A PERFORMANCE EVALUATION OF VARIOUS NOZZLE DESIGNS FOR WATERJET SCALING IN UNDERGROUND EXCAVATIONS

by

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ABSTRACT

The goal of this research was to evaluate the performance of various waterjet nozzles for the purpose of scaling in underground operations. While the benefits of waterjet scaling are known to various groups within the mining industry, a parametric evaluation of assorted nozzles has not been published and such information is not easily accessible to those interested in the technology. This research will help demonstrate the types of nozzles available for waterjet scaling and compare the performance characteristics of each. This research will also serve as grounds for future work in the implementation of waterjet scaling in the mining industry and further research dedicated to the improvement of waterjet scaling methods.

There was limited numerical evidence promoting any single nozzle over the others during the course of this research. The scaling experiments were conducted exclusively in hard rock excavations through the Idaho Springs Gneiss formation, which introduced an abundance of variables in the rock mass and made each scaling experiment unique. The conclusion of this research is, therefore, a subjective review of the operating performance of each nozzle with respect to the others.

Recommendations for the continuation of research would include experiments in more homogeneous rock types, the implementation of automated transverse motion, and further investigation into the optimization of pressure and flow rate.

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1. INTRODUCTION

1.1 Overview

A large number of accidents in underground mining are caused by rock falls and ground failure. A significant percentage of these injuries occur while scaling, which refers to the removal of loose and unstable rock from underground mine openings. A review of the Mine Safety and Health Administration (MSHA) accident and fatality reports for underground metal and nonmetal mines showed that nearly 1/4 of all fatalities were related to rock falls (O'Neil, 2001). About 1/3 of these fatalities involved scaling. Many of these accidents and fatalities could be eliminated through the implementation of technical ground control and drill-and-blast innovations. Safety could be improved by an integration of technical developments such as:

- Controlled blasting practices
- Remote scaling technology
- Roof support
- Ground monitoring systems

The focus of this research was to examine one component of this integrated strategy: remote scaling technology. It is believed that the utilization of a properly designed waterjet scaling system will provide significant improvements in worker safety over that of conventional manual or mechanized scaling methods by removing miners from hazardous areas and reducing their exposure to rock falls. Additional benefits of high pressure water include the increased scaling efficiency and substantial improvements in the adhesion characteristics of sprayed concrete as a ground support membrane.

1.2 Objective

The specific aim of this research was to evaluate the effectiveness of various nozzle types as viable alternatives to manual and mechanized scaling methods. The types of nozzles included a single orifice continuous jet, a dual orifice self-rotating jet, an acoustically pulsed single orifice jet, and a mechanically oscillated single orifice jet. To facilitate these project aims, a parametric analysis was proposed in order to compare the characteristics of each nozzle under a fixed set of operating parameters such as system pressure and flow rate. A research methodology was built upon the empiric results of prior work and procedures were formulated to address challenges identified during earlier experimentation.

This research was funded by the National Institute for Occupational Safety and Health (NIOSH) as a means of improving safety in underground excavations. This report provides an evaluation of the relative performance of various waterjet nozzle designs and is intended to serve as a basis for those interested in configuring a waterjet scaling system for a given set of operating conditions.

1.3 Background

The equipment and techniques used in scaling have remained essentially unchanged in the last twenty years. Mechanized scalers, which consist of hydraulic hammers or claws mounted to mobile carriers, are common in large underground operations. Manual scaling bars, however, remain standard-issue tools throughout the hardrock mining industry. Each method has advantages and disadvantages depending on the circumstances in which they are used. The introduction of waterjet technology is intended to substantially improve and, in many cases, replace conventional scaling methods in routine drill-and-blast operations.

1.3.1 Manual Scaling

A manual scaling bar usually consists of a hollow steel or aluminum rod, four to ten feet in length, with a solid pointed end (Figure 1.1). The end piece is pressed in or attached by a bolt and is slightly curved to provide a prying mechanism between rocks.

In general, the scaling bar is thrust repeatedly toward the rock surface and the resultant sounds help the miner determine if a particular rock is solid or loose. Hollow, dull tones indicate that a rock is loose, while solid, ringing tones are indicative of competent rock. Some rocks fall upon impact and others need to be pried down.

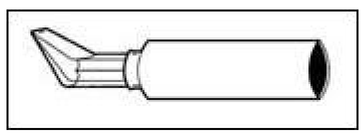

Figure 1.1 Tip of manual scaling bar

Scaling is a procedure performed at the start of a shift and intermittently as needed to insure that an area is safe. It is most commonly performed after a blast and therefore involves working atop loose and blocky material. The difficulty of walking over crushed rock while scaling is further compounded by the fact that freshly blasted surfaces must be wet-down in order to control dust. These conditions make it physically challenging to maintain footing while working over head and limit the miner’s ability to escape rapidly in the event of immediate danger from falling rock.

In underground developments of extreme size, man-lifts are commonly used to elevate workers for the purpose of scaling.

While this practice eliminates the tripping hazards associated with muck piles, the process remains extremely labor-intensive, and working from the confines of an elevated cage exposes miners to an entirely new set of hazards. One such incident involving a man lift was reported in an online publication by NIOSH (Pappas, 2003). According to the narrative, two miners were scaling from a man lift when a large rock fell and struck the corner of the basket. The weight of the large rock caused the boom of the man lift to bend toward the mine floor until the rock fell, at which point the boom catapulted upwards and threw the miners from the basket.

Manual scaling, whether performed from ground level or an elevated platform, puts the health and safety of miners at risk by exposing them to numerous hazards. The most significant exposure is to rock fall, caused not only by the act of scaling itself, but by the natural tendencies of unsupported ground to loosen and crumble. Additional hazards include trips, falls, and physical exhaustion which can reduce a miner’s ability to react to any of the aforementioned hazards.

1.3.2 Mechanized Scalers

Mechanized scalers are common in large underground operations. They are easily transported to new headings and are arguably the best tool for removing extremely large and unstable slabs from hard to reach places. They are usually mobile, diesel-powered vehicles equipped with hydraulic jack-hammers at the end of a heavy-duty extendable boom (Figure 1.2). Alternative designs may include a large, sharpened claw at the end of the boom with several axes of rotation and powerful prying action. Mechanical scalers are designed with dozens of features meant to keep the operator safe, but because of the inherent danger of scaling and the unpredictable nature of unsupported ground, accidents are known to happen.

Figure 1.2 Dux® DS30RB scaler

Mechanical scalers are impractical for smaller mining operations, where limited budgets and smaller tunnel dimensions may prohibit their use. In larger operations, they are confined by the specific operating envelope for which they are designed and are limited by height, access, and floor conditions. Models equipped with hydraulic jack-hammers are notorious for digging into softer varieties of rock and often create or propagate fractures adjacent to the point of impact. Unnecessary damage, inflicted upon the rock mass while scaling with high-powered equipment, increases the potential for rock fall.

2. LITERATURE REVIEW

2.1 Kiruna Mine Tests

The use of high pressure waterjet scaling has been tested in Sweden at LKAB's Kiruna mine as an alternative to mechanical scaling (Malmgren, 1999). A prototype rig was built which used a water pressure of 2900 psi and a flow rate of 55 gal per minute. The main ground support system at the mine consists of un-tensioned, fully grouted dowels and a sprayed concrete layer with an average thickness of 1.6 inches. Test were performed to evaluate the adhesion strength of sprayed concrete applied to rock surfaces cleaned by low pressure water and scaled with a high pressure waterjet. 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.

2.2 Skanska Tests

Results of a test project by the Swedish construction company Skanska to evaluate waterjet scaling are summarized in (Lundmark, T. and Nilsson, L. 1999). The tests were performed at the tunneling project in Halandsås, Sweden, from November to December 1998. A pressure of 4350 psi and a flow rate of 58 gallons per minute were recommended for use through a 0.177 inch nozzle.

The tests indicated that waterjet scaling requires less total time than mechanical scaling, especially when the number of blast rounds with under-break is minimized.

Verifying that waterjet scaling is less harmful to the rock than mechanical scaling was more difficult. It could, however, be visually observed that waterjet scaling caused less damage to the rock than a hydraulic hammer. The fact that the equipment did not have physical contact with the rock indicated that the forces transferred to the rock were not as high as with a hydraulic hammer.

The tests also indicated that the bond strength of shotcrete 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 water can not completely replace mechanical scaling in all cases, but is a good complement to mechanical scaling.

2.3 Falconbridge Tests

The results of a project intended to evaluate a water based liner material called TekFlex as a replacement for wire mesh are outlined in Swan, G. and Henderson, A. 1999. The work was performed by Falconbridge Limited at the Sudbury Operations, Ontario. TekFlex is supplied by the company Fosrok Inc. of Georgetown, Kentucky. 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 3600 psi water pump delivering 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, rock. 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, that is for the removal of large-scale loose in very blocky conditions.

2.4 MIRARCO

The Mining Innovation, Rehabilitation, and Applied Research Corporation, founded in 1998, is a not-for-profit applied research and technical service company formed through collaboration between Laurentian University and the private and public sectors. A division of MIRARCO known as The Centre for Mining Technology, located in Sudbury, Ontario, has conducted investigations into the applicability of high pressure waterjet scaling for underground hard rock drift development (Dunn, 2005). The ultimate aim of the project was to increase drift development rates. The project has been 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.

The waterjet research conducted by MIRARCO and Laurentian University utilized a 1500 psi jet running at approximately 60 gallons per minute. 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 6.5 and 10.0 feet. Refer to Figure 2.1 for a photograph of the waterjet scaling rig in action.

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 12 ft. scaling bar. 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. It was also envisaged that operations utilizing waterjet scaling would realize less damage to equipment where rock fall can be minimized.

Figure 2.1 Waterjet scaling rig by MIRARCO, Sudbury, Canada

The material that was removed during the waterjet scaling experiments was collected on tarps. The estimated weight of material removed during scaling ranged from 1,100 to 6,600 lb, and the largest single rock removed weighed approximately 1,100 lb. Laser scanning was also conducted on some of the drift headings before and after scaling. The difference in volume between the two modeled surfaces was divided by the actual surface area of the heading to convert the data to an average thickness of material removed.

2.5 CSM Tests

A series of experiments was conducted at the Colorado School of Mines Experimental Mine with the purpose of determining the change in adhesion strength of sprayed concrete as a function of the water pressure used to treat the underlying surface (Kuchta, 2002).

2.5.1 Determination of Working Pressure

Tests were performed on a concrete test wall, and on a section of drift in the Idaho Springs Gneiss rock type. In each case, as series of panels were first cleaned with high-pressure water, after which the panels were covered with sprayed concrete. The pressures used were 100, 1000, 2000, 3000, 4500, and 6000 psi. Bond strength was tested using sophisticated test equipment purchased from the company Swedish Concrete and Grouting Equipment AB.

The test results on the rock wall were inconclusive. Most of the breaks occurred in the rock itself instead of the concrete/rock interface due to the low tensile strength of the Idaho Springs Gneiss. However, the results on the concrete test panel showed a clear increase in bond strength as a function of the water pressure used to clean the underlying surface. Test results show an increase in adhesion strength by a factor of four on a concrete test wall cleaned with water at 3000 psi as compared to a surface cleaned at 100 psi. Tests at 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 3000 psi would be the optimal working pressure for further research in waterjet scaling.

2.5.2 Preliminary Waterjet Scaling Tests

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, Lorig, 2004). The carrier vehicle was a refurbished shotcrete truck donated to CSM by the Climax Molybdenum Company, which was 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. The dimensions of the drift were approximately 10 ft by 10 ft, and each advance was about 6 ft. The diameter of the drill holes was 1-5/8 inches, and smooth wall blasting was performed along the ribs and back. After each blast, the majority of the blasted rock was removed from the drift. The floor was then covered with a large tarp in order to collect the rock that would be 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 Figure 2.2.

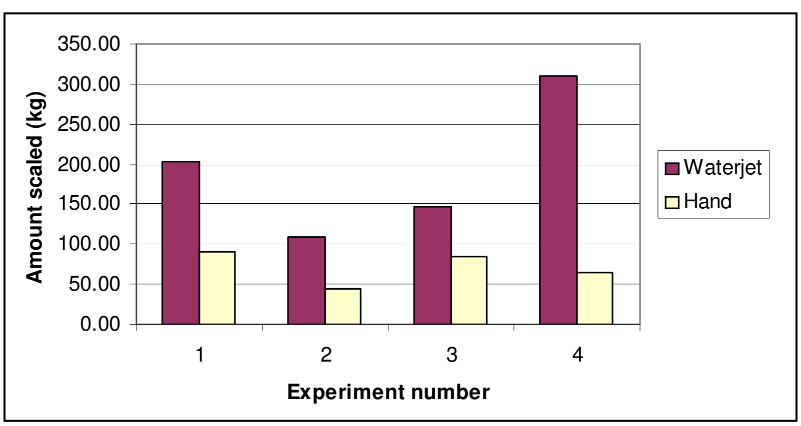

Figure 2.2 Material removed in four preliminary experiments

In each case, the amount of rock removed by the waterjet exceeded the amount removed by hand 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. 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, but a significant amount of material was removed by the waterjet scaling. Surprisingly, nearly as much material was removed again by the second hand scaling. This experiment also illustrates one of the dilemmas with trying to quantify the effectiveness of a scaling operation. It appears that the longer one scales the more material can be brought down. The results of the experiment are shown in Figure 2.3.

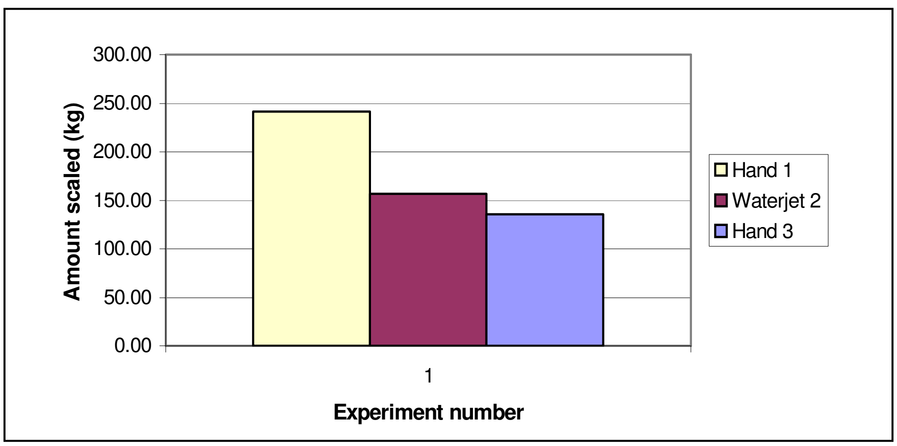

Figure 2.3 Material removed in fifth preliminary experiment

One additional scaling test was performed using a self-resonating pulsed waterjet nozzle purchased from Dynaflow, Inc. In this test, approximately 3200 lbs of rock was scaled with the waterjet and 57 lbs of rock was removed by the subsequent hand scaling. While these results were significantly better than any of the previous tests using the continuous jet, it should be noted that a single experiment is not sufficient to validate the pulsed nozzle. Furthermore, the rock mass that was scaled was highly altered and contained a great deal of clay like minerals, which can also partially explain the large amount of material that was scaled.

2.5.3 Conclusions

By observing the six waterjet scaling experiments, it was felt that the overall effectiveness of the scaling operation could be improved by rapidly moving the jet across the rock face. This idea was reinforced by observing that the loose rocks seem to fall just after the jet has passed. The rapid movement of the waterjet nozzle could be achieved by using a specially designed rotating nozzle, or by using an oscillating hydraulic head cylinder mounted at the end of the boom.

2.6 Additional Sources

A number of other companies, universities, and government agencies have also investigated the use of high-pressure waterjets in applications similar to rock scaling (Miller, 2007). These applications extend from the excavation and scarification of concrete liners to the removal of soot and diesel contaminants from tunnel surfaces. While this research has led to the commercialization of some of these technologies, much of the work has gone unpublished due to concerns over intellectual property and issues involving funding. Among the groups pursuing this type of research were the University of Missouri Rolla, Kidd Creek Mining Company, Canadian National Research Council, the U.S. Bureau of Mines, Fluidyne Corp., NLB, Hammelmann, Flow International, and International Engineering Technology, Inc.

Of particular relevance was a collaborative project conducted between Kidd Creek Mining and Fluidyne Corp. in the early 1990’s (Miller, 2007). This research focused on the use of high velocity, low frequency fluid pulses being produced by a water cannon to dislodge rocks inside of draw points accessing sublevel stopes. While the fluid pulses showed tremendous promise, the high stagnation pressures used (150,000 to 300,000 psi) created numerous mechanical problems related to seal life. This challenge eventually led to the discontinuation of the project.

3. WATERJET DYNAMICS

3.1 Introduction

This chapter outlines the characteristics of waterjets that make them effective for so many applications including scaling. The fundamental properties of various types of jets are described as well as the advantages and disadvantages they may have in certain applications.

3.2 Anatomy of a Waterjet

As water emerges from a nozzle, aerodynamic drag acts at the boundary of the stream, partially slowing the velocity of the jet (Conn, 1995). The aerodynamic forces cause the stream to spread, which often gives a false impression as to the quality of the jet. Inside the apparent spreading boundary is a central core that transmits the primary source of energy when impacted on the target surface. An exaggerated illustration of the central core and spreading boundaries are shown in Figure 3.1.

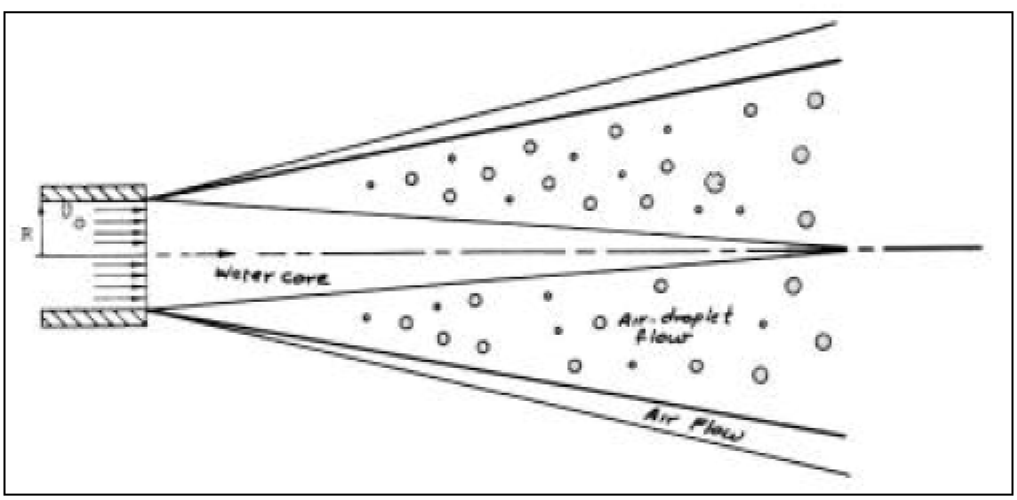

Figure 3.1 Water cone within a jet stream (Eddingfield, 1981)

The length of the central core region will vary depending upon nozzle design and flow conditions within the system. Poorly designed nozzles with sharp edges and poor upstream conditions, including abrupt discontinuities between the entry pipe and nozzle, can cause the stream to break up immediately after leaving the nozzle (Conn, 1995). For well designed nozzles operating under good conditions, the length of the central core may be 150 to 200 times the diameter of the nozzle orifice (Summers, 1995). Certain applications, such as cutting and machining, rely upon the convergence of the waterjet stream at a precise distance for optimal productivity.

Beyond the tip of the pressure cone, the free stream disintegrates into a highly complicated flow pattern that eventually separates into individual droplets. The mass and velocity of these water droplets are still capable of transmitting force upon a surface and doing productive work, but their behavior is less predictable and the process becomes less efficient. For certain applications, such as commercial cleaning at relatively lower pressures, this type of jet behavior may be acceptable.

3.3 <u>Kinetic Energy</u>

From a simplistic viewpoint, the energy per unit volume transmitted to a target surface by a waterjet can be represented by the basic equation for kinetic energy, which is:

$$E = \frac{1}{2} M V^2 \qquad (3.1)$$

M	: Mass Flow Rate	[kg]
V	: Velocity	[m/s]

It should be noted that this equation does not take into account the velocity components of aerodynamic drag and individual flow elements within the stream. The calculation of kinetic energy does not necessarily designate the productivity of a waterjet, which is a complex function of nozzle design, flow conditions within the delivery system, and operational parameters such as standoff distance and nozzle motion. Without proper considerations of such parameters, a highly energetic fluid stream may be incapable of doing productive work.

The calculation of kinetic energy is most often used as a basis for determining the efficiency of a waterjet system, wherein potential energy (pressure) is converted to kinetic energy (velocity). The efficiency of the system can, in turn, be used to calculate power consumption and the size of pump needed to generate the desired pressure at the target surface. Moreover, system efficiency is widely used as criteria for component design and selection.

3.4 <u>Jet Velocity</u>

Water is traveling at very high velocity when it leaves the orifice of a high pressure nozzle. For a known volumetric flow rate, the speed at which high pressure water leaves the nozzle orifice can be illustrated through the following basic principle of fluid mechanics:

$$V = \frac{Q}{A} \tag{3.2}$$

V : Velocity		[ft/s]
Q : Flow Rate		[ft^3/s]
A : Cross-Sectional Area of Nozzle		[ft^2]

For a waterjet known to operate at 28.5 gpm (0.0635 ft^3/s) through a nozzle of diameter 0.140 inches (area 1.069 x 10^{-4} ft^2), the resultant velocity of the fluid is as follows:

$$V = \frac{0.0635 \frac{ft^3}{s}}{1.069x10^{-4} \, ft^2} = 594 \frac{ft}{s} \tag{3.3}$$

This calculation assumes a discharge coefficient of unity. The discharge coefficient is an experimental factor which accounts for the flow cross-sectional area of a nozzle being less than the actual cross-sectional area (Conn, 1995). All values of discharge coefficients are less than unity, and typically range from 0.6 for poorly designed nozzles to 0.9 for well designed nozzles. The above calculation, performed without the discharge coefficient, provides a low estimate of jet velocity by assuming a maximum value for the cross-sectional area of the nozzle. Inserting a discharge coefficient (C_d) of 0.9 to the above calculation would appear as follows:

$$V = \frac{Q}{(C_d) * A} = \frac{0.0635 \frac{ft^3}{s}}{(0.9) * 1.069x10^{-4} \, ft^2} = 660 \frac{ft}{s} \tag{3.4}$$

The velocity of a waterjet can also be estimated based on the operating pressure. The following equation is generally regarded as a quick and relatively accurate means of determining jet velocity based exclusively on system pressure (Conn, 1995):

$$V = 12.19 * \sqrt{p} \tag{3.5}$$

V: Velocity [ft/s]

p: Pressure [psi]

For a waterjet operating at 3200 psi, the calculation of jet velocity is as follows:

$$V = 12.19 * \sqrt{3200} = 689 \frac{ft}{s} \quad (3.6)$$

The discharge coefficient can be accounted for by simply multiplying the result of the previous calculation by the necessary value. For the waterjet operating at 3200 psi through a nozzle with a discharge coefficient (C_d) of 0.9, the calculation is as follows:

$$V = C_d * 12.19 * \sqrt{p} = 0.9 * 12.19 * \sqrt{3200} = 620 \frac{ft}{s} \quad (3.7)$$

3.5 **Transverse Speed**

Transverse speed is the velocity at which the waterjet nozzle is moved across the work surface. In most applications such as cleaning, the energy efficiency of a waterjet increases with nozzle traverse velocity. The introduction of rotating waterjets was one of the most significant advancements in efficiency for applications where high traverse speed is required. Attempting to move a single orifice, continuous jet laterally across a work surface at several hundred feet per second is difficult, but rotating the nozzle at high speeds can be accomplished rather easily with modern mechanical components. Most industrial cleaning operations are done with rotating nozzle heads.

It may also be possible to move the jet too fast in certain applications such as the cutting of thick metals, where the jet must be allowed time to penetrate the material. Finding the optimal traverse speed requires calculations based on the type of application, properties of the target surface, and the jet pressure and flow rate employed.

3.6 Failure Mechanisms

Waterjets are able to perform work because of several fundamental mechanisms that correlate the properties of the target medium with the impingement characteristics of water.

3.6.1 Pore Pressure

For many cleaning and cutting applications, the destructive force of a continuous round waterjet can be credited to its ability to exploit the imperfections in the surface of a medium. One of the most useful applications of waterjets is for the cleaning of coke ovens, heat exchanger tubes, and piping networks. The material deposited on the walls of such systems is difficult to remove mechanically, yet it's typically vulnerable to waterjets. This is the consequence of the jet attacking the contaminant in a preferential manner through point loading and the penetration of the material's matrix. Failure mechanisms include tensile and shear.

3.6.2 Granular Erosion

Applications associated with the cutting of sandstone, granite, concrete, and other similar materials with continuous waterjets rely on direct granular erosion. The process of direct granular erosion involves the removal of the weakest elements within the rock mass and a resultant breakdown of the material matrix. As one layer is being stripped from the surface of the slot, the waterjet continues on its path and begins to strip the next. Granular erosion also describes the cutting of softer materials such as food products, where the porosity and granular structure of the material is irrelevant due to the low strength of the material and high speed of the jet. In either case, the material is simply taken away by the waterjet stream.

3.6.3 Shear and Tensile Failure

A pulsed waterjet modulates or disrupts the flow of water at a specific frequency and generates a series of individual water slugs within the stream. The impingement of a pulsed stream produces discrete loading and unloading on the material surface, which very quickly leads to fatigue. The behavior of the material under shear and tensile failure is not always as predictable as with granular erosion, but it can be valuable in hydro-demolition and cleaning of very hard materials.

3.7 Applicability in Scaling

While the dynamics of waterjets and material behavior for numerous applications has been thoroughly examined and modeled by researchers worldwide, the nature of scaling and the number of variables in a scaling environment have thus far prevented such detailed analysis.

It is believed that there are several principles at work simultaneously when waterjets are used for scaling. One basic theory asserts that the differential loading caused by the passing of a high energy water stream provides the force necessary to remove fractured rock from its position. As the jet impinges upon the rock surface, displacement occurs along the discontinuities, and when the load is removed the frictional forces are overcome and the rock falls. This theory is validated by the observations noted in previous research, where some of the rock seemed to fall once the jet has passed (Kuchta, 2002).

Another principle at work is the penetration of the water within the cracks and voids of the fractured rock mass. As the jet passes over a discontinuity, the void is rapidly pressurized and the material on opposing sides of the crack is forced away from each other. This theory may also be referred to as the water wedge theory.

Another principle is described as a type of keystone theory. As water enters the shallowest of cracks and discontinuities in the rock mass, small and oddly shaped pieces of rock are the first to be removed. The absence of these pieces exposes further cracks and discontinuities and leads to the loosening of larger pieces beyond. Although the same type of progression takes place when scaling by hand, the waterjet accomplishes the task in fractions of a second and provides a remarkably clean surface by removing fines.

4. METHOD AND APPROACH

4.1 Introduction

This chapter describes some of the general attributes of the research including the location of the research facility, basic methodology, equipment, and procedures.

4.2 Location of Research Facility

The waterjet nozzle tests were conducted at the Colorado School of Mines, Edgar Experimental Mine in Idaho Springs, CO. The Edgar Mine was an active base metal and silver mine until it was handed over to the Colorado School of Mines in 1921. It is located about 30 miles west of Denver on Interstate 70. The general location is shown on the map of Colorado in Figure 4.1.

Figure 4.1 Location of Edgar Mine indicated by red star at left

The mine property used in this research originally consisted of one long tunnel, known as the Miami Tunnel, when it was acquired by CSM. Decades of student training brought about several interconnected drifts, and a U.S. Army research program provided a second adit to the west known as the Army Adit. The two systems of drifts were connected in 2006, and the connecting drift became the home to the waterjet nozzle testing experiments. A complete and current map of the Edgar Mine workings can be seen in Appendix B.

4.3 Geology

The Edgar Mine lies within the Precambrian Idaho Springs Formation, which is made up of highly altered gneiss, pegmatite intrusions, schist, and granite. 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. More detailed accounts of the geologic features and conditions present for each experiment can be found in the Chapter 6.

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 through the workings of the mine, and the infrastructure of discontinuities above and below the main level of workings are known to run with water during wet seasons. Though a majority of the host rock is rather hard, the geologic features and climatic conditions require that the underground workings receive periodic attention to prevent small-scale failures and rock fall.

4.4 <u>Basic Methodology</u>

The content of this research included ten experiments with four different types of waterjet nozzles. Each nozzle was tested twice and two additional experiments were performed in reverse order (manual scaling, then waterjet). The reverse order experiments demonstrated the effectiveness of waterjets over manual scaling by proving that more material could be brought down afterward. All material removed during scaling experiments was collected on tarps and weighed using five gallon buckets and a portable spring scale. Rocks and boulders too large to weigh were given estimated weights.

The material removed during the first five experiments was screened as a means of determining the differences in material size distribution between manually and waterjet scaled material. All of the material below 1.5″ screen size was split into smaller samples for screening and the results were applied proportionally to the whole.

There were two types of blasting methods used between the first and last five experiments. The first five experiments were shot exclusively with ANFO and stick powder boosters in representation of conventional blasting procedures. For the last five experiments, smooth wall blasting techniques were applied, wherein more perimeter holes were drilled and loaded with less powerful explosives for a smoother resultant surface. The smooth wall blasting was conducted in order to demonstrate the correlation between controlled blasting, rock mass damage, and the amount of scaling required.

4.5 Equipment

A waterjet scaling system requires many of the same components used in other waterjet applications, including:

- High Pressure Pump
- Flow Controls and Safety Accessories
- Power Source (Electrical System)
- Water Supply
- Nozzle Motion System
- Hoses and Fittings

4.5.1 High Pressure Pump

The pump used to supply high pressure water to the nozzles was a Wheatley Quintuplex model 5P-323 purchased in August of 2002 from Armstrong Machine Company of Pocahontas, Iowa. The pump was mounted on skids together with a rebuilt 480-volt, 100 HP General Electric motor. The pump was originally fitted with one-inch plungers and the pump/motor system was configured to run at 500 rpm. According to the specifications delivered with the pump, this configuration was to provide 27 gpm at 5100 psi.

During an extended period of inactivity at the Colorado School of Mines Edgar Mine, the pump cylinders developed leaks and failed to operate according to specification. In order to provide optimum performance during the conduction of these experiments, the pump was transported locally to an authorized Wheatley service center in December of 2005. Repairs were performed on critical seals to eliminate leakage and new plungers were installed to provide an operating pressure of approximately 3500 psi at 30 gpm. Figure 4.2 contains a photograph of the pump.

The pump was positioned underground in a crosscut that was close to the research area yet protected from blasting concussions and fly rock. To avoid frictional losses that can be expected in extended lengths of high-pressure hose, the pump was kept within 200 feet of the scaling experiments.

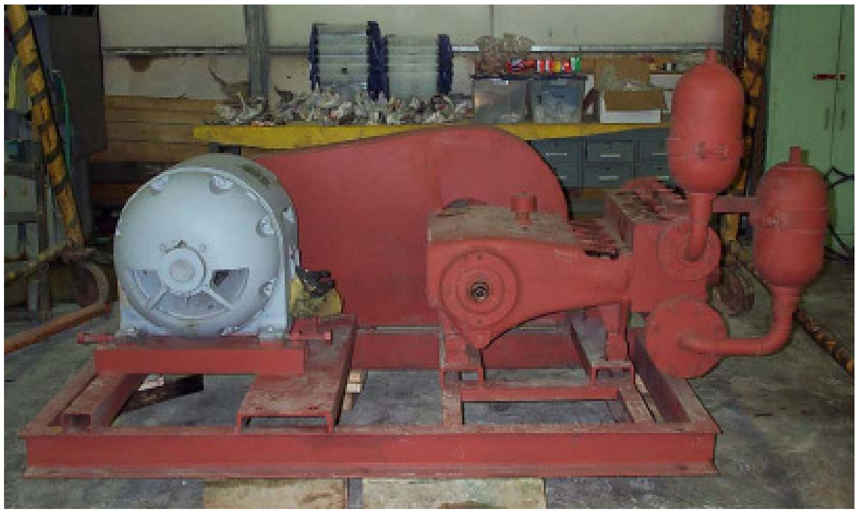

Figure 4.2 Wheatley Quintuplex high-pressure pump

Determination of the operational parameters of the pump, including pressure and flow rate for any given nozzle diameter, required a repetitive testing process with several different nozzles. The graphical results of such a test are commonly referred to as a pump curve, where pressure and flow rate are plotted along the X and Y axes respectively. The curve provides a quick reference of the relative pressures and flow rates that can be achieved by the pump. The curve generated by the rebuilt Wheatley Quintuplex pump is shown in Figure 4.3, and detailed records of the data can be found in Appendix C.

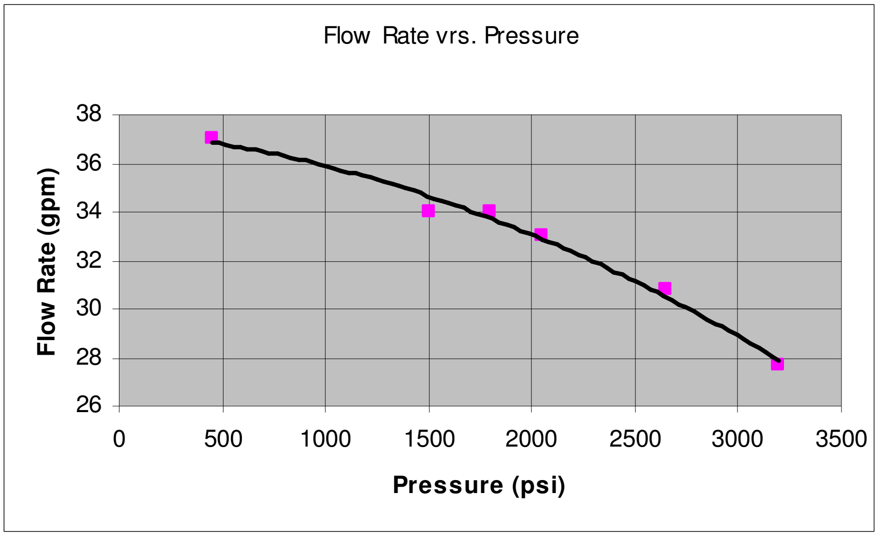

Figure 4.3 Pump Curve for Wheatley high pressure pump.

4.5.2 Flow Controls and Safety Accessories

The outlet of the pump was equipped with an assortment of valves and fittings designed to ensure safety during operation at high pressure. The assembly consisted of a pressure gauge, a flow control valve with bypass circuit, and a rupture disc. A generic photograph of similar flow controls, from right to left respectively, is shown in Figure 4.4.

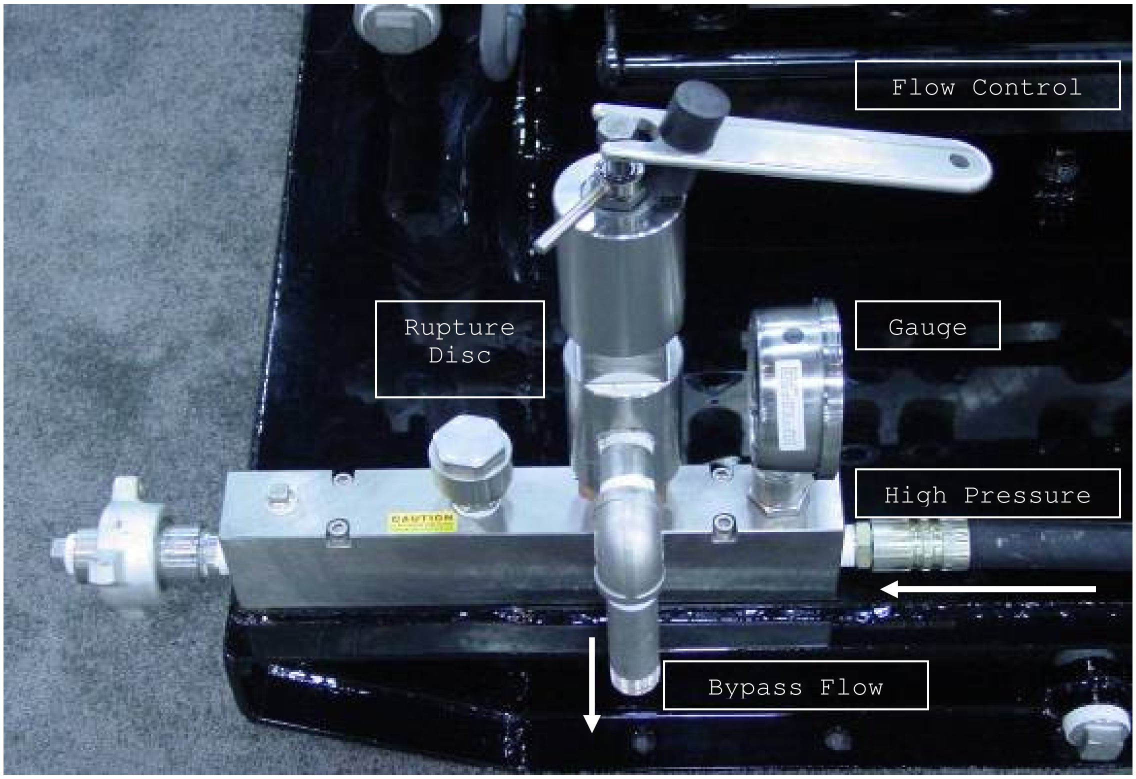

Figure 4.4 High pressure flow controls.

The pressure gauge was a standard analog needle type with surge dampener that read from 0 to 5000 psi in 100 psi increments. The flow control valve was used to increase and decrease the pressure of water going to the nozzle at the beginning and end of each use. When in bypass mode, it directed the flow of water through an auxiliary hose at low pressure, eliminating sudden increases in system pressure when the pump was turned on. A rupture disc acts as an emergency pressure relief valve in the event of a malfunction within the system. In the presence of extreme pressure (5000 psi), the replaceable disc is designed to fail.

4.5.3 Electrical System

A 480 volt electrical substation was installed near the research area to accommodate the operation of the pump and other high-powered underground equipment. The substation, which distributes power supplied from the surface, was located on a raised concrete platform with several four inch, concrete-filled steel pipes standing vertically at its perimeter. A heavy duty motor starter was also required to supply power to the 100 hp pump motor. The motor starter was mounted to vertical rails, which were anchored in the rib of the crosscut next to the pump.

4.5.4 Water Supply

Water was supplied from a 4800 gallon plastic water reservoir system located approximately 300 feet away from the high pressure pump. A 10 hp rotary pump, capable of maintaining 100 psi and up to 100 gpm in the water supply lines, was located at the reservoir. It is always necessary to supply a high pressure pump with adequate flow rate in order to avoid internal damage. The water reservoir and 10 hp supply pump can be seen in Figure 4.5.

Figure 4.5 Water reservoir and priming pump

4.5.5 Carrier Vehicle

The vehicle used to provide motion to the waterjet nozzle was a custom-built Eimco® shotcrete application rig donated to the Colorado School of Mines by the Climax Molybdenum Company. The vehicle was donated to CSM in good running condition many years before the launch of this research and came fitted with a 15 ft extendable, hydraulically-actuated boom. The original setup of the vehicle was unknown. A photograph of the waterjet carrier vehicle is shown in Figure 4.6.

Figure 4.6. The CSM waterjet carrier vehicle

The carrier vehicle is equipped with a six cylinder Deutz® diesel engine, which also supplies power to the hydraulic system. The extendable boom can be operated manually by a series of five hydraulic valves and levers or remotely with a 12-volt electric joystick box, which was purchased and installed specifically for this research.

4.5.6 Hoses and Fittings

Water at high pressure was conveyed to the nozzle by heavy duty 3/4" internal diameter flexible hose. The thick-walled, multi-ply hose measured approximately 1.5" outside diameter and was rated for 10,000 psi. Two individual pieces at lengths of 100 ft were purchased, but only one was used until the distance from pump to scaling area exceeded 100 ft. When needed, the two hoses were connected by quick-release high pressure couplers.

A 20 ft length of high pressure 3/4" hose was mounted to the boom of the carrier vehicle. The rear end connected to the other conveying lines by means of an additional quick-release coupler. The forward end had a female threaded fitting matched to a ten inch high pressure pipe. The purpose of the pipe was to provide a clamping surface at the boom interface and to straighten the flow of the high velocity, high pressure water before it entered the nozzle. The hose, fitting, and pipe are shown in Figure 4.7.

Figure 4.7. High pressure hose, female end fitting, and pipe.

Each of the nozzles had a female threaded end capable of mounting directly to the ten inch pipe. The nozzles were tightened to the pipe using an open end wrench and a pipe wrench. Teflon tape was wrapped around the pipe threads each time a nozzle was removed and installed.

4.6 Setup and Preparation

Each of the nozzle tests was preceded by several days of preparation. The completion of the setup work depended upon the reliability of the mining equipment, the schedules of the mine employees and facilities, the weather, and the chance of unforeseen problems. The routine of preparatory activities included the following:

- Clear drift floor
- Drill new round

- Load and blast
- Partially remove/level muck pile

Though the list appears short and simple, each of these activities required preparation and setup in its own respect.

4.6.1 Clearing of Drift Floor

For any nozzle test, preparation would begin by clearing the drift floor of any remaining muck from the previously blasted round using a Wagner LHD with a two cubic yard bucket. The duration of this task depended upon the amount of muck that needed to be moved, the size of blocks present in the muck and the difficulty involved in loading it, the distance to the nearest muck storage bay, and the dependability of the equipment.

4.6.2 Drilling of New Round

Each new round was drilled using a single-boom Atlas-Copco drifter capable of drilling holes 10.5 feet in length and up to 4.0 inches in diameter. The holes that were drilled for the experiments were 1.875 inches in diameter and 10 feet long.

For each experiment, a series of holes was drilled in the back and left rib of an existing drift. This method of expanding the cross sectional area of a drift is commonly referred to as slashing. Slashing provided the freshly blasted surface on which the scaling experiments were conducted, yet it saved time and money over the development of a new, full-sized drift. In most of the experiments, the existing drift was eight feet high and eight feet wide and was expanded to twelve feet in both dimensions. Each drill pattern was unique but typically consisted of two columns of holes along the left rib and two rows of holes along the back. Several additional holes may have been required depending upon the shape of the drift.

The spacing between the perimeter holes and, thus, the total number of holes drilled depended upon the type of blasting that was being practiced. Two types of blasting were used during the course of this research. The first five experiments utilized standard blasting techniques, in which all holes, except for the lifters, were loaded primarily with a blasting agent called ANFO (Ammonium Nitrate and Fuel Oil). The perimeter holes were spaced between 2.0 and 2.5 feet when ANFO was being used as the main explosive. A typical drill pattern for slash rounds being shot with ANFO is shown in Figure 4.8.

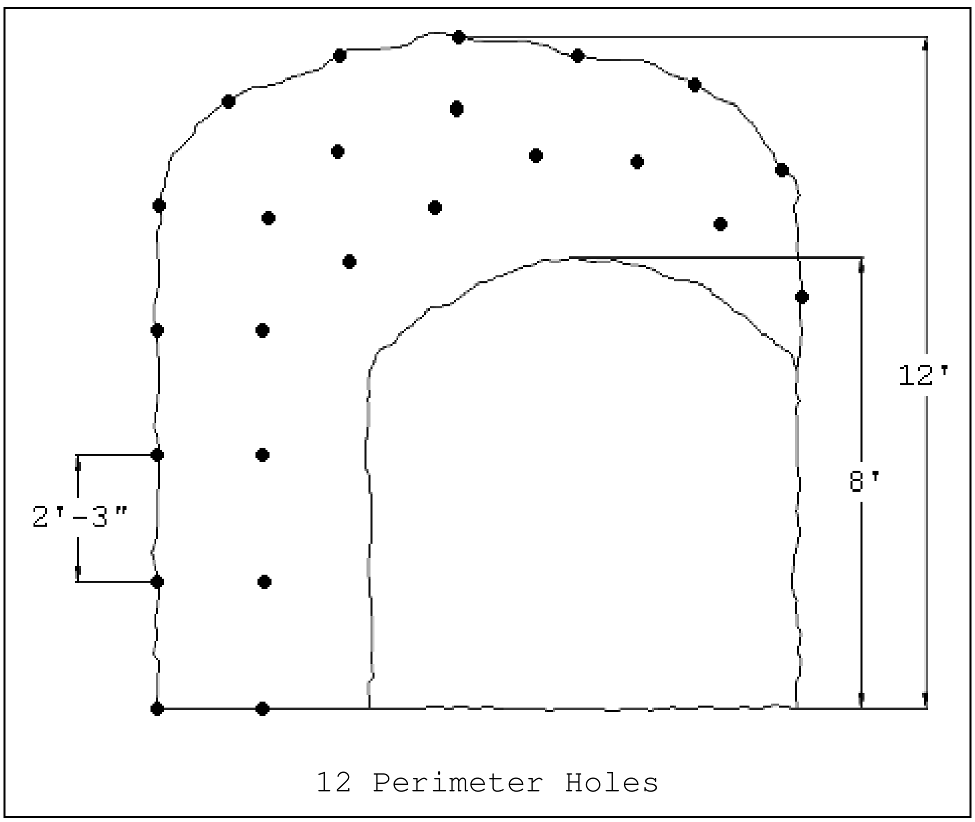

Figure 4.8 Blast pattern for use with ANFO blasting agent

The last five experiments utilized smooth wall blasting techniques, in which a small amount of high explosives are used to initiate detonation, and the rest of the hole contains a less powerful explosive. The use of less powerful explosives resulted in less damage to the rock mass and a smoother finished surface.

In order for the less powerful explosives to fracture the rock, the holes have to be spaced slightly closer together. A typical drill pattern for slash rounds shot with smooth wall blasting techniques is shown in Figure 4.9.

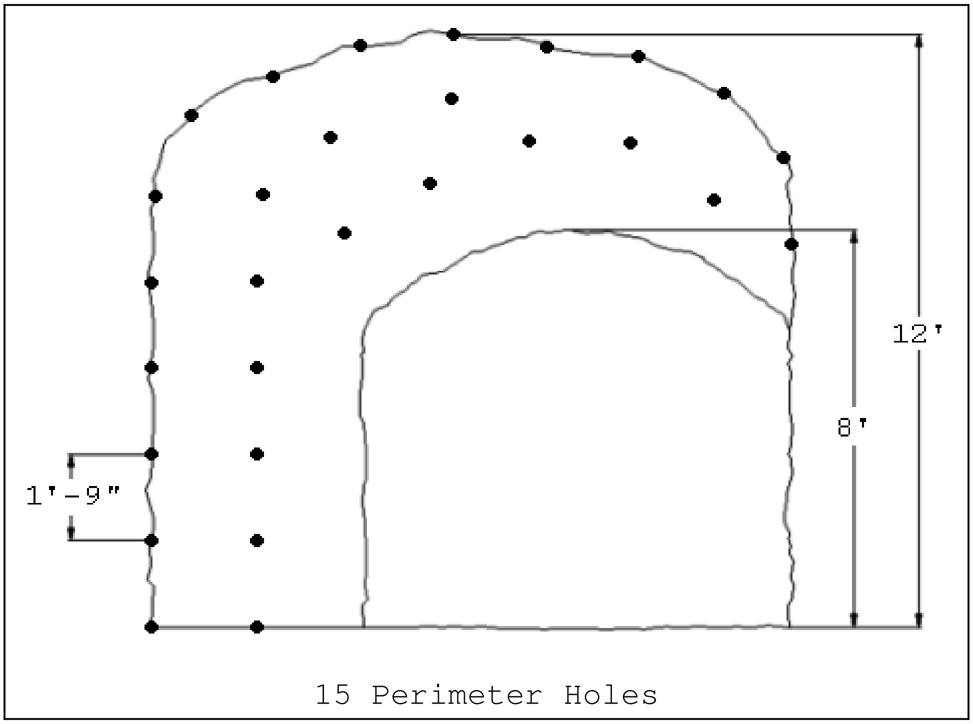

Figure 4.9 Blast pattern for use with smooth wall explosives

4.6.3 Loading and Blasting

The process of loading a round required several hours and, ideally, would commence at the start of the day. Edgar Mine policy required an inventory of the explosives magazine before any items were removed, and all specific equipment had to be set up underground prior to obtaining the explosives.

All personnel and equipment required for the continuation of the scaling experiment had to be in place before proceeding with loading and blasting. If the heading was blasted but a lack of working machinery prevented the continuation of the experiment, the freshly blasted rock surface could have been left sitting for several days before scaling. This had to be avoided for the sake of balance between experiments, because the air slacking of the fragmented rock over time may have produced abnormal amounts of fallen material compared to a surface that is scaled immediately after blasting. Rounds would primarily be shot late in the morning, allowing the blasting fumes to ventilate during lunch and opening up the entire afternoon for scaling.

4.6.3.1 Standard Blasting Technique

The first five experiments were charged with standard explosives consisting primarily of ANFO. Each hole was primed with an eight-gram blasting cap and a stick of emulsion, and approximately 9 feet of the hole was filled with compacted ANFO. The lifters were charged with packaged emulsion to prevent interaction with water. Figure 4.10 shows the cross sectional diagram of a typical drill hole loaded with standard explosives.

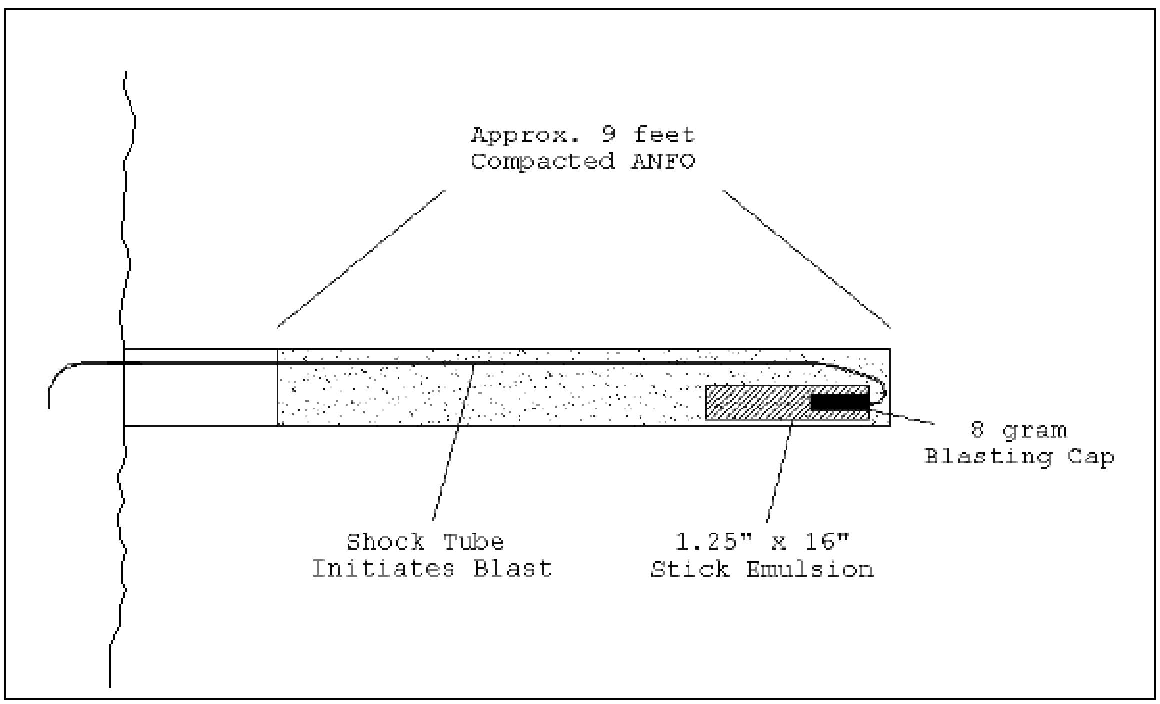

Figure 4.10 Cross section of drill hole loaded with standard explosives (not to scale)

4.6.3.2 Smooth Wall Blasting Techniques

In the last five experiments, smooth wall blasting was practiced, in which fracturing of the rock mass between perimeter holes was accomplished by less powerful explosives. Each of the perimeter holes was primed with an 8-gram blasting cap, a stick of emulsion, and approximately 1 foot of compacted ANFO to keep the emulsion in place. The rest of the hole contained a hollow, red plastic tube approximately one half inch in diameter that was filled with explosives. This tube was known as 200 grain detonating cord. Drill holes that were not on the perimeter of the drift profile were charged with ANFO, and lifter holes were charged with packaged emulsion to prevent interaction with water. Each of the perimeter holes was plugged with a rubberized plastic cone that was forced into the hole with a specialized hammer. Figure 4.11 shows the cross sectional diagram of a typical perimeter drill hole loaded with smooth wall blasting explosives.

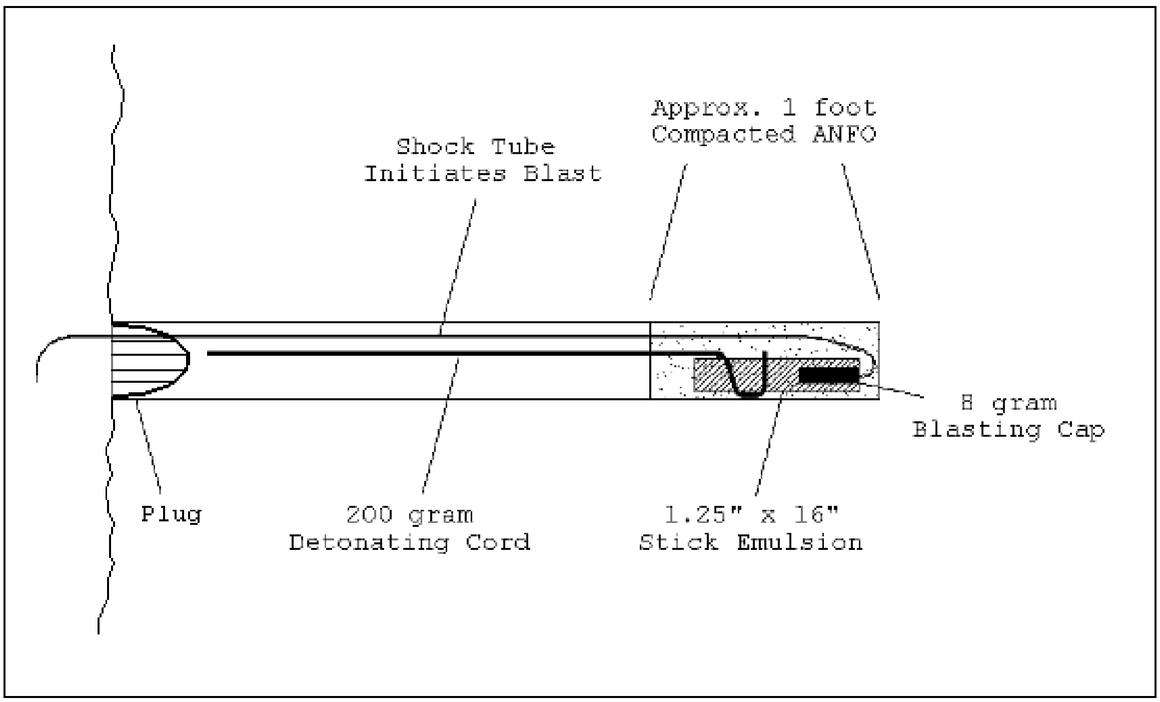

Figure 4.11 Cross section of drill hole loaded with smooth wall explosives (not to scale)

The 200-grain detonating cord was inserted twice through the stick of emulsion in order to reduce the chance of misfiring. It also helped prevent separation between the emulsion and the detonating cord in the event that the explosives had to be pulled from the hole for any given reason. A photograph of the 200-grain detonating cord and shock tube attached to the stick of emulsion is shown in Figure 4.12.

Figure 4.12 Stick of emulsion primed with an 8-gram blasting cap and attached to a 200-grain detonating cord

4.6.4 Partial Muck Removal

Removal of the freshly blasted rock began by spraying the mine road and the muck pile itself with water. This process reduced the amount of dust generated during mucking and allowed the muck pile to be inspected for misfires from the previous round. Several buckets were then removed by the LHD, and the remaining muck was leveled and used as a platform for scaling.

4.7 Scaling Procedures

The execution of nozzle tests required a strict routine to ensure safety and regularity between tests. The procedures involved with the execution of the experiments included the following activities.

4.7.1 Spreading Tarp

Below the freshly blasted heading, a tarp was laid out to catch the material that fell during scaling. The extra-large tarps were usually centered on the heading with several feet of coverage beyond the ends of the scaling zone. The corners were weighed down and the edges were pushed to the ribs to avoid the loss of scaled material.

4.7.2 Positioning of Scaling Vehicle

The carrier vehicle used to control the motion of the waterjet was most often parked underground, in a non-active crosscut of the Army drift. When moved into position for an experiment, it was first parked in a relative proximity to the heading. The first stage of the boom was then manually extended, and the vehicle was given its final position when the end of the boom was beneath the scaling area. The tires were chocked for the duration of the experiment.

The vehicle was usually left running from the time it was parked to the time the scaling experiment was over, as the diesel power was needed to operate the hydraulics of the boom. The lights mounted to the vehicle provided additional illumination in the drift.

4.7.3 Work Lights

Primary lighting was provided by a halogen industrial lamp mounted to an extendable tripod. The unit was placed as close to the heading as possible without interfering with the motion of the boom.

4.7.4 Photographs

When lighting for the experiments had been set up, pre-scaling pictures were taken of the empty tarp and blasted rock surface. Photographs were also taken immediately after the scaling experiment was complete.

4.7.5 Hoses

The high-pressure conveying hoses were unreeled from their resting position near the pump to the rear of the scaling vehicle. A single 100-ft hose was used for the first few experiments, and an additional 100-ft hose was later added when needed. The ends of the hose were wrapped with cotton rags when not in use to avoid contamination from dust and rocks.

4.7.6 Flushing of Water Lines

When the hoses were reeled out and connected to the scaling vehicle, the priming pump located at the water reservoir was turned on. With the high pressure pump turned off, water was flushed through its intake, cylinders, and output, and through the conveying hoses to the nozzle interface. The nozzle was removed during the flushing of the lines to avoid unnecessary abrasion with the dirty water that was likely to come through the lines for the first few minutes. When the water ran clear, the valves were closed and the nozzle was attached.

4.7.7 Remote Control Joysticks

The manipulation of the hydraulic boom was controlled by dual electronic joysticks, which were connected to the carrier vehicle's hydraulic valve system and 12-volt power through a heavy duty 24-pin connector and cable. The joysticks were purchased through Shotcrete Technologies of Idaho Springs, CO as they were originally designed for shotcrete application.

The joystick box was attached to a canvas strap which was worn around the neck of the operator. Functions included tilt, swing, and extension of the main boom, as well as tilt and rotation of the nozzle. An auxiliary button, capable of supplying power for oscillation of the nozzle, was not used. The joystick apparatus is shown in Figure 4.13.

Figure 4.13 Joysticks for operation of hydraulic boom

4.7.8 Recording Time and Notes

Before the initiation of the scaling experiment, the time was recorded in a field notebook along with any significant points of interest. Additional notes typically consisted of predictions whether the jet would perform well, observations of the rock quality, and comments on the working condition of the equipment.

4.7.9 Waterjet Scaling

Scaling would begin as soon as the high pressure pump was brought to full pressure. At the start of the experiment, the boom would be retracted, and scaling would commence by sweeping the boom left and right between ribs. The boom was extended approximately 6 inches each time the nozzle came to a rib, and the height of the boom was adjusted as the height of the back changed in an attempt to maintain a standoff distance of approximately 12 inches. The top 1 – 2 feet of each rib was scaled by tilting and rotating the nozzle as needed. Areas noted before the start of the experiment as being highly fractured were usually given special attention and targeted from several different angles.

4.7.10 Material Collection

When waterjet scaling was complete, an additional tarp was spread over the fallen material, and manual scaling was performed immediately thereafter. By doing so, the back was scaled more thoroughly before mine employees entered the area to collect rocks from the floor. The material was gathered in five-gallon buckets and weighed from a hanging spring scale. Rocks that were too large to fit in a five-gallon bucket were hung from the scale by a makeshift sling, and rocks that were too large for the sling were given estimated weights.

4.8 Screening Procedures

The material collected during the first four experiments was screened in order to determine the particle size distribution. The following sections describe the methods used to collect the screen analysis data.

4.8.1 Transport of Scaled Material

The material that was removed during waterjet scaling was saturated with water and required several days to dry before it would be able to pass through screens. All of the material was transported immediately after the termination of the experiment to an empty cross cut near the site of the tests. The material was allowed to dry for 2-4 days and was protected from disturbance by its somewhat remote location. Large blocks were loaded into an excavator bucket for transport, and the rest of the material was carried in 5 gallon buckets.

4.8.2 First Stage of Material Sorting

Classification of the screened material began with all material greater than 6.0 inches in any single dimension. Measurement was provided by a custom-made wooden frame with a single 6.0 inch square opening, and all material was passed through manually. Quick visual inspection was the basis for selection of material to measure, and all rocks judged to be close were measured.

The next size down in classification was for material greater than 4.0 inches but less than 6.0 inches. Measurement was provided by a similar custom-made frame, and visual inspection was again the basis for determining which individual rocks to measure.

The next three sizes in classification were separated using large rectangular screens. Each screen was 18 x 26 inches in overall width and length, which was convenient for the volume of material that needed to be sorted. The sizes of the three screens were 3.0 inch, 2.0 inch, and 1.5 inch.

Once the scaled material had been reduced to minus 1.5” screen size, the sample was reduced using a sample splitter. Shown in Figure 4.14, the splitter is loaded from the top and directs flow of the material into two directions. Half of the sample was split again, and a total of approximately 1/4 of the material below 1.5" was taken back to the CSM campus for further sorting.

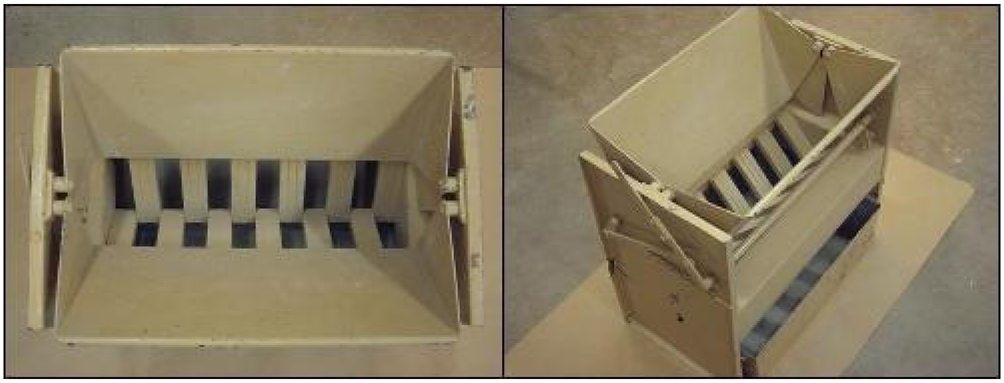

Figure 4.14 Sample splitter

4.8.3 Sorting of Fines

The amount of material taken back to the CSM campus for sorting usually occupied two 5-gallon buckets. A tarp was spread out over the floor of a general use laboratory and the material was shaken through standard 8" diameter screens. The sizes of screens used (in inches) included:

- 1.0
- 0.742
- 0.500
- 0.375
- 0.263
- 0.187

All the material below 0.187 inches in size was categorized as a single component. The weight of material in each individual size classification was taken using a precise metric scale. The numbers were recorded in grams, and conversions were performed to represent the weight to the nearest tenth of a pound.

5. THE NOZZLES

5.1 <u>Introduction</u>

This chapter describes and illustrates the nozzles that were tested during the course of this research. Unless otherwise noted, the photographs provided are of the actual nozzles used in the experiments.

5.2 <u>Single Orifice, Continuous Jet</u>

The most basic waterjet nozzle directs and accelerates water through a single orifice and emits a continuous stream. The assembly used in this research consisted of a small, machined carbide nozzle with a 0.140” orifice held in place by a steel fitting. The single orifice nozzle and fitting used are shown in Figure 5.1.

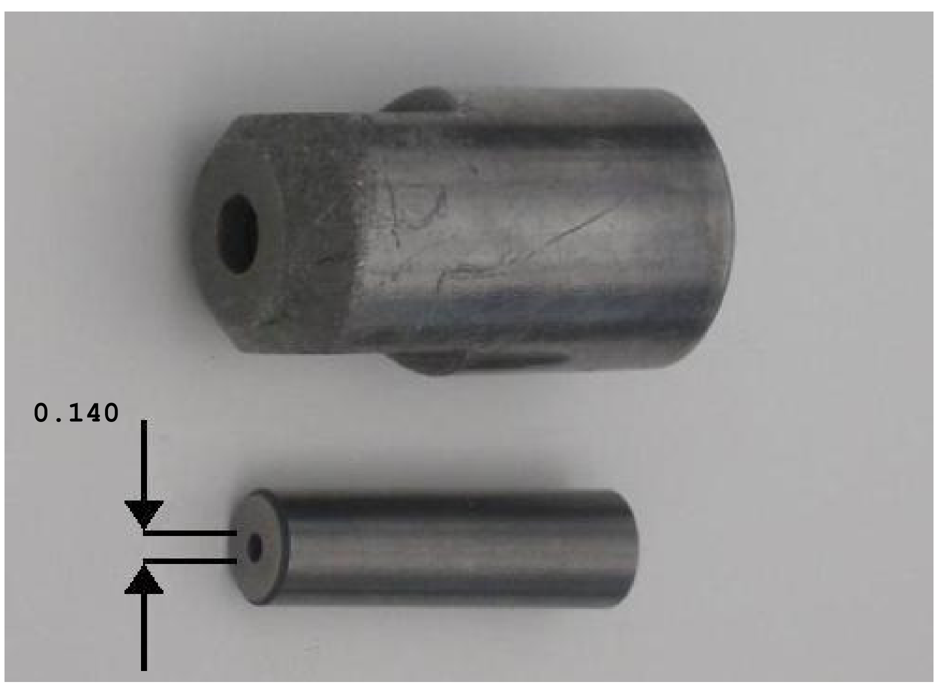

Figure 5.1 Single orifice continuous nozzle with holder

The threaded steel fitting mounted directly to the high pressure pipe and held the nozzle in place. A cross sectional representation of the single orifice nozzle assembly can be seen in Figure 5.2.

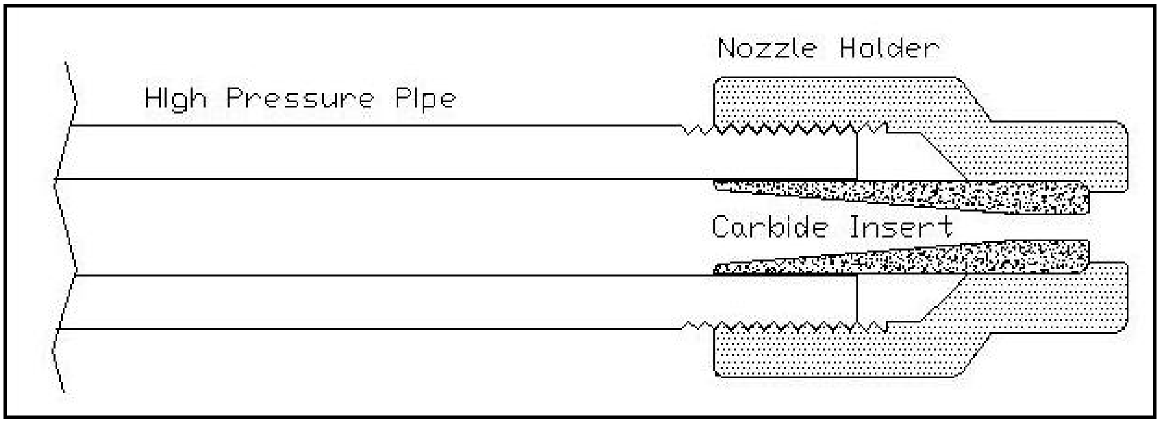

Figure 5.2 Single orifice nozzle cross section

Though basic in design, the manufacturing of a high pressure single orifice nozzle requires precision. The internal surface of the nozzle must be finished to a high degree of smoothness or excess wear and poor stream dynamics will result. The carbide nozzles used in this research cost slightly more than $100 each and were readily available in many different orifice sizes. For the experimental setup used, the single orifice, continuous nozzle of 0.140 inches in diameter produced and operating pressure of 3200 psi at 27.7 gpm.

5.2.1 <u>Advantages</u>

The advantages of a single orifice nozzle are its simplicity and low cost. All nozzles wear after a number of hours in use, and the cost of operation, downtime, and replacement can be major considerations in the design of a system. The availability of parts is also a consideration when trying to introduce the technology to the mining industry.

5.2.2 Disadvantages

The major disadvantage of using a basic single orifice, continuous nozzle is the difficulty in optimizing productivity. While high pressure continuous jets are a staple in precision cutting operations, applications such as cleaning and scaling that require large surface area coverage may require some type of motion system to accomplish as much work as possible.

5.3 Dual Orifice, Self Rotating, Continuous Jet

The second nozzle used in this research consisted of dual orifice inserts mounted to a fluid-damped, rotating head. The nozzle was designed and manufactured by Stonage® Waterjet Tools Inc. of Durango, CO for use in pipe and sewer cleaning applications. The nozzle is shown in Figure 5.3.

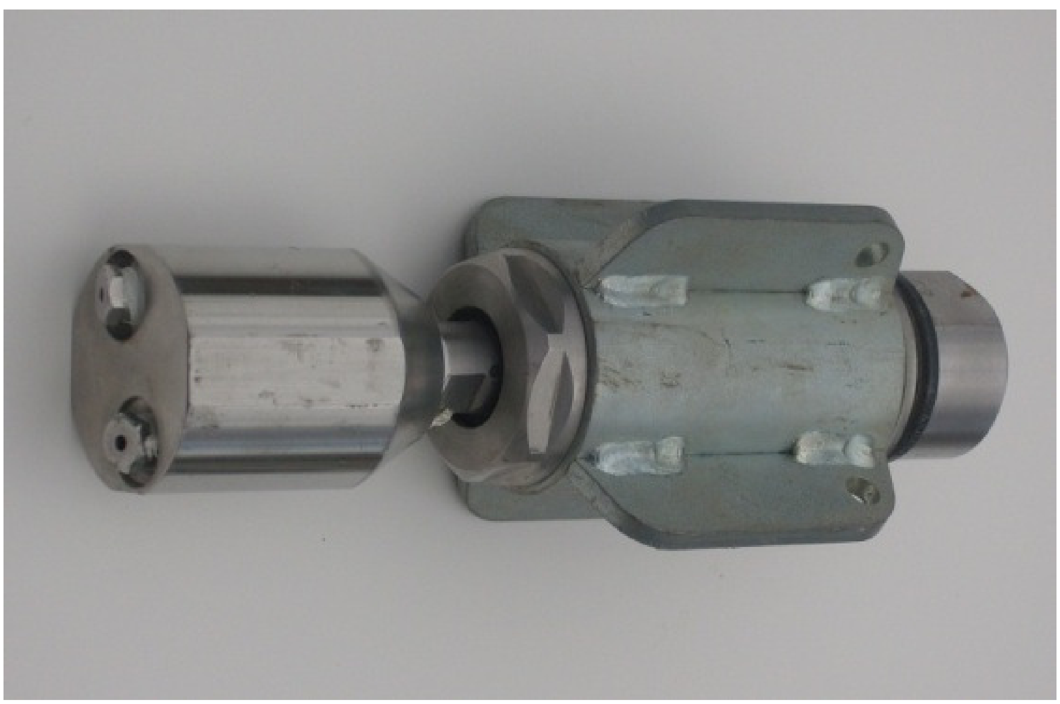

Figure 5.3 Dual Orifice, self rotating, continuous nozzle

The galvanized steel jacket covering the main body was designed to prevent contact between the nozzle and the internal surface of a pipe. Since it did not interfere with the process of testing the nozzle for scaling, it was left intact.

The two replaceable nozzle inserts are angled in opposing directions to provide thrust for the rotating head. The speed of rotation is controlled by a viscous fluid governor in the main body of the unit. The operating pressure of the dual orifice jet was 3000 psi, and each of the inserts had a 0.065" orifice that emitted 14.4 gpm. The total cost of the nozzle was about $1,000 and the inserts can be replaced for about $30.

5.3.1 Advantages

The major advantage to the self-rotating nozzle is the increased surface coverage. As mentioned previously, providing motion to a waterjet is essential to optimizing productivity, and one of the most efficient ways of increasing coverage is by rotating the jet. As the boom of the scaling rig is swept across the surface of the rock, the surface area treated by the rotating nozzle is much larger that that of a single orifice jet. The width of the contact zone is determined by the standoff distance and the offset angle of the nozzle inserts.

Another advantage to the design of this dual orifice nozzle is the replaceable inserts. Though the new cost of the fluid governor and rotational head may seem high, they are designed with a long operational life span. The inserts can be expected to wear after 30 – 40 hours, but the cost of replacement is relatively low.

5.3.2 Disadvantages

The disadvantage to a dual orifice nozzle is the 50% decrease in flow rate through each of the orifices. Although there are essentially two nozzles in operation, the amount of energy applied to the target surface by either orifice at any given time will never be as high as a single orifice nozzle operating at the same overall pressure and flow rate. In this regard, the dual orifice nozzle may not perform as well against stubborn material for a given flow rate. The configuration of smaller orifices also reduces standoff distance and introduces more frictional losses.

Another disadvantage is 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 if desired, steady pressure can not be applied to obvious weaknesses and discontinuities in the rock mass.

Also worth noting is the negative angle of attack necessary to propel the nozzle head in rotation. Considering the rough and irregular rock surface associated with scaling, it may be difficult to prove whether or not the angle of attack affects scaling performance. The clarification of such a theory is beyond the scope of this thesis.

5.4 Single Orifice, Acoustic Pulsed Nozzle

The third nozzle tested was an acoustic pulsed nozzle, which emits a stream of water with individually formed slugs of water traveling in progression. The result is a high frequency series of impacts with the target surface and more dynamic loading characteristics than a continuous waterjet stream.

There are two general methods of producing a pulsed waterjet stream, which are passive and mechanical. A mechanically pulsed nozzle requires the implementation of a stream-inhibiting mechanism. Such systems are complex and expensive, as they are designed to handle high pressure water at very high frequencies. A passive or acoustic nozzle functions without intervention from additional moving parts. The internal surface of the nozzle is machined in such a way that the flow of water at the designed pressure and flow rate generates a standing wave. The wave propagates at high frequency through the water stream, and as it leaves the nozzle orifice, bunching occurs between areas of high and low stream pressure. A photograph of an acoustically pulsed waterjet stream is shown in Figure 5.4.

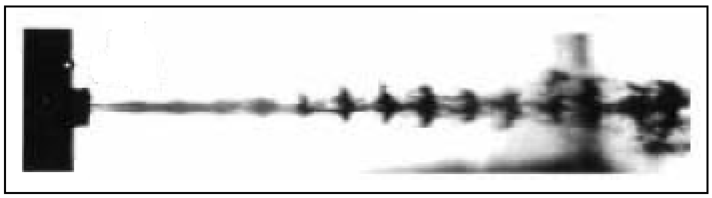

Figure 5.4 Pulsed waterjet stream (Chahine, 1983)

The acoustic pulsed nozzle used in this research was designed and manufactured by Dynaflow Inc. of Jessup, MD. It was chosen over other mechanically derived pulsed systems because it was commercially available and was being used in the waterjet cleaning industry. A photograph of the nozzle assembly used is shown in Figure 5.5.

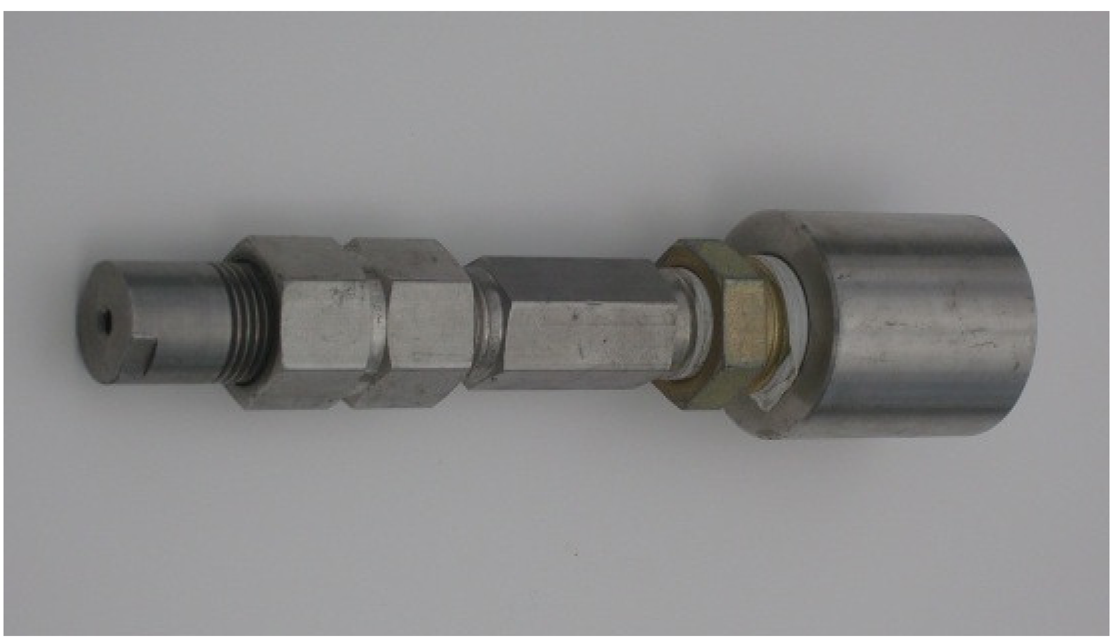

Figure 5.5 Acoustic pulsed nozzle assembly

The various components visible in the photograph 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 pulsed waterjet nozzle used in this research cost approximately $1,800. None of the parts are individually replaceable, but a replacement assembly was available for approximately $600 at the time of purchase. The orifice was 0.135 inches in diameter, and the jet operated at 3400 psi and 26.6 gpm.

5.4.1 Advantages

The advantages associated with a single orifice have been discussed with respect to the continuous nozzle in Section 5.1. 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, wherein the vibrations associated with the high frequency impacts would help overcome frictional forces holding certain surfaces together.

Other potential advantages include larger impact stresses, due to water hammer pressure, which enhance the local intensity of the jet impingement (Chahine, 1983). Self-resonating waterjets are known to be more effective than continuous jets in many cutting and cleaning applications.

5.4.2 Disadvantages

Unfortunately, because of the thick sleeve of mist that results from aerodynamic drag on the pulsed stream, it can be very difficult to assure optimal standoff distance during use. 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 keep the nozzle within a certain range of the rock surface. In the same regard, it may also be difficult to avoid collision between the rock and the nozzle without decent visibility. Damage to the nozzle would lead to the next great disadvantage of the pulsed unit; the cost of replacement.

The cost of the acoustic pulsed nozzle, for both new and replacement units, is very high. Because 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. Given a cost of replacement several times greater than other nozzles, this type of pulsed nozzle would likely experience very little acceptance in the rugged industries of mining and tunneling.

5.5 Single Orifice, Continuous Jet with Mechanical Oscillation

The last type of nozzle tested for use in scaling was a mechanically oscillated, single orifice, continuous waterjet. The concept is similar to the self-rotating nozzle in that motion is being provided to the waterjet, but this design utilizes external power for rotation and emits water through a single orifice.

Two separate mechanically oscillated systems were tested during this research. Given that only two experiments were designated for mechanically oscillated nozzles, each was tested only once. Additionally, given the difference in blasting procedures between the first and last five experiments, each mechanically oscillated system was tested under different rock conditions. The results of these two experiments can hardly be considered definitive, but the overall experience offered much needed insight. The general advantages and disadvantages of mechanically oscillated, single orifice systems are described as follows.

5.5.1 General Advantages

These systems offer the power (flow rate) of a single orifice nozzle with the surface coverage of the dual orifice, self rotating jet. The absence of disadvantages associated with standard single and dual orifice rotating systems is also a favorable attribute. The lack of productivity in a single orifice, continuous jet is alleviated by the external motion system, and the reduction in flow rate through dual orifices is averted altogether. Another advantage, depending on the setup of the system, would be the ability to disable oscillation with the flip of a switch and target specific features in the rock mass.

5.5.2 General Disadvantages

The need for additional utilities, whether electrical, pneumatic, or hydraulic, can be considered a disadvantage of mechanical oscillation. Especially when considering a waterjet scaling nozzle as a retrofit to existing machinery, the addition of extra hoses and hardware may not be welcomed.

5.5.3 Air-Powered Mechanical Oscillator

The first mechanical oscillator used in the scaling experiments was designed and manufactured by Stoneage® Waterjet Tools Inc., of Durango, CO. The unit, pictured in Figure 5.6, incorporates a pneumatic motor to drive the rotation of a short, bent pipe with a replaceable nozzle insert.

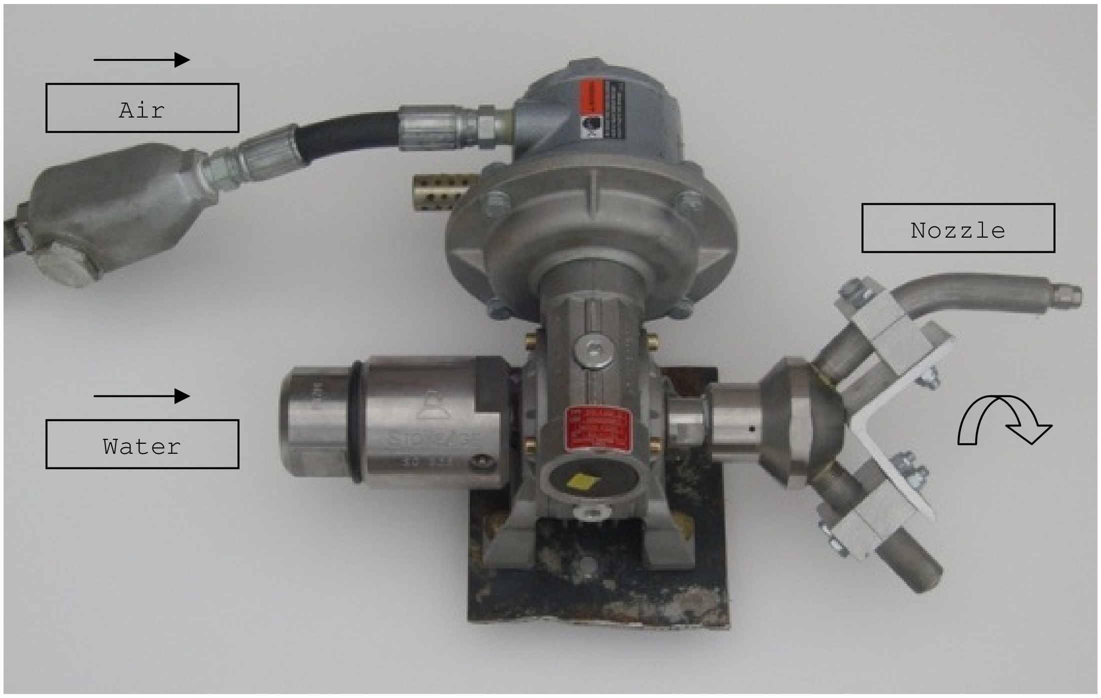

Figure 5.6 Air-powered mechanical oscillator by Stoneage® Inc.

The air motor and gear box were designed as a universal waterjet oscillation unit, available with several options applicable to industrial cleaning operations. As evident in the photograph, the head is capable of accommodating dual orifices. The purpose of the test was to use a single orifice, thus the inactive nozzle was plugged and braced for greater durability.

The stream of water exiting the nozzle traveled nearly parallel to the axis of rotation, due to the angle at which the short pipe had been designed. This feature results in a relatively cylindrical jet profile, as illustrated in Figure 5.7. With a cylindrical jet profile, the surface area covered by the jet remained constant regardless of standoff distance.

The cost of the air-powered oscillation unit was $1,986, and the orifice insert can be replaced for less than $100. The cost of replacement for all other parts varies. The orifice size was 0.140 inches in diameter, and the nozzle operated at 3200 psi and 27.7 gpm.

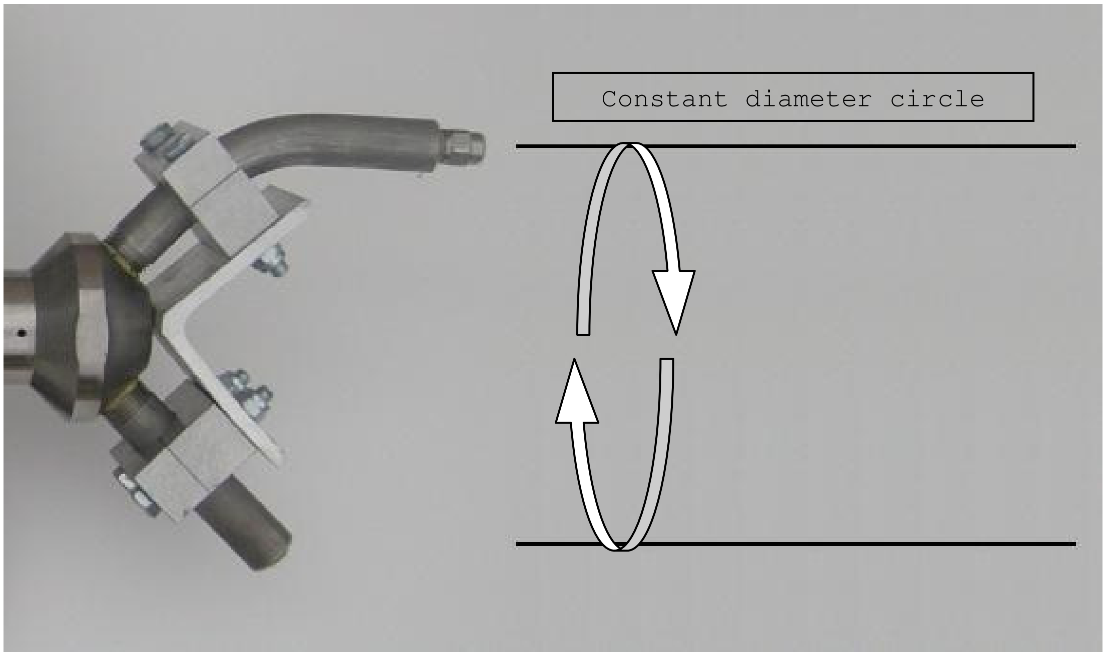

Figure 5.7 Constant width of coverage for air-powered oscillator

5.5.3.1 Advantages

The major advantage of the mechanically oscillated unit was better surface coverage than a regular continuous nozzle and more flow rate per orifice than the self-rotating nozzle.

5.5.3.2 Disadvantages

The design of the rotating head, with its protruding, angled pipe, seems inherently delicate. It may not be optimal for the rugged environments of mining and tunneling, where equipment is pushed hard and expected to endure misuse. Contact between the angled pipe and the rock surface could easily lead to broken parts.

Being a universal waterjet oscillator, the mounting brackets and metal casing were not designed with weight saving in mind. The unit is exceptionally heavy considering its position at the end of a 15 ft boom, and would probably not be considered optimal for retrofit to existing machinery.

As mentioned previously, the implementation of compressed air is a slight inconvenience in that another high energy source must be handled to set up and execute scaling. Also, the air motor produces a loud siren-like howl, though considering the level of noise produced by the waterjet itself; it poses no real safety hazard.

5.5.4 Custom Hydraulic Oscillator

As a measure against the characteristic of the air-powered oscillating system, a custom mechanical oscillating system was ordered for the second such experiment. The system was designed by Shotcrete Technologies Inc. of Idaho Springs, CO and built by CMC Machine Shop also located in Idaho Springs. It utilizes an external 12 volt hydraulic pump and a small hydraulic motor at the boom/nozzle interface to initiate oscillation. The pump and reservoir, filled with Automatic Transmission Fluid, are mounted to the main body of the scaling vehicle, and two long hydraulic hoses run alongside the boom.

The custom mechanical oscillator was intended to be used in combination with the standard single orifice, continuous nozzle, but since the clamp interface was designed to hold the high pressure pipe, the system is compatible with virtually any nozzle desired. The custom oscillation unit cost $1,850 and is shown in Figure 5.8.

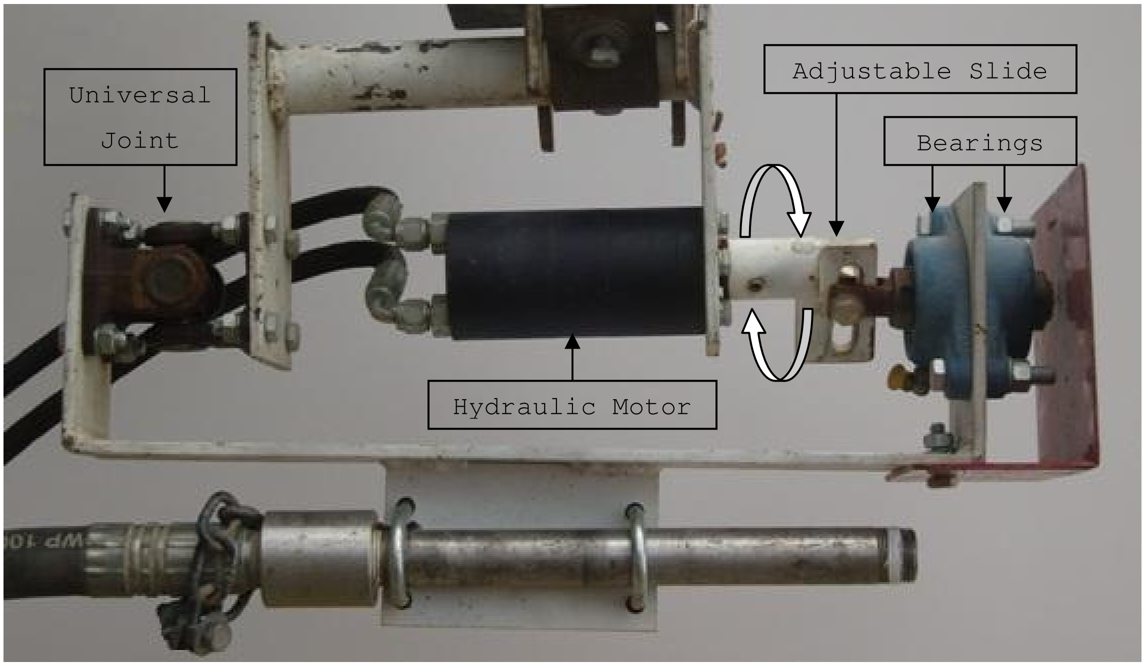

Figure 5.8 Custom built mechanical oscillation unit.

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 diameter of the cone (area of coverage) at the target surface is determined by two variables. The first is standoff distance, wherein the area of coverage gets larger as the nozzle gets farther from the rock. Additionally, 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 cone-shaped nozzle path is shown in Figure 5.9.

The speed of oscillation is controlled by a hand-operated valve near the pump/reservoir and is adjustable between 0 and approximately 90 rpm. The main power switch is also located in the proximity of the pump/reservoir, making it easy to turn the unit on and off.

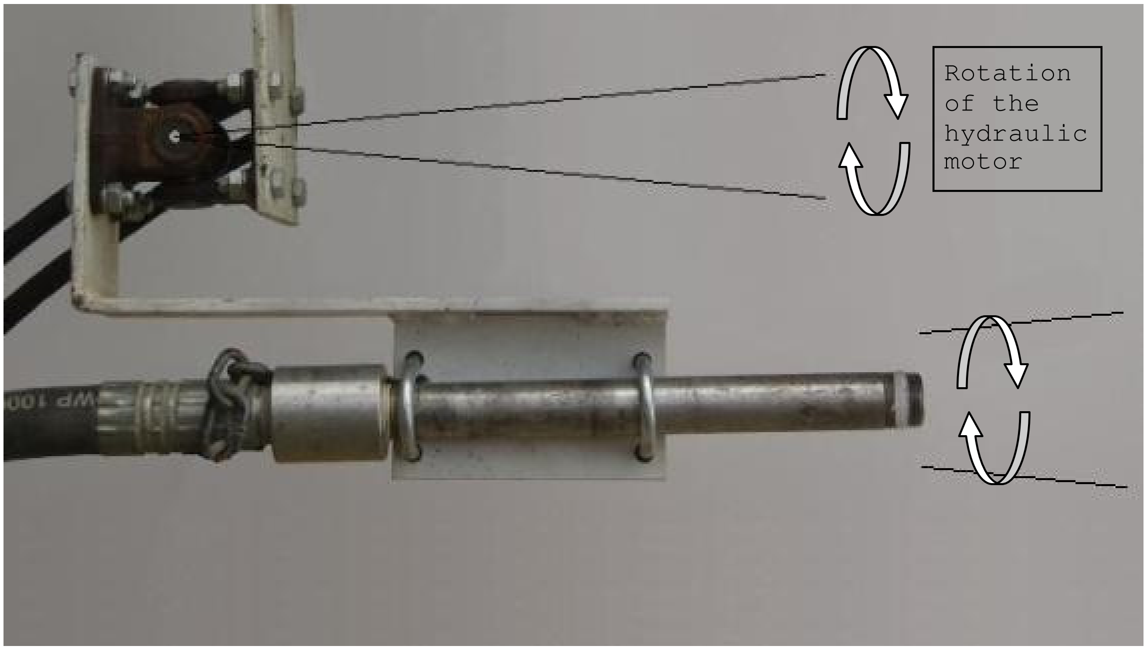

Figure 5.9 Cone-shaped jet path.

5.5.4.1 Advantages

The custom built mechanical oscillator was designed to address all the disadvantages and inconveniences of the air-powered mechanical oscillator. It's intended to be light weight and rugged, though many hours of service would be required before assertions of durability can be made. Many of the parts, such as the protective red cover and bearings, are easily replaceable.

One additional advantage is the adjustable radius of oscillation. In situations where maximum standoff is desired, the position of the bolt shown in Figure 5.8 can be moved closer to the axes of rotation to prevent excessively large coverage circles on the target surface.

5.5.4.2 Disadvantages

The hydraulic power for this particular oscillation unit was provided by an external pump and reservoir because the scaling vehicle's hydraulic system lacked room for expansion. Considering that most underground vehicles have a hydraulic system of some sort, retrofitting of an additional hydraulic device may be possible without a pump and reservoir in some instances. The need for external hydraulic power may be considered a disadvantage.

The hydraulic pump needed to power the oscillator drew an astounding 80 amps from the scaling vehicle’s 12 volt power system. If the engine was not running, the external hydraulic system would drain the automotive battery very quickly, meaning the unit had to be turned off immediately after use.

6. DATA AND RESULTS

6.1 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 (Figure 6.1). 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.

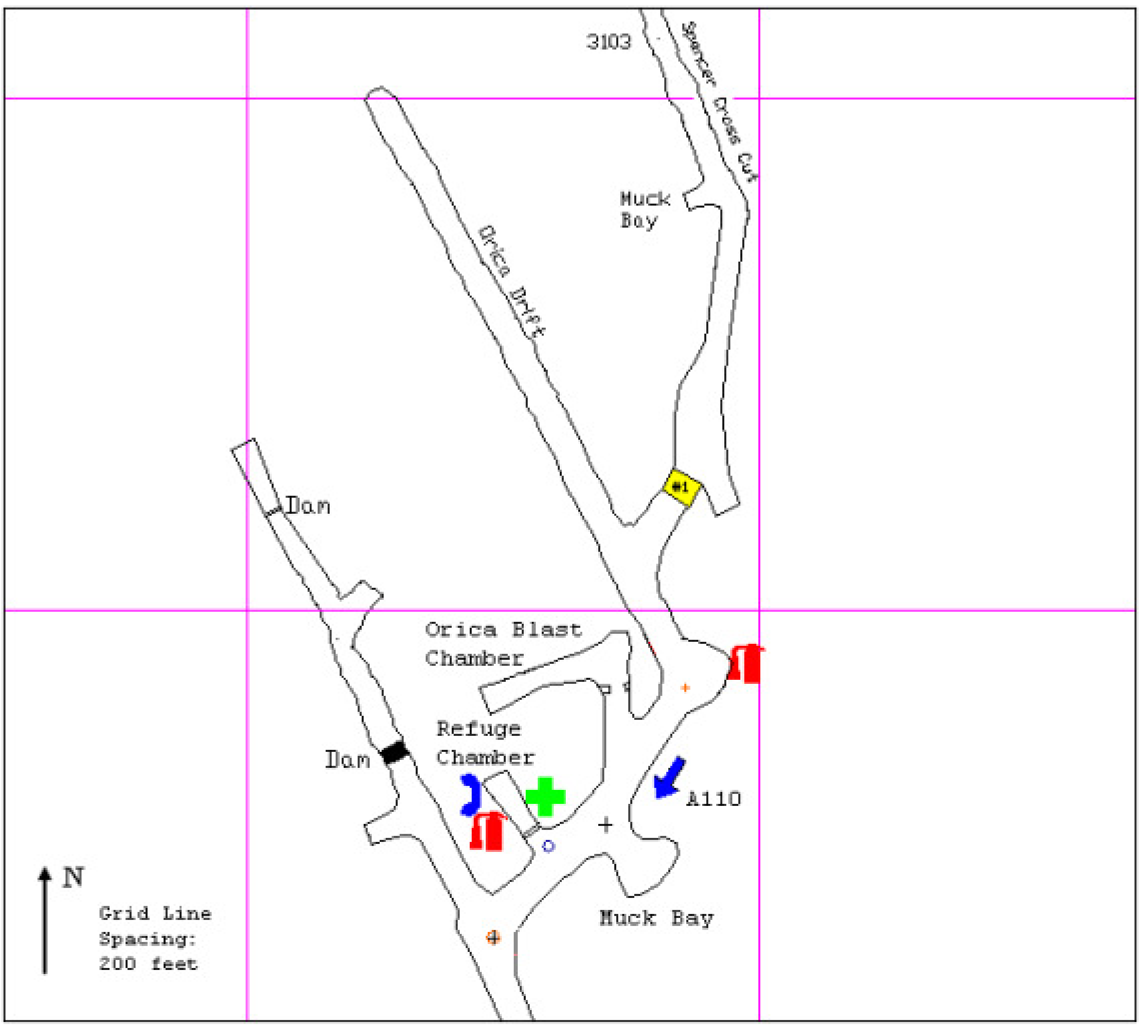

Figure 6.1 Location of Experiment #1

6.1.1 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 feature was a near-vertical discontinuity with an approximate 3/4" gap between faces. While a series of such discontinuities would present challenges 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 (Figures 6.2 and 6.3). 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.

Figure 6.2 Before Experiment #1

Figure 6.3 After waterjet scaling, Experiment #1

6.1.2 Results

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 Figure 6.4.

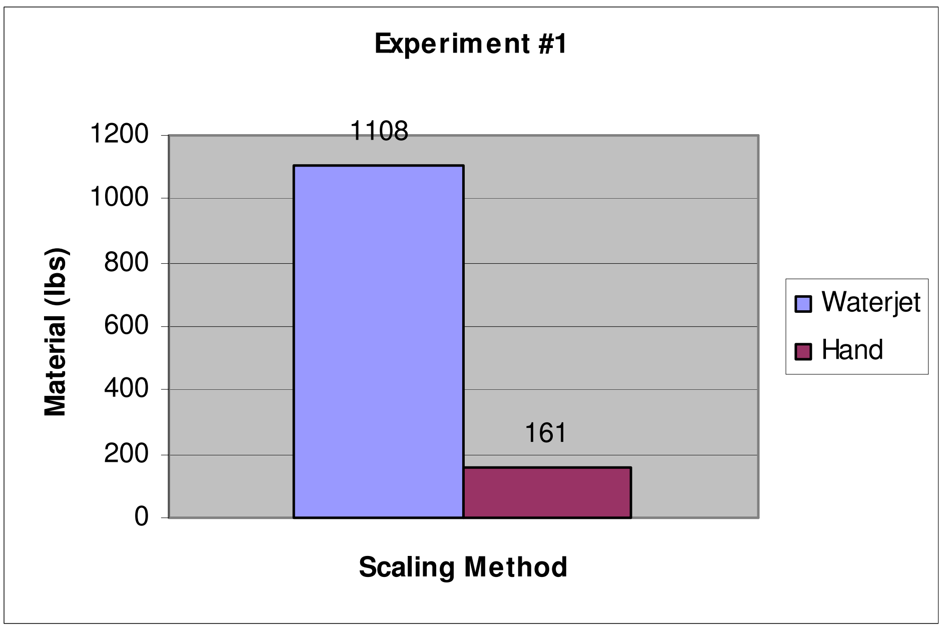

Figure 6.4 Results of Experiment #1

All of the material removed in Experiment #1 was placed on tarps in a nearby drift for screening, as shown in Figure 6.5.

Figure 6.5 Waterjet and Manual scaling results

The screening results for Experiment #1 are shown in Table 6.1 and Figure 6.6.

Table 6.1 Experiment #1 screen analysis results

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

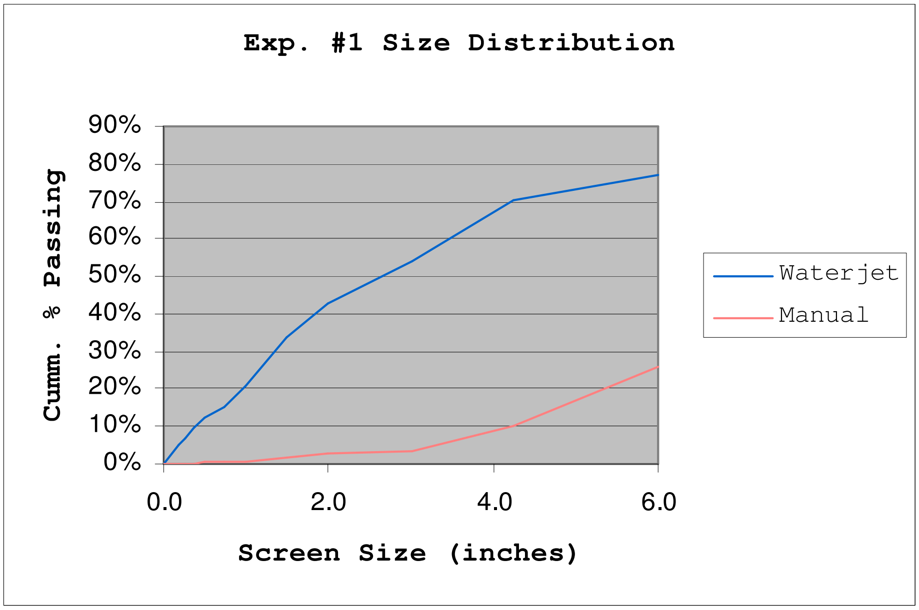

Figure 6.6 Experiment #1 particle size distribution

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.

6.1.3 <u>Notes</u>

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 as a consequence of 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.

6.2 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 Figure 6.7.

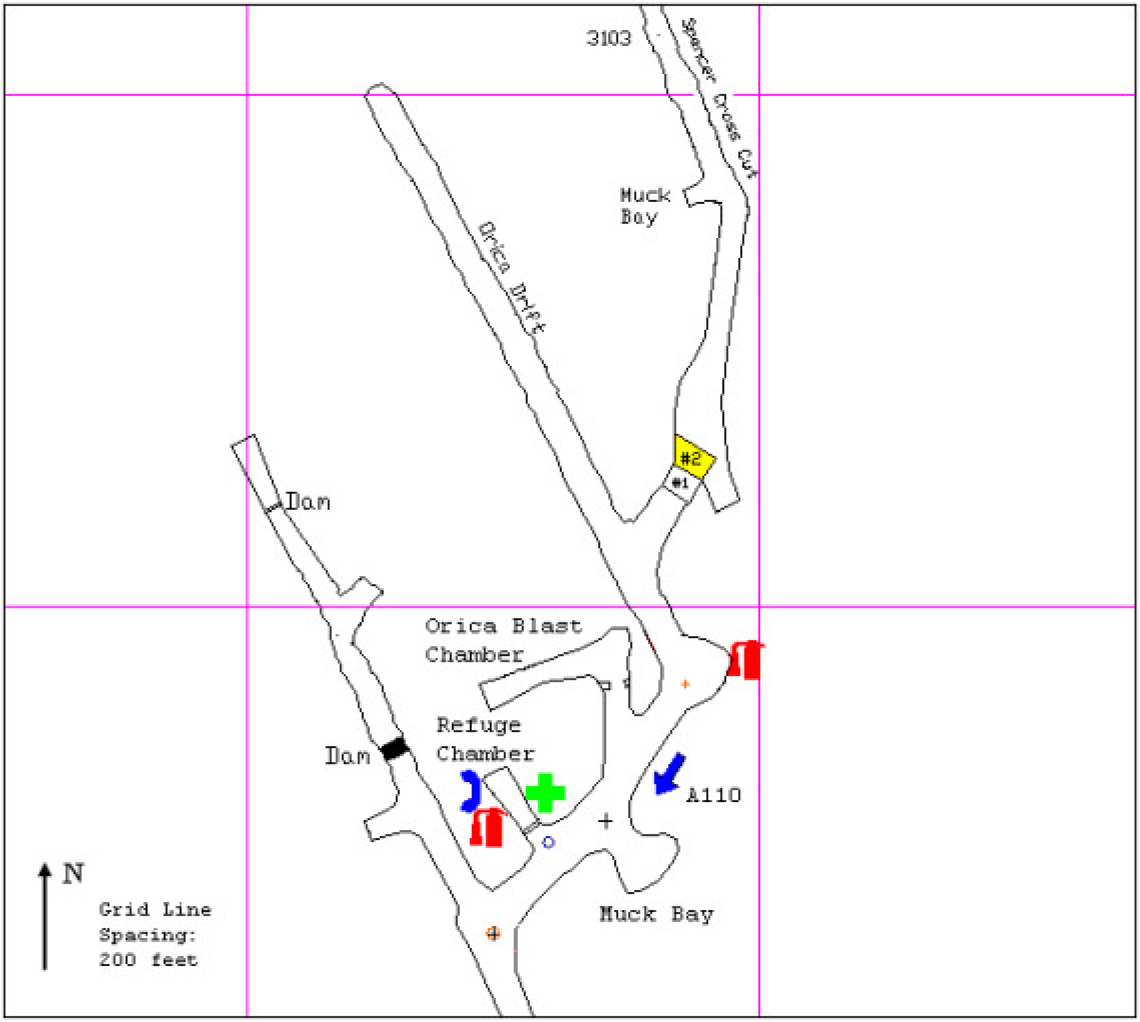

Figure 6.7 Location of Experiment #2

6.2.1 Rock Conditions

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, oxidized precipitates on the left rib. Although the material was not in the scaling zone, similar colored precipitates were 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 Figure 6.8.

Figure 6.8 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 approximate 1/8" 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 Figure 6.9 with an arrow to indicate the trend of the joint set.

Figure 6.9 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 Figure 6.8, 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.

6.2.2 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 Figure 6.10.

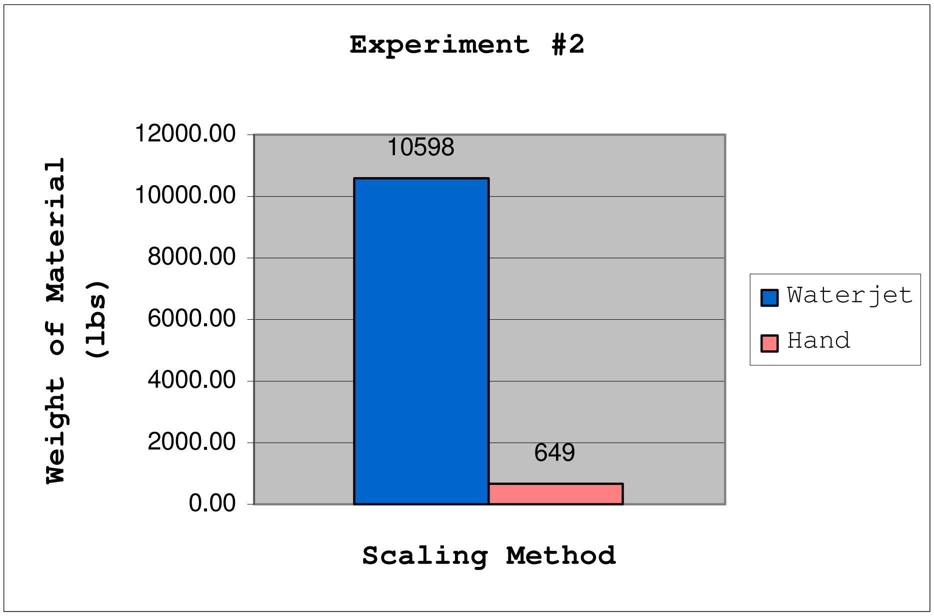

Figure 6.10 Results of Experiment #2

While the quantity of material scaled by waterjet in Figure 7.10 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 Figure 6.9. Based on the photographs of the rock 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 Figure 6.11 with the waterjet operator positioned above for scale. All of the rock in the immediate foreground fell at once.

Figure 6.11 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 6.2 and Figure 6.12.

Table 6.2 Experiment #2 screen analysis results

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

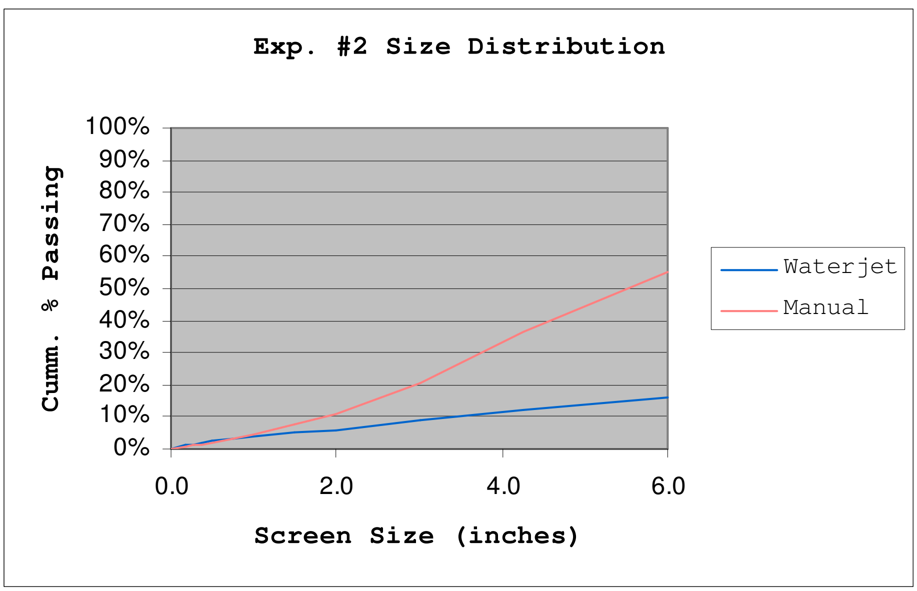

Figure 6.12 Experiment #2 particle size distribution

6.2.3 Notes

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 Figure 6.13, Table 6.3, and Figure 6.14.

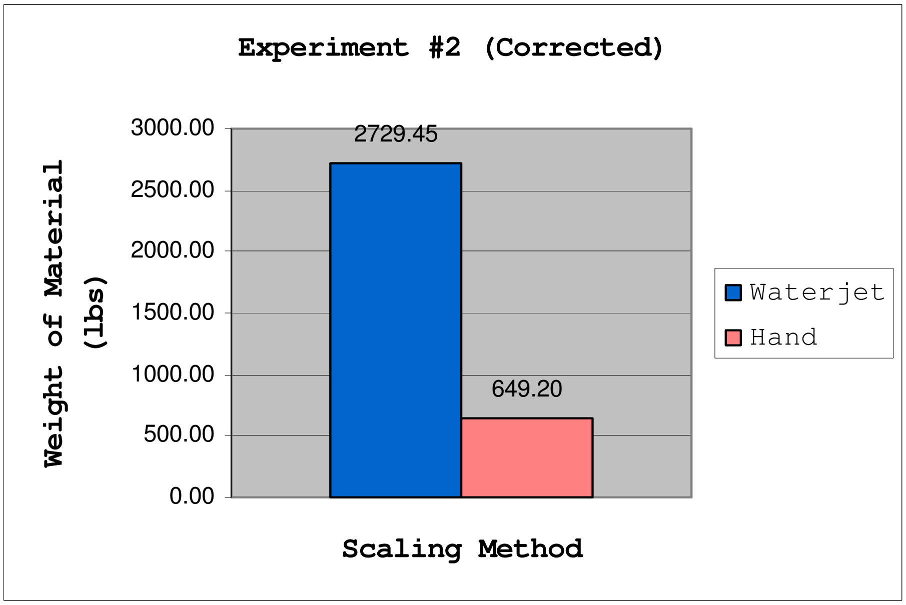

Figure 6.13 Corrected results for Experiment #2

Table 6.3 Corrected data for Experiment #2 screen analysis

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

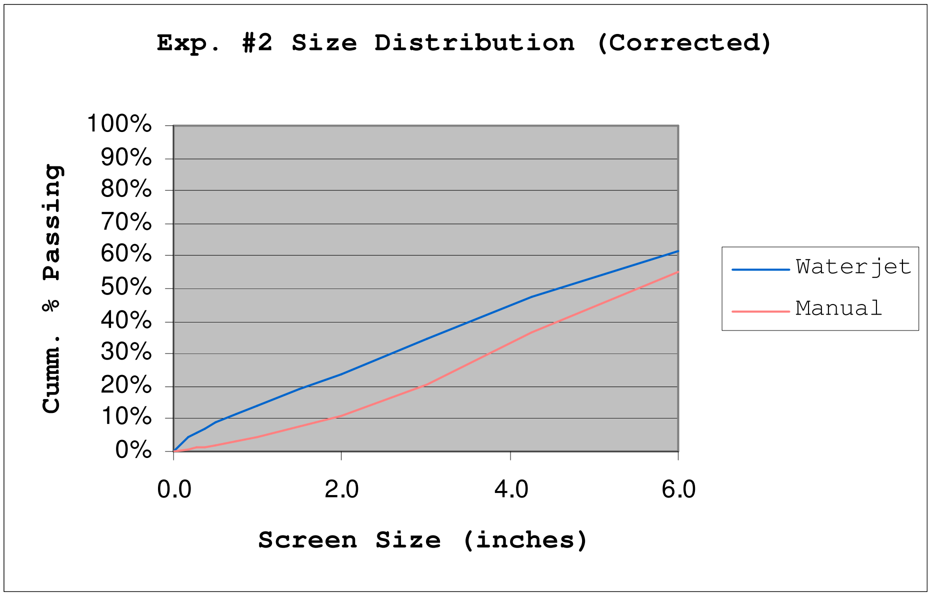

Figure 6.14 Corrected particle size distribution, Experiment #2

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.

6.3 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 Figure 6.15.

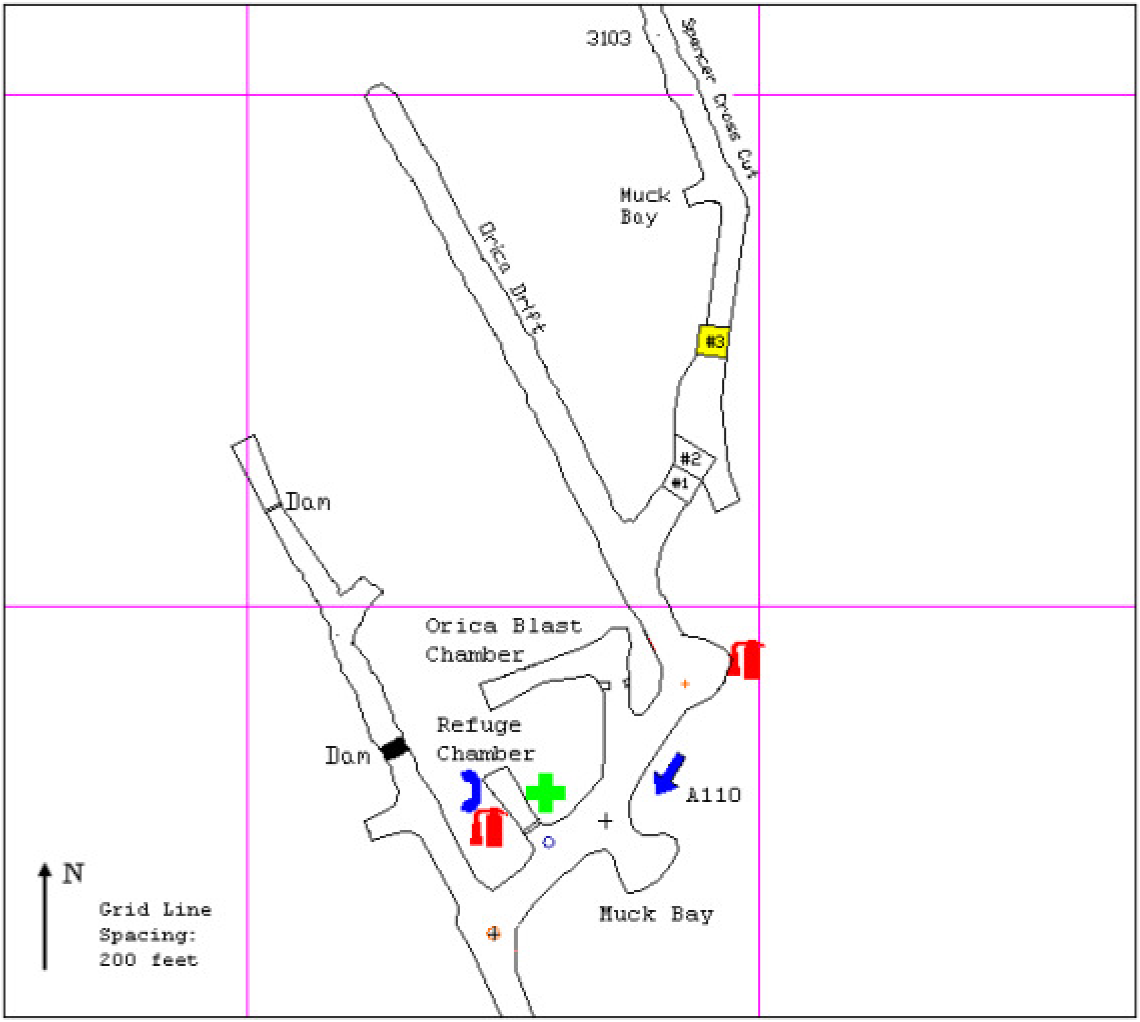

Figure 6.15 Location of Experiment #3

6.3.1 Rock Conditions

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 Figure 6.16.

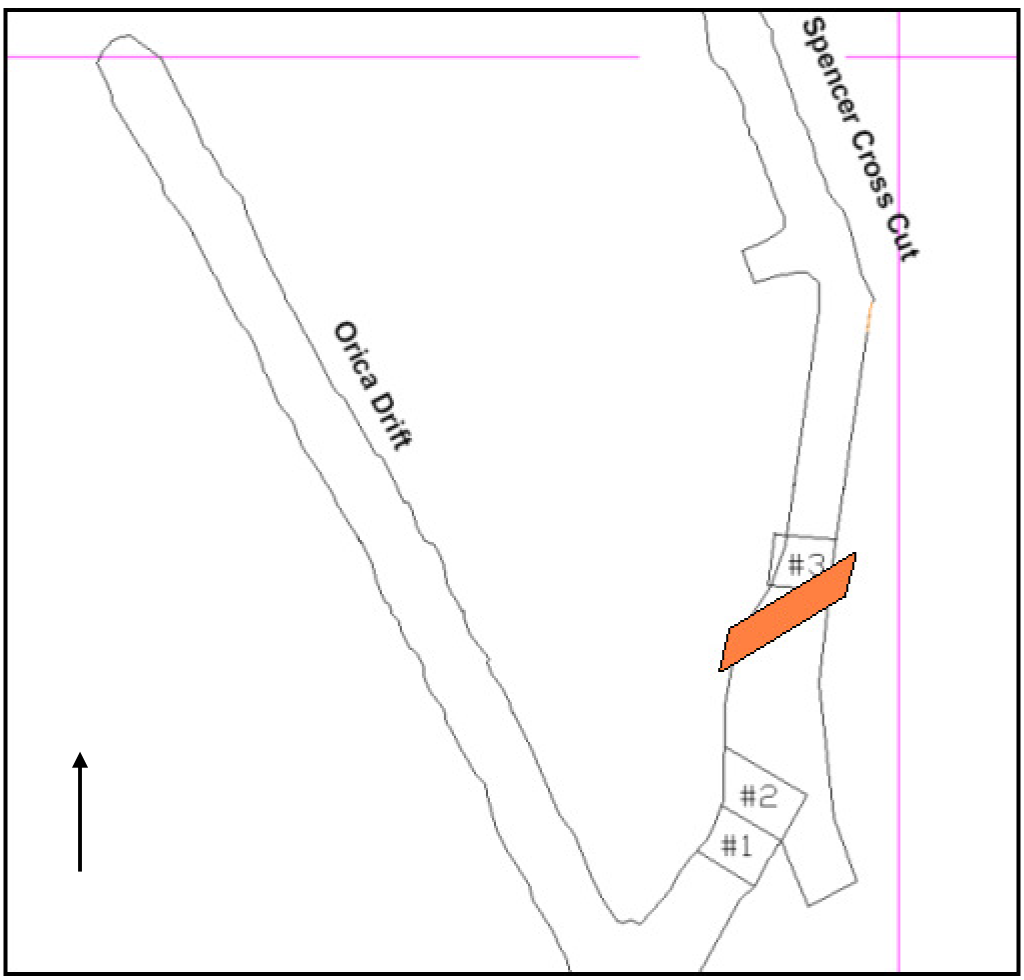

Figure 6.16 Orientation of small shear zone in Experiment #3

6.3.2 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 Figure 6.17.

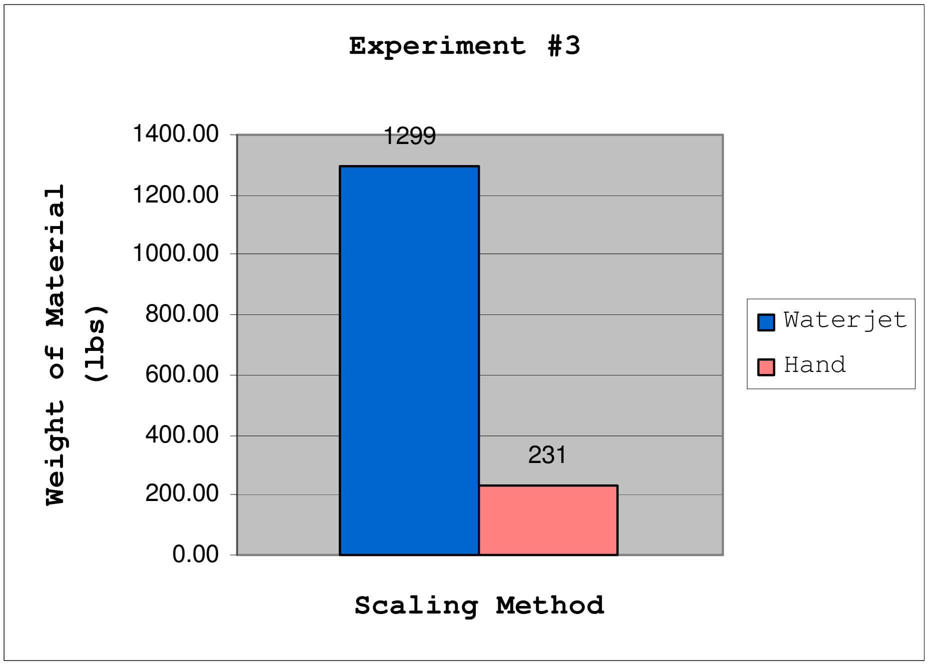

Figure 6.17 Results of Experiment #3

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 Figures 6.18 and 6.19.

Figure 6.18 Photograph taken before Experiment #3

Figure 6.19 Photograph taken after Experiment #3

The results of the screen analysis for Experiment #3 are shown in Table 6.4 and Figure 6.20.

Table 6.4 Experiment #3 screen analysis results

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

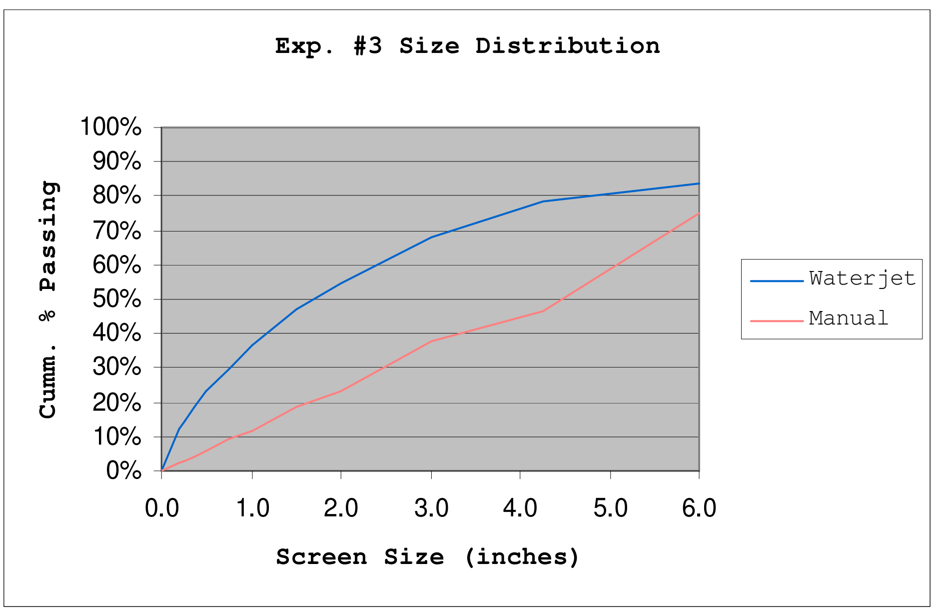

Figure 6.20 Experiment #3 particle size distribution

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.

6.3.3 Notes

Statistically, the results of Experiment #3 speak of neither excellence nor mediocrity in regards to the performance of the 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 pulsed nozzle was difficult to use regardless of its position and orientation.

6.4 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 Figure 6.21. 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.

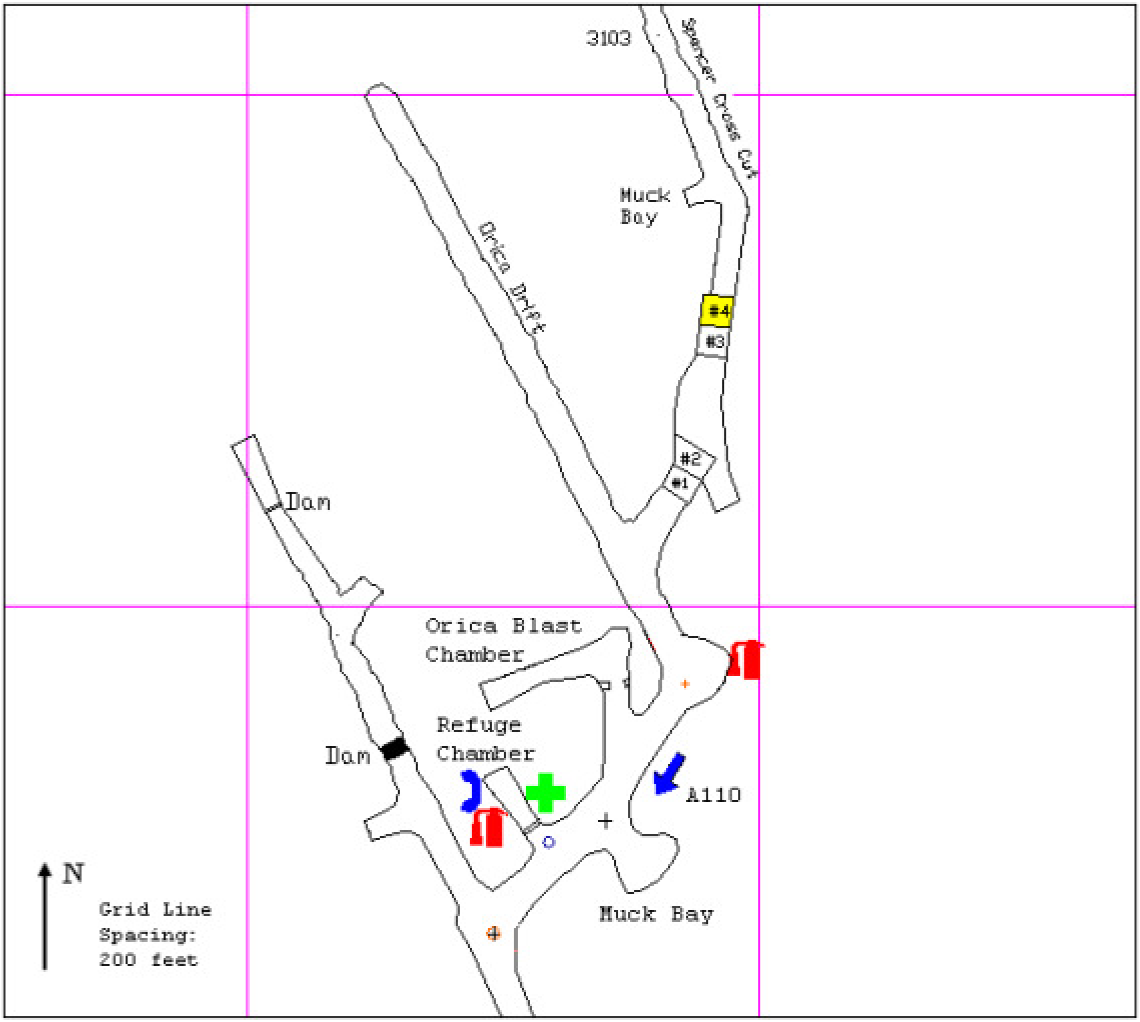

Figure 6.21 Location of Experiment #4

6.4.1 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. 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.

6.4.2 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 Figure 6.22, 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.

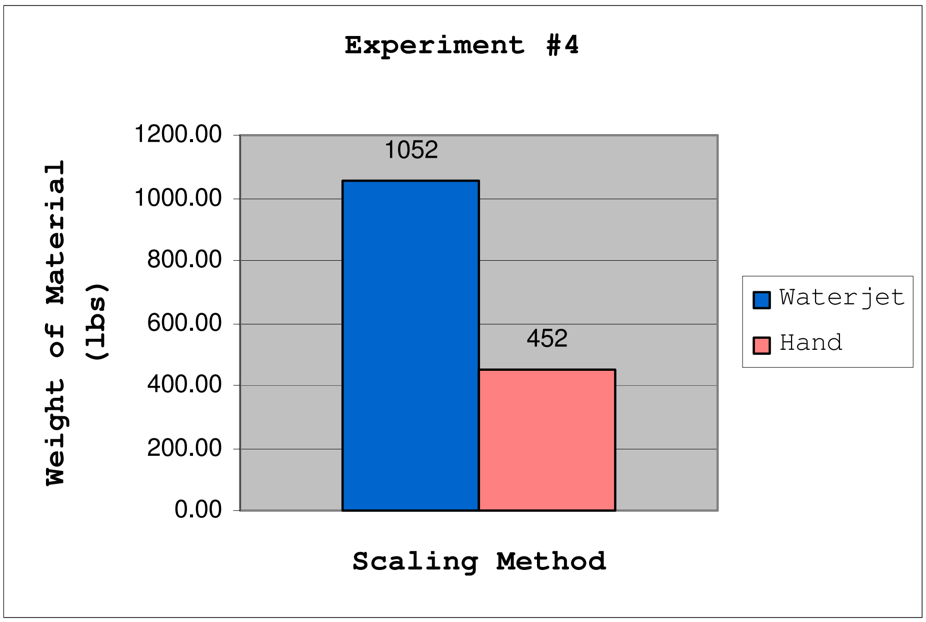

Figure 6.22 Results of Experiment #4

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 at the pressure and flow rate used. The results of the screen analysis by weight and the particle size distribution graph can be found in Table 6.5 and Figure 6.23.

Table 6.5 Experiment #4 screen analysis results

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

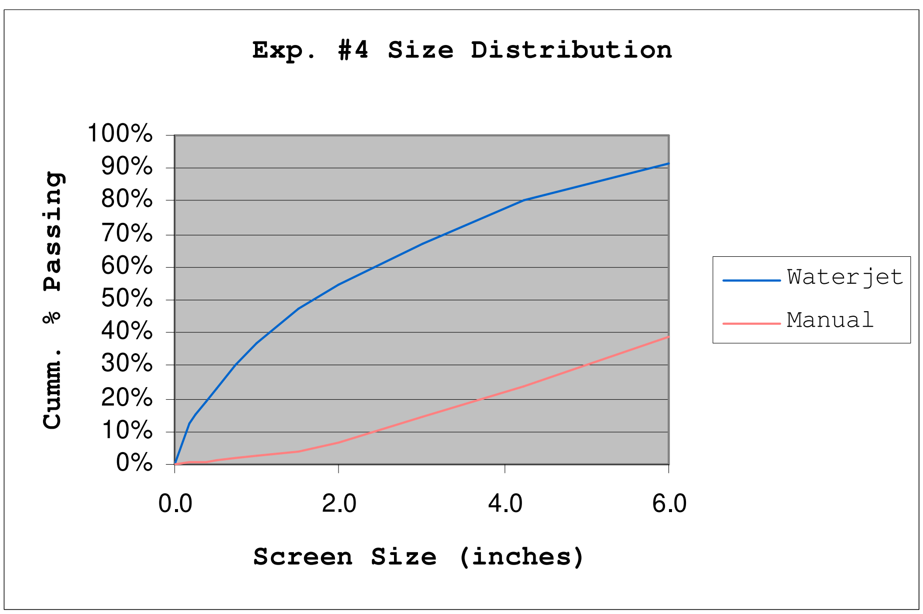

Figure 6.23 Experiment #4 particle size distribution

6.4.3 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.

6.5 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 Figure 6.24.

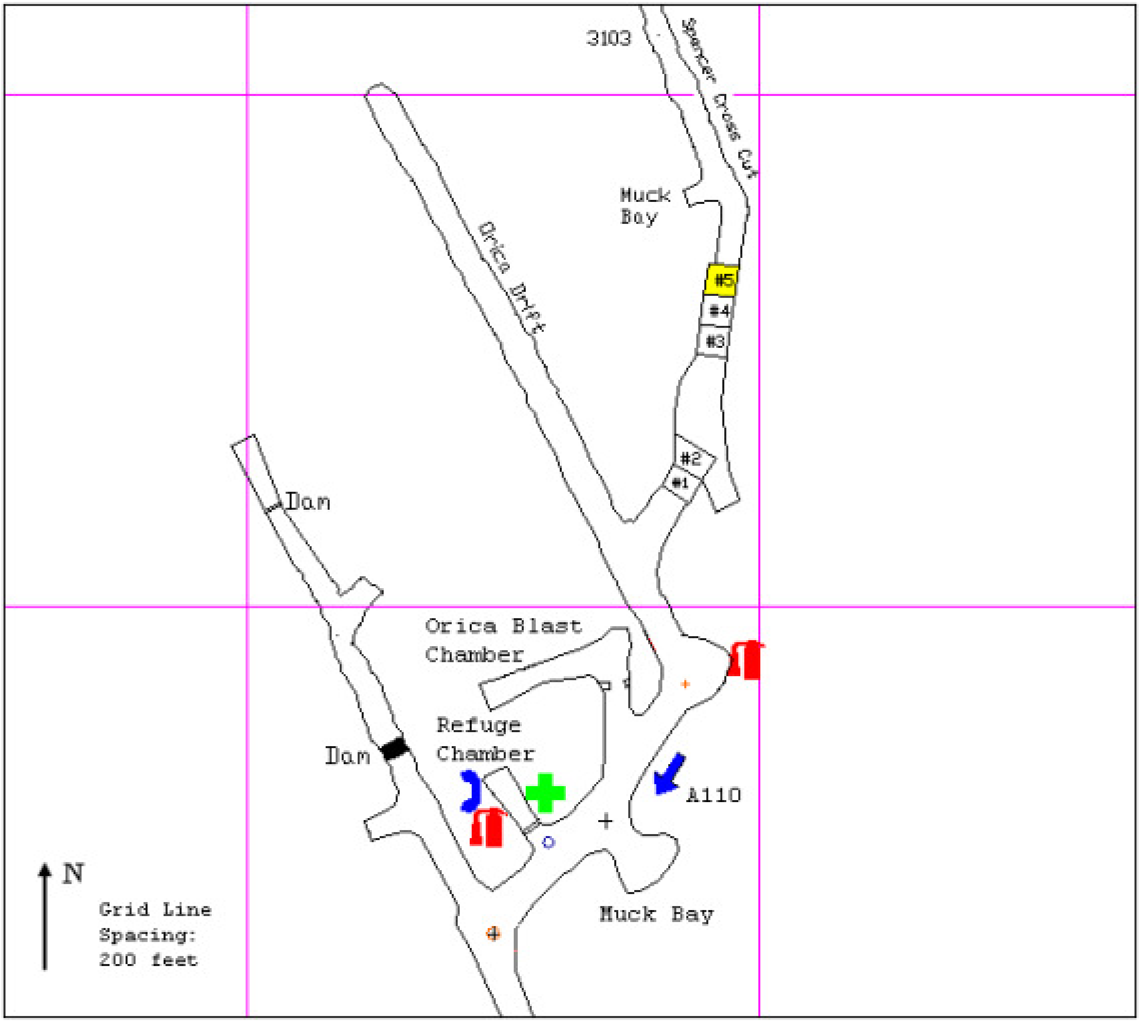

Figure 6.24 Location of Experiment #5

6.5.1 Rock Conditions

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.

6.5.2 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 Figure 6.25.

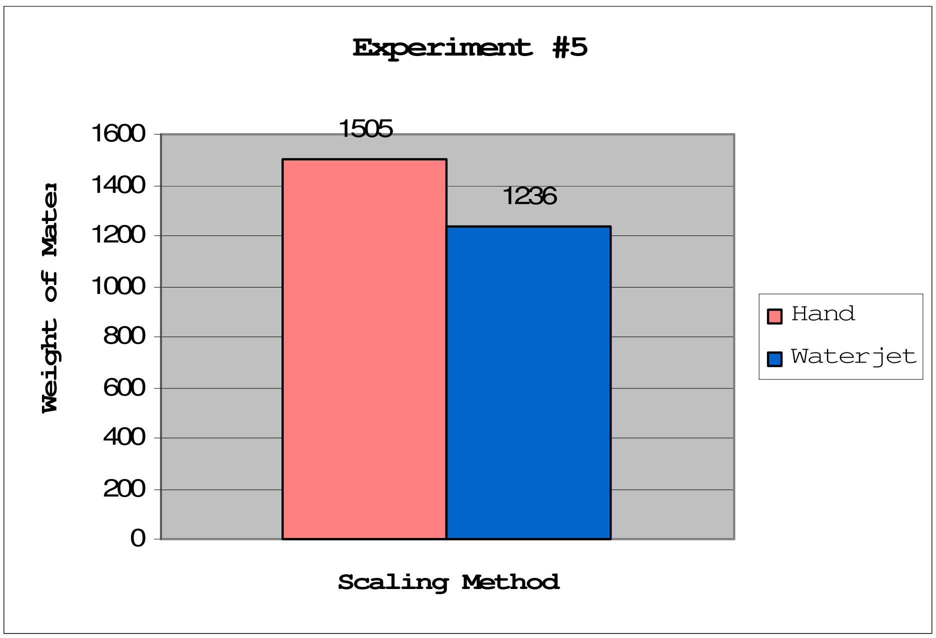

Figure 6.25 Results of Experiment #5

The task of manual scaling was completed by a combination of eight individuals and took place for roughly 75 minutes. The duration of the waterjet test, at 35 minutes, was also abnormally long because of the participation of U.S. Army Rescue personnel 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 Figures 6.26 and 6.27.

Figure 6.26 Photograph taken before Experiment #5 waterjet test

Figure 6.27 Photograph taken after Experiment #5 waterjet test

6.5.3 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 inspected by a hard rock miner with 30 years of experience and considered thoroughly scaled.

A screen analysis was not performed on the results of Experiment #5, nor any of the subsequent scaling experiments. The process of gathering and screening the scaled material after each experiment was painstakingly tedious and it was felt that enough information had been gathered.

6.6 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 Figure 6.28.

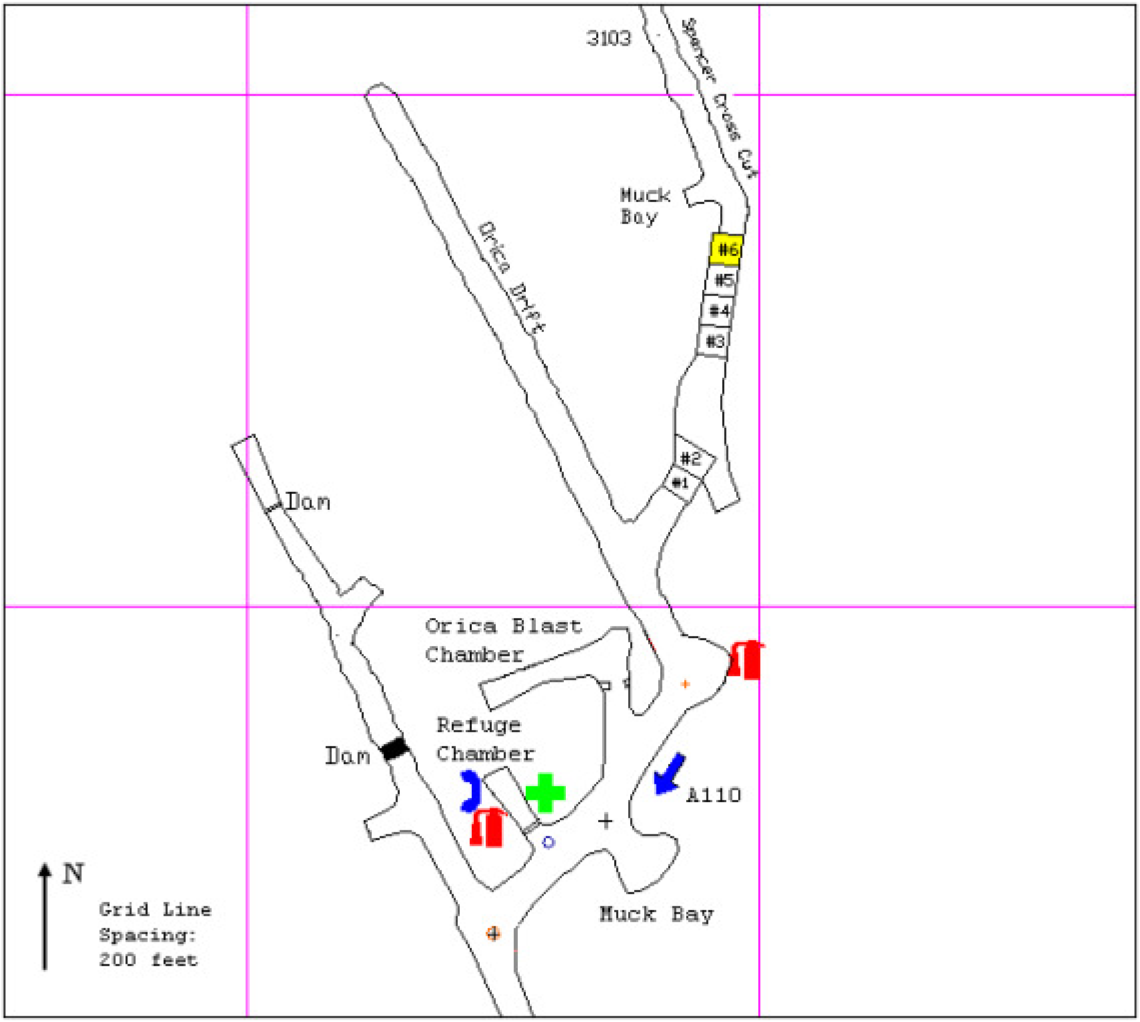

Figure 6.28 Location of Experiment #6

6.6.1 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. See Figure 6.29 for 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.

Figure 6.29 Half-cast drill holes visible after blast

6.6.2 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. See Figures 6.30

and 6.31 for a graphic representation of the results and a photograph of the tarp taken after the waterjet test.

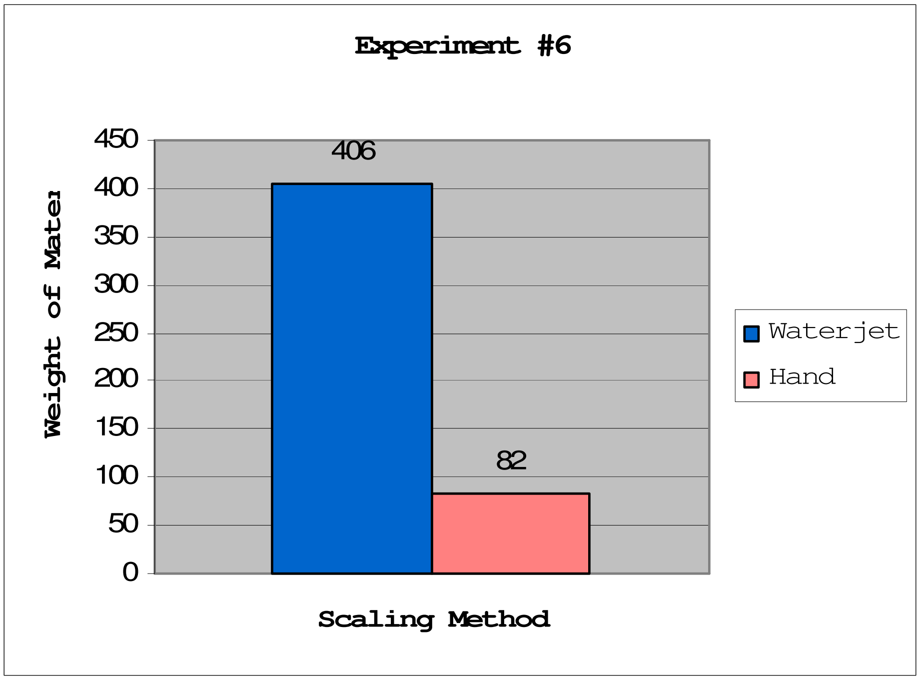

Figure 6.30 Results of Experiment #6

Figure 6.31 Material removed in Experiment #6 waterjet test

6.6.3 Notes

The photograph in Figure 6.31 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 a 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.

6.7 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 Figure 6.32. 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.

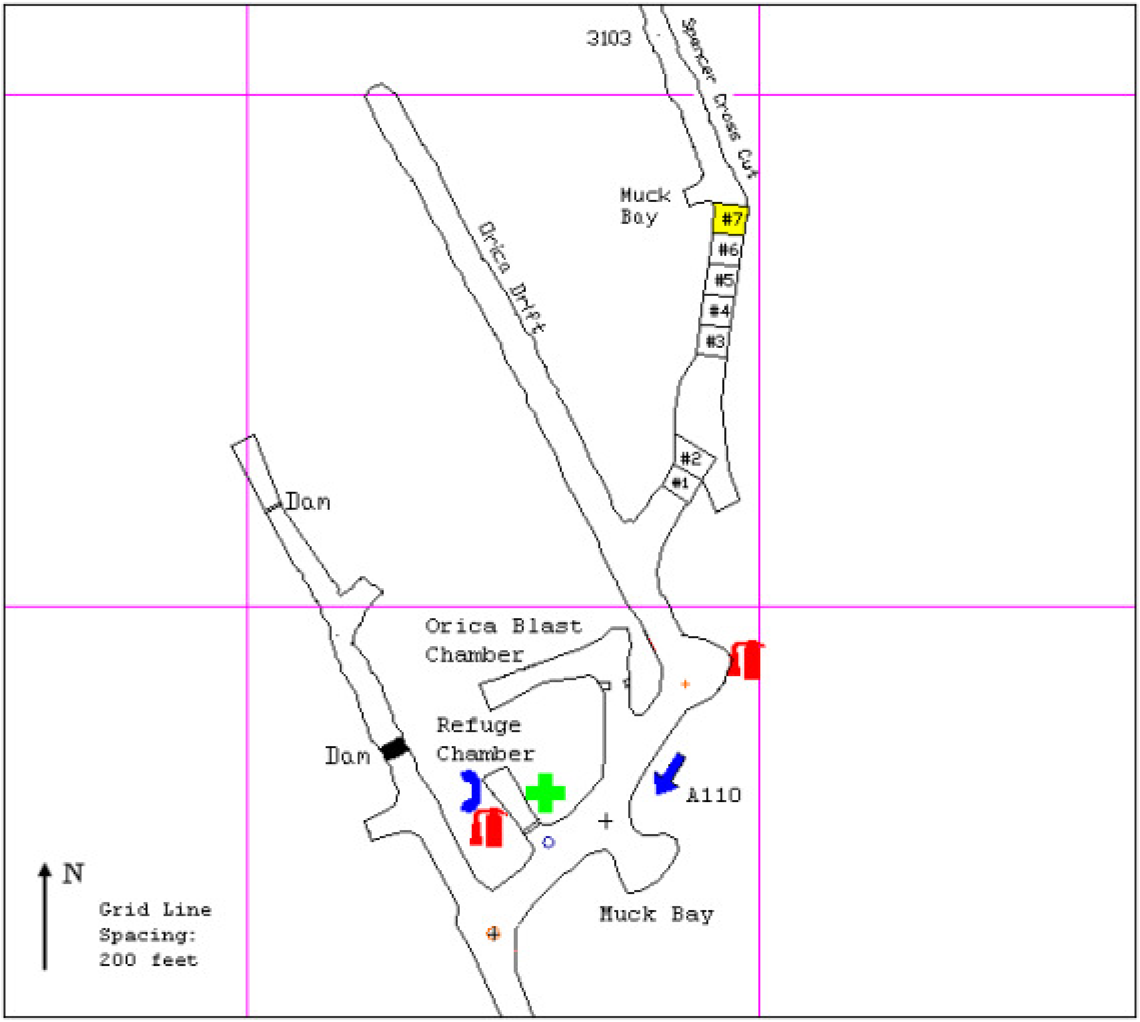

Figure 6.32 Location of Experiment #7

6.7.1 <u>Rock Conditions</u>

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 Figures 6.33 and 6.34 for photographs of the area taken before the waterjet test.

Figure 6.33 Photograph taken before Experiment #7

Figure 6.34 Fractured material in north east corner

6.7.2 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 Figure 6.34 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 Figure 6.35.

Figure 6.35 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 Figure 6.36.

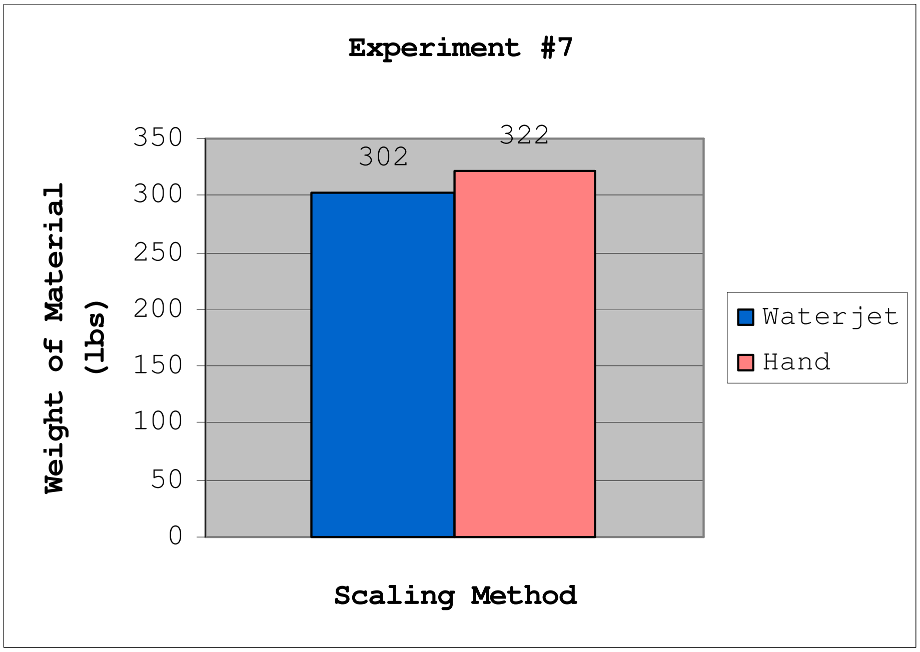

Figure 6.36 Results of Experiment #7

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.

6.7.3 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.

6.8 **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 Figure 6.37. Smooth wall blasting techniques were utilized in the back only, as the left rib was open to the muck bay.

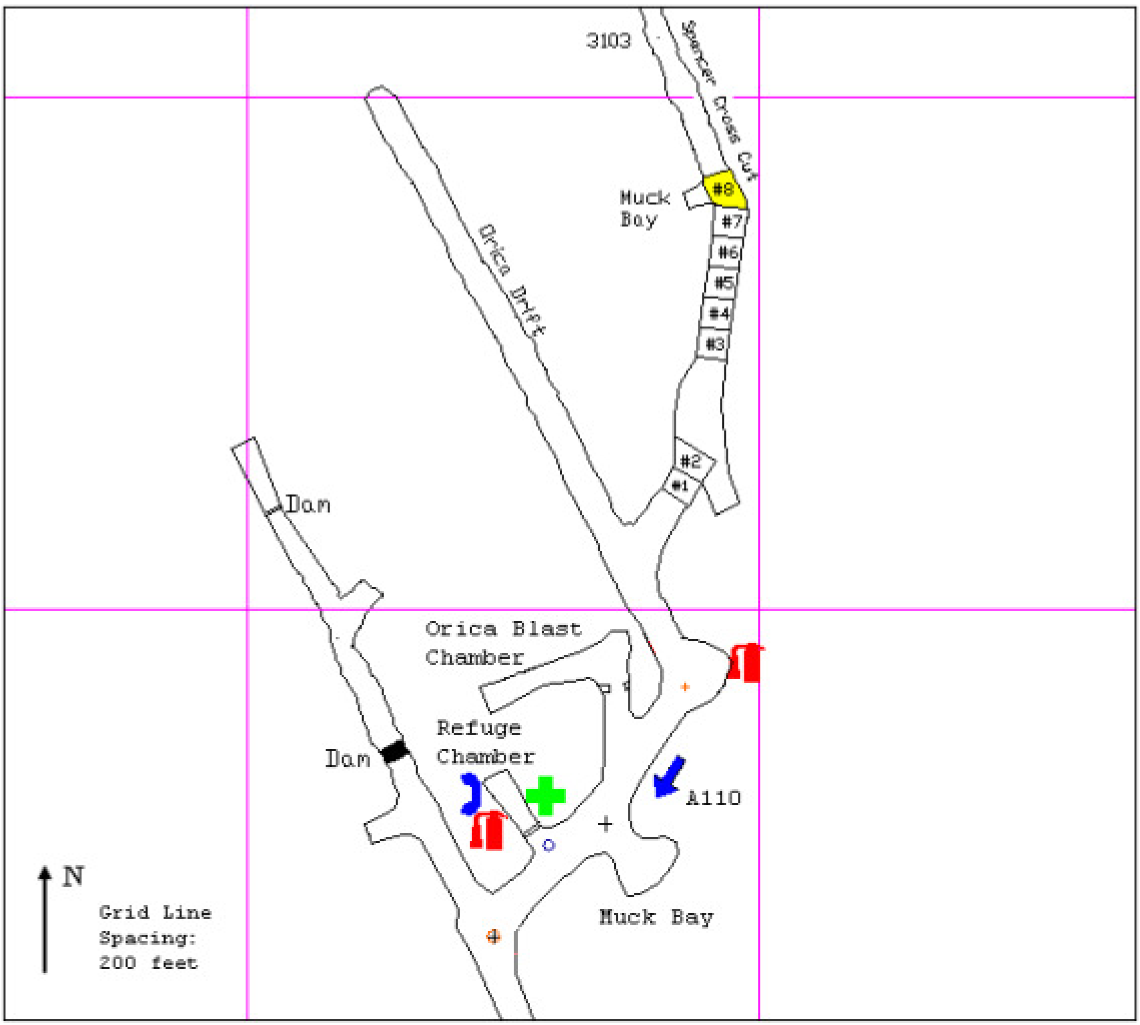

Figure 6.37 Location of Experiment #8

6.8.1 Rock Conditions

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. See

Figure 6.38 for a photograph of the area taken before the experiment.

Figure 6.38 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. See Figure 6.39 for a photograph of one of the slabs taken after the experiment was complete and rock bolts were installed.

Figure 6.39 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. Because of 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 Figure 6.40 for a closer view of the rock mass.

Figure 6.40 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.

6.8.2 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. Because of 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 Figure 6.41.

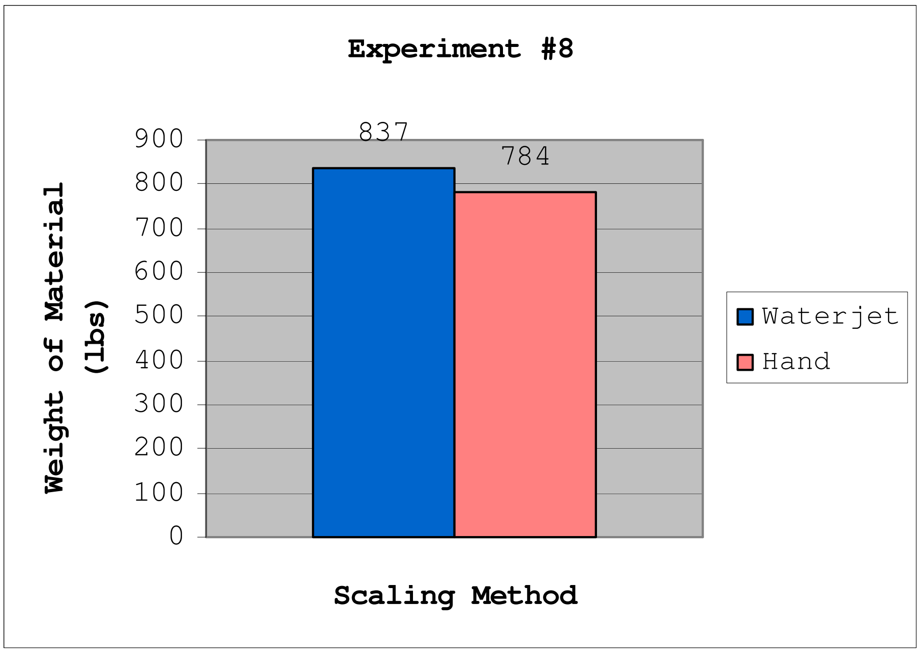

Figure 6.41 Results of Experiment #8

6.8.3 Notes

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.

6.9 **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 Figure 6.42. 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.

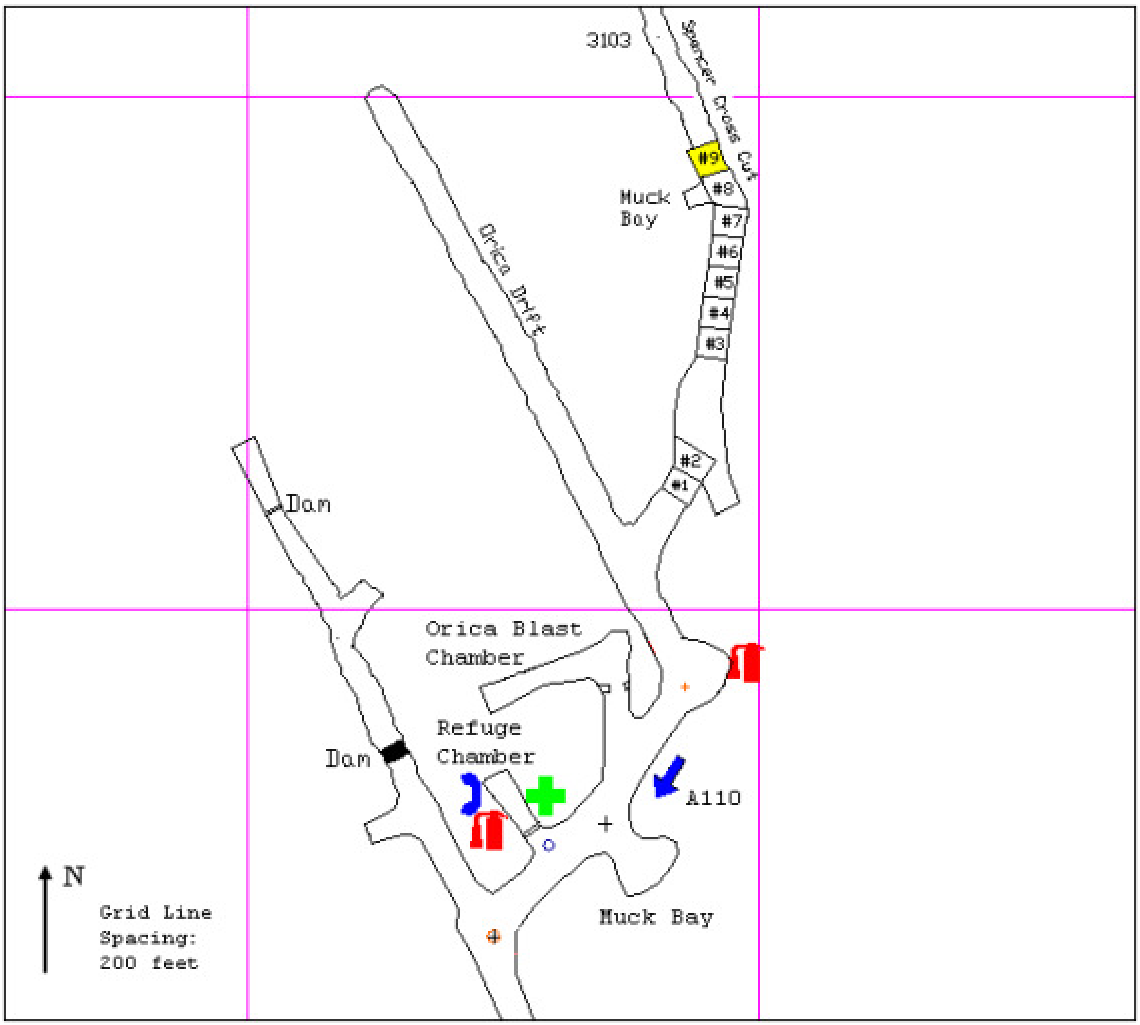

Figure 6.42 Location of Experiment #9

6.9.1 Rock Conditions

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. See Figures 6.43 for a photograph of the back taken after waterjet scaling.

Figure 6.43 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 Figure 6.44 may help illustrate the presence of the void.

Figure 6.44 Void created by waterjet during Experiment #8

6.9.2 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 Figure 6.45.

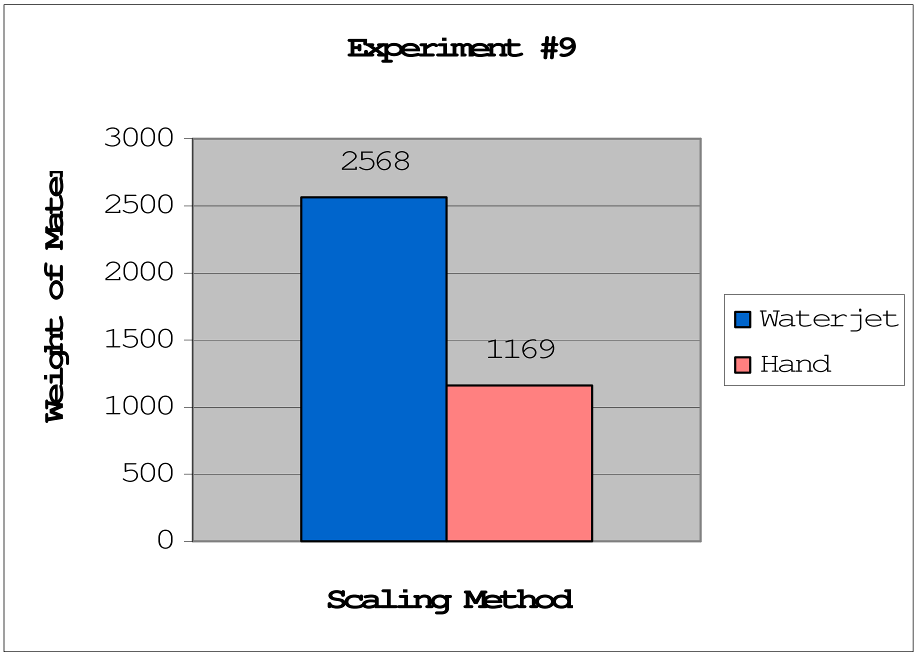

Figure 6.45 Results of Experiment #9

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.

6.9.3 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 Figure 6.46, where the north end of the tarp is seemingly bare.

Figure 6.46 Manual scaling during Experiment #9

6.10 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 Figure 6.47. 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.

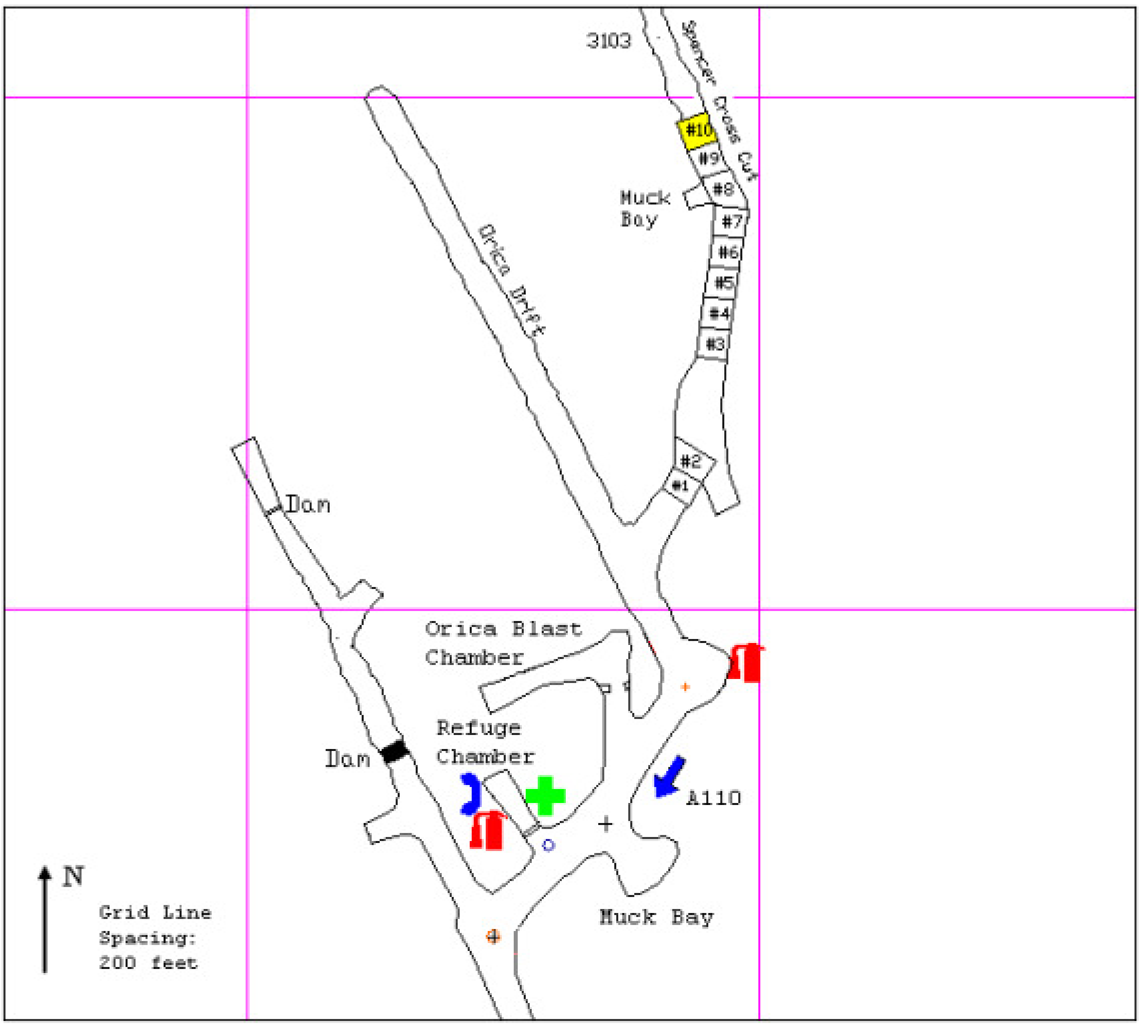

Figure 6.47 Location of Experiment #10

6.10.1 Rock Conditions

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. See Figure 6.48 for a photograph of the right rib after cleaning with the waterjet.

Figure 6.48 Right rib of Experiment #10 drift

The drill holes visible in Figure 6.48 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.

6.10.2 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 Figure 6.49.

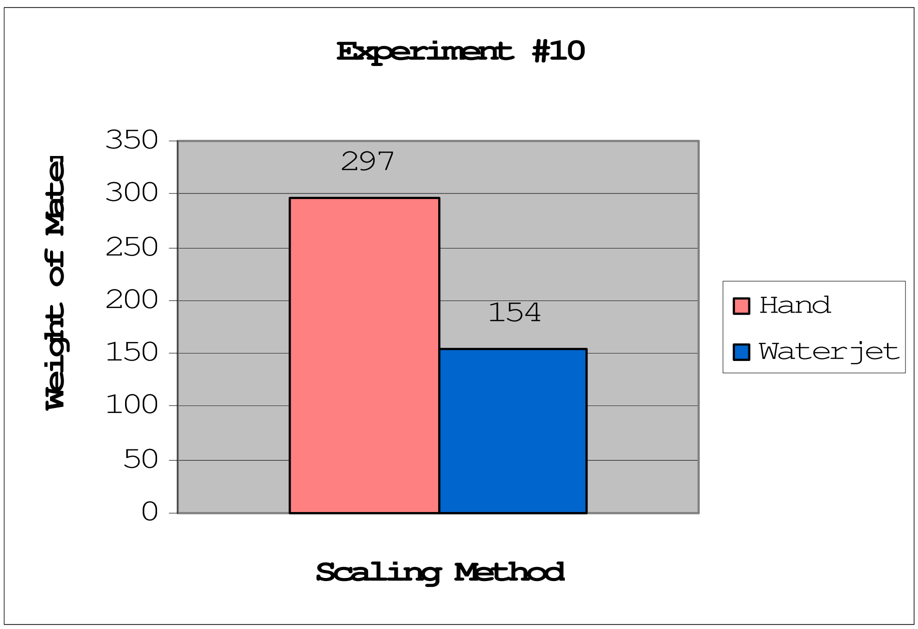

Figure 6.49 Results of Experiment #9

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.

7. SUMMARY AND DISCUSSION

7.1 Introduction

The goal of this research was to evaluate the effectiveness of various waterjet nozzles as alternatives to manual and mechanized scaling methods.

7.2 Results per Nozzle

The amount of material removed in each of the two experiments performed with each nozzle can be seen in Figures 7.1 through 7.4. The results of the two reverse order experiments are shown in Figure 7.5. From this point forward, the results of Experiment #2 will exclude the weight of the oversized boulders that fell during the waterjet test.

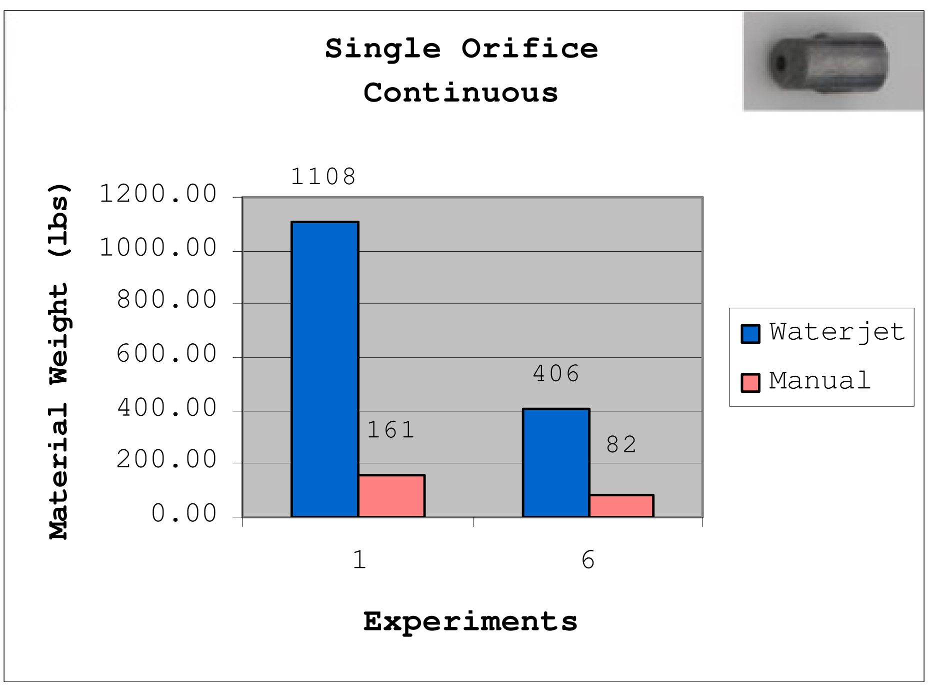

Figure 7.1 Results of Experiment Numbers 1 and 6 performed with Single Orifice, Continuous Nozzle

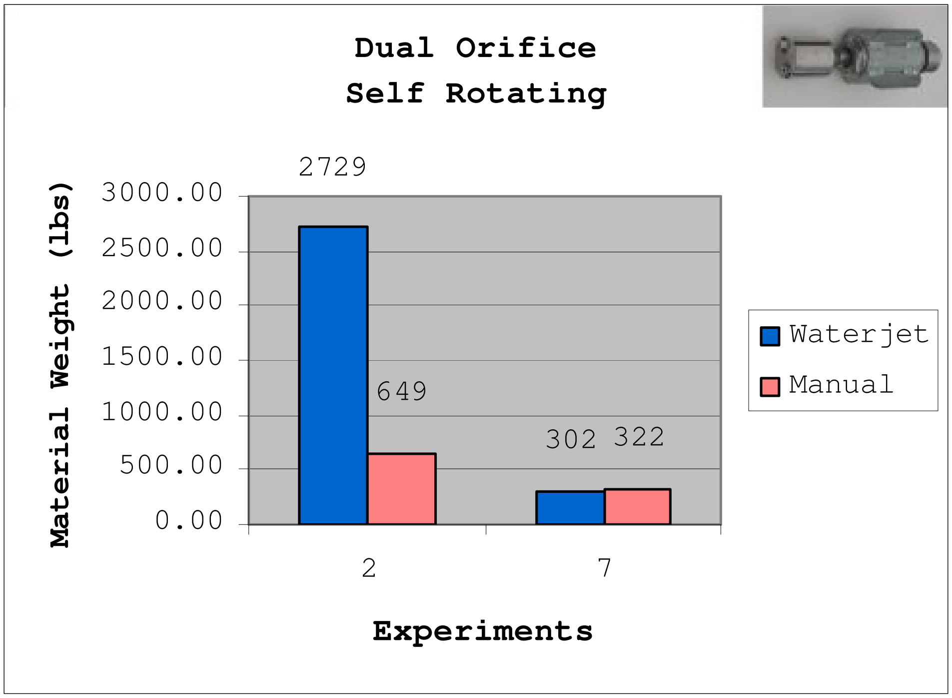

Figure 7.2 Results of Experiments 2 and 7 with Dual Orifice, Self Rotating Nozzle

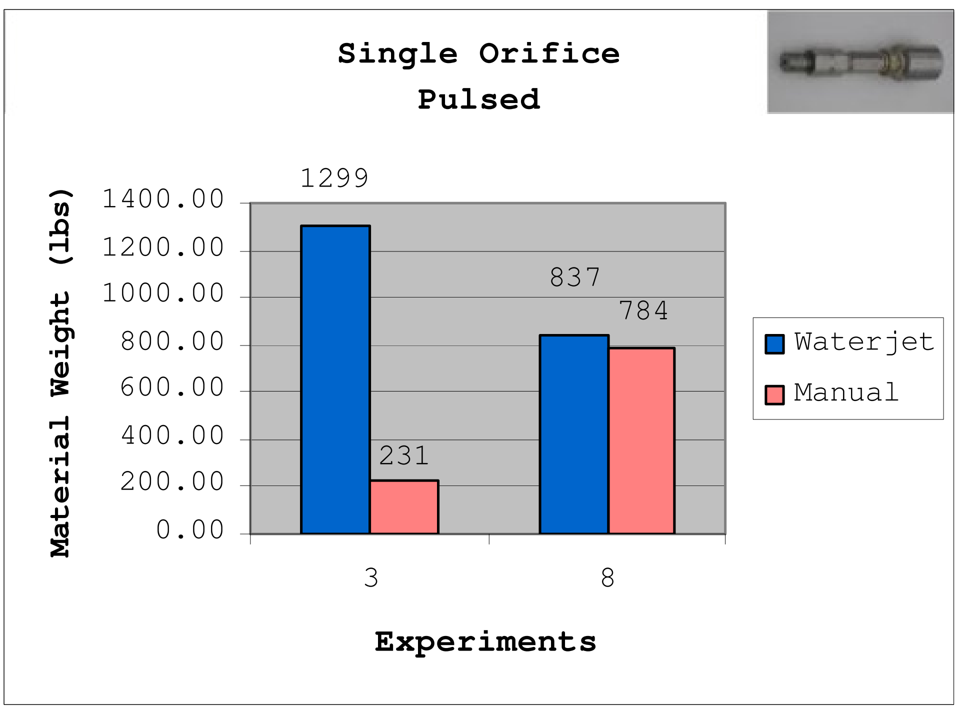

Figure 7.3 Results of Experiments 3 and 8 with Single Orifice, Pulsed Nozzle

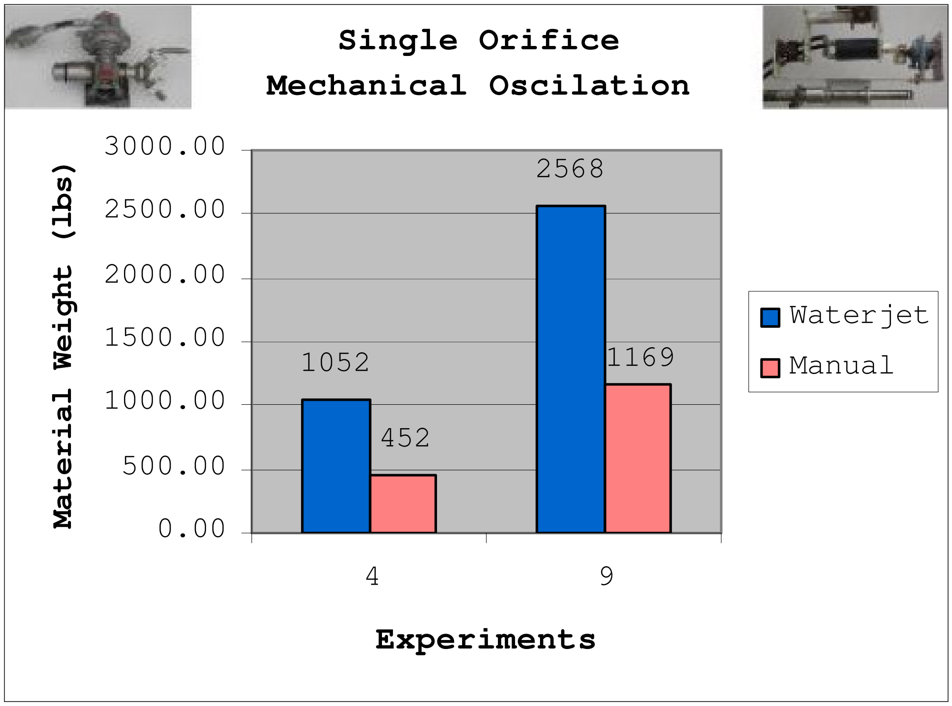

Figure 7.4 Results of Experiments 4 and 9 with Single Orifice, Mechanically Oscillated Nozzles

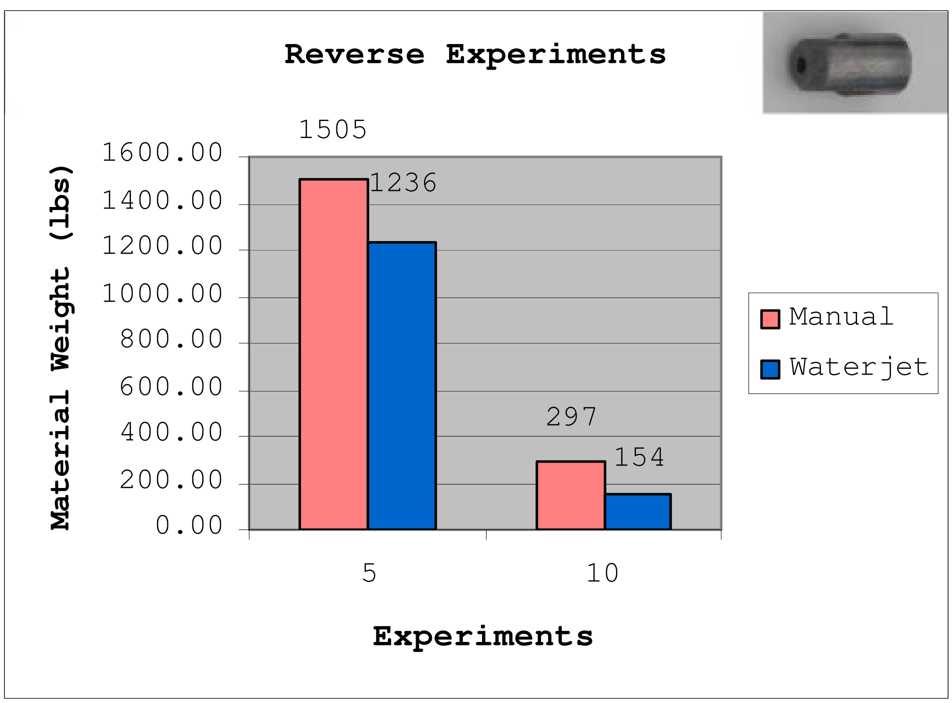

Figure 7.5 Results of Reverse Experiments 5 and 10

7.3 Cumulative Results

Figure 7.6 shows the weight of all material removed during each of the ten scaling experiments.

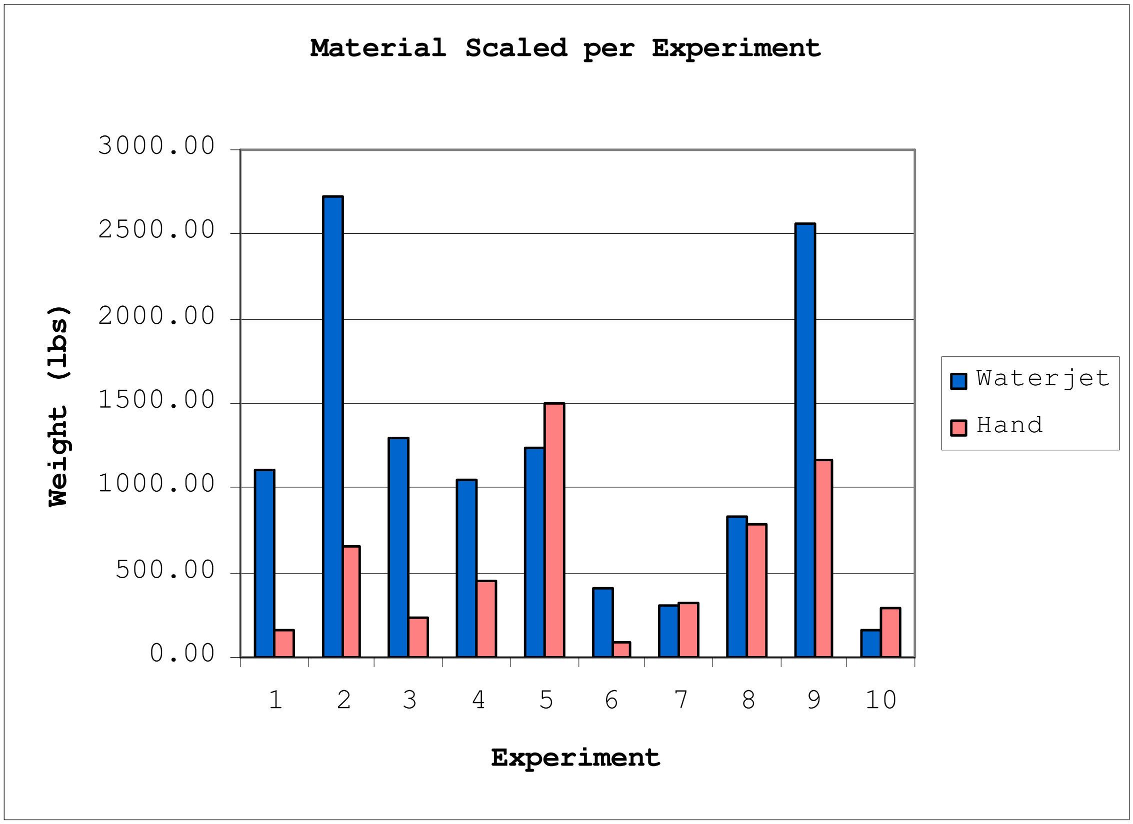

Figure 7.6 Cumulative Results of all experiments by weight

As shown in Figure 7.6, nearly twice the material was removed in Experiments 2 and 9 as compared to the other experiments performed. For a more neutral comparison, the cumulative results of all ten experiments can also be conveyed in terms of percentage of material removed by each scaling method. The percentages were calculated using the weight of material removed by each scaling method, divided by the total weight per experiment. A graph of the cumulative results in terms of percentage is shown in Figure 7.7.

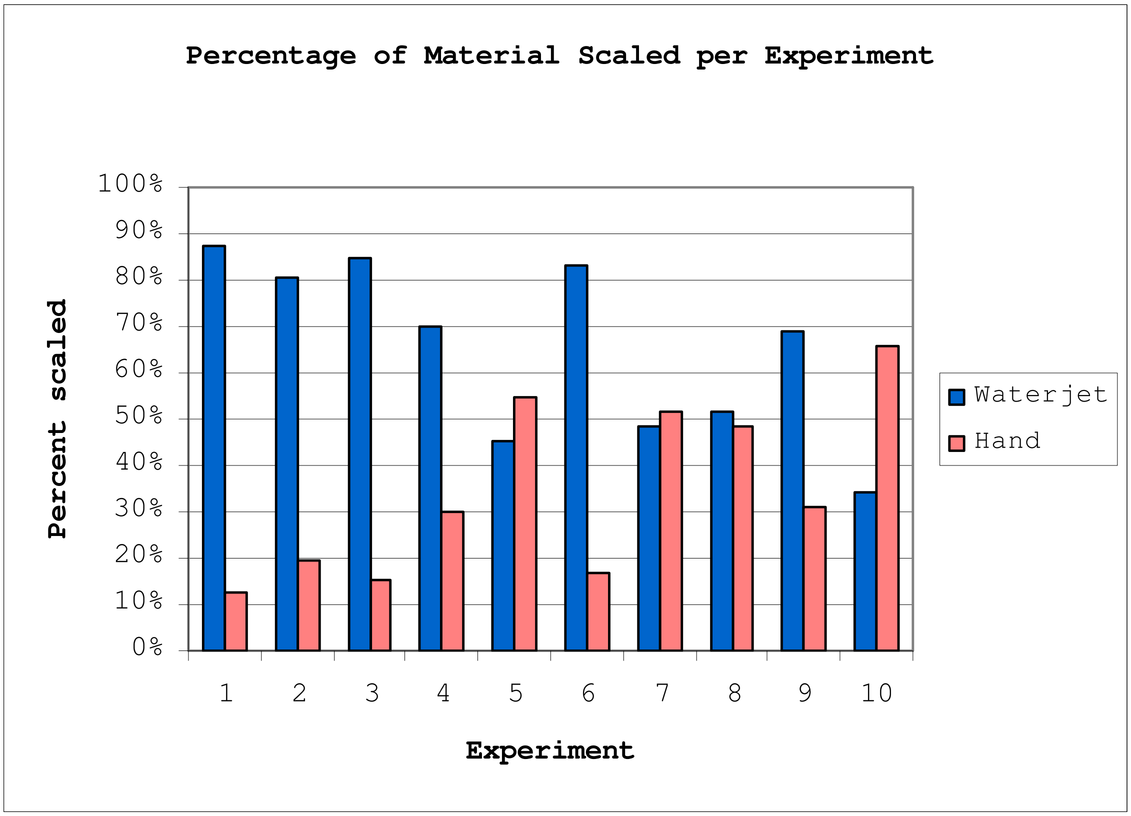

Figure 7.7 Percentage of material removed per scaling method in each experiment

7.4 Cumulative Size Distribution

The particle size distribution measured for the first four experiments can be summarized in one graph. The total amount of material in each screen size classification was added together from each experiment for both manual and waterjet scaled material. The overall results are shown in Figure 7.8.

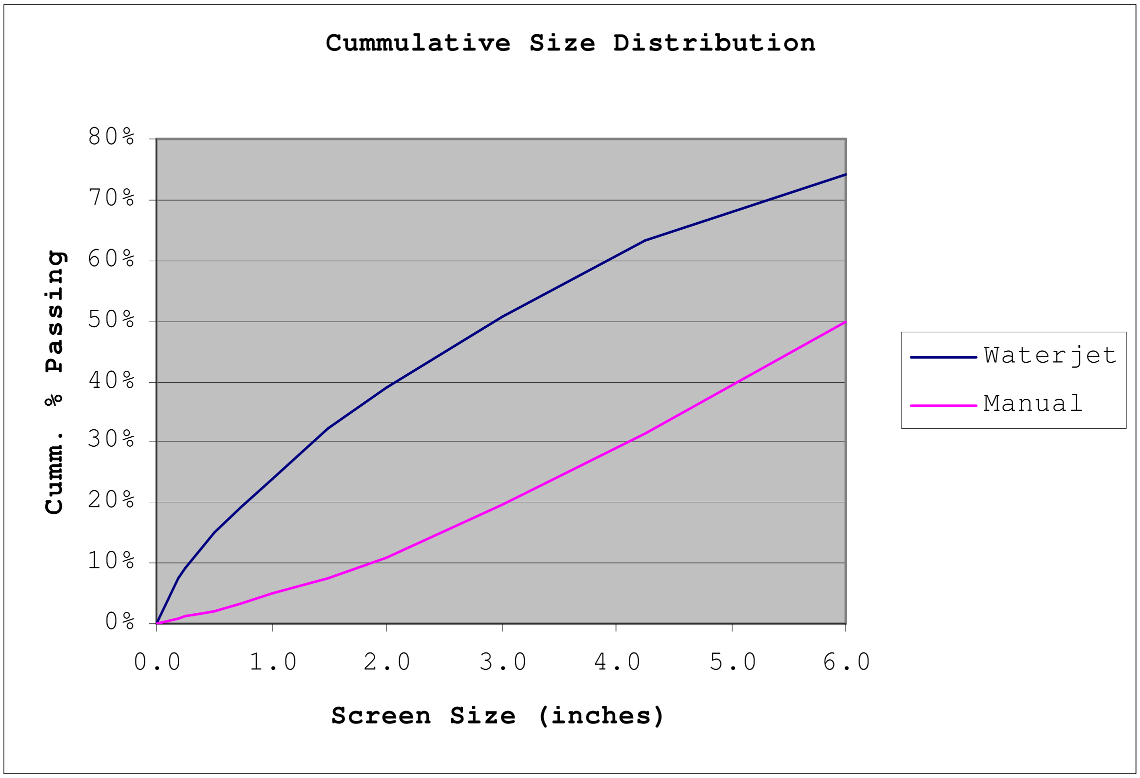

Figure 7.8 Particle size distribution for Experiments 1-4

7.5 Discussion

The indication of a successful nozzle, based on numbers alone, could be taken from an experiment where the waterjet scaled material far outweighed the manually scaled material. As shown in Figure 7.7, however, each of the first three experiments resulted in a ratio of at least 5:1 in that regard. The mechanically oscillated systems each resulted in a ratio of just over 2:1, leaving one to believe that the first three nozzles tested were equally effective.

The definition of a poorly performing nozzle, based on numbers alone, could theoretically be considered one whose results were matched by the subsequent manual scaling. As shown again in Figure 7.7, the dual orifice and pulsed nozzles used in

Experiments 7 and 8 produced such results. Based on these assumptions, the single orifice, continuous nozzle would be considered the most effective scaling tool. Such an assertion, however, can not be made without considering more detailed information such as the variability in geology and rock conditions between each experiment.

Results from the two reverse order experiments supported the assertion that a waterjet is more efficient than manual scaling in removing small to moderately sized material. The particle size distribution analysis shows that waterjets remove more of the fine material. This in turn will increase the adhesion properties of shotcrete applied subsequently.

The information that should be more closely regarded in the selection of a waterjet scaling nozzle concerns other aspects of operation, including cost and convenience.

7.6 Limitations

Several limitations throughout the course of this research resulted in operating conditions and findings other than those anticipated.

7.5.1 Statistics

The greatest limitation of this research is in the lack of statistical evidence promoting any single nozzle over the others. Two experiments can not provide enough information to mathematically establish the effectiveness of a waterjet scaling nozzle, and unfortunately, the amount of time and money required to complete setup and preparation of each experiment prevented a more thorough examination of each system.

7.5.2 Variables

Another limitation was the abundance of variables that disallowed a true parametric evaluation. In that regard, the very nature of scaling in a hard rock underground mine makes it all but impossible to reproduce any specific series of conditions or events. The style and quality of blasting, the type of rock, extent of weathering, presence of groundwater, and even stresses in the rock mass may play a role in the amount of material that requires scaling after blasting.

7.5.3 Human Element

The amount of material removed or missed by any given nozzle in any given experiment depended heavily upon the tendencies of the human operator. Though it is believed that human interaction would be required to most effectively interpret and target the rock surface in a real scaling situation, the dependence upon visibility and judgment made the operation of the waterjet different in each experiment.

7.5.4 Pressure Losses

Although the operating pressure of the pump was measured with a gauge at the output, the actual pressures emitted by each nozzle were never determined. General pressure losses were assumed based on the length of high pressure hose used, but the actual losses incurred by various fittings and the efficiencies of the nozzles themselves were not taken into account. The operating parameters were kept relatively constant rather than optimized for each nozzle, and thus the performance of one or more nozzles may have suffered as a result.

7.5.5 System Optimization

The operating parameters of the waterjet system, particularly pressure and flow rate, were not investigated and optimized specifically for scaling. Previous research conducted at CSM (Kuchta, 2002) recognized an optimal working pressure of

3000 psi, at a flow rate of 14 gpm, based on the adhesion strength of shotcrete applied afterwards. Financial constraints and limited access to a variety of high pressure equipment prevented further experimentation with other pressures and flow rates. Likewise, this research was conducted within a relatively narrow range of pressures and flow rates, and thus the results of the nozzle tests may be irrelevant for waterjet systems operated in different configurations.

8. CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

Based on numbers alone, all nozzles appear to be capable of scaling more effectively than hand-held scaling bars, and no single waterjet nozzle can be declared superior to the others. When issues of cost and convenience are considered, however, there are clear advantages and disadvantages to certain nozzles.

The acoustic pulsed nozzle, costing approximately $1800 off the shelf and requiring $600 in replacement parts, has a clear disadvantage in being considered for industrial use. The amount of mist generated during testing also limits its favorability in everyday use. Additionally, the nozzle must be manufactured to exacting specifications depending on the operational pressure and flow rate of the intended pump system. If those parameters change over the course of time due to wear or the variation of specifications between original and replacement pumps, the pulse-generating ability of the nozzle will not be guaranteed.

The dual orifice, self rotating nozzle seems relatively robust but would cost around $1000 to replace if damaged. The inexpensive and widely accessible nozzle tips offer hope for industrial acceptance, and the self-rotating action is actually quite pleasant to watch in action. Also worth considering is the possibility that cheaper self-rotating nozzles may be available from other companies that can perform just as well. The main disadvantage of the dual orifice, self rotating nozzle is the 50% decrease in flow rate through each of the nozzle tips.

The single orifice, continuous nozzle is by far the easiest to use and least expensive to replace. Damage to such a simple and robust design would almost require intentional misuse, and the straightforwardness of a single orifice guarantees that any pump rated within a certain range of pressures and flow rates will accomplish the task without vigilant calculations. The only downfall of the single orifice nozzle is the lack of transverse motion.

The single orifice, mechanically oscillated nozzle is believed to be the most effective tool for waterjet scaling. While the air-powered unit was dissatisfactory in performance, the custom built hydraulic system worked extremely well, and any number of mechanical configurations can be designed and implemented depending on the requirements of the individual application.

8.2 Recommendations

In consideration of the data presented in this report and the experience gained while collecting it, there are several recommendations to be made for the future of waterjet scaling both in research and in the quest for industry acceptance.

8.2.1 Continued Research

If additional information is desired regarding the effectiveness of various waterjet nozzles, there are several ways to pursue it. A more robust parametric evaluation could be achieved by automating the transverse motion of each nozzle, thereby guaranteeing constant surface coverage and exposure time between tests. Implementing such a system, however, would not eliminate variations in the rock mass that make each test unique. Another recommendation, therefore, would be to conduct further waterjet scaling research in a more predictable rock mass and maintain strict regulations on the blasting practices used. Maximum efficiency and effectiveness against certain rock conditions could also be evaluated by the research of alternative flow rates and pressures.

It should be noted that the aforementioned recommendations call for extreme measures both financially and methodologically. Automated machinery, spare high pressure pumps, and new test sites are not cheaply or easily obtained.

8.2.2 Industry Acceptance

The purpose of this research was to improve underground safety, yet the benefits of remote waterjet scaling technology remain unknown to many in the industry. An economic analysis would help answer questions of energy and water consumption in comparison to standard scaling techniques, and a detailed conceptual model would illustrate the advantages in safety and efficiency of waterjets for those who express doubt.

Waterjet scaling technology may also be promoted by comparing it head-to-head with a mechanical scaler, which may in turn lead to the development of a hybrid piece of machinery. A vehicle capable of scaling with high pressure water and removing stubborn blocks with mechanical force would have the potential of setting industry standards for both safety and efficiency.

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APPENDIX A

RMR Analysis

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.

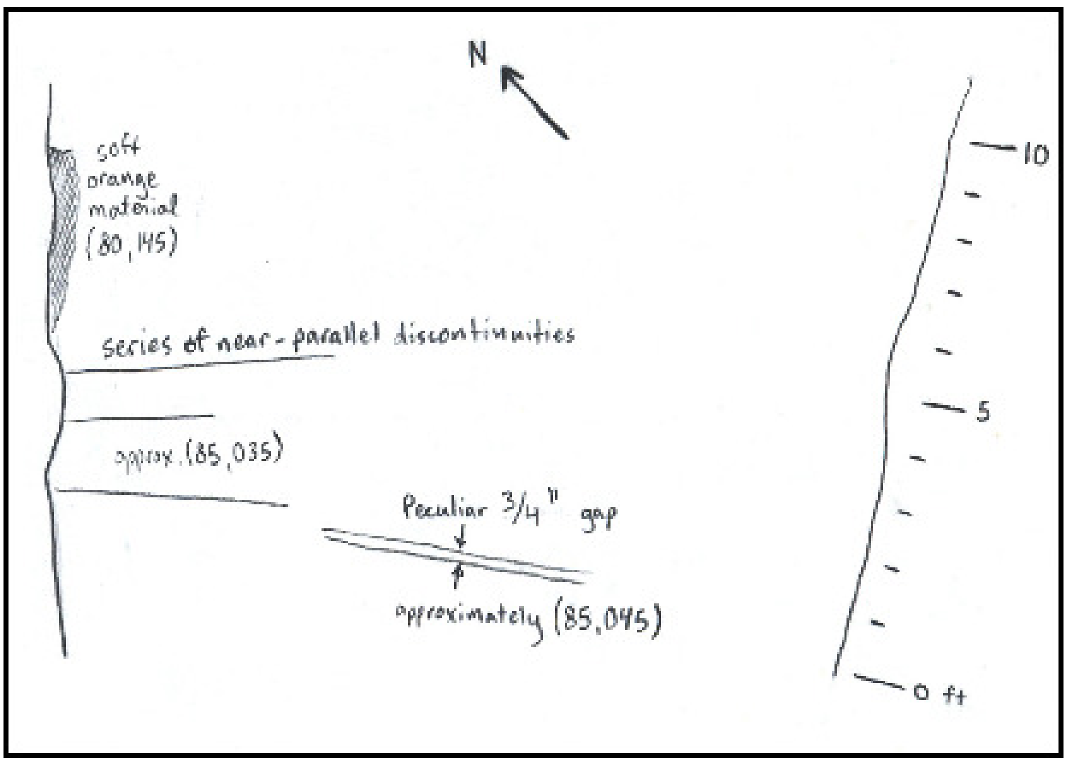

Figure A.1 Map of geologic features noted in Experiment #1

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. Condition of Discontinuities – 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. Groundwater – Moist during rainy seasons.
   Score: 11

RMR Total: 70

RMR Analysis

Experiment #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.

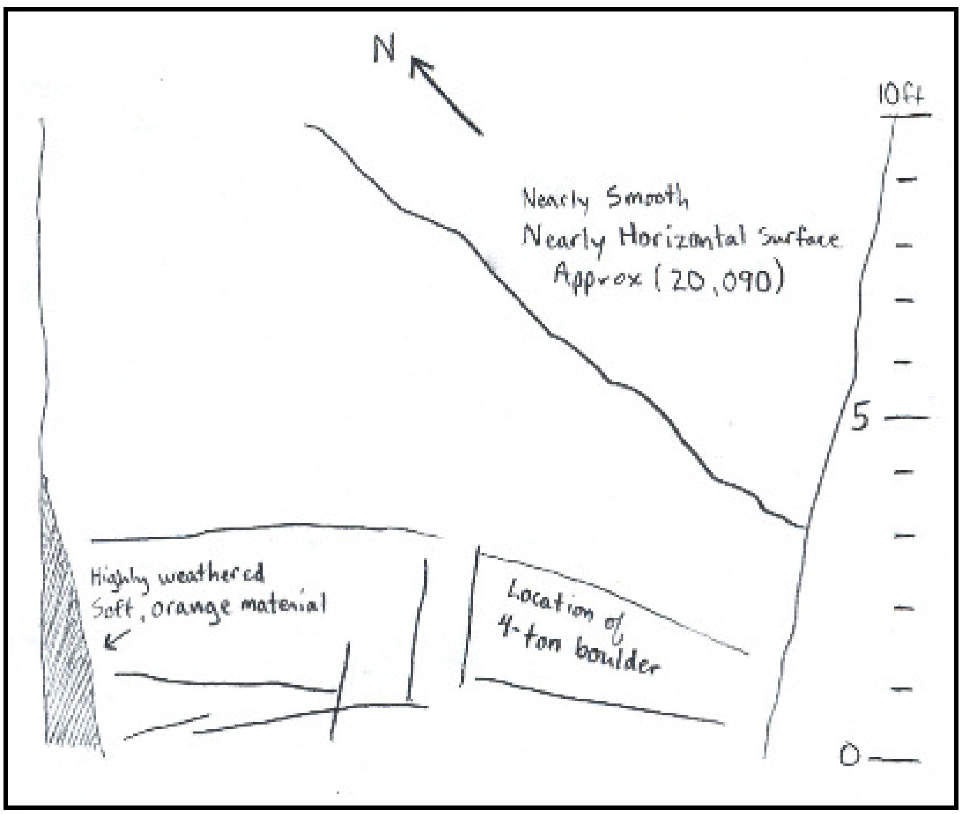

Figure A.2 Map of geologic feature noted in Experiment #2

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

Description: 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.

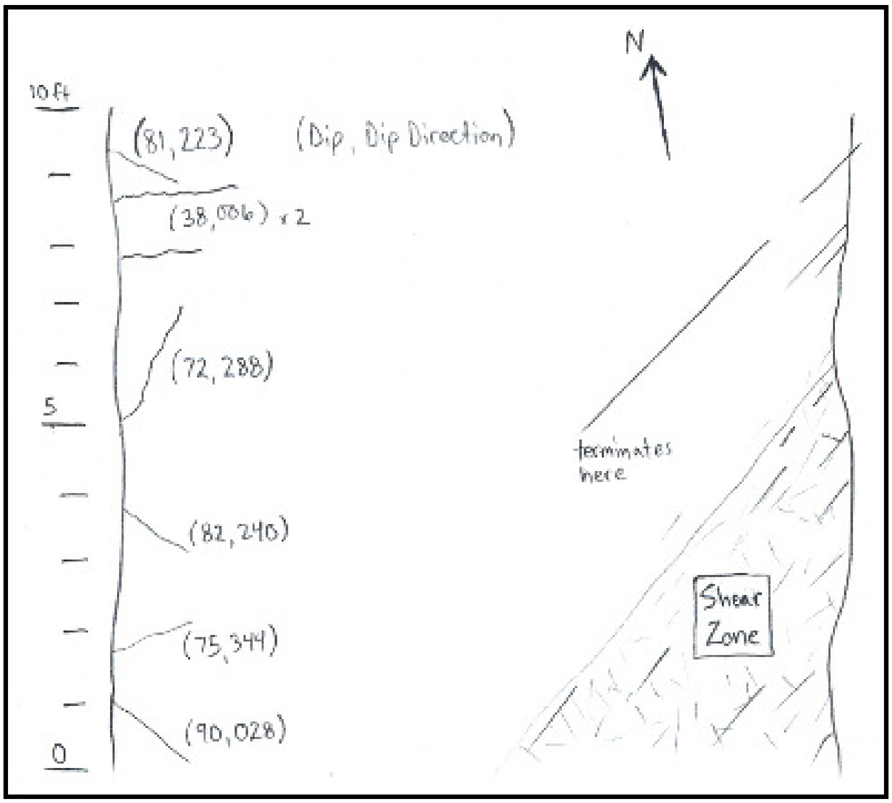

Figure A.3 Map of geologic features noted in Experiment #3

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

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

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

4. Condition of Discontinuities – 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. Groundwater – 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.

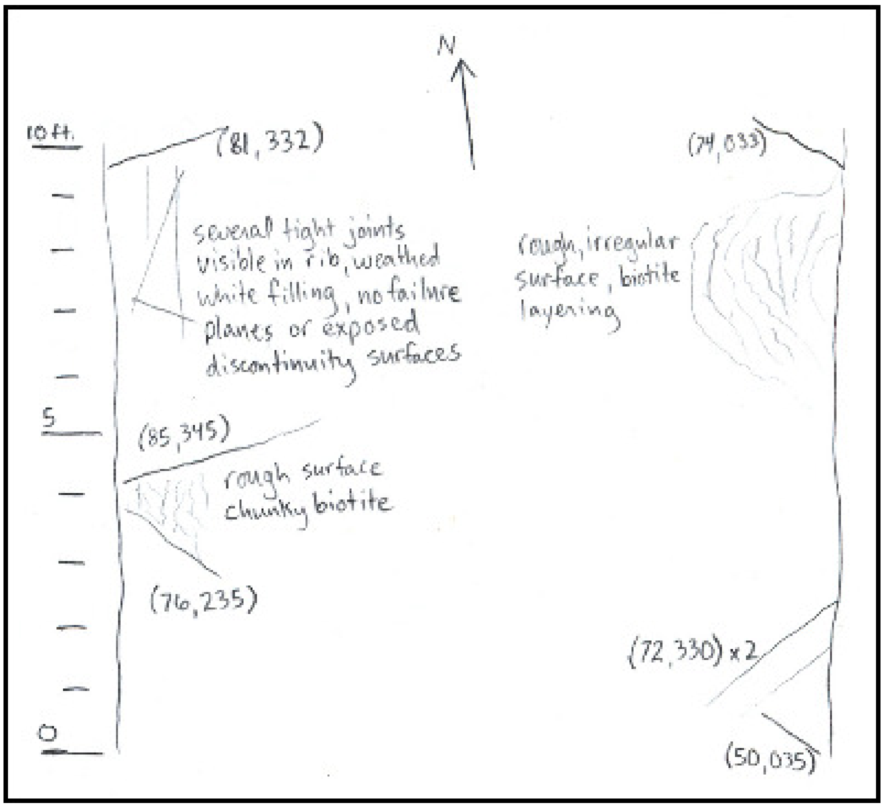

Figure A.4 Map of geologic features noted in Experiment #4

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.

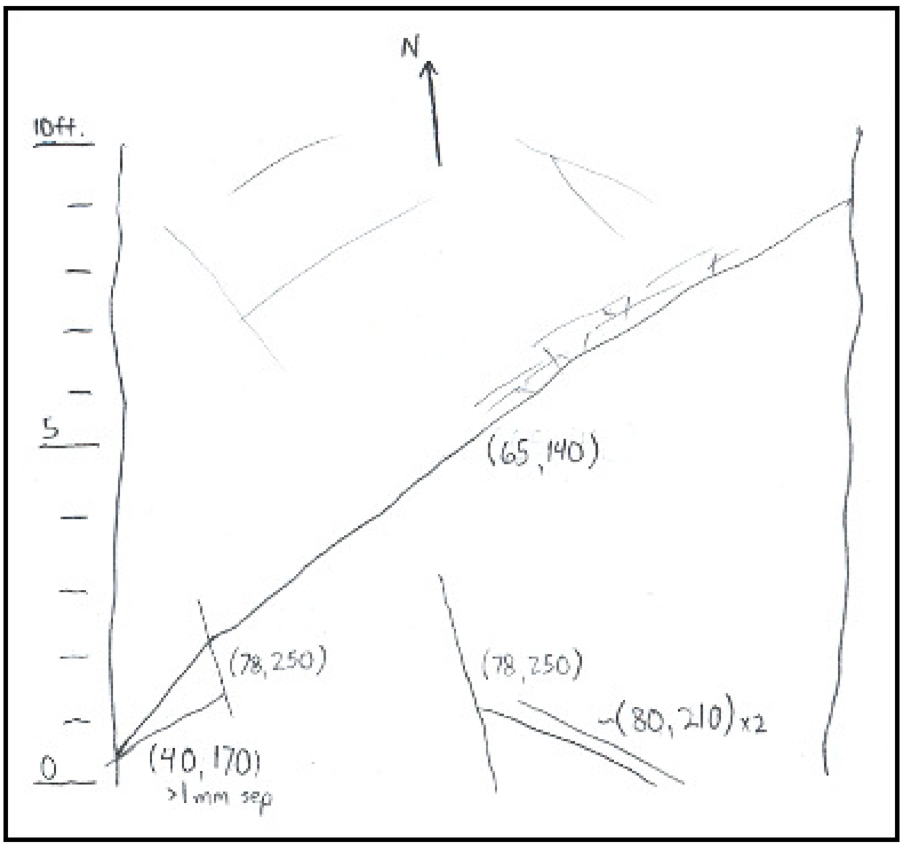

Figure A.5 Map of geologic features noted in Experiment #5

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.

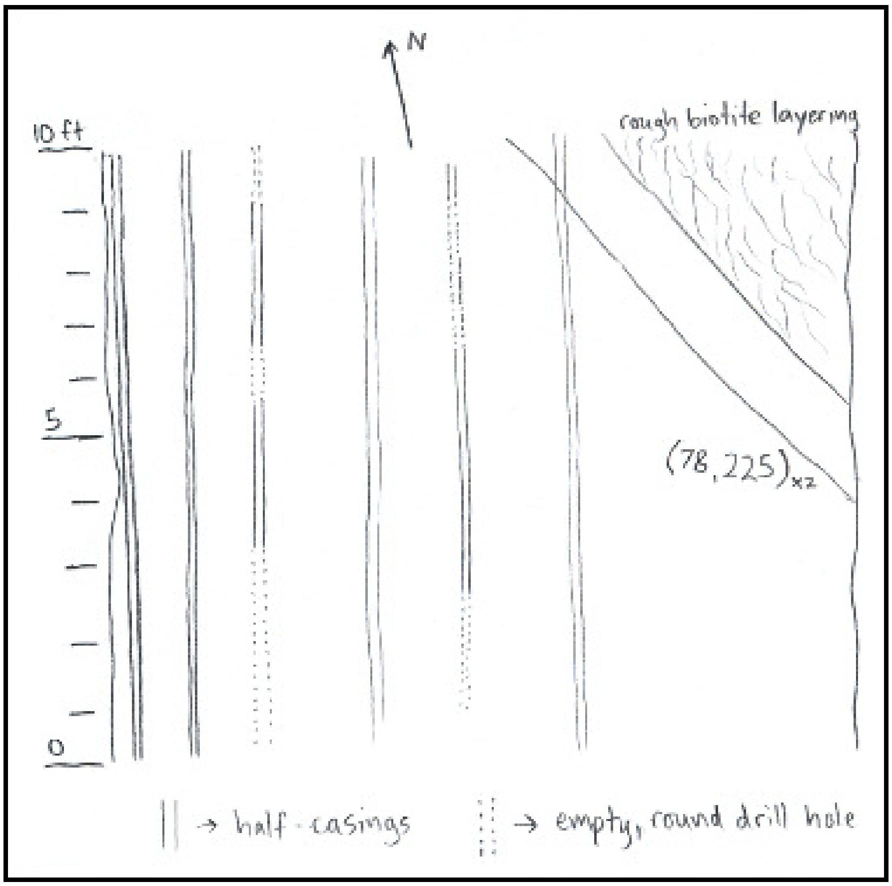

Figure A.6 Map of geologic features noted in Experiment #6

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.

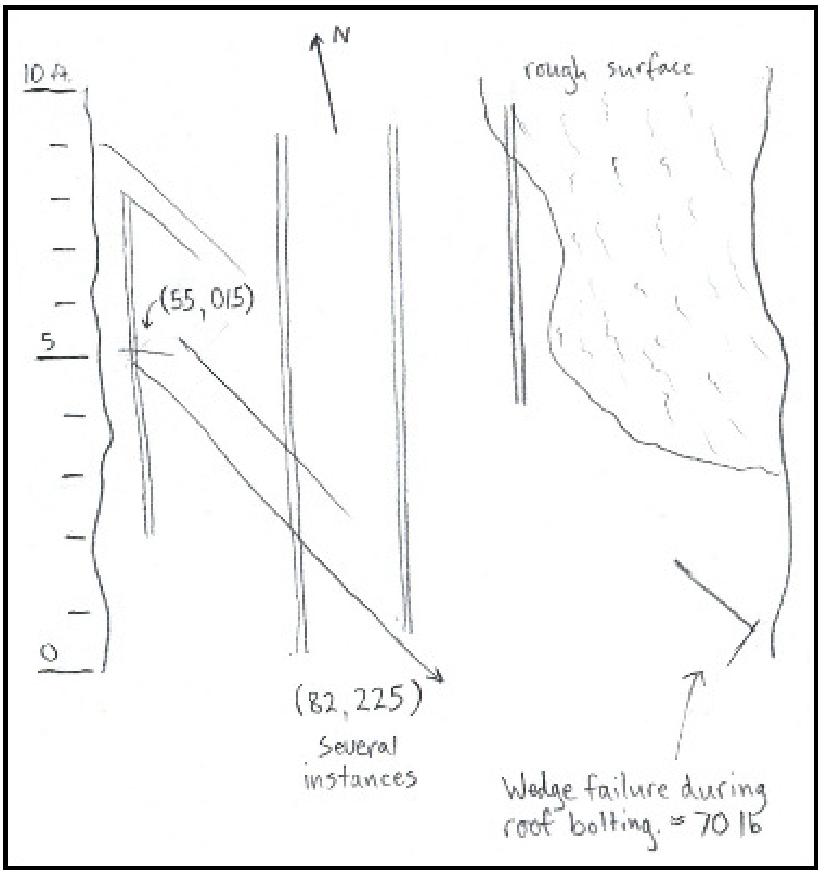

Figure A.7 Map of geologic features noted in Experiment #7

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.

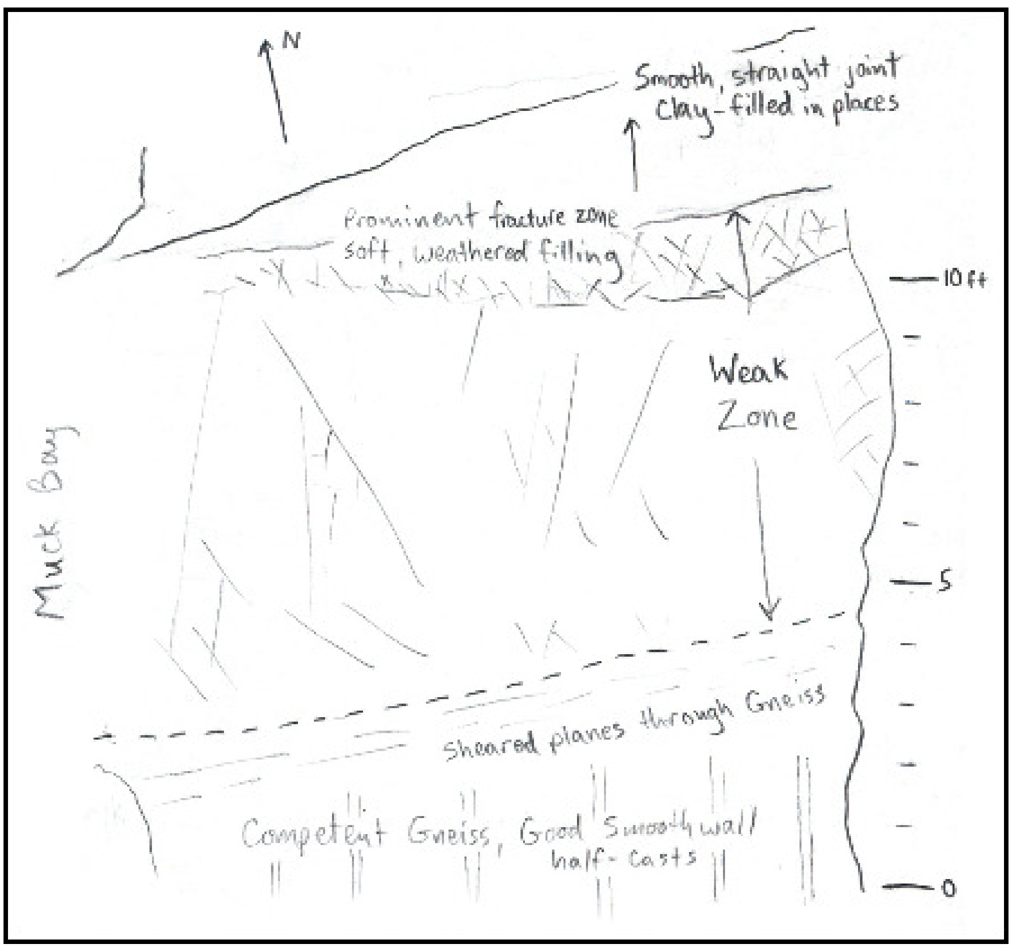

Figure A.8 Map of Geologic features noted in Experiment #8

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.

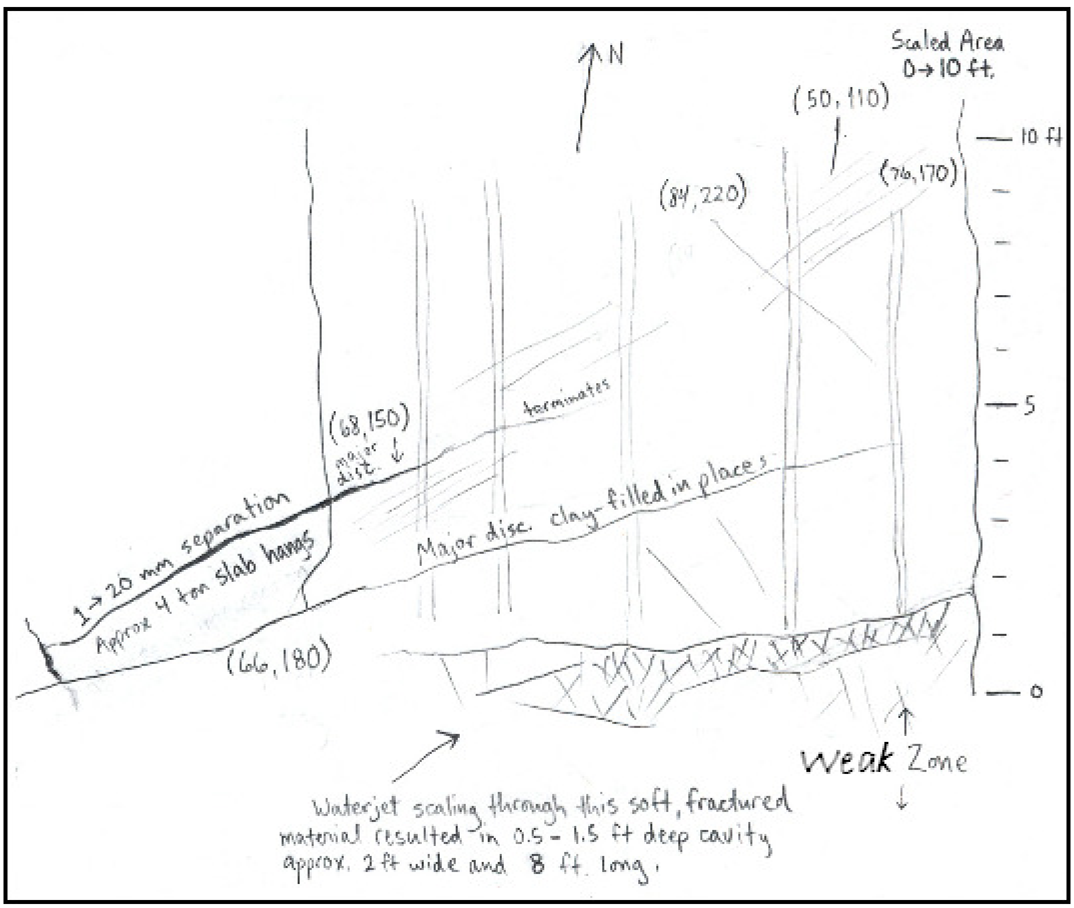

Figure A.9 Map of geologic features noted in Experiment #9

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 Analysis

Experiment #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.

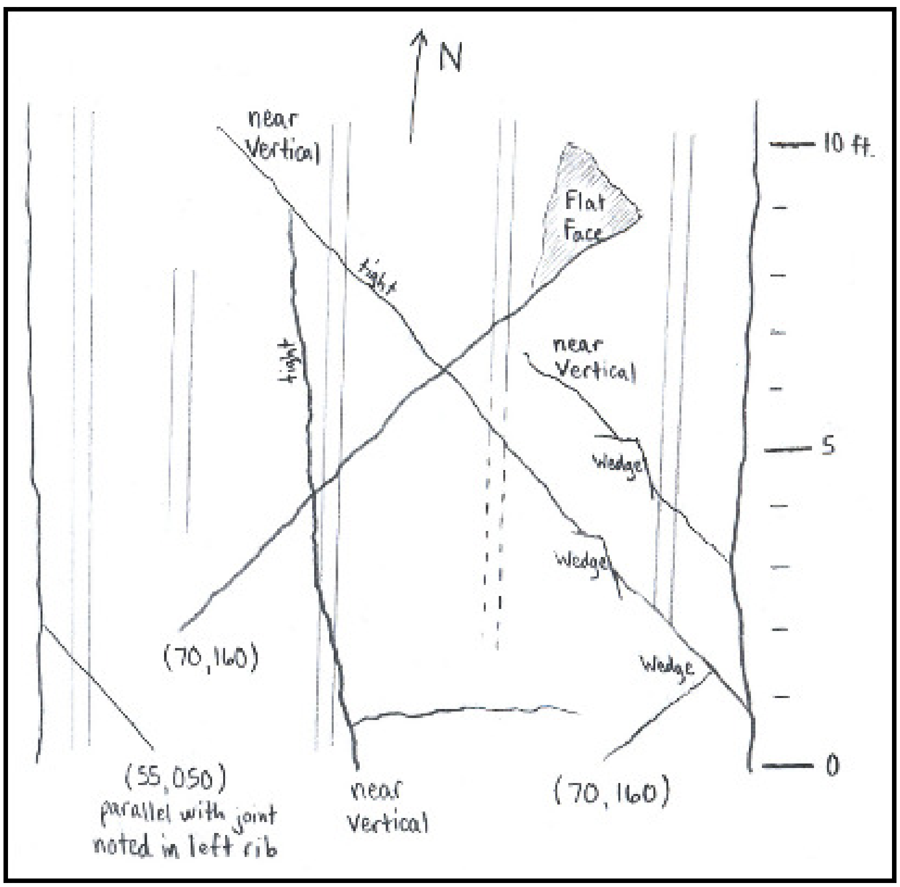

Figure A.10 Map of geologic features noted in Experiment #10

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

Mine Maps

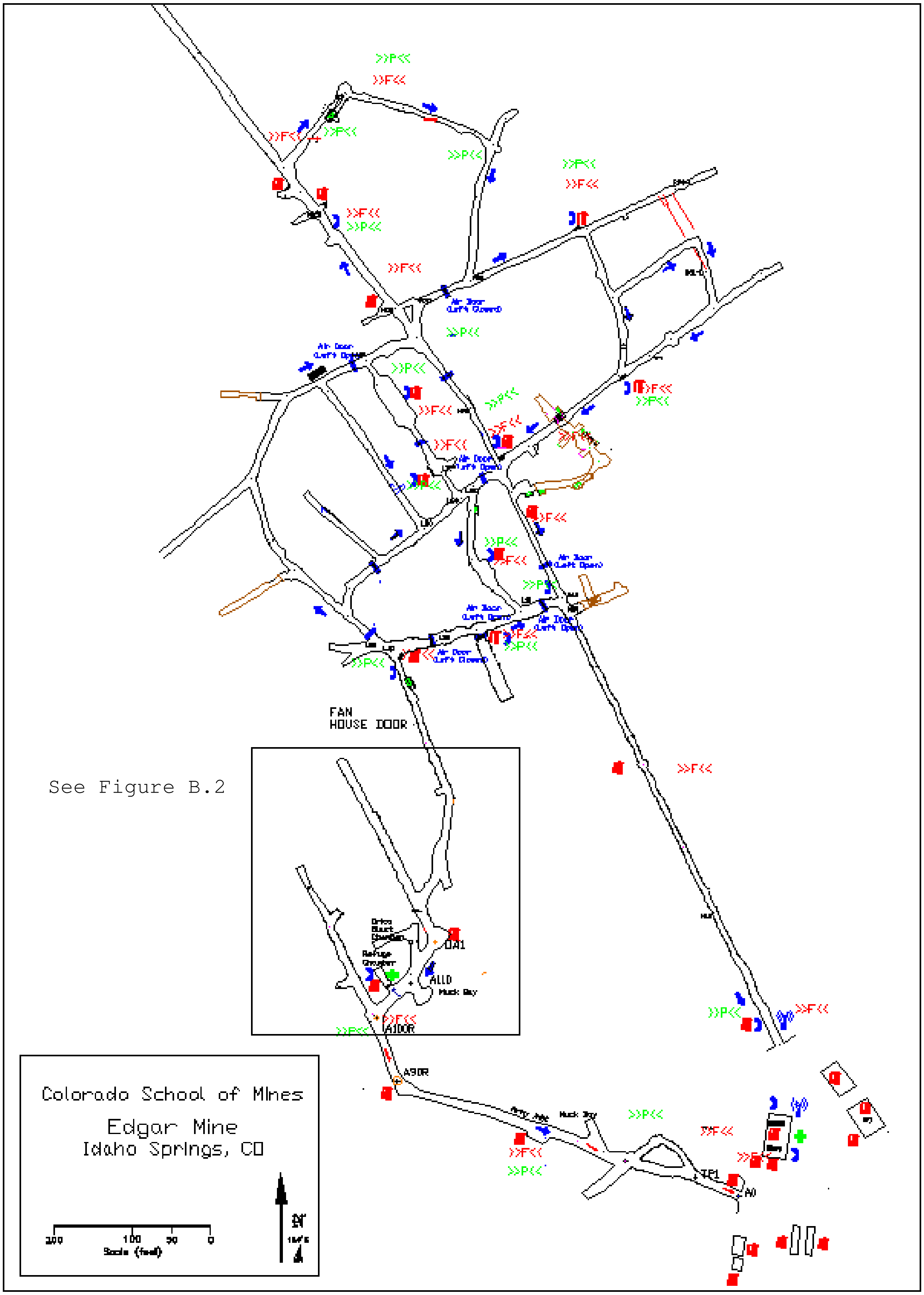

Figure B.1 Map of Edgar Mine workings

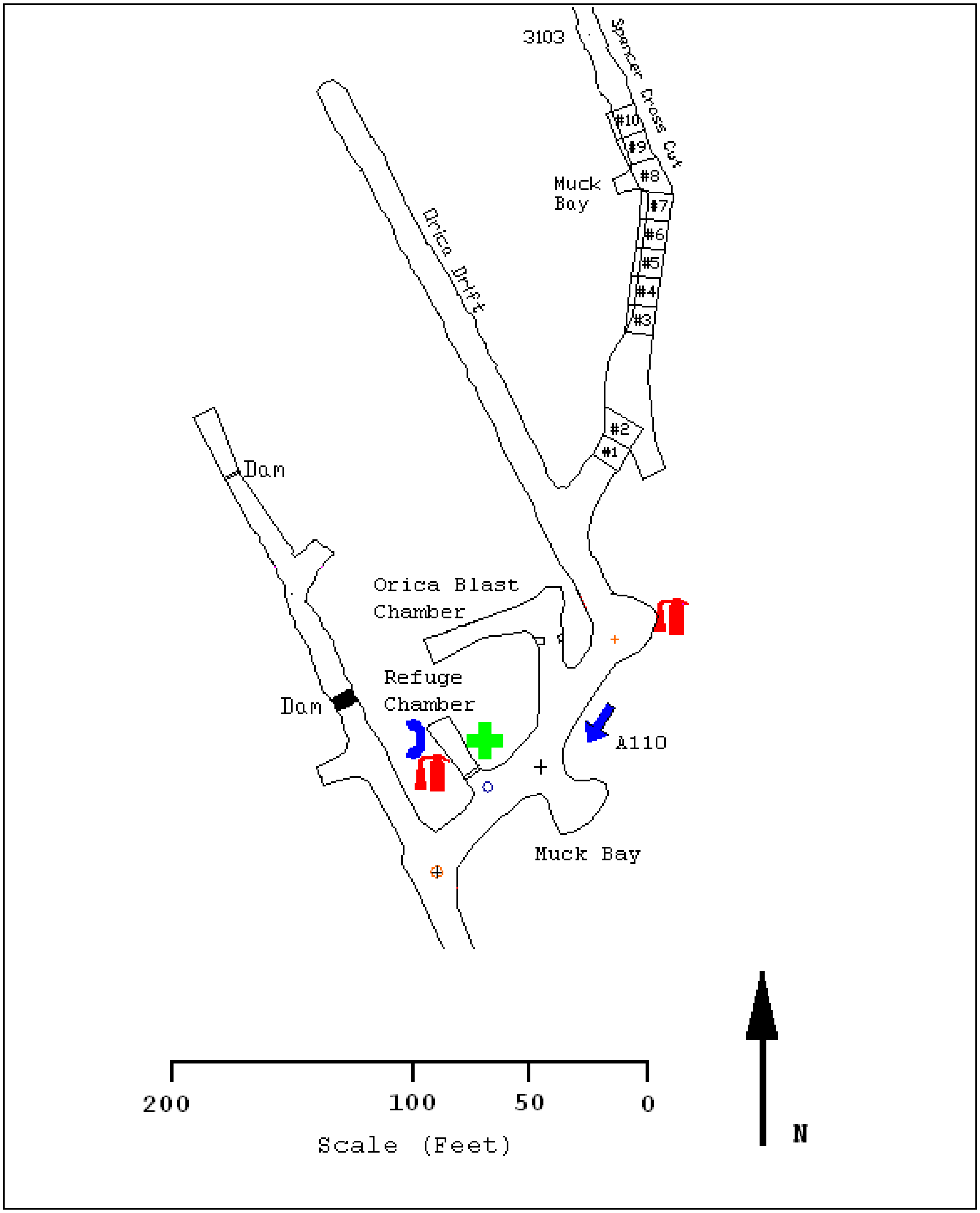

Figure B.2 Location of Experiment Numbers 1 - 10

APPENDIX C

Wheatley Quintuplex Pump Curve Data

Measurements were taken on June 11, 2006 at the Edgar Mine using nozzles of various diameters to determine the flow rate versus pressure curve of the rebuilt Wheatley Quintuplex Pump. A nozzle diameter versus pressure curve was also generated from the data.

For each test, the time required to fill a 136-gallon tank was recorded, and the pressure in psi was read using a pressure gauge mounted at the pump. The hose diameter connecting the pump to the nozzle assembly was 3/4 inch, and a total length of 50 feet of hose was used. The actual pressure at the nozzle was not measured.

Table C.1 Data collecteded for pump curve generation

Measured Orifice Diameter (in)	Pressure (psi)	Time Start	Time end	Time	Duration	Flow Rate (gpm)
0.250	450					37.0
0.203	1500	10:23:00	10:27:00	0:04:00	4.00	34.0
0.187	1800	10:40:30	10:44:30	0:04:00	4.00	34.0
0.167	2050	10:57:00	11:01:07	0:04:07	4.12	33.0
0.149	2650	11:14:30	11:18:55	0:04:25	4.42	30.8
0.138	3200	11:30:00	11:34:55	0:04:55	4.92	27.7

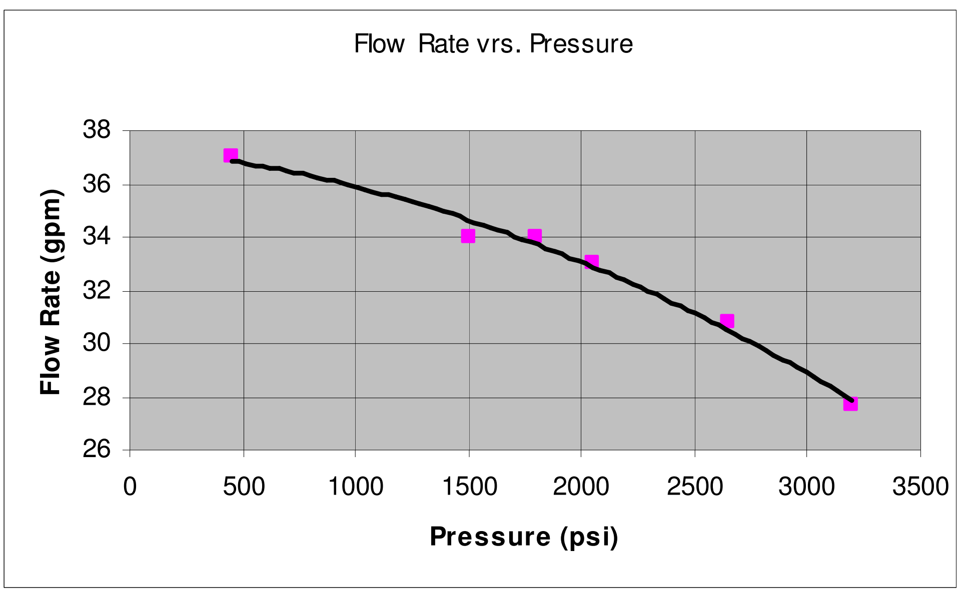

Figure C.1 Flow rate vs. pressure for rebuilt Wheatley pump

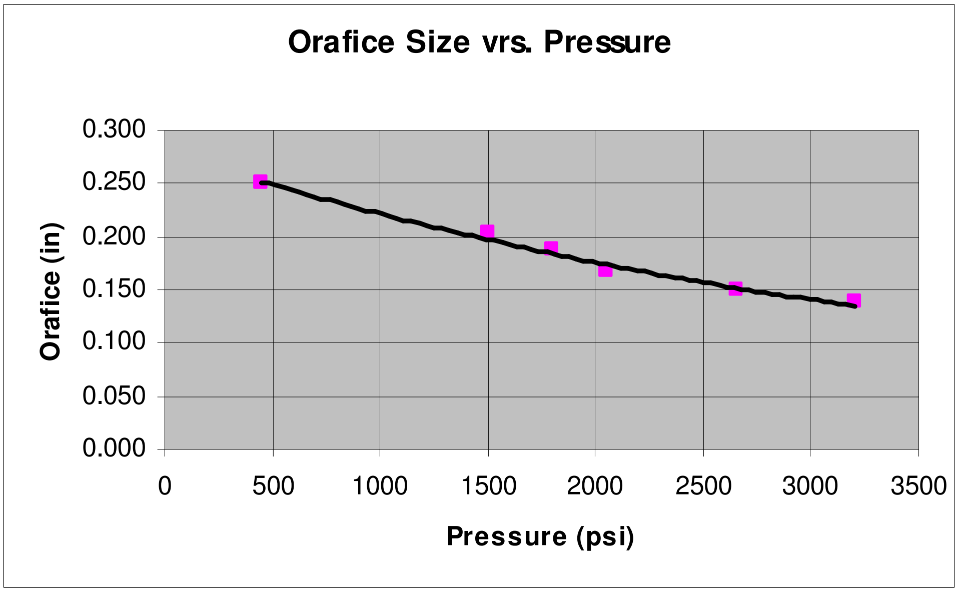

Figure C.2 Orifice size vs. pressure for rebuilt Wheatley pump