acknowledgments

The authors would like to express their sincere thanks to National Institute for Occupational Safety and Health (NIOSH) for the financial support of this research project. This publication was supported by Cooperative Agreement Number R01 OH08709 from the Centers for Disease Control and Prevention. Its contents are solely the responsibilities of the authors and do not necessarily represent the official views of NIOSH.

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Appendix A

RMR Analysis Experiment #1

Description: Several prominent vertical joints creating potential for large rock fall. Left rib contains mineralized vein-like formation with soft orange material that crumbles under almost no load. Extensive biotite layering in the rough Gneiss that makes up most of the area. Blasting has left the back in poor condition with very irregular surfaces. After a particularly wet winter and spring, dripping and slow seepage occurred randomly through the area. Two bore holes located approximately 5ft to the south flowed heavily at 5-10 gpm while rock mass drained in early summer. Discontinuity dip and dip direction were not measured due to back height and safety concerns, working from a ladder upon a sloped surface. Most discontinuities can be considered near vertical unless otherwise noted.

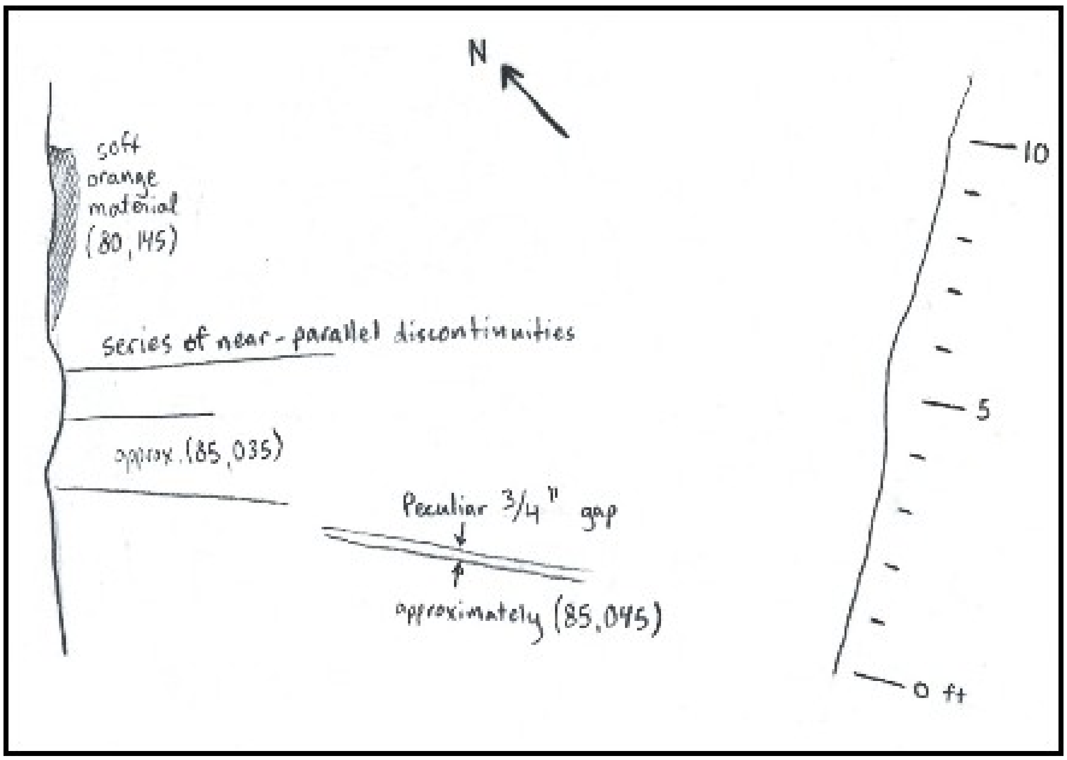

Fig. A.1 Map of geologic features noted in Experiment #1

1. Strength – Intact strength of Idaho Springs Gneiss is moderate to high.
   Score: 12

2. RQD – Estimated at 60 – 70% through the area.
   Score: 14

3. Spacing – Approximate average of 1 – 2 ft through area. **Score: 13**

4. <u>Condition of Discontinuities</u> – Vertical joints are slightly rough and slightly weathered. One notable discontinuity has approximately 20mm separation. Variation in joint properties, likelihood of unknowns, and close proximity to soft mineralized formation reduce confidence in this particular area.
   Score: 20

5. <u>Groundwater</u> – Moist during rainy seasons.
   Score: 11

RMR Total: 70

RMR AnalysisExperiment #2

Description: Blast holes drilled to raise back height at intersection of ramp with old Spence Crosscut. Several prominent vertical discontinuities as in Experiment #1 create potential for large rock fall. In that regard, Experiment #2 will be remembered for the sudden collapse of approximately 4 ton boulder with waterjet. The left rib contains a continuation of the mineralized vein-like formation noted in Experiment #1, which includes soft orange material that seems to stay wet almost all year long.

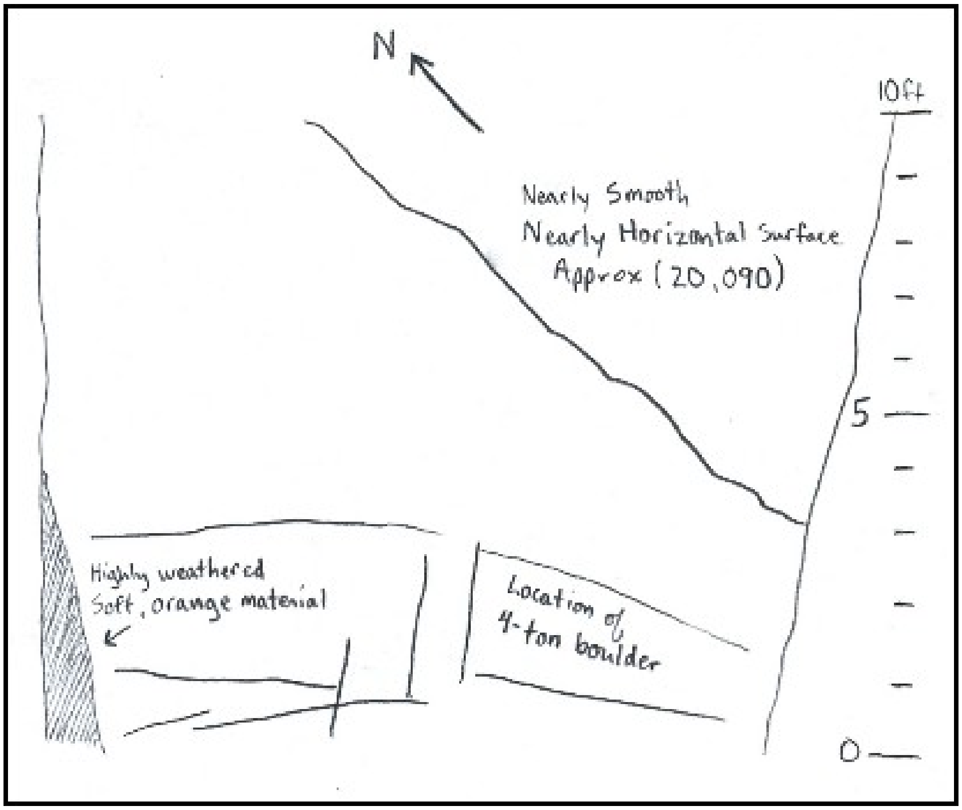

Fig. A.2 Map of geologic feature noted in Experiment #2

1. Strength – Intact strength of Idaho Springs Gneiss is moderate to high.
   Score: 12

2. RQD – Estimated at 70 – 80% through the area.
   Score: 17

3. Spacing – Approximate average of 0.5 – 1.0 ft through area. **Score: 16**

4. Condition of Discontinuities – Vertical joints are slightly rough and slightly weathered. Most are flat and straight. Considering the collapse of the large boulder, it may be assumed that some of the vertical joints give way when supporting material is removed.
   Score: 20

5. Groundwater – Most of the back is normally dry. Random drops of water are known to bother employees that pass through the area. The left rib seems to be damp almost all year long. The presence of moisture and drops of water are considered moderate signs of potential hazards over time.
   Score: 10

RMR Total: 75

RMR Analysis Experiment #3

<u>Description:</u> The left rib and most of the back are comprised of generally competent rock. Smooth wall blasting was not utilized, but several half-cast drill holes are present, indicating the strength of the intact rock and continuity of the rock mass. Part of the back and right rib consist of a 4 – 5 ft wide shear zone. Numerous joints, clay banding, and pyrite filling indicate the potential for small scale rock fall.

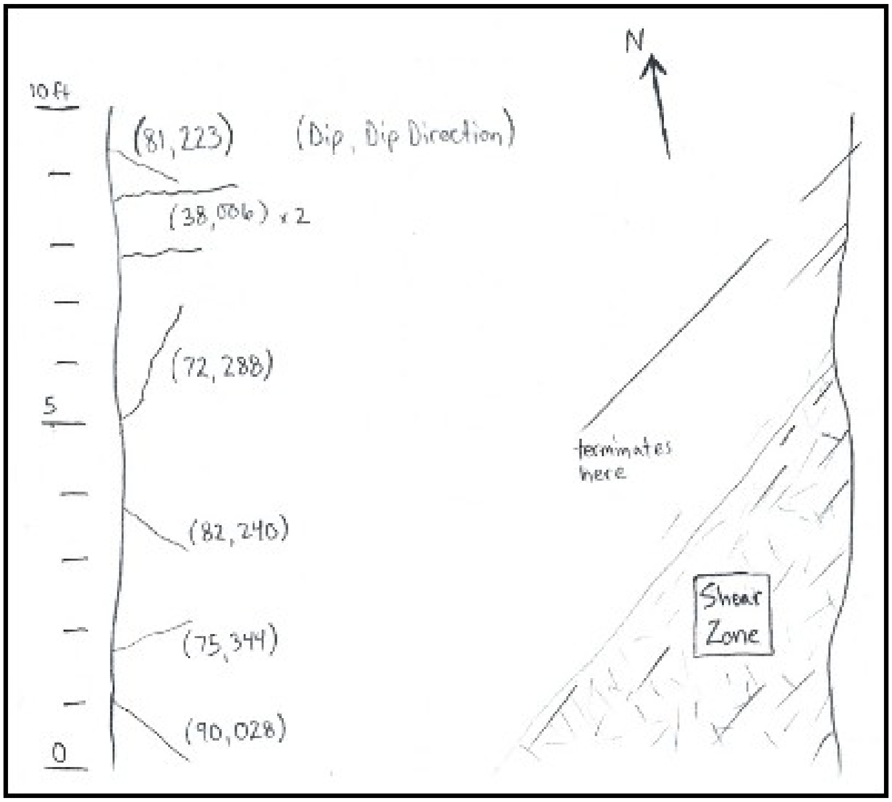

Fig. A.3 Map of geologic features noted in Experiment #3

1. <u>Strength</u> – Intact strength of Idaho Springs Gneiss is moderate to high.
   Score: 12

2. <u>RQD</u> – Estimated at 70 – 80% through competent areas of drift. Presence of shear zone slightly reduces score.
   Score: 15

3. <u>Spacing</u> – Approximate average of 1 – 2 ft through competent areas, but the presence of the shear zone lowers score. **Score: 9**

4. <u>Condition of Discontinuities</u> – Discontinuities seem slightly rough and mostly straight with separation less than 1 mm. Some discontinuities in shear zone are weathered and clay filled.
   Score: 20

5. <u>Groundwater</u> – Completely dry.
   Score: 15

RMR Total: 71

RMR Analysis Experiment #4

Description: Generally competent rock. The features noted on the map are for minor classification purposes and do not necessarily designate hazards. Smooth wall blasting was not utilized, but back and left rib did not sustain significant damage. The right rib, as with most slash rounds taking place in the Spencer Crosscut, was not blasted.

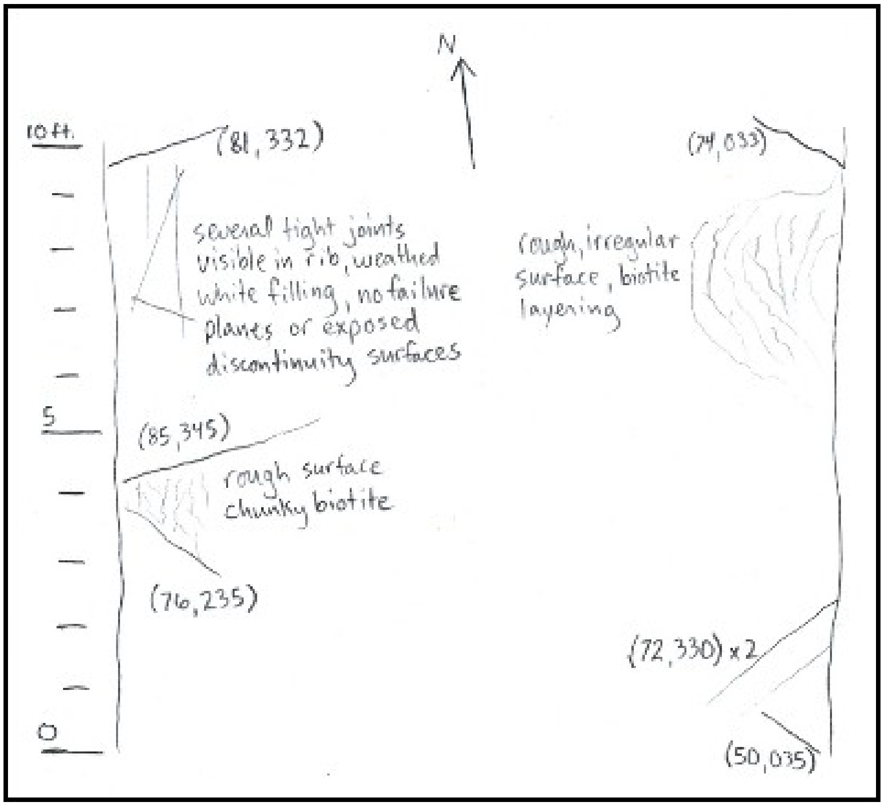

Fig. A.4 Map of geologic features noted in Experiment #4

1. Strength – Intact strength of Idaho Springs Gneiss is moderate to high.
   Score: 12

2. RQD – Estimated at 80 – 90% through this area.
   Score: 18

3. Spacing – Approximate average of 1 – 2 ft through area. **Score: 13**

4. Condition of Discontinuities – Slightly rough, not much weathering. Some indication of pyrite in certain joints.
   Score: 24

5. Groundwater – Completely dry.
   Score: 15

RMR Total: 82

RMR Analysis Experiment #5

Description: Back characterized almost entirely of irregular, blocky surface. Small, intersecting joints in many places suggest moderate blast damage. One shallow dipping (40) discontinuity has several millimeters of separation and pyrite filling. Area appears to need additional scaling, as thin biotite layering weathers and small blocks loosen up.

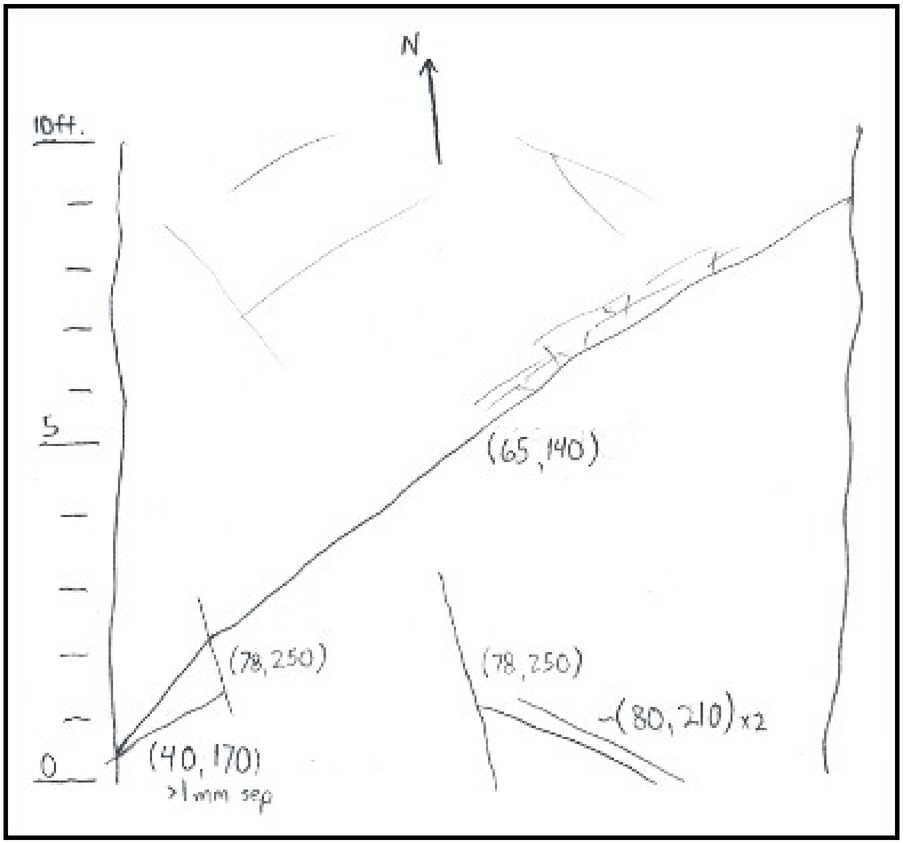

Fig. A.5 Map of geologic features noted in Experiment #5

1. Strength – Intact strength of Idaho Springs Gneiss is moderate to high.
   Score: 12

2. RQD – Moderate RQD estimated through this area, possibly between 55 – 65%.
   Score: 13

3. Spacing – Several closely spaced joint sets in the range of 3 – 6 inches. **Score: 8**

4. Condition of Discontinuities – Most are rough, some joints are smooth. Separation visible in more than one discontinuity. Some weathering, especially noted by surface discoloration near pyrite-filled joints.
   Score: 20

5. Groundwater – Completely dry.
   Score: 15

RMR Total: 68

RMR Analysis Experiment #6

Description: This was the first round scaled in which smooth wall blasting techniques were utilized. The results are exceptional compared to previous rounds. The left rib and back contain several half-cast drill holes, as well as empty holes where breakage failed to occur. No major features to note on left rib or back, except in the northeast corner. There is a rough and irregular surface bound one of two long discontinuities.

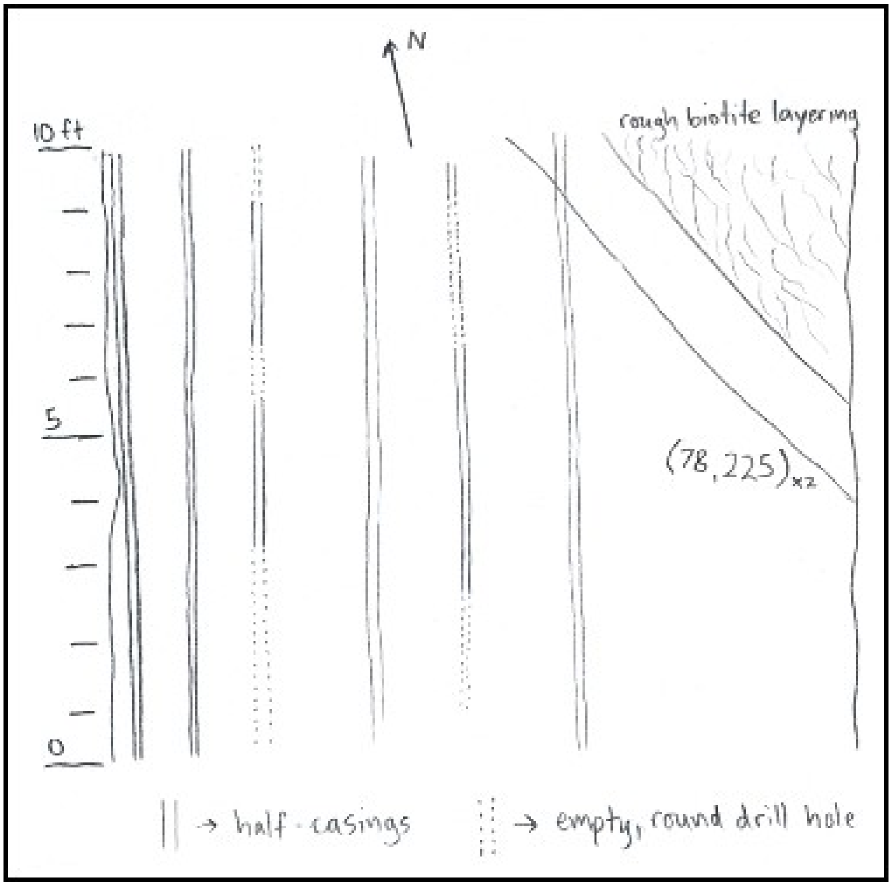

Fig. A.6 Map of geologic features noted in Experiment #6

1. Strength – Intact strength of Idaho Springs Gneiss is moderate to high.
   Score: 12

2. RQD – Fairly high RQD estimated through this area, possibly between 70 – 80%.
   Score: 17

3. Spacing – Approximately 1.5 ft between the only mapped discontinuities. **Score: 18**

4. Condition of Discontinuities – Slightly rough, very little weathering if any. Separation less than 1 mm.
   Score: 25

5. Groundwater – Completely dry.
   Score: 15

RMR Total: 87

RMR Analysis Experiment #7

Description: The results of the smooth wall blasting technique are again moderate to good. Rock mass is mostly featureless, aside from a few long discontinuities. One such discontinuity extends from the previous segment of drift, where Experiment #6 was performed. The northeast corner of the back turned out rough after the blast, with moderate layering of biotite and pegmatite.

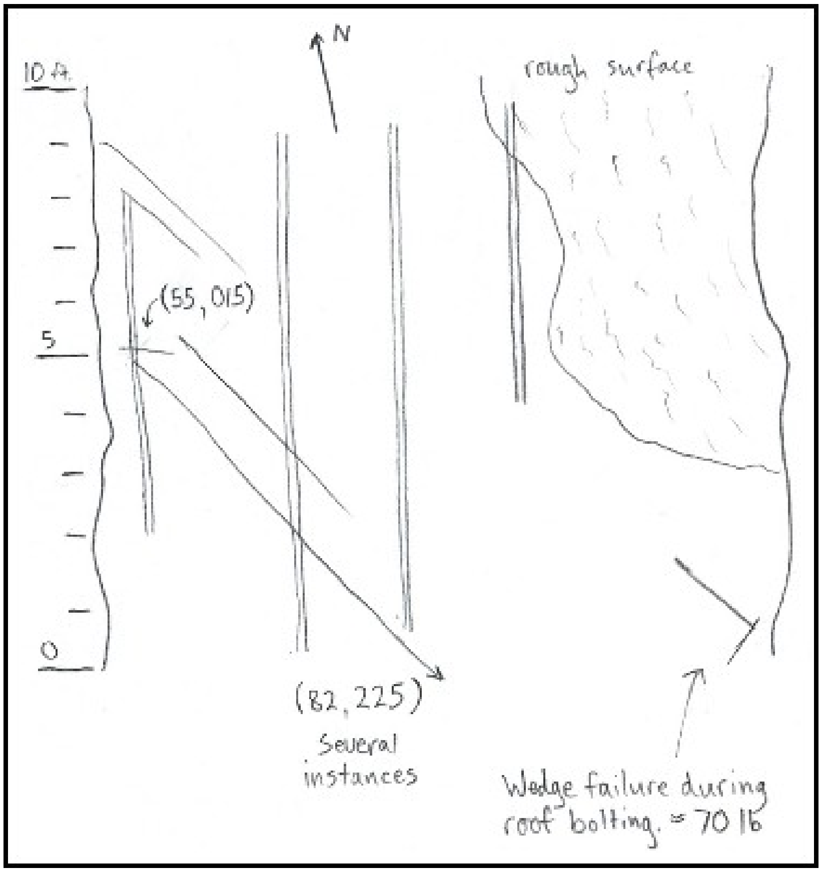

Fig. A.7 Map of geologic features noted in Experiment #7

1. Strength – Intact strength of Idaho Springs Gneiss is moderate to high.
   Score: 12

2. RQD – Fairly high RQD estimated through this area, possibly between 70 – 80%.
   Score: 17

3. Spacing – There are a few instances of closely spaced joints in the range of 4 – 8 inches, located far from each other.
   Score: 15

4. Condition of Discontinuities – Slightly rough, very little weathering if any. Some joints contain pyrite, and none of them have separation greater than 1 mm.
   Score: 22

5. Groundwater – Completely dry.
   Score: 15 **RMR Total: 81**

RMR Analysis Experiment #8

Description: Large weak zone approximately 8 – 10 ft wide encompasses most of Experiment #8. The rock mass is extremely fractured, blocky, weathered, and contains oxidized discontinuity filling. The material present air-slackens fairly quickly, and new material can be scaled within hours. Clay slips and visible, open fractures pose a large risk for those entering the area. It should be noted that several thousand gallons of water from lengthy waterjet tests drained through the floor in less than 2 days.

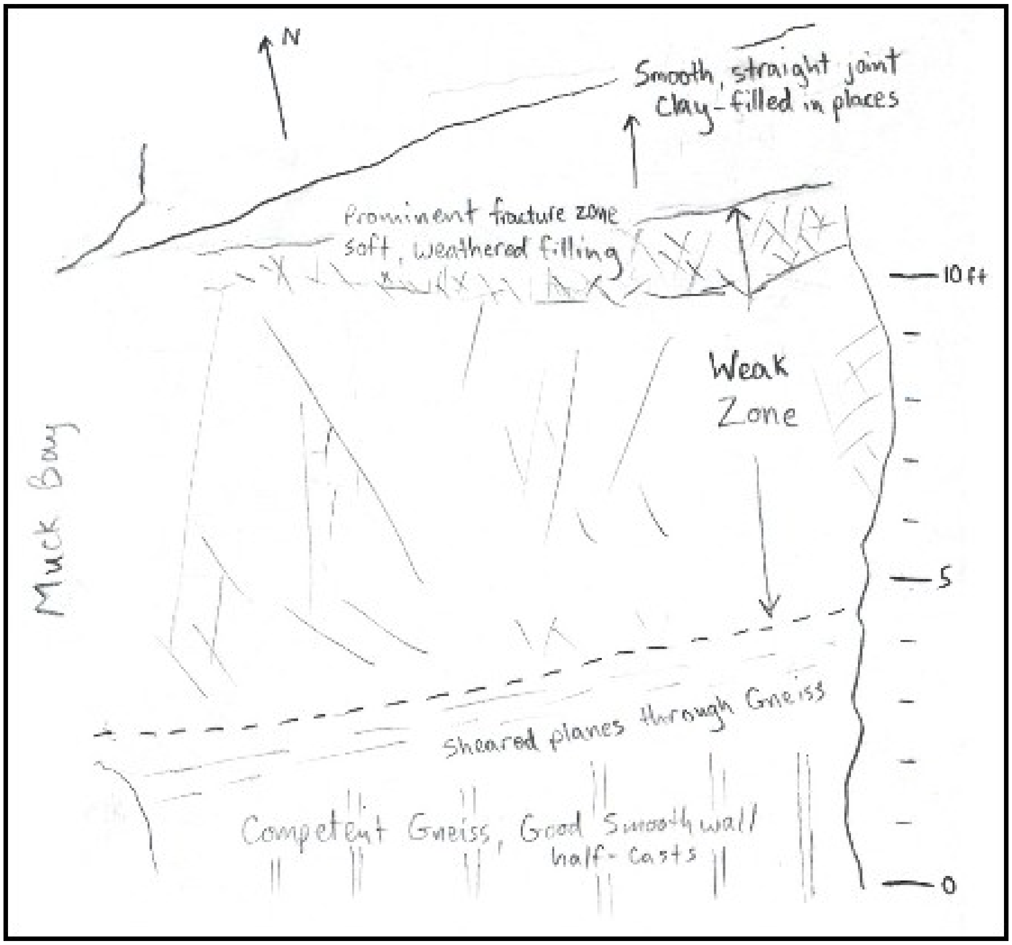

Fig. A.8 Map of Geologic features noted in Experiment #8

1. Strength – Intact strength of Idaho Springs Gneiss is moderate to high, but the strength of the rock mass is rather low.
   Score: 10

2. RQD – RQD is estimated at less than 50% through the weak zone.
   Score: 8

3. Spacing – Average joint spacing of 0.5 to 1 ft through entire area.
   Score: 10

4. Condition of Discontinuities – Some discontinuities are highly weathered and several have clay filling. Most fractures have less than 1 mm separation and are slightly rough
   Score: 15

5. Groundwater – Usually dry, but porosity of rock mass indicates past flow of water and possible moisture during wet seasons.
   Score: 13

RMR Total: 56

RMR Analysis Experiment #9

Description: Aside from close proximity to weak zone and resultant shear planes, the rock mass was comprised mostly of competent gneiss. There was very little biotite and pegmatite alteration, leaving a consistent grey surface. Results of smooth wall blast were excellent. A majority of the scaled material came from the first 2 feet of the drift, where extensive fracturing and weathering gave way to large quantities of loose rock while scaling. The presence of a large slab on the rib of the muck bay required special attention.

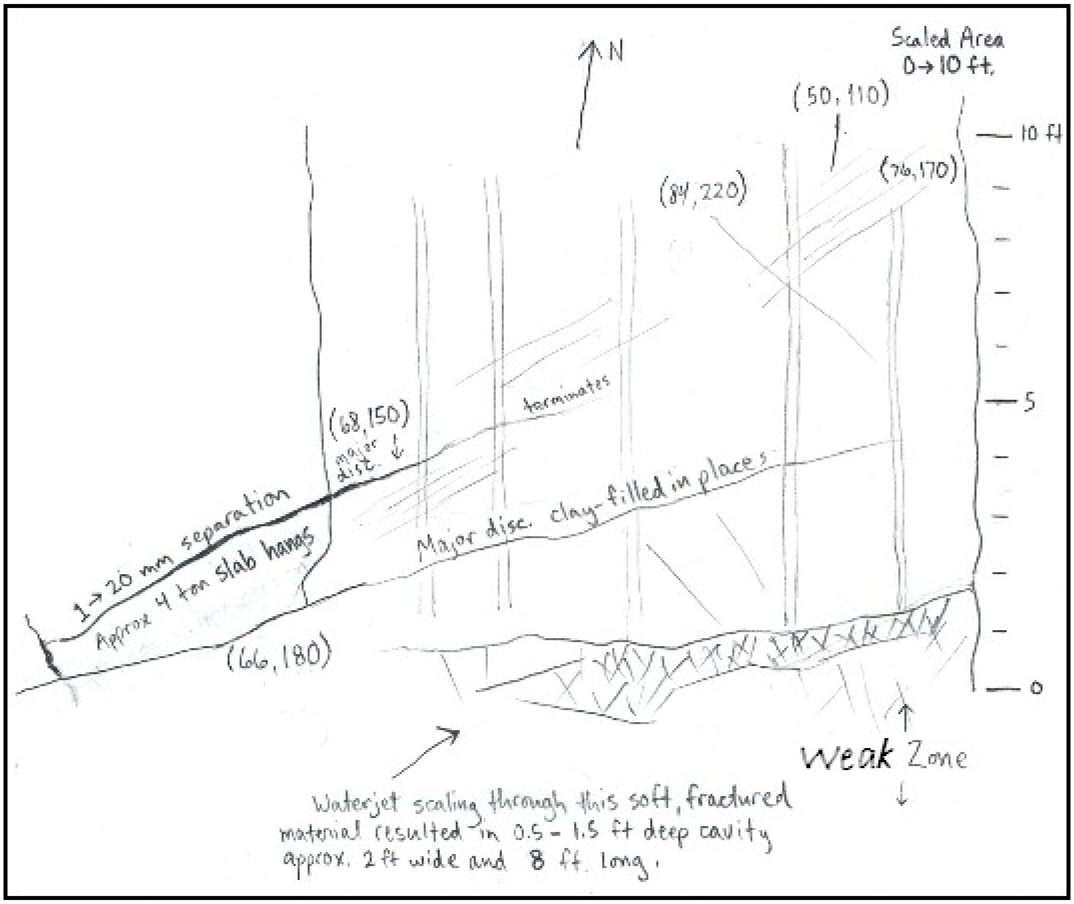

Fig. A.9 Map of geologic features noted in Experiment #9

1. Strength – Majority of the rock is intact and of high strength.
   Score: 14

2. RQD – RQD is estimated at 80% or better through a majority of the drift.
   Score: 17

3. Spacing – Aside from fractured material in weak zone, the average spacing of discontinuities appears to be in the range of 2 ft.
   Score: 15

4. Condition of Discontinuities – The presence of the large slab bound on each side by slickened planes indicates the possibility of clay through the network of joints that run parallel to the weak

zone. Otherwise, joints appear slightly rough with very little weathering.
Score: 20

5. Groundwater – Primarily dry.
Score: 14

RMR Total: 80

RMR AnalysisExperiment #10

Description: The drift is comprised of fairly competent rock, is mostly dark in color, and contains less pegmatite alteration than average. One prominent discontinuity in left rib exposed planar surfaces after blast, but none of the joints in the back appear as severe. Several intersecting planes gave way to small wedge failures during the blast. Several of the discontinuities are long, irregularly oriented, and contain a very thin white filling, the origin of which is unknown. Several half-cast drill holes indicate the success of the smooth wall blast technique.

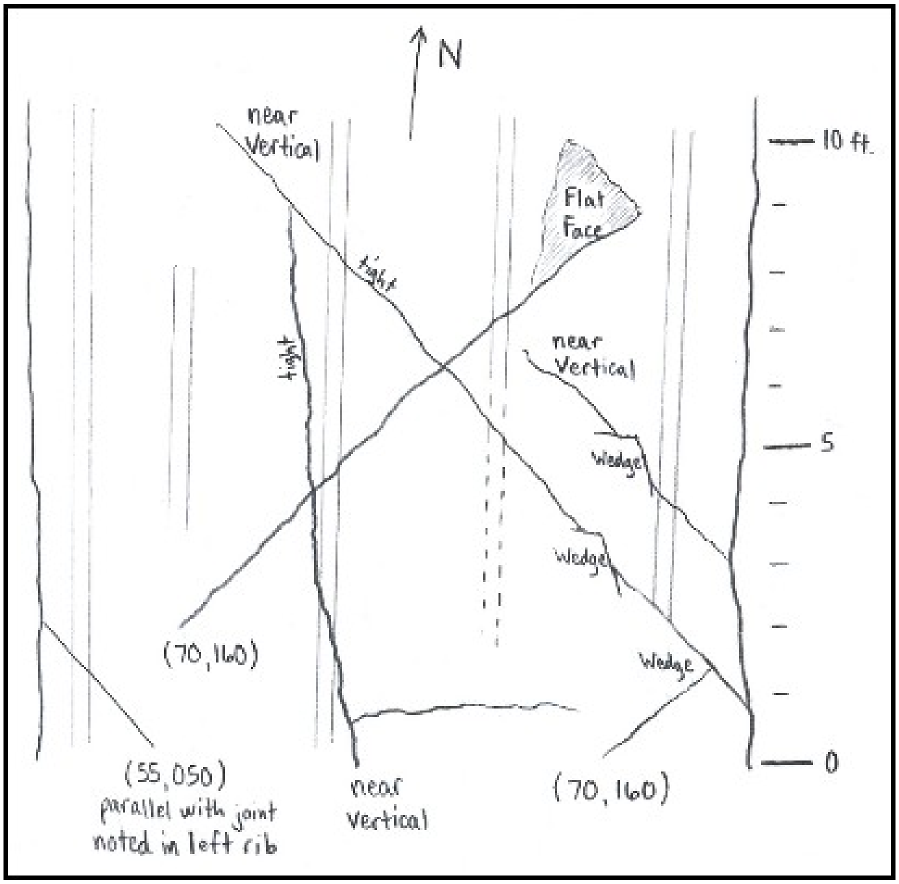

Fig. A.10 Map of geologic features noted in Experiment #10

1. Strength – Majority of the rock is intact and of high strength.
   Score: 14

2. RQD – RQD is estimated at 80% or better through the area.
   Score: 17

3. Spacing – Average range between 1.5 and 6 feet.
   Score: 15

4. Condition of Discontinuities – Discontinuities are very tight, slightly rough, and only slightly weathered if at all. Properties of vague white filling unknown.
   Score: 24

5. Groundwater – Primarily dry.
   Score: 14

RMR Total: 84

Appendix B

Industrial Hygiene Monitoring of Scaling of Waterjet and Conventional Scaling in Underground Mining

Report Date: August 7, 2007

Location: Edger Experimental Mine, Idaho Springs, Colorado

Contact:
Jefferey L. Burgess, MD, MPH
Director
Division of Community, Environment and Policy
Mel and Enid Zuckerman College of Public Health
University of Arizona
1295 N. Martin Ave, Room A235
Tucson, AZ 85724
Phone: 520-626-4918
Fax: 520-882-5014
Email: jburgess@u.arizona.edu

Objectives: The primary objectives of this work were to quantify differences in noise, dust and silica exposure between waterjet scaling and conventional (manual) scaling activities. This research will supplement a safety analysis that is currently being conducted by researchers internally within CSM.

Monitoring Dates: The research was conducted over a period of 4 days (June 26 to June 29, 2007) and monitoring data was collected over a series of scaling experiments utilizing either waterjet or manual techniques.

Instrumentation used:
Noise: Quest Q-400 Dosimeters (2)
Dust: SKC Pumps (6) were used, Model # 224-PCXR3 and 224-PSXR8
3 piece PVC, preweighed, 37 mm filters, with aluminum cyclones, flow rate 2.5 L/m
for NIOSH 7500 (respirable silica)
for NIOSH 0600 (respirable dust)
IOM PVC 25 mm filter, preweighed, for used with IOM, flow rate 2.0 L/m
for NIOSH 0500 (inhalable dust)

Waterjet scaling nozzles used:
(1): Single oriface
A= oscillating jet
B=traversing jet
(2): Two oriface self-rotating head
(3): Acoustic pulse jet

Noise Monitoring: (Using ACGIH criteria (85 dBA averaged over 8 hours, 3 dB exchange rate))

Table 1. Noise monitoring for waterjet scaling

6/28/2007	Units:	Nozzle 1A (Trial 1)	Nozzle 1B (Trial 2)	Nozzle 1B (Trial 3)	Nozzle 1B (Trial 3 cont.)*	Nozzle 2 (Trial 4)
Peak	dBA	129.8	127.9	130.1	123.5	128.5
Dose	%	116.0	85.8	66.6	0.6	85.5
TWA	dBA	85.6	84.3	83.2	62.9	84.3
Duration	min/sec	43:50	37:42	26:17	30:31	20:18

6/29/2007	Units:	Nozzle 2 (Trial 5)	Nozzle 2 (Trial 6)*	Nozzle 2 (Trial 6 cont.)	Nozzle 3 (Trial 7)	Nozzle 3 (Trial 8)	Nozzle 3 (Trial 9)	Nozzle 1A (Trial 10)
Peak	dBA	126.7	127.9	117.7	131.1	133.0	122.7	136.6
Dose	%	41.6	12.9	38.6	141.7	51.4	40.9	61.3
TWA	dBA	81.1	76.1	80.8	86.5	82.1	81.1	82.8
Duration	min/sec	39:08	7:55	11:25	19:50	18:42	16:04	25:16

* For the second phase of Trial 3 and the first phase of Trial 6, the waterjet had low pressure problems and therefore the noise measurements do not reflect normal waterjet function.

Table 2. Noise monitoring for manual scaling

6/28/2007	Units:	Handscaling with long bar (Trial 1)	Handscaling with short bar (Trial 1 continued)	Handscaling with short bar (Trial 2)
Peak	dBA	134.0	140.2	128.6
Dose	%	10.2	2.6	8.3
TWA	dBA	75.0	69.0	74.1
Duration	min/sec	50:05	15:00	42:10

6/29/2007	Units:	Handscaling (Trial 3)	Handscaling (Trial 4)	Handscaling (Trial 5)	Handscaling (Trial 6)	Handscaling (Trial 7)
Peak	dBA	134.5	130.9	132.0	128.4	134.4
Dose	%	5.5	4.5	6.9	3.3	9.9
TWA	dBA	72.3	71.5	73.3	70.2	74.9
Duration	min/sec	37:36	23:31	25:52	22:44	22:17

Dust monitoring:

Analysis by ESIS Environmental Health Laboratory, 100 Sebethe Drive, Suite A-5, Cromwell, CT 06416, (860) 635-6475, Lab Accreditations: AIHA and ELLAP Lab #100127

Table 3. Inhalable Particulates (Gravimetric sampling; Mod. NIOSH 0500 - PVC-I Filter)

June 28		Sample	Total time	Air Volume		**Concentration**
Subject		Number	(Minutes)	(Liters)	ug	(mg/m^3)
Waterjet scaler	AM	HD01A	122	254	276	**1.1**
Waterjet scaler	PM	HD01B	129	252	89	**0.35**
Manual scaler	AM	HD02A	177	357	397	**1.1**
Manual scaler	PM	HD02B	42	80.0	126	**1.6**
		Blank		---	<20.0	
June 29		Sample	Total time	Air Volume		**Concentration**
Subject		Number	(Minutes)	(Liters)	ug	(mg/m^3)
Waterjet scaler	AM	TD01A	96	188	101	**0.54**
Waterjet scaler	PM	TD01B	83	163	79	**0.49**
Manual scaler	AM	TD02A	87	161	403	**2.5**
Manual scaler	PM	TD02B	44	81.2	100	**1.2**
		Blank		---	<20.0	

Table 4. Respirable Crystalline Silica (Xray Diffraction; NIOSH 7500 - PVC Filter)

June 28						
		Sample	Time	Air Volume		
Subject		Number	(Minutes)	(Liters)	ug	**mg/m^3**
Waterjet scaler	AM	HR01A	123	316	<10.0	**<0.032**
Waterjet scaler	PM	HR01B	76	192	<10.0	**<0.052**
Manual scaler	AM	HR02A	175	448	11.0	**0.025**
Manual scaler	PM	HR02B	43	108	<10.0	**<0.092**
		Blank		---	<10.0	*Reporting Limit: 10.0 ug*
June 29						
		Sample	Time	Air Volume		
Subject		Number	(Minutes)	(Liters)	ug	**mg/m^3**
Waterjet scaler	AM	TR01A	96	233	<10.0	**<0.043**
Waterjet scaler	PM	TR01B	83	201	<10.0	**<0.050**
Manual scaler	AM	TR02A	87	209	<10.0	**<0.048**
Manual scaler	PM	TR02B	44	106	<10.0	**<0.095**
		Blank		---	<10.0	*Reporting Limit: 10.0 ug*

Crystalline silica analysis performed by an external lab. The lab is accredited by AIHA (ISO 17025) in this specific field of testing. No cristobalite and tridymite was detected in the samples above the Reporting Limit of 10.0 ug each.

Summary:

Although peak exposures were similar, waterjet scaling produced more noise than manual scaling. When fully functioning, the waterjet ACGIH TWA ranged from 80.8 to 85.6 dBA, while manual scaling ranged from 69 to 75 dBA. The ACGIH TLV 8 hour averaged standard is 85 dBA.

For dust exposure, both forms of scaling were below the Particles (insoluble or poorly soluble) Not Otherwise Specified [PNOS] inhalable standard of 10 mg/m^3. The waterjet scaling exposure averaged 0.62 mg/m^3 and the manual exposure averaged 1.6 mg/m^3.

Due to the brief duration of sampling for each trial, it was not possible to measure silica exposures below the ACGIH TLV TWA of 0.025 mg/m^3. The single exposure above the detection limit for our assays was 0.025 mg/m^3. To better characterize exposures, a longer duration of sampling would be needed.